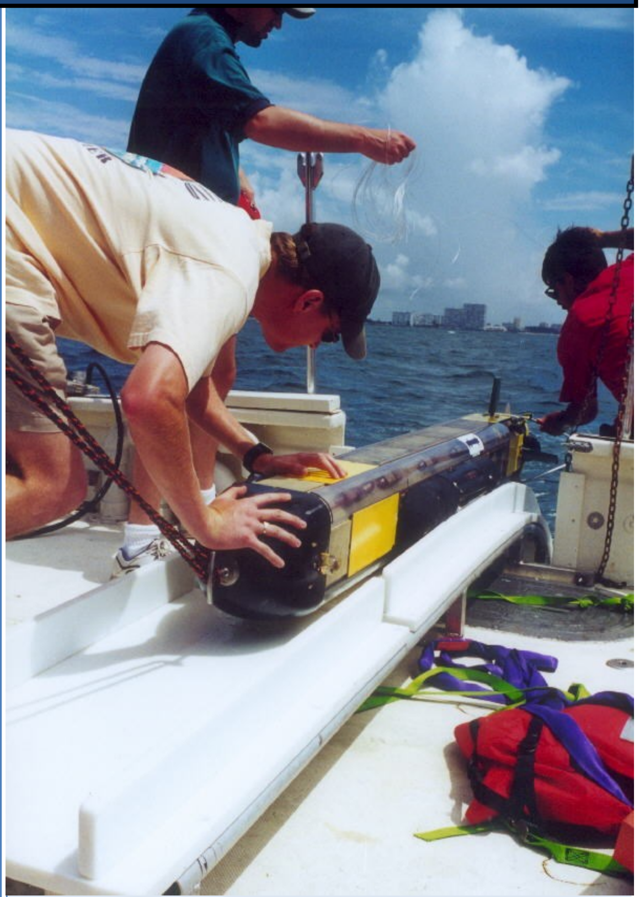
Mid Term Review –
Signal Processing for a Networked Battlespace
30 September 2015



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Scope of Report

We are now at the half way point of the UDRC research programme and this document gives an overview for the Mid-term review panel on the following items requested by EPSRC in their Briefing document (dated 17/8/15). This mid-term review report can be read along with our 2.5 year progress report and the panel are asked to use this second document to find more detailed information if required.

Background to the programme: This can be found in our Introduction, more information can also be located in the Directors Introduction in the 2.5 year progress report as well as on our website, www.mod-udrc.org

Vision and Ambition: This can be found in our section called Vision and Ambition which includes our future research strategy for the remaining 2.5 years.

Research Programme: A high level summary of each work package can be found in the Vision and Ambition section. Our significant research highlights including our most influential publications are included in the Research highlights section of the 2.5 year progress report. A more detailed account of our work can be found in the progress report in the work package updates as well as a complete list of publications found towards the end of the progress report.

Added Value: This can be found in our Leadership and Management section and Impact and Advocacy section, more detailed examples of added value can be found in each work package chapter in the progress report.

Leadership and Management: This can be found in our Leadership and Management section, more information on working practices and people can be found in the Work Package chapters in the progress report.

Impact and Advocacy: This can be found in our Impact and Advocacy section, more information can be found in our progress report in Management, Coordination and Engagement and also our work package chapters under Interactions which explain specific examples in more detail.

Introduction

Research focuses on 6 fundamental areas within the field of Signal Processing for the Networked Battlespace and each research area is led by a senior academic and supported by other academics, research associates and PhD students. The research is divided into the areas below and as the research advances, overlap and synergies are appearing amongst the programmes of work as well as significant interest from industry and the defence sector.

WP 1 Sparse Representation and Compressed Sensing

WP 1.1 Efficient subNyquist sampling schemes

WP 1.2 Compressive imaging with sensor constraints

WP 1.3 Compressed Sensing, beyond imaging

WP 2 Distributed Multi-Sensor Processing

WP 2.1 Fusion and Registration

WP2.2 Distributed Decentralised Detection

WP 3 Unified Detection, Localization, and Classification (DLC) in Complex Environments

WP 3.1 Estimating targets in scenarios with spatio-temporally correlated clutter

WP 3.2 Physical Modelling for DLC

WP 3.3 Man-made object detection

WP 4 Context-driven Behaviour Monitoring & Anomaly Detection

WP 4.1 Detecting anomalous behaviour in audio-video sensor networks

WP 4.2 Mobile vehicle monitoring, resource allocation and situational awareness

WP 5 Estimation Framework for Multi-target Detection/Tracking and Sensor Management

WP 5.1 Hierarchical sensor management for target tracking

WP 5.2 Computationally tractable solutions

WP 5.3 Multi-objective sensor management

WP 6 Efficient Computation of Complex Signal Processing Algorithms

WP 6.1 Efficient parallelization of Sensing Processing

WP 6.2 Implementation of Distributed Signal Processing Algorithms

WP 6.3 Algorithm/computation resource management

Research Programme Highlights

The first year of UDRC established an exciting and challenging research programme with the creation of a team with diverse expertise in the field of signal processing. The second year has built steadily on this and developed world leading**,** focused research in signal processing for defence, addressing critical gaps for defence application. During the period, April 2013 to September 2015 the Edinburgh Consortium have produced 69 papers in total, made up of 1 patent, 14 journal papers, 47 conference papers with a further 7 papers submitted or due to be submitted.

WP1 Sparse Representations and Compressed Sensing

A sub-Nyquist Radar ES framework has been developed which, in a realistic ES simulation setting provided by Thales, outperformed a canonical rapidly swept super heterodyne receiver (RSSR) by up to 20 % true positive detection for a fixed false positive rate.

In collaboration with WP6, fast GPU implemented SAR imaging algorithms based on decimation strategies and parallel processing have been developed providing 330 times speed-up over single core standard back projection.

Proposed autofocus SAR imaging using the sparse nature of dominant targets in scenarios where only partial data is acquired. The proposed integrated autofocus algorithm is 20dB better than post-processing with a traditional phase gradient approach.

A new fast spectral decomposition toolbox has been produced for Raman Spectroscopy based on the signal sparsity and non-negativity. It is capable of separating component fractions down to 5% and can also identify the presence of unknown substances from the spectra. Current run time is approximately 1 second on a single core of a 2.0 GHz Intel Xeon processor.

WP2 Distributed Multi-Sensor Processing

Proposed a cooperative sensor self-registration algorithm for distributed fusion networks. This algorithm allows the platforms to locate themselves in Global Positioning System (GPS) denying environments, based on detections collected from non-cooperative targets and without transmitting these measurements in the network to other sensor platforms.

