University Defence Research Collaboration (UDRC)

Engineering and Physical Sciences Research Council
& Defence Science Technology Laboratory

Loughborough, Surrey, Strathclyde, Cardiff and Newcastle
(LSSCN) Consortium

"Signal Processing Solutions for the Networked Battlespace"

Third Year Progress Report
March 2016

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Contents

Reporting to Sponsors in Year III

The year began by Dstl kindly agreeing that the original three-month reporting cycle could shift to a six-monthly one on the basis of strong progress. Therefore the ninth report was delivered to Dstl in September 2015 and this three-year report is delivered ahead of the 31st March 2016 deadline.

A mid-term review of the operation of the LSSCN consortium was undertaken on 14th October 2015 and various reports were delivered to the panel and the sponsors including a mid-term progress report as part of the process.

The consortium was asked to prepare a further response document in January 2016 to address points raised as part of the mid-term review and this was accepted by the panel and sponsors on 25th February 2016. This process was extremely valuable to the consortium and we expect to benefit considerably in our operation over the next two years from the suggestions. One of which is that our CSG now includes an international, Professor Moeness Amin, Villanova, USA, and two UK independent experts with broad experience in defence signal processing and its applications.

This report will therefore additionally focus upon progress against the on-going sub-tasks defined in our current Gantt chart, primarily over the last six-months, which will be reviewed in our next CSG meeting in Strathclyde 11th-12th April 2016.

One matter of some sadness that should be mentioned is the early retirement of Professor David Parish towards the end of 2015 after several months of compassionate leave. We acknowledge his considerable contribution over the first two-years of our operation and more broadly at Loughborough University. His role and the activity in network anomaly detection is now led by Professor Jonathon Chambers with support from Dr Alex Gong.

We are currently either extending the contracts of the current RAs employed on the project for a further two-years or recruiting replacements. As part of this process we are delighted that Dr Carmine Clemente, who has benefitted greatly from both UDRC I & II, has secured a very prestigious Chancellor's Lectureship at the University of Strathclyde and will therefore switch to an academic role as part of the consortium from 1st April 2016. We are sure he will develop into one of the UK's leaders in radar signal processing and be a considerable asset to Dstl for many years. We wish him every success in his new role.

Technical Highlights for Year III

- L_WP1 (Anomaly Detection) 1) theoretical and experimental verification of "Delta Divergence" as a suitable measure for classifier incongruence; 2) enhancement of cyber intrusion detection through incorporation of domain knowledge; 3) improvement in activity recognition and anomaly detection in heterogeneous spatio-temporal data using temporal and discriminative analysis.

- L_WP2 (Handling Uncertainty and Domain Knowledge) 1) a non-Markov jump hybrid model-based approach to tracking the entire trajectory of a ballistic missile from launch to impact on the ground; 2) use of non-cooperative game theoretic techniques in jointly optimising detection performance and transmission parameters including power and waveforms in distributed radar and establishing the existence and uniqueness of the Nash equilibrium.

- L_WP3(Source Separation and Broadband Beamforming) 1) study sparse array configurations for robust underwater acoustic localisation and tracking. The sparse array technique has the potential to overcome the limitation that the maximum sensor spacing must be half of the wave length, in order to avoid spatial aliasing, allowing us to have arrays with larger apertures whilst having fewer sensors and robustness to sensor failure; 2) designed a new factorisation technique suitable for larger polynomial matrices.

- L_WP4 (MIMO and Distributed Sensing) 1) the first extensive study of the ambiguity function for distributed radar systems; 2) fractional Fourier based waveform for a joint radar-communication system to attain spectral efficiency and meet size, weight and power consumption constraints; 3) Krawtchouk moments for SAR based ATR to better understand the capabilities of the object/vehicle under examination.

- L_WP5 (Efficient Implementation) 1) further in depth analysis of the performance and computational efficiency of the recently devised polynomial eigenvalue decomposition (PEVD) algorithms; 2) growing expertise in DSP, FPGA and GPU platforms.

- Premier journal outputs for example in IEEE Trans. Signal Processing continue to be generated and presentations are being delivered at leading international conferences such as ICASSP and Radar 2016.

Revised Vision Statement for Consortium (After Mid-term Review)

The future battlespace will be a complex environment characterised by known and unknown threats, modern and legacy sensor systems, a congested RF spectrum, and mobile and static forces. Information is key in warfare but future conflicts are likely be characterised by an increased level of complexity in intelligence gathering and analysis. Unless such complexity can be overcome, the effectiveness of critical decision making and operational actions will be reduced.

Legacy, current and future sensor systems will provide ever more data for subsequent analysis hence advances in technology will be essential to ensure that they can be optimally exploited. The outputs of sensors of different modalities, capabilities and locations within the battlespace will need to be combined in multiple ways so that such optimal exploitation can be ensured in a wide variety of operations at all levels of conflict. However, at the same time, the electronic environments in which such conflicts will take place are likely to pose greater problems as the availability of bandwidth becomes ever more restricted.

On the basis of a unique consortium of academic experts from Loughborough, Surrey, Strathclyde, Cardiff and Newcastle Universities, we will provide transformational new signal processing solutions which exploit multi-sensor and multimodal data, whilst retaining bandwidth and computational efficiency, to maximize the UK's defence capabilities and its broader academic and industrial skill-base in signal and data processing. In particular, we believe that networked-enabled distributed sensing might provide new capabilities such as combating stealth. However this potentially increases the complexity of the processing task. This might be mitigated by new signal-separation/beamforming algorithms possibly utilising sparsity concepts. Control of distributed sensors could be costly in terms of network traffic so systems that are able to interact without central control would be preferable. Networking also allows for new types of data to be available such as GIS data in a tracking problem. This could be used to enhance sensor processing but requires a new approach to handling uncertainly. Increased information implies the need for something like anomaly detection in order to reduce operator work load. Finally, in order to protect this new networked-enhanced sensing paradigm, aspects of cyber-security will be important.

Sub-Tasks and Main Research Staff for each Work Package

WPs, PDRAs & PSs	Sub-Tasks
WP1 Anomaly Detection NU-PDRA1*, SU-PDRA4, CU-PDRA8, LU-PS1,	1.1-1 Baseline system (and adaptation to any new datasets, e.g. the Wasabi dataset); 1.2-1 Contextual model inference (and adaptation to any new datasets, e.g. the Wasabi dataset) 1.1-2 Radar SAM mode change detection (and Ballistic missile detection); 1.2-2 Data quality modelling 1.1-3 Discriminative anomaly detection; 1.2-3 Incongruence detection 1.1-4 Fusion of multiple anomaly detectors; 1.2-4 System integration 1.1-5 Adv. anomaly detect. sys. design; 1.2-5 Comp. netwk. anomaly detect.
WP2 Handling Uncertainty LU-PDRA2, LU-PDRA3, LU-PS2	2.1-1 World modelling; 2.2-1 Convex optimization and robust SP 2.1-2 Pooling data sources; 2.2-2 Radar and sensor applications 2.1-3 New adaptive algorithms; 2.2-3 Dynamic modelling of uncertainty 2.1-4 Bayesian inference; 2.2-4 Game theory; 2.1-5 Multiple sensor platforms; 2.2-5 Bayesian games
WP3 Signal Sep. & BF SU-PDRA5, CU-PS7, NU-PS3, SU-PS4, SU-PS5,	3.1-1 Multichan. SS with PEVD; 3.2-1 Sparse recovery and comp. sensing 3.1-2 Low-rank approx. IC in BF; 3.2-2 Adaptive dictionary learning & SS 3.1-3 PM-SVD & Sparse PEVD; 3.2-3 Noise robust T-F masking 3.1-4 Semi-blind SS & domain know.; 3.2-4 Variational Bayesian modelling 3.1-5 Complex applications and evaluations; 3.2-5 Multimodal signals
WP4 MIMO & Distributed Sensing ST-PDRA6, ST-PS6, ST-PS7, ST-PS8	4.1-1 Waveform design for DMRS; 4.2-1 Ballistic missile classification; 4.1-2 Sparsity in DMRS; 4.2-2 DMRS based clutter mitigation; 4.1-3 Pruned OMP; 4.2-3 Information fusion in DMRS; 4.1-4 Complexity reduction; 4.2-4 Advanced ATR for DMRS 4.1-5 Passive DMRS; 4.2-5 Decentralised processing for DMRS
WP5 Efficient Implementation. ST-PDRA7	5.1 Data reduction & distributed processing; 5.2 Hardware realisations
* *PDRA1 was based in Loughborough in the first three years, and then in Newcastle in the final two years.*	

Mid-term Gantt Chart

This will be refined following following the April 2016 CSG Meeting in Strathclyde.

WPs	Sub-Tasks	Year				
		1	2	3	4	5
WP1	1.1-1; 1.2-1					
	1.1-2; 1.2-2					
	1.1-3; 1.2-3					
	1.1-4; 1.2-4					
	1.1-5; 1.2-5					
WP2	2.1-1; 2.2-1					
	2.1-2; 2.2-2					
	2.1-3; 2.2-3					
	2.1-4; 2.2-4					
	2.1-5; 2.2-5					
WP3	3.1-1; 3.2-1					
	3.1-2; 3.2-2					
	3.1-3; 3.2-3					
	3.1-4; 3.2-4					
	3.1-5; 3.2-5					
WP4	4.1-1; 4.2-1					
	4.1-2; 4.2-2					
	4.1-3; 4.2-3					
	4.1-4; 4.2-4					
	4.1-5; 4.2-5					
WP5	5.1; 5.2					

Work-Package Updates

L_WP1 (AD) Automated Statistical Anomaly Detection and Classification in High Dimensions for the Networked Battlespace

1 Staffing

Work Package Leaders: Prof. Josef Kittler (SU), Prof. Jonathon Chambers (LU) and Dr. Yulia Hicks (CU)

Research Associates: Dr. Cemre Zor (SU), Dr. Francisco Aparicio-Navarro (LU),

Dr. Ioannis Kaloskampis (CU)

Affiliated Research Stud. Mr. Pengming Feng (LU), Mr. Mahmud Abdulla Mohammad (CU)

Lead Project Partner: Mr. Angus Johnson (Thales)

Other Project Partners: Mr. John Griffin and Mr. George Matich (Selex-ES)

Dstl contacts: Dr. Gavin Pearson and Dr. Jacob Suresh, Mr. Alasdair Hunter, Mr. Jonathan Crew, Mr. Richard Green

2 Aims and Introduction

Work Package 1 (L_WP1) is concerned with the development of algorithms for automatic detection of anomalies from multidimensional, under-sampled, non-complete datasets and unreliable sources.

The aim is to advance the state of the art in anomaly detection by developing a methodology that is not only effective and computationally efficient, but also provides insight into the nature and statistical characteristics of the detected anomalies in complex high-dimensional network environments, which include interference, communications and video signals and cyber-attacks.

3 Data

Currently we have access to the following data sets:

- Portsmouth harbour ship monitoring data (Thales)
- Tank and helicopter data (DSTL)
- WASABI (Wide Area Surveillance Activity-Based Information) dataset (not received yet)
- Video segmentation VSB100 (Vide Segmentation Benchmark 100) [11]
- Breakfast dataset [12]
- Engineering activities dataset [13]
- Glucometer calibration dataset [14]
- IEEE 802.11 network traffic dataset (LU)
- Netflow measurements from a virtual network testbed (LU)
- Netflow measurements from a segment of the campus network at Loughborough University (LU)
- LTE emulation measurements collected at Cobham/Aeroflex [1] (LU)

4 Outline of the Research Approach

We propose a comprehensive methodology for anomaly detection, which builds on mechanisms that would enhance the efficiency of the detection, and allow various types of anomaly and their nuances to be identified and distinguished. The proposed mechanism includes sub-units responsible for data quality assessment, classifier outlier detection, classifier decision confidence assessment, model-drift detection and classifier incongruence detection in addition to the main operational system. In our case, the main operational system is a machine perception system interpreting input sensor data in a hierarchical manner by engaging non-contextual and contextual labelling processes.

The methodological advances in anomaly detection offered by the proposed anomaly detection system architecture are expected to be validated on diverse applications. These applications include: 1) Detection of anomalous ship behaviour using information retrieved from Automated Identification System (AIS) to aid maritime traffic control, safety and surveillance in Portsmouth harbour. 2) Network anomaly detection with the aim to increase the efficiency of flagging network intrusion. 3) Anomaly detection in surveillance videos with the objective of developing an accurate, data-driven methodology which is computationally efficient and can incorporate domain knowledge.

L_WP1 has two strands as given in Table 1.

1.1-1 Baseline system	1.2.-1 Contextual model inference
1.1.-2 Radar SAM mode	1.2-2 Data quality modelling
1.1-3 Discriminative AD	1.2-3 Incongruence detection
1.1-4 Fusion of ADs	1.2-4 System integration
1.1-5 Advanced AD system	1.2-5 Communications network AD

Table 1 Two strands of L_WP1

5 Overview of the Technical Progress in Year 1 and Year 2

A summary of the contributions that have taken place in the first two years in terms of the theoretical foundations and the development of three baseline systems (on network, video and maritime anomaly) can be given as follows:

- A novel anomaly detection system architecture has been proposed which includes several distinct mechanisms such as classifier incongruence detection, data quality assessment, classifier confidence gauging, model-drift detection to detect anomalous events and facilitates their characterisation.

- As part of the anomaly detection system, incongruence detection has been investigated in detail and two novel surprise measures, Δ_{avg} and Δ_{max}, have been proposed. Theoretical analyses including error sensitivity of the proposed measures have been carried out and the results have led to guidelines on determining an appropriate threshold for incongruence detection.

- For maritime anomaly detection application (in Portsmouth area), a methodology has been developed for detecting potential anomalies in ship behaviour exhibited in the main shipping lanes. The methodology was based on measuring incongruence between two detectors: detector of ship spatial location, and a direction of sailing detector.

- As for the network anomaly detection application, the focus was on developing methods to automatically generate labelled network traffic datasets. We developed a novel approach, based on the outcome of an anomaly-based Intrusion Detection System (IDS), to automatically label frames as malicious and non-malicious within the analysed network traffic datasets. Work was also undertaken to implement an automatic feature selection process for metric selection. A genetic algorithm based approach was developed to select the set of metrics that best intrusion detection results provide, using the resulting labelled datasets. All these activities are in line with objectives of this project defined in the sub-task 1.2-2 Data Quality Modelling.

- The effort during the second year concentrated on developing different approaches to incorporate contextual information, user's cognitive information, and Situational Awareness (SA) into the intrusion detection process to increase the efficiency of the developed anomaly-based IDS. We proposed three approaches, based on the use of a Fuzzy Cognitive Map (FCM) in conjunction with our anomaly-based IDS. The activities carried out during the second year tackled the objectives defined in the sub-task 1.2-1 Contextual Model Inference, contributed in the ongoing sub-task 1.1-3 Discriminative anomaly detection defining novel algorithms to effectively differentiate between malicious and non-malicious information in communication networks.

- In the area of anomaly detection in surveillance videos, we develop an accurate, data-driven system which is computationally efficient, can handle heterogeneous spatio-temporal data and can incorporate domain knowledge to detect anomalies. The proposed system features: i) a low-level feature extraction component; ii) a mid-level feature representation component which organises the extracted features in an efficient manner, incorporating techniques such as dimensionality reduction, feature clustering (depending on the application, video segmentation, bag-of-words, Fisher vectors may be used); iii) a situational assessment component which fuses low and mid-level feature representations from various sources and infers about the current system state (ontologies and sequence formulation techniques may be utilised); iv) a high-level inference model which encodes the temporal dependencies between different system states, characterises the event underlying the input data (event/activity recognition and anomaly detection) and predicts the future system states.

- As part of the framework's mid-level feature representation component, a video segmentation algorithm is being developed. In the third year of the project, the algorithm was extended to handle the research problems of spatial coherence in segmentation, high dimensionality and exploiting motion in video segmentation.

- We developed a situational assessment component based on ontologies to detect anomalous behaviour in videos of road scenes, where anomalies are related to the degree of risk of collision. In this case, mid-level feature representations extracted with our video segmentation algorithm were used as input.

- As part of our framework's high-level inference model, we developed a new temporal model capable of recognising complex human behaviour and showed that this model can work efficiently with high dimensional low-level video features.

- As part of the evaluation of our framework, in addition to standard, publicly available datasets, we also investigated the applicability of our algorithms to several defence-related datasets, including video streams from UAVs (in collaboration with WP2 - Loughborough) and the tank dataset provided by DSTL.

6 Technical Progress in Year 3

6.1 Overview

Within the third year of the project, the progress taken place for each sub-task annotated in Table 1 can be summarised as follows:

a) 1.1-1 Baseline system

Baseline anomaly detection systems, which are used in communication networks and in applications based on analysing heterogeneous spatio-temporal data (including video and the AIS maritime monitoring dataset), have further been improved.

Anomaly detection in ship behaviour analysis, which was initially developed for the behaviours of transport vehicles moving on the main shipping lanes, have been extended to cover other vessels including ferries.

In terms of anomaly detection in video, the baseline system developed in years 1 and 2 of the project was enhanced with a new high-level inference model with both discriminative and temporal encoding capabilities. In our experiments we showed that the proposed model is suitable for analysing data from a wide variety of sources, including high dimensional low-level video features. This work will appear in [19].

Furthermore, we enhanced our system's mid-level feature representation component, specifically, the video segmentation facility. Our research focused on the problems of spatial coherence, dimensionality reduction and combining motion cues with colour and spatial information. Towards this effort we incorporated pixel clustering techniques to our video segmentation algorithm. This approach reduces the dimensionality of the segmentation problem by definition since pixel clusters are used rather than single pixels. Accuracy seems to improve as well which can be attributed to: (a) pixel clusters taking into account the detected image boundaries and (b) pixel clusters averaging the feature values of the pixels over the region they encompass, which helps to solve the "bleeding" problem sometimes encountered previously in our results. Additionally, due to the fact that some motion representation is required to distinguish moving objects of similar colours we experimented with incorporating motion cues in the feature set used for video segmentation. This work will appear in [20].

b) 1.2-1 Contextual model inference

Recent advances in autonomous vehicle technology pose an important problem of anomaly detection in videos of road scenes. In our work anomalies are related to the degree of risk of collision. We addressed the problem by proposing a novel ontology tool for assessment of risk in unpredictable road traffic environment, as it does not assume that the road users always obey the traffic rules. The key entities in the road scene (vehicles, pedestrians, environment objects etc.) are organised into an ontology which encodes their hierarchy, relations and interactions. The ontology tool infers the degree of risk of collision in a given scene using as knowledge video-based features, related to the key entities. This work is described in [21].

c) 1.1-2 Radar SAM mode change detection

This work was superseded by the work on Ballistic Missile Detection and has been completed in WP4 although it has provided a tracking context in WP2 which is on-going;

d) 1.2-2 Data quality modelling

Data quality modelling in video streams is handled by our system's mid-level feature representation component. Specifically, a large deviation between the models generated by our video segmentation algorithm for two consecutive frames can be linked to low quality input data. The deviation can be measured with the method from [15]. Research is in progress in this domain.

e) 1.1-3 Discriminative anomaly detection

As part of the network anomaly detection application, we have developed and evaluated the approaches that we proposed in [5]. These approaches add contextual information provided by the user into the intrusion detection process by the use of FCMs (Fuzzy Cognitive Maps). The aim of these approaches is to improve the efficiency of the IDS (Intrusion Detection System) discriminating between benign and malicious communication network traffic.

We have also carried out experiment to evaluate the efficiency of the IDS detecting a larger number of network attacks. In [9], we tackled the problem of detecting virtual jamming attacks in an IEEE 802.11 network, in collaboration with the University of Naples - Parthenope. This is the fourth type of Injection attack in Wi-Fi networks that we have experimentally proven to be able detect with our unsupervised anomaly-based IDS. Additionally, we have proposed in [10] a novel Hybrid IDS to improve the detection capabilities of our IDS against virtual jamming attacks on IEEE 802.11 networks. The hybrid approach combines the advantages of signature-based IDSs, with the ability to detect novel attacks of anomaly-based IDSs.

For anomaly detection in video, the high-level inference model proposed in year 3, used for activity recognition and anomaly detection bears discriminative feature capabilities, stemming from its capacity to discover important elements in discrete time sequences representing activities. This work will appear in [19].

f) 1.2-3 Incongruence detection

A new decision cognizant classifier incongruence measure, delta divergence, which is based on information theoretic foundations, has been developed and its properties investigated both theoretically and experimentally. The relationship of the proposed divergence to some baseline measures is demonstrated experimentally, showing its superiority.

g) 1.1-4 Fusion of multiple anomaly detectors

For network anomaly detection, we have made initial effort to adapt the use of Snort (www.snort.org), along with our anomaly-based IDS. The problem with signature-based IDSs such as Snort is that these systems commonly produce absolute outcomes. Snort rules are composed of multiple elements. In normal operation, rule-based IDSs trigger one alarm when all the elements in the rule are met. When an attack is identified, Snort generates a single alert of the attack. However, our IDS needs belief values in order to work correctly. We have tried to modify the internal structure of Snort (source code) in order to generate beliefs from the signatures, based on the computed percentage of triggered/non-triggered elements for each signature. In the future, we will use other publicly available signature-based IDSs such as Bro (www.bro.org) or Suricata (suricata-ids.org) to evaluate the combined used of these IDSs.

Moreover, we have designed in [10] a detection system architecture that fuses signature-based IDSs and anomaly-based IDSs. The former type of IDS detects attacks by comparing the network traffic profile with signatures of well-known threats or attacks. Signature-based IDSs are generally very accurate, but fails to identify attacks that do not belong to the set of known threats, while anomaly-based IDSs can successfully detect novel and unseen attacks.

In the context of anomaly detection in video, fusion of multiple anomaly detectors was investigated for the tank dataset, provided by DSTL. The dataset comprises videos captured from an exercise which has the purpose of assessing a gunner's ability to track a tank. Two tasks were identified for this dataset, namely vehicle detection/tracking and anomaly detection. In this dataset anomaly could be the disappearance of the vehicle from the scene (e.g. due to occlusions). To tackle the problem of efficiently detecting the location of the target we developed in collaboration with Surrey a method which employs an ensemble of object detectors via utilizing an incongruence measure. The aim is to show an increase on the performance of a given non-contextual classifier by firstly aiding it with contextual information to create a contextual classifier. The incongruence between the contextual and non-contextual classifiers is then used to control the decision making process.

h) 1.2-4 System Integration

The anomaly detection system components developed by partners are being integrated into a virtual comprehensive anomaly detection system. The integration and reasoning about component outputs will require classifier confidence modelling.

i) 1.1-5 Advanced anomaly detection system design

The design of the advanced detection system is evolving in the context of anomaly detection in communication networks throughout the project duration. A single piece of software is being built as new functionalities are proposed and evaluated. All these functionalities have been implemented by Loughborough University, developed in the C programming language, and incorporated into our unsupervised anomaly-based IDS.

j) 1.2-5 Complex network anomaly detection

Algorithms for anomaly detection in networks comprising a single communication technology have been evaluated in the first two years of this project. The experiment results presented in [2-4] both make use of network traffic collected from IEEE 802.11 networks deployed at Loughborough University.