Developed an online algorithm for simultaneous localisation and tracking in clusters of sensors (e.g., clusters of bearings only sensors) in GPS denying environments. This algorithm is for centralised processing at the cluster head and has a quasi-linear complexity. It features scalability with the number of sensors, whereas the polynomial complexity of the conventional approaches would become prohibitive for several sensors. It is also capable of accounting for additional location information provided by received signal strength measurements at the receiver front-end of the fusion centre.

In collaboration with WP5, we advanced Probability Hypothesis Density (PHD) Filters and Cardinalized Probability Hypothesis Density (CPHD) filtering algorithms which are capable of computing the level of confidence for the estimates of number of targets in arbitrarily selected regions. This quantity has the potential to enable regional information-based decision making in sensor network management.

WP3 Unified Detection, Localization and Classification

A complete theoretical framework for sonar Multiple-Input Multiple-Output (MIMO) systems has been developed. By highlighting the theoretical differences between sonar and radar MIMO, new avenues for the application of MIMO systems for recognition, tracking and imaging over a wide range of underwater acoustic problems have been explored.

A new MIMO formulation for broadband MIMO sonar systems which includes a statistical framework for large MIMO sonar has been developed and have demonstrated that large coherent MIMO systems can provide super-resolution imaging by de-correlating the scatterers present in a single resolution cell. We have also shown that the number of scatterers in a cell can be estimated very accurately and that can lead to automatic target detection and recognition as the majority of objects of interest only have a few important scatterers.

Explored the MIMO design requirement for fully independent MIMO array. Design parameters and their impact on the correlation of the various views offered by MIMO systems have been studied in detail and compared to equivalent Synthetic Aperture Sonar systems. The MIMO system proposed is a coherent one and requires precise positioning of the transmit and receive elements. Autofocus algorithms for auto-calibration of the MIMO array have been developed. As a by-product, we have demonstrated that automatic target depth, speed and orientation estimations can be achieved using well-chosen delays between the transmit signals at each element.

The ability to track moving target using defocused time-reversal algorithm has been presented. To validate our theoretical models, a 3D MIMO physics based simulator was developed. Recently, International trials with DRDC Atlantic and DSTL on novel low and medium frequency systems for Mine Counter Measures (MCM) were organised. In these trails, 3 systems were run together in the same test range were several targets were deployed. The first system was a state of the art SAS system (high frequency), the second system was HWU wideband sonar (medium range frequency) and the last system was the DRDC ex-raise system (very low frequency). A unique dataset spanning an large frequency band was acquired and will be used shortly to analyse the benefits of each system for target detection and recognition.

Single photon counting LIDAR systems offer the possibility of getting data from targets even with a very low photon count and are ideally suited to detect targets in difficult environments (for instance under foliage). We have worked on multispectral LIDAR for the detection of targets casted as an anomaly detection problem. The use of multispectral systems enables the detection of anomalies both in term of discrepancy of the 3D signature but also in terms of the spectral response of the potential target with respect to the surrounding terrain. To date, we are evaluating performance on the detection of several man-made objects and anomalous spectra hidden in a dense clutter of vegetation. As a by-product, our analysis may also allow tree species classification.

WP4 Context Driven Behaviour Monitoring and Anomaly Detection

Novel research on machine learning of target context, looking at social, spatial and temporal aspects, has demonstrated that subtle anomalies enacted by people in surveillance may be detected by the use of “gazing” patterns in the scene (as well as more basic features) which allows for groups and subtle contextual anomalies to be found which cannot be achieved with any other method, to date.

The development of “intentional priors” which aggregate spatial and temporal priors over multiple features. This has unified the “contextual” and “pattern-of-life” into basic target tracking. A novel algorithm for learning target pattern-of-life from Wide Area Motion Imagery (WAMI) is under development, and will form the basis for a new spatio-temporal “intentional prior” and in the Dstl challenge all of the rare and subtle anomalies were found.

In addition to providing contextual cues about expected target behaviour, the algorithm can also identify anomalous targets.

WP5 Estimation Framework for Multi-target Detection/Tracking and Sensor Management

Development of unified estimation framework for detection, tracking, and classification of an unknown number of objects in cluttered environments from heterogeneous sensors, design and implementation of a multi-object filter derived from this framework. Application on a maritime surveillance scenario involving target classification.

Incorporation of sensor management policies to multi-object estimation framework. One solution based on population activity for tracking algorithms derived from Finite Set Statistics framework or novel unified estimation framework. One solution based on information-theoretic decisions for tracking algorithms derived from novel unified framework, but adaptable to traditional track-based approaches.

Exploitation of the novel estimation framework for a space situational awareness scenario with a Doppler radar, in view of the integration of the UK ground-based assets for space surveillance (radars, telescopes, lidars, etc.) in a single estimation algorithm.

Exploitation of the novel estimation framework for sensor calibration in multiple-target detection and tracking scenarios.

WP6 Efficient Computation of Complex Signal Processing Algorithms

The accuracy and reliability of state-of-the-art classifiers on Synthetic Aperture Radar (SAR), Synthetic Aperture Sonar (SAS) and visual datasets have been evaluated which can detect and classify a variety of objects including pedestrians and mine-like shapes. Methods have been investigated for improving reliability, and are able to demonstrate the ability to detect objects belonging to previously unseen classes. This application is able to identify 44% of objects belonging to a previously unseen task and this is important for tasks requiring human operators and high-level decision algorithms which will act based on the results from object detectors.

A pedestrian detector which responds to uncertain images with less confident prediction scores has been produced. This is a significant improvement over existing state-of-the-art detectors, which are often extremely overconfident in the presence of uncertain samples. A Graphics Processing Unit (GPU) implementation of a Gaussian Processes Classifier was written and performed favourably when compared to existing approaches. GPU-accelerated implementations of state-of-the-art image formation algorithms for SAR imaging have also been developed.

Computer vision algorithms for distributed anomaly detection and object recognition have been implemented on an Android smartphone. A simulator is being developed to simulate resource constrained smartphone and bandwidth limited environment to develop distributed algorithms based on contexts and priorities. A client-server architecture has been used to investigate uploading images or features from a smartphone to a server for faster processing, and when it is most power-and time-efficient to do so.