During this third year, initial effort has been made to evaluate our anomaly-based IDS on networks comprising multiple and heterogeneous communication technologies. One of these communication technologies is LTE (Long Term Evolution). We have gathered LTE emulation measurements collected at Cobham/Aeroflex [1], comprising traces of a Denial-of-Service (DoS) attack. Initial anomaly detection experiments have been carried out to analyse these LTE measurements with our IDS. Although, encouraging results have been generated, our IDS should be further developed in order to efficiently detect all the malicious traffic.

Furthermore, we have evaluated the efficiency of our IDS by using netflow measurements both from a virtual network testbed and from a segment of the campus Ethernet network at Loughborough University. These measurements have been used in the experiment results presented in [5].

One of our research goals for the next two years, tackling the objectives defined in the sub-task, is to develop a framework in which our IDS could implement the anomaly detection process in multiple and heterogeneous communication technologies seamlessly without the need of tailoring its detection characteristics to the respective communication technology.

6.2 Technical Highlights

In this section, technical highlights concerning the sub-tasks *1.2-3 Incongruence detection, 1.1-1 Baseline system,* and *1.1-3 Discriminative anomaly detection* will be provided**.**

6.2.1 Incongruence Detection (Sub-task 1.2-3)

Following the analysis carried out in the first two years, the desirable properties of the ideal measure of classifier incongruence can be listed as:
1) Overriding focus on dominant hypotheses
2) Independence of surprisal content
3) Minimum clutter effect
4) Symmetry (independence of the choice of distribution as a reference)
5) Bounded range of incongruence measure values
In the first two years of the project, we had heuristically attempted to formulate two incongruence measures (namely Δ_{max} and Δ_{avg}) satisfying the above mentioned properties. In the third year, our objective was to develop a classifier incongruence measure with a solid theoretical underpinning by demanding that it is a proper divergence. The proposed novel measure, called 'Delta Divergence', is theoretically and experimentally shown to overcome the limitations of Bayesian surprise and some other baseline measures.

Consider a problem where two classifiers voice their opinions about the membership of a given pattern into one of the mutually exclusive classes, $\omega_i, i = 1, \dots, m$. Let us denote the a posteriori probability output by these experts for a given class, ω_i, as P_i and $\widetilde{P}_i$. We set to develop an incongruence measure which is a member of the family of divergences $h(\phi)$ of functions

$$h[\sum_i \phi(P_i, \widetilde{P}_i)]$$

where h and ϕ are polynomial, logarithmic, poly-logarithmic, quasi-polynomial, or quasi-polylogarithmic functions or convex functions. This family, which includes Bregman, Renyi and Cziszar f-divergences, is the most general family having the potential to source the starting point of our development. The requirement that our starting point satisfies the property that the contribution to divergence is dependent purely on differences in probabilities, rather than their action values (Property 2) retains only the 'Total Variation Distance' from this family, defined as

$$D_T = \frac{1}{2}\sum_i |P_i - \widetilde{P}_i|$$

This measure is symmetric and bounded, taking values from the interval [0, 1]; however, it is still affected by clutter of non-dominant classes. The effect of clutter can significantly be reduced by the following argument: When we compare the outputs of two classifiers, there are only three outcomes of interest: the dominant class ω identified by the classifier with probability distribution P, the dominant class $\widehat{\omega}$ identified by the other classifier, and neither of the two, in other words $\widehat{\widehat{\omega}} = \Omega - \omega - \widehat{\omega}$. Thus, we define a new decision cognizant divergence D_Δ, which we name Delta divergence, as

$$D_\Delta = \frac{1}{2}[\sum_{i\{\omega,\widetilde{\omega}\}} \left| \widetilde{P}_i - P_i \right| + \left| \widetilde{P}_{\widehat{\omega}} - P_{\widehat{\omega}} \right|]$$

After analysing the cases of label agreement and disagreement in the most probable hypotheses output by the two classifiers separately, it has been shown that D_Δ is equal to

$$D_\Delta = \begin{cases} \left|\widetilde{P}_\omega - P_\omega\right| & \omega = \widetilde{\omega} \\ \max\{\left|\widetilde{P}_{\widetilde{\omega}} - P_{\widetilde{\omega}}\right|, \left|\widetilde{P}_\omega - P_\omega\right|\} & \omega \neq \widetilde{\omega} \quad A \geq 0, B \geq 0 \\ \frac{1}{2}[\left|\widetilde{P}_{\widetilde{\omega}} - P_{\widetilde{\omega}}\right| + \left|\widetilde{P}_\omega - P_\omega\right|] & \omega \neq \widetilde{\omega} \quad \begin{cases} A < 0, B < 0 \\ A \geq 0, B < 0 \end{cases} \end{cases}$$

where $A = \left|\widetilde{P}_{\widetilde{\omega}} - P_{\widetilde{\omega}}\right|$ and $B = \left|P_\omega - \tilde{P}_\omega\right|$.

In other words, the incongruence measure is defined either by the maximum absolute value difference between the probabilities output by the two classifiers for the respective dominant hypotheses or by the average of these differences. This, in fact, applies even when the dominant hypotheses are the same.

Delta divergence is shown to exhibit the properties required for an optimal surprise measure as listed above, and some additional ones such as being a metric under the two class scenario. We have carried out experimental analysis to demonstrate some of its characteristics such as its superiority over the other measures and its resistance to clutter. Below, a representative set of experiments have been presented from this study.

Robustness to clutter

The advantage of D_Δ over D_T can be demonstrated by comparing the contributions of the non-dominant hypotheses to these two measures. This superiority has been analysed both theoretically and experimentally:

Figure 1 represents the scatter plot of clutter injected in the total variation divergence against the clutter of delta divergence. The values of the clutters are computed by sampling the populations of a posteriori class probability distributions of the two classifiers (P and $\tilde{P}$) for a six class problem (where the number of samples is equal to 10^6).

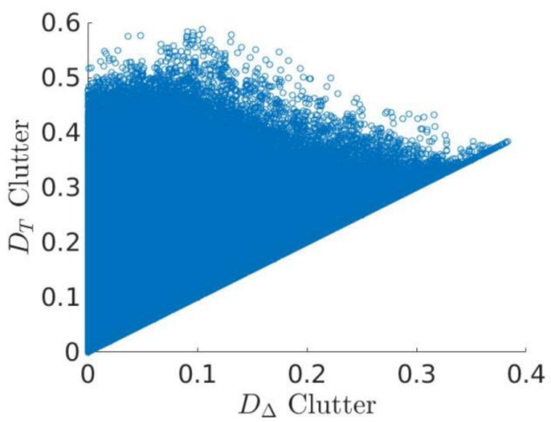


Figure 1. Scatter plot of D_T clutter against D_Δ clutter, affecting the outputs of two classifiers using these two divergences. The values are computed for samples from a population of probability distributions defined over six classes

Relationship of D_Δ with Bayesian Surprise (Kullback-Leibler divergence, D_K)

In Figure 2 and Figure 3 the comparison of D_Δ with K-L divergence has been carried out for six and three class problems by sampling the probability distributions P and $\tilde{\mathrm{P}}$ for a fixed value of D_Δ. We note a number of observations: First of all the range of values assumed by the K-L divergence is much greater, which would make it difficult to set a suitable threshold between classifier congruence and incongruence. The unbounded range reflects the dependence of K-L divergence on the surprisal values of the additive terms in the expression for the K-L divergence. In the plot, the observed values greater than DK = 8 are not shown to avoid undue data compression.

We also note that the greater the number of classes, the greater the variation of K-L divergence values caused by the contribution of the clutter of non-dominant classes. The clutter is responsible for a significant overlap of K-L divergence values for the classifier congruence and classifier incongruence cases. This can be seen by drawing horizontal lines cutting the scatter plots at different K-L divergence thresholds and noting the resulting distributions (data scatters). For instance setting the threshold to D_K = 3 will retain many cases with a high value of D_Δ in the congruent category, leading to under-detection of incongruence. Lowering the threshold to, say, 0.75 will miss many cases with low value of Delta divergence, resulting in a high proportion of false positives.

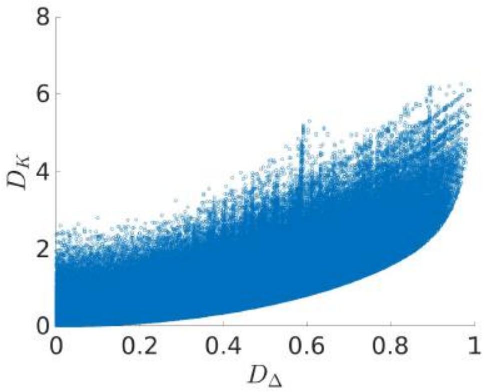


Figure 2. Scatter plot of D_K clutter against D_Δ, comparing the outputs of two classifiers sampled from a population of probability distributions defined over six classes.

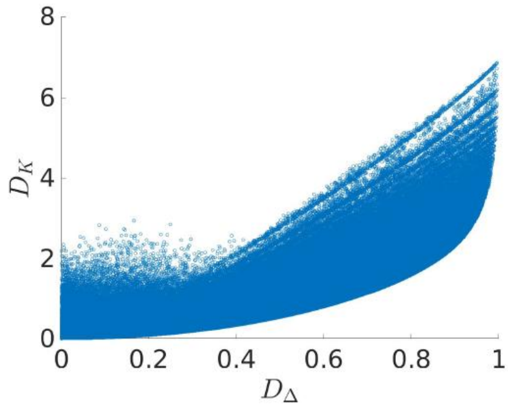


Figure 3. Scatter plot of D_K clutter against D_Δ, comparing the outputs of two classifiers sampled from a population of probability distributions defined over three classes.

6.2.2 Anomaly Detection in Ship Behaviour in Portsmouth Area (Sub-task 1.1-1)

As part of Sub Task 1.1-1, detection of anomaly in ship behaviour has been studied on the data around Portsmouth area, provided by Thales. The data consists of spatial and temporal information of the ships, provided by Automated Identification System (AIS).

In the first two years of the project, we implemented an anomaly detection methodology to be employed on ship behaviour exhibited on 4 major shipping lanes, which are mainly used by transport vessels. In the third year, we have adopted a more generic approach, which covers detecting anomalies in the behaviours of not only transport vessels, but also ferries and other types of ships.

The proposed approach consists of a hierarchical system in which the primary layer labels all given ship movement in the test set at every time step, t. At the second layer, the system outputs a final decision for a given time interval of interest, T, after aggregating inputs from the primary layer. The labels produced by the first layer are defined as follows:

- Label 1: No reporting (incomplete data)
- Label 2: Ship not moving (normal behaviour)
- Label 3: Ship exhibiting "normal move" with respect to training data
- Label 4: Ship exhibiting "anomalous move" with respect to training data
- Label 5: Reported coordinates are out of boundaries of the region of interest (faulty data)
- Label 6: Reported coordinates have not previously been visited in training data (anomalous behaviour)
- Label 7: Consecutive coordinate reporting times are too far from each other to obtain accurate results (incomplete data)

The test data assigned labels 1, 5 and 7 by the first layer is discarded by the second layer, as it is deemed either faulty or incomplete. The strategy of the second layer system is to mark the whole interval of movement T as anomalous, if a proportion of the data within it is assigned Label 4 or 6. The proportion threshold is given as an input to the system.