A simulator for evaluating distributed localization algorithms has been developed allowing the implementation and testing of the methods for detecting and localizing hostile Radio Frequency (RF) emitters in scenarios with limited processing power and communication bandwidth available. This develops and improves the localization algorithms used on devices running in a mobile ad-hoc network (MANET), with the objective of minimising localization error, power consumption and the volume of data transmitted over a ‘friendly’ distributed network. Preliminary results show a 37% reduction in data transmission compared to centralised localisation at the cost of 10m RMS (100m^2 Mean Squared Error) increase in localisation error.

Leadership & Management

The UDRC has established an effective management structure with formal processes to manage the day to day running of the project, research collaborations and communication. The Edinburgh Consortium is managed by Director, Mike Davies and Deputy Director Yvan Petillot. They meet on a monthly basis along with the Project Manager Janet Forbes to review activities, progress and outputs across the Consortium.

Internal meetings are held quarterly and allow the academics, researchers and the project management team to update on progress, discuss the way forward so ensuring the efficient and effective implementation of the UDRC research. The researchers meet fortnightly to discuss the status of work, collaboration opportunities and future perspectives. These meetings serve as a forum for the researchers to communicate their work and ideas in order to foster collaboration between different work packages. UDRC researchers have also established a journal reading club which will catalyse the interactions further.

During the course of the programme, PhD topics have been identified to help enhance the UDRC research programme. To date all of the 9 proposed studentships have now been filled.

In May this year the researchers and the academics met for an away day activity where each group answered a set of predetermined questions about the research and its desired impact. The outcomes from this activity have fed into the mid-term review process and the future research strategy for the remaining 2.5 years.

Examples of added value within the Edinburgh Consortium include the provision of a 9 month contract to utilise Dr Shaun Kelly's knowledge of fast GPU implemented SAR imaging algorithms to work within the confounds of WP1 and WP6 to produce high calibre work in this area. Using an EPSRC Platform grant we have been able to employ an extra researcher to cover the areas of distributed signal processing for distributed localisation of autonomous systems, MIMO and Synthetic Aperture Sonar, this is especially valuable for expanding the collaborations within WP2 and WP3.

A data repository has been set up to allow for the storage of data, research and software allowing both universities to work together more efficiently. This area allows for the storage and sharing of large amounts of data and algorithms. A wiki area has also been established. This ensures that all important documents relating to UDRC are easily accessible to the team. Documents in this area include presentations, minutes, instructions and templates.

The Strategic Advisory Group (SAG)

As well as the academic management structure, a Strategic Advisory Group (SAG) was set up at the beginning of the project and terms of reference were developed and agreed. The SAG meet every 6 months; the purpose of this group is to provide critical feedback to the consortium on the research it is performing, advise on potential opportunities and to ensure that the research outputs continue to target areas of national and international importance for the defence sector.

The value of the research is judged with regard to MoD priorities, academic world class quality, relationship with other MoD and UK industrial research and the relevance to the needs of the UK defence industry (including practicality of implementation). The SAG also provides feedback on the engagement activities, judging them on the facilitation of stronger links between signal processing research groups, defence industries and the provision to the government defence sector. The members also advise on the development of a single Community of Practise for defence-related signal processing research, spanning academia, industry and government. All SAG members have signed a Supporter Engagement Agreement which allows the industrial organisations, our independent external expert and the funders to support the Project, but to safeguard any confidential or sensitive information arising from or exchanged during the course of the engagement.

SAG Membership

Angus Johnson, Thales UK
Andrew Baird, Dstl
Alfred Hero, University of Michigan
Jonathan Evans, SeeByte Ltd
Dean Thomas, Roke Manor Ltd
Jordi Barr, Dstl
Stephen Clark, Selex ES
Malcolm MacLeod, QinetiQ
Nigel Birch, EPSRC
Paul Thomas, Dstl
Henry White, BAE Systems
Ros Knowles, Dstl

This year we have asked for our Strategic Advisory Group to comment more formally on the research. These comments are very important and the results from this review coupled with the away day discussion will lead to the development of our strategy for the remaining programme of research.

The membership of the SAG has changed since the commencement of the Programme. This is a positive restructure as it enables interaction with other contacts that have a different knowledge base and experience and this will ultimately improve the programme with fresh ideas and advice.

Research Team

The Edinburgh Consortium comprises signal processing experts from the University of Edinburgh and Heriot-Watt University and is one of the two Consortia funded for phase 2 of the UDRC.

The Joint Research Institute of Signal and Image Processing is a partnership between these two universities and incorporates the activities of:

- Institute for Digital Communications (IDCOM), University of Edinburgh.
- The Research Institute of Signals, Sensors and Systems (ISSS), Heriot-Watt University.

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Impact and Advocacy

Communication and dissemination are key to the success of the UDRC and the Edinburgh Consortium have set up a detailed communication and engagement strategy which aims to create a two way communication channel between UDRC and interested stakeholders.

Edinburgh's communication strategy is split in two parts; the coordination part which is the development of the events and engagement on behalf of LSSC and Edinburgh Consortiums. Events are a key part in the success of the UDRC and as part of the coordination process a number of meetings, workshops and events have been organised and managed by Edinburgh Consortium in partnership with LSSC Consortium and Dstl. These include the delivery of an annual conference and a summer school as well as two themed meetings a year. In addition we support the development of an annual Dstl Knowledge Transfer Meeting and manage ad-hoc meetings which come out of specific work packages or interest groups such as the Advanced Processing for Sonar meeting with Dstl and Thales, Signal Processing for Large Sonar Arrays workshop with Dstl and industry partners, the Tracking Framework meeting with Dstl and a number of industrial partners and the Dstl Academic workshop. We also manage communications to a database of over 800 people through email updates and newsletters, manage a LinkedIn account for the UDRC Group and have developed and actively manage two websites. We have written articles about the UDRC that were published online in the Glasgow Herald, Forbes magazine, MOD Defence Bulletin and the Financial Times.

We work closely with the Knowledge Transfer Network (Electronics, Sensors and Photonics) and the Centre of Excellence for Sensor and Imaging Systems (CENSIS) and have attended events to increase the UDRC profile and disseminate research activities. We have also worked closely with a University of Edinburgh initiative, the Sensors and Signal Processing Aim Day which invites industry to submit research questions and meetings are set up to develop solutions with industry.