First Layer – Technical Details

The proposed system working on the first level is based on a system of hierarchical grids. The input data for anomalous ship movement detection is expected to be composed of second-by-second location information reported in the form $L(k,l)$ for a given ship, where k denotes the longitude and l the latitude.

Assume that our initial grid is of size $n \times m$, and named $G_{n,m}$. Each cell of this grid can be named as $G_{n,m}(x,y)$ where $1 \leq x \leq n$, $1 \leq y \leq m$, x is the row index, y is the column index, and $G_{n,m}(1,1)$ is the left-most cell belonging to the bottom row. An example grid, drawn in black, is shown in Figure 4. It is then possible to transform a given location $L(k,l)$ into the form $G(x,y)$ using quantization, to find out which G cell it falls into. Note that $G(x,y)$ can be mapped onto a vector form, denoted $\tilde{G}(z)$.

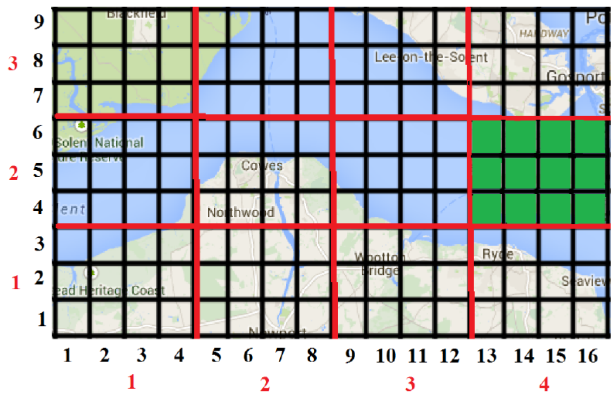


Figure 4. Two layers of grid fit onto a region of interest.

Let us denote the secondary $k \times l$ grid as $G'_{k,l}$; where $k \leq n$ and $l \leq m$; and the corresponding vector form as $\widetilde{G'}$. An example of this coarser grid is shown in Figure 4 using red lines. A $\tilde{G}(z)$ cell lying within a given $\widetilde{G'}(z')$ satisfies $\tilde{G}(z) \epsilon \widetilde{G'}(z')$.

The proposed ship behaviour model is defined as a distribution of transitions characterising ship behaviour within each cell $\widetilde{G'}(z')$ by generalizing over $\tilde{G}(z) \epsilon \widetilde{G'}(z')$. Let us denote a transition likelihood from an initial state $\tilde{G}(z)$ to a second state $\tilde{G}(z^*)$ as $P(z^*|z)$. This transition likelihood can also be referred to as $\bar{P}(\theta|z)$ where θ represents the direction of travel of the given ship from the state $\tilde{G}(z)$ to $\tilde{G}(z^*)$ in terms of radians.

While carrying out the generalization using $\bar{P}(\theta|z)$, we simply marginalize out the location variable, z , and end up with

$$\bar{P}_{S(z')}(\theta) = \sum_{z \epsilon S(z')} \bar{P}(\theta|z) P(\tilde{G}(z))$$

where $S(z')$ is the set of z satisfying $\tilde{G}(z) \epsilon \widetilde{G'}(z')$ for a given z' and $P\left(\tilde{G}(z)\right)$ is the probability of the ship being in cell $\tilde{G}(z)$. As $k, l \rightarrow \infty$, (and hence, as cell size goes to zero), the range of possible directions gets close to infinity, which is only limited by the precision of the AIS. Then, $\bar{P}(\theta|z)$ becomes a function behaving closely to Dirac function for each z, and $\bar{P}_{S(z')}(\theta)$ for a given z' is obtained as a normalized histogram using all data points $z \epsilon S(z')$.

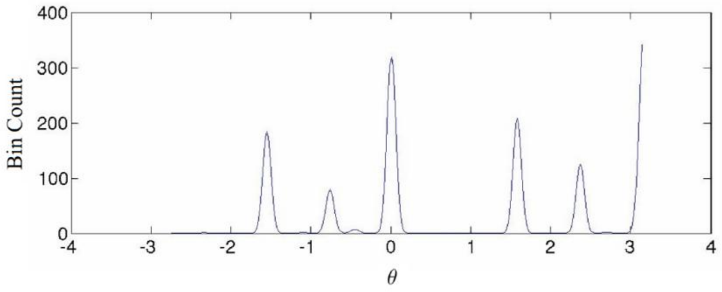


Figure 5. Direction (*θ*) histogram of $\widetilde{G'}(8)$, measured in the region of interest given in Figure 4. Two layers of grid fit onto a region of interest., after convolution with a Gaussian

It should be mentioned here that, while $\bar{P}_{S(z')}$ for each z' is obtained from an histogram, sharp transitions are expected between the probabilities of adjacent θ. In order to overcome this, we propose the use of convolution with a Gaussian on the histograms obtained. Figure 5 exemplifies the resulting smoothed histogram, describing the ship behaviour exhibited in $\widetilde{G'}(8)$ (represented by green colour in Figure 4). The Gaussian, *N*, used for convolution has the parameter set $N(\mu = 0, \sigma = 3)$, where *μ* is the mean and *σ* is the standard deviation.

After obtaining $\bar{P}_{S(z')}$, $\forall z'$, an anomaly in a test ship's movement from state $\tilde{G}(z_{t_1})$ to $\tilde{G}(z_{t_2})$ within $\tilde{G}(z')$ can be detected by checking whether the probability of the direction of travel, θ is below a given threshold r,

$$f = \begin{cases} 1 & \bar{P}_{S(z')}(\theta) < r \\ 0 & o.w. \end{cases}$$

where *f* is an anomaly indicator, with *f*=1 signifying anomalous behaviour.

6.2.3 Network Anomaly Detection (Sub-task 1.1-3)

The focus of the work during the third year was to continue developing and evaluating novel algorithms to efficiently differentiate between malicious and non-malicious information in communication networks. In the last few years, there has been considerable increase in the efficiency of IDSs. However, networks are still victims of intrusions and cyber-attacks. As the complexity of the attacks keeps increasing, new and more robust detection mechanisms need to be developed. We argue that the next generation of IDSs should be developed with the capability of integrating to the intrusion detection process contextual information, SA and cognitive information, pertaining to the experts' judgment on the network behaviour.

Current IDSs utilise measurable network traffic information from the protected system or signatures of known attacks during the intrusion detection process, but these systems do not take into account available high-level information (i.e. above the network operation) regarding the protected system to improve their effectiveness [6]. The problem faced is how to represent this information and then how to incorporate it into the intrusion decision process. In a similar manner to [7], we advocate the incorporation of human cognition as part of the detection process to improve the detection effectiveness. The approach that has been considered by Loughborough University for this matter is the FCM [8].

We have developed and evaluated the approaches that we proposed in [5], which deals with the problem of adding contextual information provided by the user into the intrusion detection process by the use of FCMs. The different approaches are used to fine-tune some of the techniques used by our anomaly-based IDS, improving the anomaly detection results. Our IDS provides three levels of belief or Basic Probability Assignment (BPA) values, for each analysed instance. These are belief in *Normal*, *Attack*, and *Uncertainty*. Once these values have been generated, the BPA values are fused using Dempster-Shafer (D-S) theory of evidence. All the proposed approaches to integrate FCM in the detection process are based on the generation or modification of the BPA values used by D-S theory.

The experiments that we carried out are based on the utilisation of the time and date in which three applications are scheduled to operate in a virtual network testbed. Three processes were scheduled to generate network traffic data; downloading a webpage (wget), securely copying a file over the network (ssh), and streaming video (VLC). We have collected Netflow measurements gathered during 168 hours (7 days) from the network testbed. The network traffic throughput, represented in Figure 6, has been collected to identify possible anomalies in the traffic (i.e. unexpected increase in the throughput value).

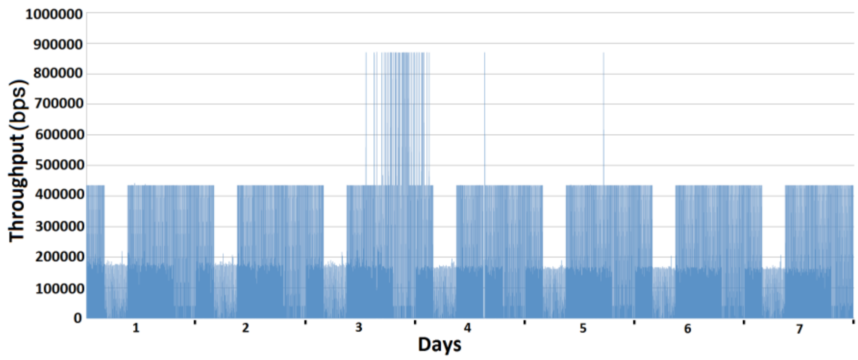


Figure 6. Throughput measurements – 168 hours

Three users with knowledge about the virtual network contributed to the FCM model. Each of them provided their opinion on whether the throughput measurements were normal or abnormal, based on the time and the different scheduled services. Initially, the users defined the main events relevant for the virtual network, the relationships among these events and the level of influence. In total, 13 events were defined, which have been sorted in Table 2. The FCM events $C_{1\text{-}3}$ define the three scheduled services. The events $C_{4\text{-}7}$ define four throughput levels that are considered normal when one of the services is running. The four events $C_{8\text{-}11}$ define the periods of time at which the different services are scheduled. Both C_{12} and C_{13} are the two possible outcome decisions about each state. Using the input from each user, three adjacency matrices were generated. The adjacency matrices were merged and the combined knowledge of the expert has been tabulated in the *13x13* adjacency matrix presented in Figure 7.

FCM Events	Events Definition
C1	SSH
C2	WGET
C3	VLC
C4	Throughput < 50000
C5	50000 < Throughput < 200000
C6	200000 < Throughput < 450000
C7	Throughput > 450000
C8	00:00:00 - 03:59:00
C9	04:00:00 - 08:59:00
C10	09:00:00 - 18:59:00
C11	19:00:00 - 23:59:00
C12	Normal
C13	Abnormal

Table 2 List of FCM Events

	[c1]	[c2]	[c3]	[c4]	[c5]	[c6]	[c7]	[c8]	[c9]	[c10]	[c11]	[c12]	[c13]
[c1]	0	0	0	-0.17	-0.17	0.50	0.04	0	0	0	0	0.40	0
[c2]	0	0	0	-0.17	0.50	-0.17	0.04	0	0	0	0	0.40	0
[c3]	0	0	0	0.50	-0.17	-0.17	0.04	0	0	0	0	0.40	0
[c4]	0	0	0.54	0	0	0	0	0	0	0	0	0.47	0
[c5]	0	0.54	0	0	0	0	0	0	0	0	0	0.47	0
[c6]	0.54	0	0	0	0	0	0	0	0	0	0	0.47	0
[c7]	0	0	0	0	0	0	0	0	0	0	0	0	0.90
[c8]	0.24	0.24	0.24	0.54	0.54	0.54	0.07	0	0	0	0	0	0
[c9]	0	0.24	0.24	0.54	0.54	0.07	0.07	0	0	0	0	0	0
[c10]	0.24	0.24	0	0.07	0.54	0.54	0.07	0	0	0	0	0	0
[c11]	0.24	0	0.24	0.54	0.07	0.54	0.07	0	0	0	0	0	0
[c12]	0	0	0	0	0	0	0	0	0	0	0	0	0
[c13]	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7. Combined Adjacency Matrix

By the use of FCM, we can model how changes in the throughput, time and date affect the two events C_{12} and C_{13}. In one of the proposed approaches, these two events are used to adjust the BPA values defined prior to the data fusion process. Another of the proposed approaches uses the outcome of the FCM process as an extra set of BPA values to be fused using the D-S theory along with the rest of the network metrics.