The second part of the communication strategy is closely linked to our exploitation goals within the Edinburgh Consortium. We have set up a Commercialisation group to manage exploitation activity. This is led by Dr John Jeffrey, the Business Development Manager for the University of Edinburgh with support from Mr Robert Goodfellow, Head of Technology Transfer for Heriot-Watt University. To fully explore such possibilities, potential alternative markets for the developed signal processing technologies will be investigated. The group meet 6 monthly to agree the route to impact for each new technology emerging from the UDRC project. Whilst the commercial potential in sensing systems is a key output from the successful completion of this project, we also believe that the research undertaken will have wider benefits for use in non-military areas, for example; robotics, medicine, remote sensing and disaster response. We plan to organise a cross-sector industrial day in 2016 to address this.

Working closely with Dstl is an essential part of the project's exploitation. Each of the work packages have been given Dstl exploitation points of contact and meetings are set up regularly to allow a two way exchange of information to ensure that research is versatile and adaptable in order to meet the requirements of defence and industry. The Dstl Project Team review the outputs and progress through an ongoing relationship with Edinburgh's Programme Director and Manager and through regular reporting and SAG meetings. Also, both the Edinburgh and LSSC Consortium Directors meet at Dstl for a 6 monthly Governance meeting to review the project. An enabling contract between Dstl, University of Edinburgh and Heriot-Watt University has been set up. This has led to 4 finalised contracts with 4 in discussion on fields of interest including tracking methods for space situational awareness, signal processing for large sonar arrays and a recently distributed invitation to bid for a Dstl project on a modelling task for a Mobile Ad-Hoc Sensor Network.

As well as UK defence, we have taken part in international trials in Halifax, Canada. This has come out of our work within WP3 and is a collaboration with DRDC Atlantic and Dstl on experiments imaging the same target field using a Low Frequency SAS (8-40 KHz), our Wideband Sonar and a high frequency SAS (250 KHz+-60 KHz). This has provided a unique dataset to explore target detection and classification strategies using wideband systems.

The UDRC themed meetings that we organise every 6 months have been another way to incorporate added value within the project. These meetings always present two Dstl challenges and attendees from the meeting are asked to submit solutions. Edinburgh has successfully developed solutions and has been awarded further work, for example, extra work on Temporal Anomaly Detection and on a sparse regularised model for Raman spectral analysis have been requested by Dstl.

Working with industrial partners has proved to be successful, resulting in jointly funded PhD studentships. We now have 3 CASE studentships; SAR 3D imaging with Selex ES, adaptive waveform design in a crowded spectrum with Selex ES and wide area surveillance with Roke Manor Research. We are working with Seebyte and BAE Systems on Maritime Collaborative Enterprise (MarCE) Task on Assured Detection and Classification of Mines. QinetiQ have offered to assist us with SAR data interpretation in our recent joint-proposal to the Centre for Defence Enterprise (CDE) themed competition: “What's inside that building?” We are meeting with Thales to discuss future opportunities for our subNyquist ES technology. One of our academics is now seconded to Selex ES for part of the week to facilitate research and exploitation opportunities.

Since the grant started, the Edinburgh Consortium has directly funded 6 PhDs to research subjects aligned to the 6 work packages. We also have over 12 associated PhDs, supervised by Edinburgh Consortium who link in with the subject of signal processing for a networked battlespace.

Vision and Ambition

Vision

Our ambition is to develop new signal processing algorithms and methodologies which will enhance and build upon existing sensor technologies in defence, and will provide integrated multi-sensor systems while simultaneously limiting the data overload and maximising data relevance within the network through data acquisition, processing and sensor management.

Key objectives

- Develop novel signal acquisition and processing techniques to address the needs of the MOD.
- Develop the theory of networked sensor integration to enable future competitive advantage.
- Apply methods in real and simulated data demonstrating effectiveness of the algorithms.

Developing our Future Strategy

The process of developing our future strategy for the next 2.5 years has involved a number of steps. Firstly, feedback from our Strategic Advisory Group started the process. We asked them to comment on our research to date to facilitate our understanding as to whether the research was going in the right direction, if it had a viable application domain and if there was an interest in exploitation.

This feedback was crucial for the development of our strategy and following this, 2 team away days were organised, one for the research associates and the PhD students and one for the academics. They each met and answered a series of questions about the research which allowed them to evaluate the research successes. These questions promoted discussion between the different work packages, the results of which helped develop and agree the resulting plan and strategy.

In the original proposal we incorporated a wider breadth of research which has been successful in developing a baseline for the more defined research areas which we have suggested in this strategy. The reasons are that in collaboration with industry and defence, we have been able to comprehend what research can be applied more effectively to the networked battlespace and how this will give impact and exploitation opportunities in the latter half of the project.

Priorities

As well as publications in high profile journals and conferences, our priority for the next 2.5 years is to explore how our research can be beneficial to Dstl and industry through technology transfer and exploitation, developing demonstrators, enabling contracts and consultancy. We aim to:

- Utilise the research knowledge built from the first half of the project to identify and develop the specific research areas that have shown promise in terms of exploitation and impact
- Investigate with industry partners ways of developing the research in partnership
- Continue to work closely with Dstl Exploitation Points of Contact to ensure that research is addressing real challenges and has exploitation potential
- Collaborate internally across WPs to ensure that, where possible, linked research can be leveraged to give greater impact

These priorities are explained in detail below for each of the work packages within the context of the original objectives.

WP1 Sparse Representations and Compressed Sensing

Introduction

Sparse signal modelling is the main drive of this work package. Such a signal model allows us to overcome some of the conventional limitations in sensing and imaging applications. The main focus is on radio frequency (RF) signals, while other types of signals, like spectral and sonar signals have been or will be considered. This WP has been divided to three tasks; Sub-Nyquist sampling (WP1.1); imaging with sensor constraints (WP1.2); and beyond imaging (WP1.3). In WP1.1 we investigated the problem of wideband sub-Nyquist Radar Electronic Surveillance (ES), in which the conventional sampling techniques are simply not practical, i.e. expensive, large and power hungry. We developed a new Low Complexity Multicoset sampling (LoCoMC) technique, inspired by compressed sensing technology, which can overcome these obstacles. The new technique has been tested with some realistic simulations with encouraging results [1-3]. This task is now formally completed although we are still in discussions with industry regarding potential technology transfer. WP1.2 has focused on exploiting sparsity for Synthetic Aperture Radar (SAR). We have specifically looked at the phase ambiguity of the radar returned pulses in SAR and proposed a novel sparsity based technique which compensates for these errors (autofocus) [4]. This research continues work from UDRC phase 1 and will be an essential element for volumetric SAR imaging going forward. WP1.3 has focused on detection, identification and classification. In SAR we are investigating the problem of SAR Ground Moving Target Indication (GMTI), where the moving targets are sparse within the scene [5]. Moving objects incur blurring and misplacement in the SAR image and such artefacts have to be compensated for to find the correct location and velocity of the objects. Sparse approximation has also been used for spectral decomposition, given a library of reference spectra. The immediate application of such a method is for a handheld Raman spectroscopy device [6]. The aim is to develop a fast algorithm [7] which can simultaneously identify the mixture and contribution of each element. These algorithms are due to be ported to a Snowy Range Instruments handheld spectrometer (subject to contract).