For the first approach, *BPA Adjustment Using FCM*, the results without contextual information indicate that all the anomalies in the throughput measurements have been successfully identified (i.e. Detection Rate (DR) = 100% and False Negative rate (FNr) = 0%) but at the cost of a high number of False Positive (FP) alarms. The FPr reaches up to 49% in the best-case scenario. On the other hand, when FCM is used, the performance of the detection system is greatly improved. The detection results including contextual information indicate that all the anomalies in the throughput measurements have been successfully identified (i.e. DR = 100% and FNr = 0%). The use of the FCM restricts the FPr to just 1.82%, in the worst-case scenario. This reduction in the number of FP alarms is a direct consequence of the adjustment induced by FCM.

For the second approach, *Extra BPA Values Using FCM*, the results generated when the contextual information is included are very similar to the results generated by the *BPA Adjustment Using FCM* approach. However, the FPr is on average 0.08% higher than the previous results. Nonetheless, these results show that considering the contextual information as part of the detection process significantly improves the efficiency of our anomaly-based IDS. The comparison of the FPr results with and without FCM is presented in Figure 8.

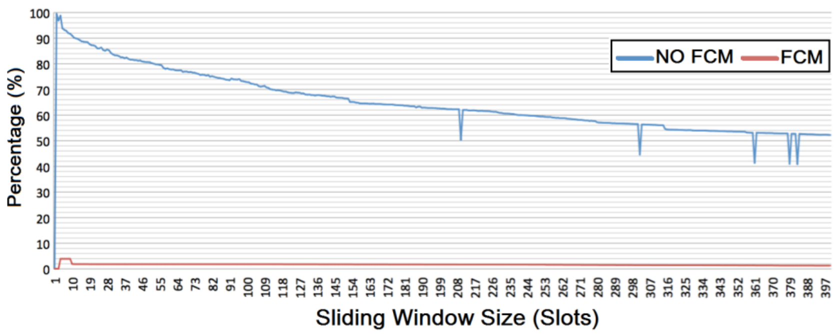


Figure 8. Comparison of the FPr Anomaly Detection Results – FCM & No FCM

Figure 9. Comparison of the FPr Anomaly Detection Results – Two Approaches

Apart from proposing novel algorithms to improve the efficiency of the IDS discriminating between benign and malicious communication network traffic, we have carried out experiment to evaluate the efficiency of the IDS detecting a larger number of network attacks. In [9, 10], we tackled the problem of detecting virtual jamming attacks in an IEEE 802.11 network, in collaboration with the University of Naples - Parthenope. In [10], we have proposed a novel Hybrid IDS to improve the detection capabilities of our IDS against virtual jamming attacks. The hybrid approach combines the advantages of signature-based IDSs, with the ability to detect novel attacks of anomaly-based IDSs. We have evaluated the performance results generated when different metrics combination are used, as well as single metrics. The solution that exhibits the best results is the use of the single metric Network Allocation Vector (NAV), which generates 100% of DR, 3.8% of FPR and 0% of FNR. Overall, the results evidenced by the hybrid IDS outperforms the detection results generated by the anomaly-based NIDS presented in [9].

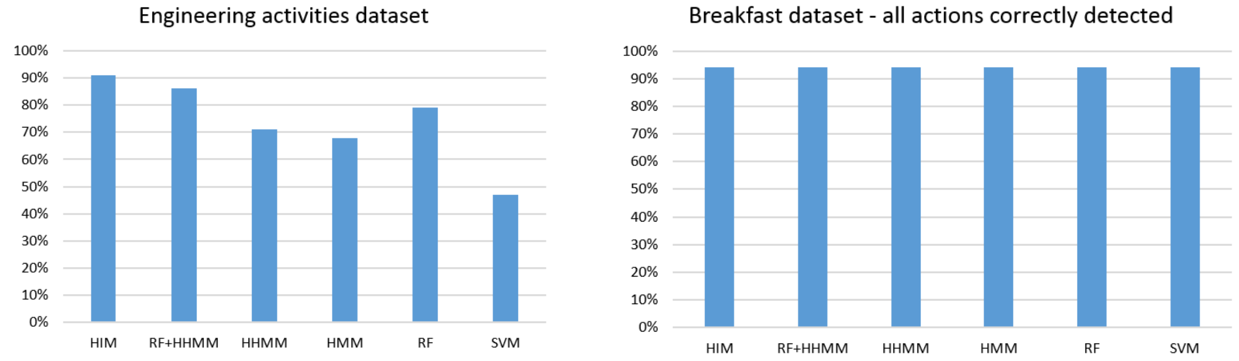
6.2.4 Anomaly Detection in Video (Sub-task 1.1-1 and 1.1-3)

As part of the research carried out in WP1 we develop a system for activity recognition and anomaly detection in heterogeneous spatio-temporal data featuring complex human behaviour. The system models human activities as temporal sequences of their constituent actions and can handle actions that occur concurrently in multiple parallel streams. It operates in a supervised manner and comprises three stages, which are extraction of action sequences from data streams, feature selection and activity recognition/anomaly detection.

In the third year of the project we developed a new high-level inference model, suitable for the recognition of composite, prolonged activities. The proposed model builds a hierarchy for each activity's constituent actions based on their importance; this hierarchy is then exploited to encode both short- and long-term temporal dependencies within an activity. We call our model hierarchical importance model (HIM). The model possesses discriminative feature capabilities, stemming from its capacity to discover important actions for an activity. Note that our approach can be applied as it stands to any task which involves prolonged, composite activities, as its structure and parameters are learned automatically from expert labelled data. Additionally our model can work efficiently with high dimensional low-level features extracted from video, such as STIPs [16].

We evaluate our method using three publicly available datasets, [13], [12] and [14]. Our approach offers higher or equal to the state-of-the-art accuracy in activity recognition and error detection than our previous work and other leading methods. Results are shown in

Figure 12. A journal article which presents our full system with an in-depth evaluation is in preparation [19].



(j) (k)

Figure 12. Comparison of the proposed hierarchical importance model (HIM) against current methods for two publicly available datasets; (a): Engineering activities dataset [13]; (b): Breakfast dataset [12].

7 Future Work

The plans for future work can be summarized as follows:

- At the University of Surrey, visiting researchers from Brazil will investigate other divergence measures and carry out a comprehensive comparative study of new and existing measures.
- Ship behaviour analysis will further be extended by making use of additional information such as time and location (on top of the already used direction information) using Gaussian Processes.
- The existing anomaly detection framework will be applied to DSTL tank classification data (exploiting classifier incongruence analysis).
- As for network anomaly detection, we will address full integration of publicly available signature-based IDSs such as Snort, Bro, or Suricata into our current anomaly-based IDS. We will also focus our work on the development of a real-time hybrid IDS able to detect a wider range of threats and cyber-attacks against wireless networks. Similarly, we will extend the implementation of the proposed hybrid IDS to other wireless communication technologies, such as LTE and WiMAX.
- Further work will investigate approaches to automatically generate the internal structure and use of ontologies. Ontologies are useful tools to structure and organise pieces of contextual information. We intend to increase the efficiency of the IDS with design of new anomaly detection techniques. We also will investigate the development of new methods to detect multi-stage attacks, as well as novel algorithms to handle uncertainty.
- We will continue with the development, in the C programming language, of the advanced detection system throughout the project duration. A single piece of software is being built as new functionalities are proposed and evaluated.
- In the area of anomaly detection in surveillance videos and heterogeneous spatio-temporal data, our work will focus on incorporating low-level video features in our

framework, such as dense trajectories [17]. We will also investigate efficient representations of such features, such as Fisher vectors [18].

- The efficiency of the evolving GMM model currently used in the video segmentation facility of our framework will be enhanced by its implementation on GPUs and FPGAs (with advice from WP5-Strathclyde). Furthermore, the algorithm's applicability to the problem of estimating the number of data sources will be investigated, in collaboration with WP3-Surrey. Another potential research path in this domain is the generalisation of the proposed evolving model to work with other distributions (e.g. complex elliptically symmetric (CES) distributions, often used for radar data).
- In the area of video segmentation, a potential research direction is the assessment of the quality of video segmentation.
- In the domain of contextual model inference, we are planning to further develop our framework for anomaly detection in road scenes to cater for anomalies in airport environments. For this task we have planned collaboration with WP2-LU.
- We are also planning to evaluate our anomaly detection framework in more military related datasets, such as the WASABI dataset which will be supplied by DSTL.

8 Publications

- G. Escudero-Andreu, K. G. Kyriakopoulos, F. J. Aparicio-Navarro, D. J. Parish, D. Santoro, and M. Vadursi, "A data fusion technique to detect wireless network virtual jamming attacks," in *Proc. of the 3rd IEEE International Workshop on Measurements and Networking (M&N)*, 2015, pp. 1-6.

- F. J. Aparicio-Navarro, K. G. Kyriakopoulos, D. J. Parish, and J. A. Chambers, "Adding contextual information to intrusion detection systems using fuzzy cognitive maps," in *Proc. of the IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*, 2016; accepted for publication.

- G. Escudero-Andreu, K. G. Kyriakopoulos, F. J. Aparicio-Navarro, D. J. Parish, D. Santoro, and M. Vadursi, "A hybrid intrusion detection system for virtual jamming attacks on wireless networks," in *IEEE Transactions on Instrumentation and Measurement*; to be submitted.

- I. Kaloskampis and Y. Hicks, "Spatially coherent online video segmentation using evolving mixtures of Gaussians". *In preparation*.

- I. Kaloskampis and Y. Hicks, "Activity Recognition in Concurrent Multimedia Streams Using Temporal and Discriminative Analysis". *In preparation*.

- M. Mohammad, I. Kaloskampis, Y. Hicks, and R. Setchi, R., "Ontology-based framework for risk assessment in road scenes using videos. *Procedia Computer Science*, pp. 1532–1541, 2015.

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L_WP2 (HU) Handling uncertainty and incorporating domain knowledge

1. Staffing

Work Package Leaders: Prof. Lambotharan (EESE, LU) and Prof. Wen-Hua Chen (AAE, LU), Dr Hyondong Oh (AAE, LU), Yu Gong (EESE, LU)
Research Associates: Dr. Anastasia Panoui (EESE, LU), Dr. Miao Yu (AAE, LU)
UDRC Research student: Mr. Tasos Deligiannis
Affiliated Research Students: Ms Gaia Rossetti, Mr Abdullahi Daniyan, Mr Michael Hutchinson and Mr. Runxiao Ding
Lead Project Partner: Prof. Malcolm Macleod (QinetiQ)
Dstl contact: Dr. Jordi Barr (Sensors & Countermeasures Department).