Future Plans

The next stage will focus on WP1.2 and WP1.3. The main focus of our work will be on Low-Frequency (LF), 3D and dynamic SAR, where sparse approximation and compressed sensing can play a key role. Dstl and industry have identified volumetric SAR imaging as a key research priority, extending beyond conventional approaches, e.g. interferometric and tomographic, and solving the true 3D reconstruction of the scene, using advanced fast reconstruction techniques from limited trajectories. The issue of out-of-focus data becomes more challenging, when the recorded pulses have to be combined for 3D SAR. We have already started to investigate the problem of phase error correction, as well as other issues in SAR imaging, for example defocusing, moving objects and non-calibrated equipment, which can be interpreted as a phase correction problem. This will be particularly interesting for LF imaging where the capability to view through foliage and into buildings is of interest. We have received the Bright Sapphire LF SAR trials data from Dstl and are currently in discussions with QinetiQ on its use for LF 3D imaging. In cross collaboration work, we also plan to explore the possibilities of extending these ideas to Synthetic Aperture Sonar (with WP3). We also plan to prioritise video SAR processing (PhD student), including the development of algorithms for image sequence generation and the incorporation of dynamic imaging such as GMTI within the image sequence.

We will continue our work on sparse spectral decomposition. The next phase will involve porting our current technology onto a portable ARM device. We also plan to investigate the possibility of incorporating task specific extensions (e.g. if chemical A is present then check for chemical B). We would also like to extend the idea to more general hyperspectral image decomposition.

Expected Impacts

Edinburgh's fast SAR imaging techniques provide efficient imaging for LF SAR and an evaluation licence for the software has been provided to SEA Ltd to evaluate its performance on Bright Sapphire LF SAR data. We were also commissioned by SEA to write a white paper on the potential of CS techniques in 3D SAR. Dstl has indicated that 3D SAR imaging is very much a priority research topic and in particular when combined with LF SAR offers the potential for imaging into buildings. Following discussions with QinetiQ we have just submitted a CDE proposal on the exploitation of LF SAR for looking inside buildings at stand-off (CDE Call: “What’s inside that building?”). This will provide a proof-of-principle demonstrator for SAR imaging into buildings using the Bright Sapphire data with assistance from QinetiQ.

Our current research in Raman Spectral Decomposition, an extension of one of Dstl challenges through the enabling contract, has provided good results and Dstl have subsequently contracted us to port the fast spectral decomposition algorithms onto Snowy Range Instruments handheld spectrometer to prototype this technology.

While the research on sub-Nyquist Radar ES from WP 1.1 has been completed, we have further discussions planned with Thales on how best to exploit this technology.

WP2 Distributed Multi-Sensor Processing

Introduction

The objective of this work package is to address challenges in detecting and tracking targets with networked sensors of various modalities. These challenges include maintaining a scalable, robust operation and a flexible structure in a changing environment while complying with resource limitations. From the beginning we have investigated distributed solutions which avoid a single designated processing centre. As the work has evolved we have widened our remit to address challenges in providing scalable solutions in centralised settings that facilitate multi-sensor exploitation.

WP2 has two main areas of investigation: WP2.1 Fusion and Registration aimed to develop scalable and efficient methods for registration/calibration of sensors in order to facilitate multi-sensor fusion, which was completed at the end of 2014 with the submission of a journal paper [8]. This article details a scalable and fully decentralised algorithm that finds respective calibration parameters of multiple sensors while they are tracking targets. WP2.2 Distributed/Decentralised Detection focuses on the generation of these detections and aims to address challenges in detecting low SNR and/or manoeuvring objects together with accuracy and complexity trade-offs in designing detection algorithms for networks of sensors.

Future Plans

We have been working in the context of WP2.2 since early 2015 with a focus on detection in a multiple radar network. We are building upon the outcomes of the research performed by associated PhD student Bogomil Shtarkalev [9, 10, 11]. Our perspective is to adopt space-time adaptive processing (STAP) to cover multiple multi-static sensors receiving reflections from an unknown number of multiple targets and noise. The main difficulty stems from the fact that the data collected in the network are stored in different locations. In order to overcome this challenge, we aim to identify "sufficient communication for distributed detection" (SCDD) in coherent, non-coherent and binary integration (or, detection fusion) of sensor nodes and investigate trade-offs between communications and the detection performance with respect to a reference, fully connected system.

Three research themes have been identified for 2016. One research direction considers the issue of joint estimation of the spatial noise distribution and target detection in order to facilitate more efficient use of the data by propagating a target model over time. A second direction, which will follow the first one aims at devising methods for efficiently communicating and combining likelihoods for "target plus interference" and "interference alone" within the network. This can be viewed as reminiscent of the big data domain in which solutions draw from theoretical frameworks for approximate probabilistic models and inference and computational statistics. A third direction aims at developing models that capture the spatio-temporal dependencies for estimation of the clutter plus noise distribution. In addition, a PhD project has started in 2015 and will be investigating maintenance of coherence across parts of a network using the target trajectory as a reference.

Expected Impacts

WP2.1 will be kept open and discussions are ongoing with Dstl on the possible applications of the developed algorithms [8, 12, 13] on real or simulated maritime multi-sensor data. These algorithms are capable of efficiently calibrating several sensors in a surveillance scenario, while they simultaneously track multiple targets using detections with false alarms. The anticipated impact is that the scalability feature of our framework can facilitate simultaneous multi-sensor calibration and multi-target tracking in this domain.

The key enabler of the decentralised calibration approach is the concept of "node-wise separable parameter likelihood" we developed in WP2.1. This concept has the potential to lead development of efficient algorithms for a variety of problems in multi-sensor fusion including distributed track assignment. It can also be demonstrated in networks of different modalities such as camera networks.

WP2.2 develops efficient detection algorithms motivated by networked radars. Our reference joint estimation framework is anticipated to be capable of addressing the challenge of Doppler processing across multiple radars. It will act as a guide to the achievable performance as the associated SCDD, however, the associated computational complexity would be exacerbated due to having more than one sensor and target. Building upon this approach, we will develop detection algorithms which feature efficient communication and computations and will be demonstrated over data obtained from DSTL. This data will possibly consist of simulated radar network data in an air defence scenario. In addition, Selex also maintains an interest in our research outcomes.

Our work extending 2016 will address processing challenges in multi-static networks and this is of interest to the defence industry and Dstl. We hope to extend the research to the sonar modality so that our algorithms can address the signal processing challenges in sonobuoy networks.

WP3 Unified Detection, Localization and Classification in Complex Environments

Introduction

The original aim of WP3 was to develop a unified framework for target detection, localization and classification in complex environments. We have successfully addressed the objectives stated in the WP proposal and completed WP 3.1 Estimating targets in scenarios with spatio-temporally correlated clutter and WP 3.2 Physical Modelling for Detection Localization and Classification (DLC).

The team has so far focused on Sonar and LiDAR modalities, utilising the investigator's areas of expertise and where data was readily available. This is likely to continue. Under WP3.1, Jose Franco (PhD student) has developed and evaluated new tracking algorithms for target tracking in complex maritime environments and implemented an accelerated version of the tracker as planned. Under WP3.2, new simulation tools for acoustic propagation in the presence of multipath and new MIMO Sonar models to improve detection and imaging capabilities have been developed [14]. Novel waveforms that can be used to make better use of the available bandwidth have also been proposed [15]. Puneet Chabbra (PhD Student) has developed new techniques to perform detection of anomalies in multispectral LiDAR [16] with the potential to detect targets hidden under a tree canopy from an aerial platform.

Future Plans

Given the prevalence of tracking across a number of work-packages, WP5 will focus on estimation, localization and tracking and WP3 will continue to focus on detection and classification in Sonar and LiDAR.

WP3.3 is dedicated to man-made object detection and will be addressed in the next phase of the work, targeting detection and classification of targets in difficult environments with a greater focus on anomaly detection and clutter rejection. We will try to develop theory and algorithms working across the wideband sonar and multispectral LIDAR modalities wherever possible.

On the Sonar side, we will explore adaptive waveforms in Synthetic Aperture Sonar (SAS) for faster and improved resolution imaging. Wideband Sonar systems offer the potential to reduce the importance of clutter by differentiating objects based on material rather than shape. We will explore its potential added benefits using data acquired during recent joint experiments with the Defense Research and Development Canada (DRDC) organisation where joint SAS, Wideband and low frequency data was gathered on the same targets. We will continue our work on MIMO Sonar with greater focus on ASW applications where a multi-static approach offers clear potential benefits. This will be done in collaboration with work package 5 (estimation and tracking).

For LiDAR, we will continue the work on multispectral approaches for target detection in complex environments. Building on previous work, we want to develop a unified approach to define the nature of anomalies in both the aerial and maritime surveillance domains. We would like to investigate whether there are notable similarities between the two domains with regards to the signal representation as a time/depth series of spectra, and if so, to what extent such a unified approach applies. This can be done in simulation, and we would hope to get real data in future to verify those results.

The specific aim of the work on anomaly detection in full waveform multi-spectral LiDAR (FW-MSL) is to learn local-patterns of co-occurring echoes characterised by their measured spectra. A deviation from such patterns defines an abnormal event in a forest/tree depth profile. To date, we are evaluating performance on the detection of several man-made objects and anomalous spectra hidden in a dense clutter of vegetation. As a by-product, our analysis may also allow tree species classification. With regard to the recognition of man-made (and possibly other!) targets from spectrally marked point clouds, there has been some preliminary work on using spatial signatures (e.g. spin images) to characterise whole objects and local features on whole objects. This has only used shape data to date, and there is a long tradition of this. In the second phase of Puneet Chhabra's PhD, the focus will be on how to represent and identify such targets in high clutter, by associating 3D points with their associated spectral signature.

Expected Impacts

Underwater Mine Counter Measures (MCM) will increasingly rely on using small autonomous underwater vehicles to perform the detection and identification of potential threats. These vehicles will be projected ahead of the fleet and can be deployed from vessels of opportunities, reducing the need for dedicated MCM ships. However, these systems will only be effective if they can operate in a wide spectrum of environments and increase the tempo of operations. To date the technology based on high resolution imaging sonars has proven its worth in simple uncluttered environments. In more complex ones, imaging alone is not sufficient and wideband systems offer the potential to reduce the importance of clutter. This could be achieved by complementing imaging systems with a dedicated wideband sonar or by trying to exploit the existing bandwidth of SAS systems to perform more advanced spectral processing, both of which will be addressed in this work. MIMO Sonar has real potential in known environments such as Port and Harbour surveillance to detect intrusions of divers or underwater vehicles and change detection on the seabed. Finally it can also be used for ASW using active systems where multi-static systems offer real advantages in terms of detection of ever quieter submarines. By using orthogonal waveforms, the tracking of these fast moving targets will be improved.

Full waveform LiDAR analysis combined with multi-spectral signatures has the potential to better isolate and characterize targets heavily camouflaged in marine and land (from the air) environments. In particular, the ability to associate measured (x, y, z) and spectral data with range (e.g. to look only at spectral returns at a given distance) is a significant advantage over passive hyperspectral imaging. The cost of LiDAR in general has dropped dramatically (consider, for example, their distance measurement capability on a golf course), and companies like Optech and Riegl are now deploying 3-wavelength LiDAR for aerial survey because they recognise the need to identify the forest floor from the canopy (https://madmimi.com/s/8507f5?o=tm) in a forested environment (not unlike a target under trees). It is also possible that full waveform multi-spectral LiDAR processing may have applications in plume detection and tracking, as this may be analogous to previous works on similar problems in monitoring fire propagation in forested environments. We await further discussion with Dstl on potential exploitation of LiDAR technology and processing.

We are working in collaboration with SeeByte Ltd for MCM and this would provide a natural route for exploitation. Hydrason, a spin out of Heriot-Watt University, may also be interested in exploiting some of the wideband Sonar work. Thales is also interested in our work in LiDAR and Sonar. We expect that the work could be taken forward using CDEs in collaboration with these companies or under the MARCE and ASUR programmes.