2. Aims and the lists of the original L_WP2 in the case for support:

Aims: *To develop a generic learning framework for handling uncertainties in the measurements acquired in the networked battlespace environment. Links to WP1 through domain knowledge; and WP3 & WP4 in handling incomplete sensor information & achieving robustness to jamming. (T3,T5)*

This WP exploits the world model of the networked battlespace to improve performance and confidence and to reduce uncertainty to an unprecedented level. Due to the abundance of previously collected information of a battlespace and increasing availability of mobile communication and storage, rich information may be available for sensor platforms when performing signal processing as they operate in a **networked** battlespace. Examples for such information are digital maps about terrain and layout of the field, historical data about the site, geometric relations between platforms, and operational conditions such as weather (e.g. the influence of shadowing on optical sensors).

WP2.1 Reducing uncertainty by incorporating domain knowledge using Bayesian inference, adaptive signal processing and sparse sampling [PDRA2]

We will consider how to quantify the information in the world model and express it in a probabilistic statement; for example, how to synthesize the information in the *prior* of the world model (e.g. geometric constraints) with the *prior* of the state variables obtained in the previous time steps to form a combined prior probability function, and how to pool different sources of information measured via different types of sensors or provided by other resources (e.g. digital maps) for statistical inference. New signal processing algorithms offering adaptivity to operational environments will also be developed by exploiting the domain knowledge. Various parameters in these algorithms (e.g. the threshold for detection) or different types of signal processing models/algorithms will be selected based on the domain information (e.g. the change of the operation conditions when the sensor platforms move, or what decisions follow from the signal processing results and their consequence). Historical data will be used to build up the *priors* in Bayesian inference for different objects of interest and different scenarios, which will reduce the reliance on real-time measurements in the battlespace. New sparse sampling measurements will be not only used to update the priors but also to confirm or reject the previous priors selected for the Bayesian learning (hypothesis tests) with the help of domain knowledge (e.g. how likely it could be that an object of interest occurs based on domain knowledge). The Bayesian inference framework will also be extended from a single to multiple sensor platforms operating in a networked environment, by fusing all the information, including the sensory capabilities and constraints (e.g. angle of field view) and geometric relationships between different sensor platforms. One research challenge here is to create a joint model for multiple sensor platforms with heterogonous attributes to gather intelligence of an object of interest (e.g. a threat), where information synthesis is of particular importance.

3. Progress made in the third year in addressing the original objectives

3.1 Overview

The original aim of this work package is "to develop a generic learning framework for handling uncertainties in the measurements acquired in the networked battlespace environment". There has not been any significant change on this stated aim, and the focus remains on the development of signal processing algorithms for handling uncertainties by incorporating domain knowledge and game-theoretical methods. Two postdoctoral research associates and five PhD students work on this work package.

3.2 Engagement with partners

The leading industrial contact for this work package is Prof. Malcolm Macleod from QinetiQ. We have also discussed with Paul Westoby and his colleague in Dstl on how to exploit the prior information for more efficient hazardous source term estimation. The current technical contact for WP2.1 and WP2.2 is Dr. Jordi Barr from the Sensors & Countermeasures Department in Dstl. Dr. Barr is an experienced signal processing expert and has provided a number of very insightful comments and suggestions to this work package.

3.3 Overview of progress

A number of achievements have been made for WP2 in the third year.

1. **Developing new signal processing algorithms aided by the a non-Markov jump modelling and particle filtering implementation (Contribute to SubTasks 2.1-1 World modelling, 2.1-3 New adaptive algorithms and 2.1-4 Bayesian inference)**

In a realistic scenario, a target(s) may manoeuvre in different ways with different types of environmental conditions. Considering this, a non-Markov jump modelling approach is proposed where multiple models are used with state-dependent mode transition probabilities. For each model, comprehensive environmental information (i.e. physical constraints and interactions between a target and the environment) is exploited for reshaping the target state distribution more accurately. Then, the Bayesian inference framework is developed for target tracking based on the proposed modelling approach. The implementation of the Bayesian framework is made by a Gaussian particle filtering, which exploits the measurement information for both efficient and effective particle sampling.

2. **Ballistic missile tracking (*highlighted technical output*, Contribute to SubTasks 2.2-4, Radar and sensor applications, 2.1-3 New adaptive algorithms and 2.1-4 Bayesian inference)**

We have proposed a new method for ballistic missile tracking. Firstly, a non-Markov jump hybrid modelling is used to reflect the realistic missile movement where multiple models are applied for three different flight phases (boost, coast and re-entry). In particular, the transition probabilities between models are defined in a state dependent way according to the domain knowledge of flight phases' dependence on the altitude. Based on this modelling, a Gaussian particle filtering-based interactive multiple model approach is applied for the missile state estimation. The relevant missile parameters are also estimated by the proposed approach, which can be potentially used for missile type identification and trajectory prediction.

<u>3. Game Theory for Distributed Optimizations (*highlighted technical output*, contribute to Sub Tasks, 2.2-1 Convex optimisation and robust SP, 2.1-3 New adaptive algorithms, 2.2-2 Radar and sensor applications and 2.2-4 Game Theory)</u>

A comprehensive study on game theoretic methods has been performed for a wide range of distributed optimization problems including waveform design, power allocation, beamforming and electronic countermeasures within the context of multi-static radars [6-8, 10-12]. This work is significant due to completion of rigorous mathematical analyses for establishing existence and uniqueness of the Nash equilibrium for various classes of game theoretic methods [6-8]. The work on waveform design demonstrates the capability of enabling distributed radars to select waveforms optimally and automatically without explicit coordination among themselves. The significance of this work is on the analysis of existence and uniqueness of Nash equilibrium [6] which is mathematically intensive due to the proof of discrete convexity using larger midpoint property (LMP). The second significant contribution is on the mathematical proofs for demonstrating that in a multi-static radar setup, certain radars may opt to be inactive, but use illuminations of other radars as the signals of opportunity for detection and the corresponding Nash equilibrium analyses [8]. This mathematically rigorous work is based on establishing dual of the convex optimization problem and deriving Karush–Kuhn–Tucker (KKT) conditions. Distributed beamformer design techniques using non cooperative games and interference mitigation methods for the co-existence of a surveillance radar with tracking radars using a Stackelberg game were also developed [7]. Finally game theoretic power allocation methods for the strategic interaction of radars and jammers have also been developed [11].

4. Technical details

4.1 Work package 2.1

<u>4.1.1. The novel Bayesian inference algorithm for target tracking aided by the new dynamic modelling approach</u>

It is unlikely that one dynamic model can reflect the complex movement of a target moving in different operational environments. To reflect the movement of a vehicle more accurately in a realistic condition, a new environmental information-aided modelling approach is proposed as shown in Fig. 1. Multiple models are exploited to model the vehicle movements in different regions. A non-Markov jump model [R1] is applied where transition probabilities between different models are represented in a state dependent way according to the surrounding environmental conditions. For a particular model, both the environmental constraints (e.g. road boundary) and interaction between the target and the environment (represented by forces as in [R2] and [R3]) are used to refine the state distribution.

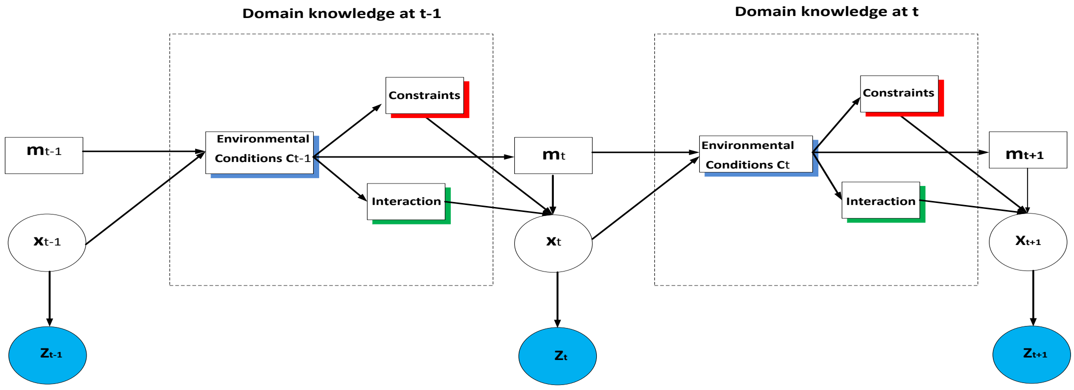


Fig. 1 The proposed modelling framework with C_t: environmental conditions, m_t: movement mode, x_t: state vector, z_t: measurement vector

Based on the new modelling approach, the Bayesian inference framework is developed for target state estimation. Considering that the environmental information (both the constraint and interaction) makes dynamic models highly nonlinear and non-Gaussian, the particle filtering is applied to implement the Bayesian inference framework. In particular, a Gaussian particle filtering-approach is developed, which exploits the measurement information for more effective particles generation.

The proposed algorithm is tested in a scenario presented in Fig. 2, where two vehicles move in different road segments (straight and bend road) with different manoeuvring types (constant velocity and acceleration for overtaking and turning). A hundred Monte Carlo simulations are performed, and the results related to vehicle 2 are presented in the below.

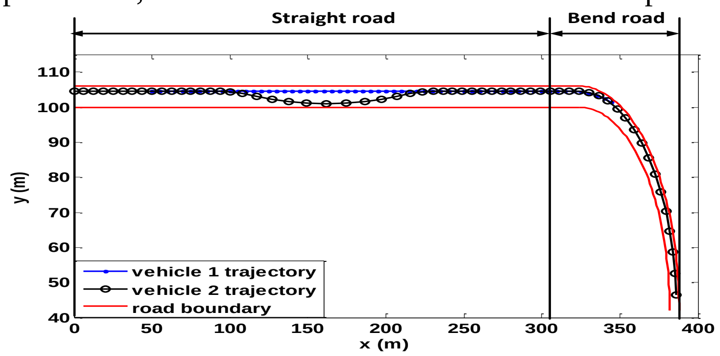


Fig. 2 The simulated trajectory for two vehicles.

Figure 3 (a) shows the position RMSEs comparison results by different modelling approaches, from which we can see that compared with other modelling schemes, the proposed non-Markov jump model which exploits both the constraint and interaction information achieves the smallest RMSEs during the majority of the time. This is because the proposed method takes advantages of the domain knowledge in a comprehensive way. From the RMSEs comparison of different particle filtering implementations as shown in Fig. 4 (b), we can see that the Gaussian particle filtering-based approach achieves a more accurate tracking result than its generic particle filtering counterpart.

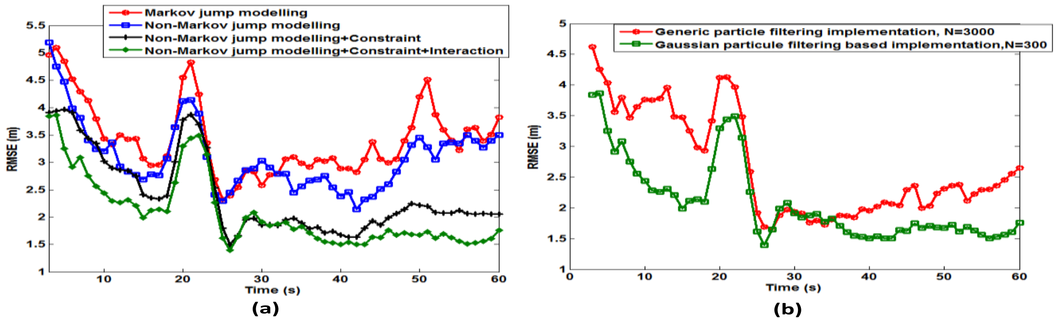


Fig. 3 The estimated RMSEs for different modelling (a) and implementation (b) approaches

4.1.2. Ballistic missile tracking (*selected highlight example*)

We have proposed a new method for tracking the entire trajectory of a ballistic missile from launch to impact on the ground. A non-Markov jump hybrid modelling system is proposed where multiple state models are used to represent the different ballistic missile dynamics in different flight phases: boost, coast and reentry. In particular, the transition probabilities between state models (i.e. flight phases) are represented in a *state dependent* way by exploiting domain knowledge (e.g. the correlation between the flight phase and the missile altitude). Based on this modelling system and radar measurements, the state-dependent interactive multiple model (IMM) approach based on the Gaussian particle filtering (denoted as the SD-IMMGPF) is developed to accurately estimate the ballistic missile information such as the flight phase, position, velocity and other relevant parameters.