WP4 Contextual Driven Behaviour Monitoring and Anomaly Detection

Introduction

In WP4 we have been researching pattern-of-life modelling and developing efficient algorithms for making predictions about future actions/behaviours based on extended pattern-of-life models. Having good representations of normal and complex behaviour allows the machine to automatically achieve anomaly detection on large datasets which is a key problem in security and defence in many domains (AIS, WAMI, CCTV etc.). We have shown strong results on wide area motion imagery by detecting rare and subtle anomalies and contributed to Dstl challenges in WAMI and TAD, leading to follow-on work. Our novel approach is based on efficient clustering to achieve Pattern of Life (POL) modelling and hence anomaly detection by using advanced deep machine learning algorithms to extract very subtle cues from visual (and other) data sources. We have unified audio-video sources by signal fusion in a tracking context and shown state-of-the-art results for speaker identification in surveillance data. We have been addressing situational awareness from a mobile platform and resource allocation in collaboration with WP6 and associated PhD students at Thales and Roke Manor.

Future Plans

Pattern of life analysis of large datasets (WP4.1) has proved to be an important topic that we will continue to research for the remaining months of UDRC. Prior state-of-the-art in visual surveillance is limited to close range targets, while techniques developed for AIS broadcasts (e.g. [22]) are too coarse for complex urban terrain. Existing algorithms are therefore unable to operate effectively on large-scale streaming data such as wide area motion imagery. Current work is on development of algorithmic techniques for trajectory clustering and divergence detection [23]. This is augmented with on-line Kernel density estimation and compression to provide an on-line adaptive algorithm for learning spatio-temporal context in large datasets. In WP4.1 our algorithms for learning spatial pattern of life and anomaly detection have been applied to wide area motion imagery provided by Dstl and to new data gathered by ourselves and annotated with anomaly 'ground truth'. To complement this evaluation, performance against benchmark datasets [24, 25] is underway [26]. The multi-dimensional clustering algorithms WP4.1 have been developing have so far been applied to 2-dimensional signals representing person and road vehicle trajectories. However, it is clear that these are not the only signals for which anomaly detection capabilities are required. We thus seek to develop a generic signal clustering method while still maintaining the ability to achieve on-line anomaly detection in multi-dimensional time-series data. Suitable time-series will be identified in discussions with Dstl and could include signals of the nature of the temporal anomaly detection challenge, as well as richer signals such as AIS ship broadcasts. In the latter, we would seek to learn and exploit the utility of associated metadata (e.g. AIS contains source, destination, and identity i.e. "soft" data). We would aim to do this over large datasets by cleverly optimising computation by e.g. parallelisation or GPU coding.

Visual feature extraction is important in certain domains as it provides very strong priors for input to tracking and hence anomaly detection algorithms in our intentional tracking work [17, 18, 19]. In future work associated PhDs will work on the deep-learning of such visual features from RGB and IR camera data and potentially the polarimetric signatures derived from such data. This would facilitate cross-work-package development as our PhD students are working on related aspects of the networked surveillance problem - see planned collaborations below. Closer integration between POL learning, anomaly detection and multi-object tracking is proposed to develop a more unified framework and to develop behaviour based tracking with modern, multi object target trackers. This has the potential to reduce tracker complexity by reducing the search space, and enables spatio-temporal target density modelling and anomaly detection. In [17] and [18] we showed that an 'intentional prior', which is some prior derived from the signal being tracked, can be integrated into a Kalman Filter to improve tracker performance. A challenging progression of this work is to integrate pattern of life models into modern multi-object tracking methods and thus achieve anomaly detection in a more unified fashion over wider areas in "real-time". This integration will provide a means of leveraging learnt spatio-temporal context within the underlying probabilistic framework, as well as providing target-density estimates as a new feature that can be modelled. This work will involve collaboration with WP5 and the trackers under consideration are the Probability Hypothesis Density (PHD) filter [27], Hypothesised and Independent Stochastic Populations (HISP) filter [28], and Distinguishable and Independent Stochastic Populations (DISP) filter [29].

Expected Impacts

A major route to impact for our research efforts is collaboration with our industrial partners, Roke Manor, QinetiQ and Thales. Wide area motion imagery (WAMI) is increasingly captured as unmanned aerial vehicles are deployed on the battlefield, for border security and for civilian peace keeping. However, these systems can only be effective in a pro-active role if suitable techniques are available to provide salient information in a timely manner. To date, algorithms for pattern of life learning and anomaly detections have tended to focus on small-scale visual surveillance problems. Such problems generally constrain the number of targets, state-space, and duration of monitoring and do not adapt well to long-stare airborne surveillance operations. In the work outlined above we will be specifically targeting sequential, online learning and detection from large streaming datasets.

We expect further impact through the production of tracking demonstrators showcasing our work on contextual/feature based tracking. Learning low-level visual features through deep learning will form a major component of work by associated PhD Alessandro Borgia, while pattern-of-life models provide higher-level features indicating expected target movement. In both cases these features can be provided back to the low-level tracking process to improve data association and prediction performance.

WP5 Estimation Framework for Multi-target Detection/Tracking and Sensor Management

Introduction

The initial objective of this work package was to develop an estimation framework with the principled incorporation of sensor management techniques in order to solve estimation problems, most notably multi-target joint detection/tracking scenarios, with limited sensor resources.

The core developments have focused on the development of an unified estimation framework for stochastic populations, [31] that allows for the principled construction of fully probabilistic solutions with abilities beyond the joint detection and tracking multiple targets covered by traditional solutions, such as the production of regional statistics to estimate target activity [33] and the ability to calibrate the sensors in conjunction with target detection/tracking. A multi-target detection/tracking algorithm [32] has been designed and implemented from this novel framework, and successfully applied to a challenging scenario within the context of space situational awareness [39]. The development of statistical tools for the estimation of the target regional activity [33], compatible with any filter from the novel unified estimation framework [31] and exploitable in the context of sensor management, was illustrated and analysed in [35] for a PHD filter [34]. An alternative approach to sensor management for multiple-target detection and tracking, based on information-theoretic decisions, has been explored in [37] in the context of closed-loop sensor management scenarios [36]. Though the methodology is a development of the advances in the theoretical framework in multi-object estimation made within the UDRC, the approach can be used within existing track-based infrastructure such as the MHT filter [38] and is thus relevant to current architectures.