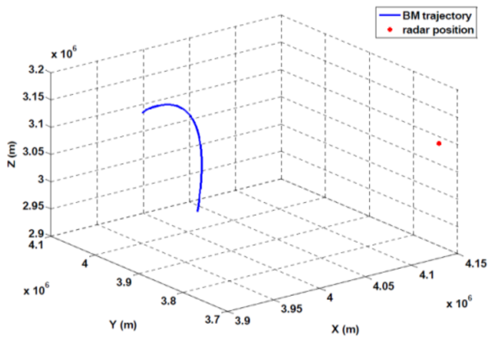


Fig. 4 Simulated BM trajectory and radar position in the ECEF coordinate system

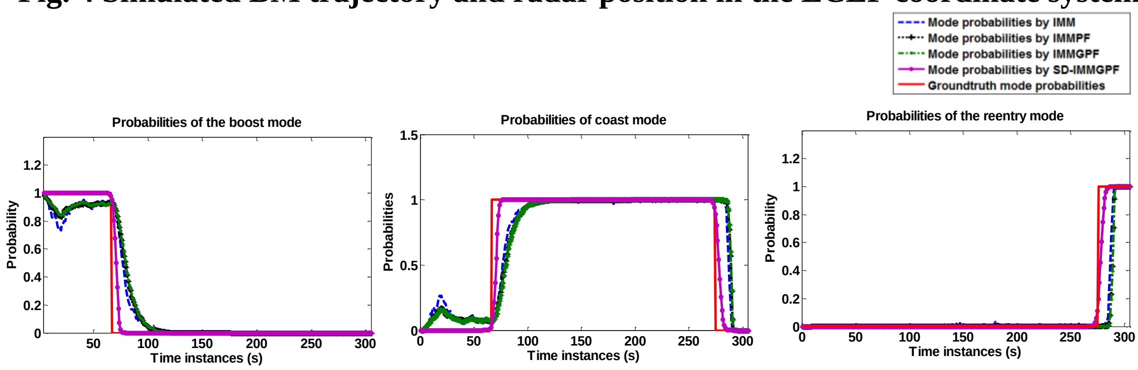


Fig. 5 Estimated mode probabilities by different methods

Comprehensive numerical comparisons are made between the proposed method and traditional IMM-based approaches using a simulated ballistic missile trajectory as in Fig. 4. The estimated flight mode probabilities and position/velocity RMSE using different methods are shown in Figs. 5 and 6. The proposed method (SD-IMMGPF) achieves the smallest position/velocity RMSEs during most of the time, especially during the time intervals right after the mode transition occurs, thanks to the more accurate mode estimation shown in Fig. 5.

The parameter estimation results using the proposed method are shown in Fig. 7, which include: initial thrust-to-weight ratio n, normalised mass burn rate q and ballistic missile coefficient β. From this figure, we can see that the estimated parameters converge to the ground truth correctly. Note that these estimated parameters can be used for the missile type identification and missile trajectory prediction.

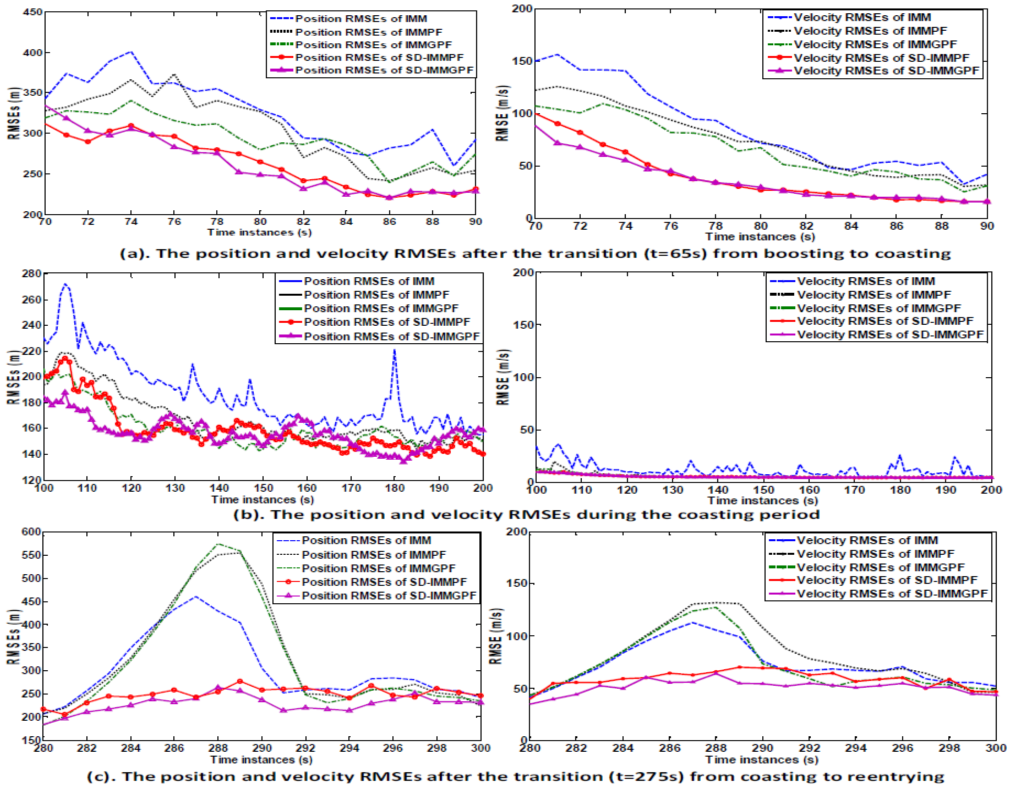
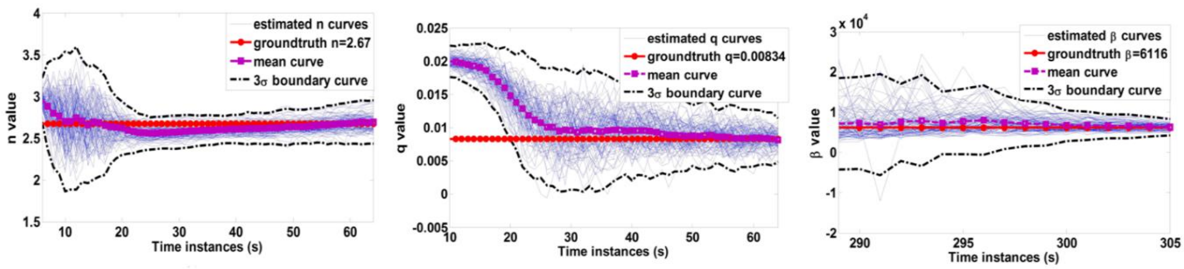


Fig. 6 The position and velocity RMSEs during different intervals



(a) n value (b) q value (c) β value

Fig. 7 BM parameter estimation from a hundred Monte Carlo simulations

4.2 Work package 2.2

4.2.1 Convex optimisations and robust SP (Sub Task 2.2-1, Completed/Ongoing)

Various convex optimization techniques have been developed for radar applications within the context of phased array radars and distributed multi-static radars in the first 24 months. The focus of the work in the last 12 months has been on convex optimization techniques for waveform design within a cognitive radar framework. Robust optimization techniques are under currently investigation.

4.2.1.1 Coordinated Waveform Design and Receiver Filter Optimization for Cognitive Radar Networks

We have developed convex optimization based waveform design for distributed cognitive radars (multi-static). The method exploits the statistical knowledge of the clutter environment and the target radar cross section to determine optimal transmission waveforms to achieve a number of desired performance criteria. The first criterion is to maximise SINR of particular radar while ensuring other radars in the network achieve a minimum required SINR. The second optimization aims to maximize the SINR of the worst case radar, i.e. Max-Min optimization. In both cases, the proposed method involves alternative optimizations for the receiver filter and the waveforms. The optimum receiver filters are designed based on generalized eigenvalue problem, while the waveforms are obtained using semi-definite relaxation based convex optimization methods.

We evaluated both the optimization techniques for the case of two radars. The initial (desired) waveforms are Fractional Fourier Waveforms that exhibit good auto-correlation and cross-correlation properties. As expected the SINR of the first radar decreases as the target SINR of the second radar increases as shown in Fig. 8 (left). For the max-min optimization, the SINRs of both radars are balanced as shown in Fig. 8 (right). The SINR seen at the first iteration is that achieved without waveform optimization (non-cognitive radar). As seen, this has been increased from -2dB to 3dB when the waveform is optimised. This performance is achieved while keeping good auto and cross correlation properties for both waveforms as shown by the auto and cross ambiguity functions in Fig. 9.

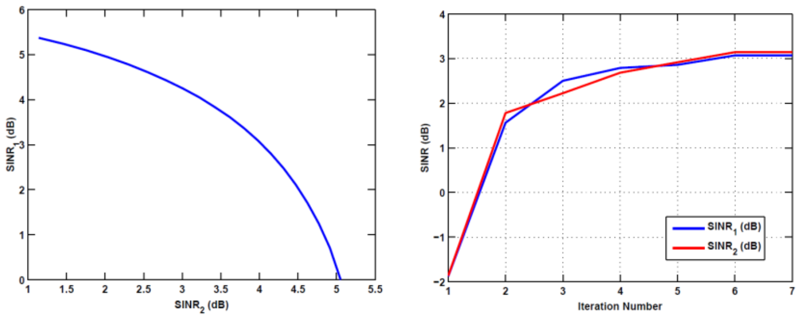


Fig. 8(left): The SINR of Radar 1 against SINR of Radar 2. Figure 8(right): The worst case SINR against iteration number.

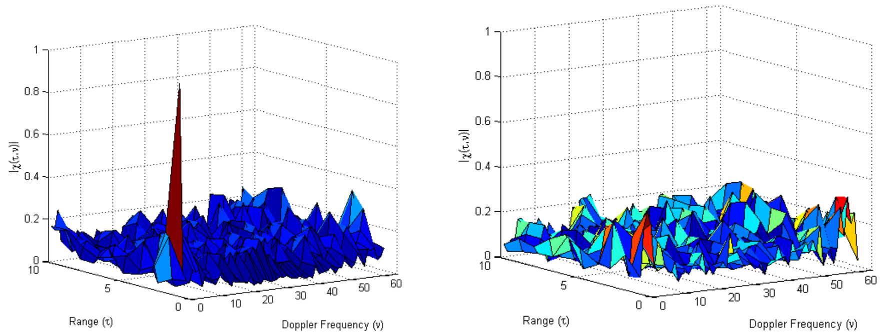


Fig. 9: Auto and Cross Ambiguity Functions of the optimized waveforms.