Future Plans

Alongside the development of the new estimation framework and the design of the DISP filter [32], we have initiated a fruitful collaboration between academia (Heriot-Watt University, Purdue University), a branch of Dstl engaged in space surveillance activities, and UK ground-based facilities for space surveillance (STFC Chilbolton Observatory, Dstl facilities in New Zealand). A key objective relevant to UK space and security interests is to fuse the information collected from the network of UK ground-based surveillance assets spread all over the Earth and develop this into a coherent picture of the objects (satellites, man-made or natural debris) orbiting around Earth. These sensing assets can be coordinated and will cue the sensors for specific surveillance missions in order to maintain an up-to-date catalogue of orbiting objects. Significant progress has been made on the development of the multi-target detection/tracking algorithm for simulated orbital targets through the DISP filter, and on the exploitation on real data collected from radar and telescope facilities. In light of this collaboration that has attracted significant interest from both academia and industry, and provides a practical challenge driving the development of novel solutions within the thematic challenges of WP5, we propose to set the coordination of the network of UK surveillance assets to produce a unified estimation framework for the space situational awareness problem as the main challenge that will motivate the future developments of WP5.

Another axis of development lies in the exploitation of the core results in sensor management scenarios for ground surveillance relevant to industry/Dstl. Since the two statistical tools developed so far have direct relevance for sensor management and are naturally designed for filtering solution derived from the novel estimation framework for stochastic populations [31], we will implement them and exploit them in a multi-target scenario exploiting either the DISP filter [32], or the computationally lighter filter for Hypothesised and Independent Stochastic Populations (HISP) [28]. Relevant sensor management scenarios in which the information acquired on specific individuals (e.g. ``tracks'') or in specific regions is valued by the operator in a hierarchical manner, and where additional costs are incurred for sensing actions (e.g. the exploitation of a sensor now will prevent its exploitation for the following time steps) will be explored through the sensor management solutions designed within WP5, enriched with additional considerations that are not directly focussed on the acquisition of information on targets.

Expected Impacts

The increased involvement of the UK in space surveillance activities has been recently highlighted as a national objective, and the UK Space Agency and Dstl's Space and Strategic Systems group aim at developing a coherent approach for the fusion of the data acquired from the system of heterogeneous ground-based assets maintained by the UK for space surveillance. We will work closely with Dstl's Space and Strategic Systems group to ensure that the unified estimation framework we are developing can handle the variety of sensors maintained by the UK (radars, telescopes, etc.), and can allow for the cueing of multiple sensors for a collaborative surveillance task (for example, follow an identified man-made object with the different UK assets spread across the Earth during on orbital pass). In order to increase the impact of our work, collaborations with the Chilbolton space surveillance research team and other UK ground based sensor facilities will aim at facilitating the integration of our solutions to Dstl's Mission Planner.

The proposed target-driven sensor management policies are developed from a generic estimation framework unifying information fusion problems under a single probabilistic umbrella in a Bayesian paradigm, and further impact can be expected from the integration of costs relevant to sensor exploitation and operational limitations. Typical sensor-based exploration missions on the modern battlefield indeed involve a range of heterogeneous sensors (radar, electro-optic and sonar, etc.) working collaboratively on a single operational objective, but with constraints on power and mobility specific to the nature of each sensing unit.

WP6 Efficient Computation of Complex Signal Processing Algorithms

Introduction

In WP6.1, we have evaluated the complexity, accuracy and reliability of state-of-the-art classifiers on synthetic aperture radar (SAR), synthetic aperture sonar (SAS) [40] and visual datasets [41]. Detectors which respond to uncertain images with less confident prediction scores, have also been designed along with GPU-accelerated algorithm implementations for SAR imaging and Gaussian process classifiers for pedestrian detection [42].

In WP6.2, a simulator for evaluating distributed localization algorithms in sensor networks has been developed. This allows us to test methods for detecting and localizing non-cooperative Radio Frequency (RF) emitters in scenarios where the processing power and communication bandwidth available to the detection network is constrained. The objective of this is to minimise the Cramer-Rao Lower Bound which predicts the estimated target location accuracy of realistic algorithms, while at the same time minimising the power expended processing and transmitting data between nodes in the receiving sensor network.

In this respect, our objectives here differ from (in fact, are orthogonal to) the localisation research carried out as part of WP2. The emphasis in WP2.2 is on distributed detection from transmitted radar returns in a GPS-denied environment as part of a self-calibration problem, while ours is on passive distributed detection under constrained inter-sensor bandwidth.

Future Plans

We plan to build on our existing WP6.2 activities and to start work on WP6.3 on algorithm and computation resource management at the end of 2015, as described in the original proposal. This will focus on multimodal sensor systems which produce high volumes of data. It may not always be appropriate or feasible to fully process all available incoming data on our available compute resources, both for computational (time) reasons, and limitations in Size, Weight and Power. We will investigate approaches for attending to individual sensors or areas of sensors, or re-tasking sensors based on the results of gathered data. This will also exploit methods developed in WP6.2 work for distributed processing and resource management. Saurav Sthapit (PhD student working in WP4 and WP6) will extend his work on image processing algorithms on distributed mobile platform networks towards efficient implementations that reduce energy consumption and maximise network lifetime.

We plan to start WP6.3 at the end of 2015 and will extend its duration from 12 months to cover the remaining period of the UDRC project. There are two reasons for this: we would like to fully develop theoretical analysis and simulations for computation management, and also extend this into practical demonstrations. This will be done in conjunction with the EPSRC Mobotarium project hardware, a Centre of Expertise from Heriot-Watt University and University of Edinburgh which will allow for data collection from multiple sensor types. We also plan to collaborate with the EPSRC Rathlin project based at Heriot-Watt University whose objective is to develop embedded vision for smart camera networks. Our collaboration will involve expressing the components of our resource management algorithms as actors within a dataflow network, once the algorithmic framework in WP6.3 becomes mature.

Expected Impact

We have made the code of the GPU implementations developed in WP6.1 publically available at this URL for the wider research community to use: http://homepages.ed.ac.uk/cblair2

We have evaluated the performance of our uncertainty methods for SAS datasets in conjunction with Seebyte, and SAR datasets in conjunction with the BAE Systems ATC as part of a recent MarCE project. We would like to discuss further applications of this work with both Dstl and other industry partners in the UDRC.

The research results and knowledge gained during WP6.2 on wireless signal localization puts us in a good position to bid for the recent UDRC MASNET call and a proposal has been submitted to Dstl. We plan to demonstrate our algorithms in WP6.2 and WP6.3 using the EPSRC Robotarium hardware platform and in conjunction with the EPSRC Rathlin project tools and platforms. We will make the results available to Dstl and other UDRC companies. We also aim to develop the distributed scene monitoring scenarios being considered by the PhD student Saurav Sthapit into a demonstration for Dstl.

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