4.2.2 Radar and sensor applications (Sub Task 2.2-1, Completed/Ongoing)

4.2.2.1 Kalman-Gain Aided Particle PHD Filter for Multi-Target Tracking

In the traditional sequential Monte Carlo probability hypothesis density (SMC-PHD) filter, the particles appear to be scattered and it is difficult to guide particles to regions of interest. The filter's ability to estimate the posterior at a given time depends on how densely the state space is populated with samples and how well the estimated measurements match the actual measurements received in that time frame. The weights are then updated accordingly. The SMC-PHD filter does not provide for particle state correction to achieve particle improvement, i.e., it does not seek to reduce error between the actual measurement and the estimated measurement irrespective of the importance density chosen. We have proposed a novel approach that aims to apply particle state correction/improvement using the Kalman-gain to guide validated particles in the SMC-PHD filter to the region of higher likelihood to better approximate the posterior at each time step.

In order to demonstrate benefits of the proposed method, we considered a two-dimensional scenario with unknown and varying number of targets observed over a cluttered region of [-200,200] × [-200,600]. A total of 4 targets enter and exit the scene at various times. Fig. 10 shows the average of 100 MC simulations of the Kalman-gain SMC-PHD (KG-SMC-PHD) filter estimates of the target trajectories in both x and y directions superimposed with true target trajectories. As seen, with number of particles per existing target, $\rho = 500$ in the presence of high Poisson clutter rate ($r = 5$), the KG-SMC-PHD filter is able to correctly track the targets in both x and y directions.

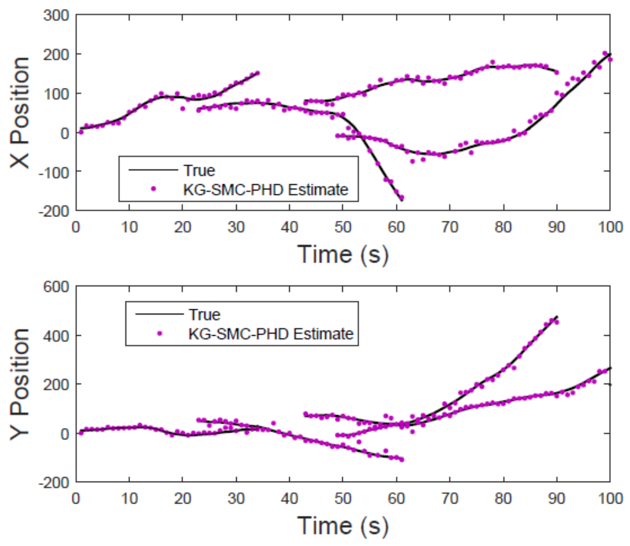


Fig. 10: KG-SMC-PHD filter estimates superimposed on true target positions in both x and y directions averaged over 100 MC runs

To further demonstrate the performance of the KG-SMC-PHD filter, the proposed filter was evaluated along with the Gaussian mixture (GM) PHD filter, the GM-unscented-SMC-PHD filter and the auxiliary particle (AP) PHD filter in addition to the traditional SMC-PHD filter. Table 2.2.1 shows the filter performance averaged over 100 MC runs with measurement set partition. Overall, under high clutter, the KG-SMC- PHD filter gives a better performance as it maintains high track continuity and low optimal sub-pattern assignment (OSPA) distance. This is mainly due to our particle state correction technique.

Table 2.2.1. Filter performance comparison in terms of OSPA distance, track continuity and CT for different filters for Poisson clutter rate = 5 per scan with measurement set partition

Filter	Track Continuity (%)	OSPA (m)	CT (s)
KG-SMC-PHD	90.38	19.06	6.07
SMC-PHD	68.94	52.26	10.45
GM-PHD	73.30	34.97	2.42
GM-USMC-PHD	83.05	26.35	16.47
AP-PHD	87.87	22.99	15.62

4.2.2.2 Game Theoretic Data Association for Multi-target Tracking with Varying Number of Targets

In multi-target tracking (MTT), the measurements received at each time step are corrupted and consist of indistinguishable measurements that may be either target originated or due to clutter. It is therefore crucial to ascertain which measurement is due to which target. The use of game theory allows for data association in non-linear and non-Gaussian scenarios and facilitates simultaneous data association rather than sequential data association. We have developed a correlated equilibria based data association techniques [10].

To demonstrate this method, tracking and association of target state estimates for four targets were considered. These targets enter and exit the tracking scene at various times. Fig. 11 shows the x and y components of each track against time. Triangular and circular dots denote the start and the end of a track respectively.

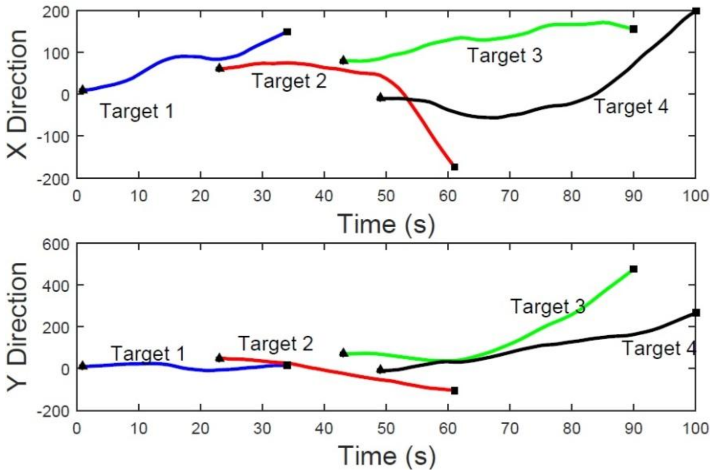


Fig. 11: Ground truth showing the plot of the true *x* and *y* components against time for the four tracks over 100 time steps.

Table 2.2.2 depicts the results averaged over 50 Monte Carlo simulations for different data association algorithms with 1000 number of particles used for the SMC-PHD filter. PDA is the probabilistic data association technique, JPDA denotes joint-PDA and GTDA denotes game theoretic data association, which is our proposed method. As seen, the GTDA provides the best performance both in terms of accuracy and computation time. The JPDA provides a similar level of performance in accuracy when compared to the GTDA but takes higher computational time. The GTDA requires a lower computation time.

Table 2.2.2: The performance of the proposed algorithm in terms of RMSE, track continuity and computation time (CT).

Algorithm	Track continuity (%) / RMSE				CT (s)
	Target 1	Target 2	Target 3	Target 4	
PDA	94.3 / 3.2	93.9 / 2.9	96.1 / 2.2	96.5 / 2.7	25.0
JPDA	95.3 / 1.1	94.4 / 1.1	96.7 / 0.9	96.0 / 1.0	22.4
GTDA	97.1 / 0.7	98.0 / 0.9	98.2 / 1.0	98.8 / 0.8	19.6

4.2.3 Game Theory (Sub Task 2.2-4, Completed)

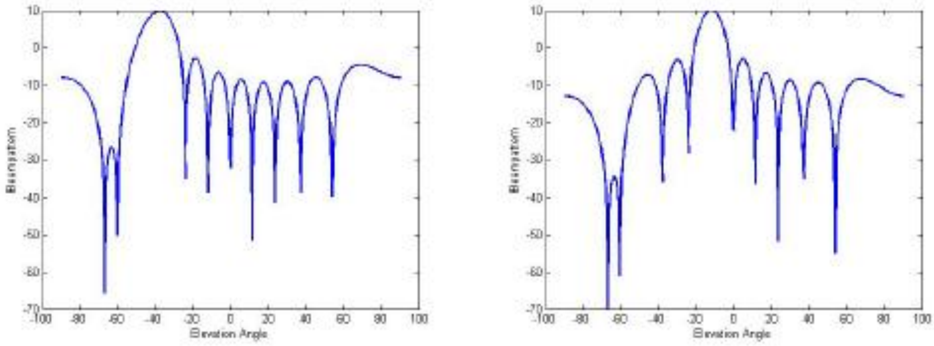
4.2.3.1 Distributed Waveform Design (reported in year 2 report and [6])

4.2.3.2 Distributed Power Allocation (reported in year 2 report and [8])

4.2.3.3 Distributed Beamforming

We have proposed and analysed a distributed beamforming and resource allocation technique for a radar system in the presence of multiple targets. The primary objective of the radars is to minimize the transmission power by performing optimal beamforming while satisfying certain SINR targets. This was solved using convex optimization methods and strategic non-cooperative game (SNG). To circumvent inefficient solution at the Nash equilibrium, we have developed a game theoretic approach incorporating a pricing mechanism, which introduces social fairness. We have also considered a scenario of co-existence of a surveillance radar with multiple tracking radars. This was solved using a leader-follower game known as Stackelberg game [7]. For all the game theoretic approaches, comprehensive mathematical analyses for the Nash equilibrium were presented [6-8].

The results for distributed radar beamforming with and without pricing have been presented in [7]. In order to demonstrate simultaneous operation of surveillance radar with tracking radars, we have considered a scenario where the surveillance radar was placed at direction 65^o from the first tracking radar and -67^o from the second tracking radar as reference. There are two targets -38^o and -12^o. Each tracking radar steers two beams towards both the targets. The beam pattern for the second tracking radar shown in Fig. 12 demonstrates that this radar steers beams towards the targets while steering deep null towards the direction of the surveillance radar (-67^o) to mitigate interference. Similar beam pattern was also observed for the first surveillance radar [7].



(a) Target 1 (dB). (b) Target 2 (dB).

Fig.12: **Transmit beam patterns for the second tracking radar.**

<u>4.2.3.4 Radar-Jammer interaction</u>

We have investigated a competitive power allocation problem for a radar system in the presence of multiple targets equipped with jammers. The main objective of the radar network is to minimize the total power emitted by the radars while achieving specific SINR targets, while the intelligent jammers have the ability to observe the radar transmission power and to consequently decide its jamming power to inflict maximum damage to the radars [11]. We solved this problem using non-cooperative game theoretic techniques and hypothesis testing. We have established the existence of the Nash solution through the Arrow-Debreu theorem. The uniqueness of this NE is guaranteed by proving that the utility function of each jammer is strictly concave and the best response function of the radar system is standard. We have also investigated a Stackelberg game for radar-jammer interaction in the presence of uncertainty.

5. Plan for the next year

For WP2.1, the focus is on:

1. Extending our current ballistic missile tracking work to the areas of missile type identification and missile trajectory prediction based on current algorithm/results for tracking/parameters estimation and more comprehensive domain knowledge; and
2. Chemical, Biological and Radiological (CBR) dispersion source estimation with the aid of local domain knowledge.

For WP2.2, the focus is on:

1. Extending the distributed game theoretic power allocation techniques in the presence of uncertainty on the radar cross section and the clutter statistics using a Bayesian game theoretic framework;
2. Extending the convex optimisation techniques for the cognitive radar waveform design to include channel and clutter uncertainty using a robust optimization framework; and
3. Developing a Bayesian framework for multiple target tracking, possibly incorporating cognitive radar environment.

6. **Outputs during the last year**:

1. M. Yu, C. Liu, WH. Chen and B. Li, “An enhanced particle filtering method for GMTI radar tracking”, to appear in *IEEE Transactions on Aerospace and Electronic Systems*.
2. M. Yu, H. Oh, WH. Chen and J. A. Chambers. “An improved multiple model particle filtering approach for manoeuvring target tracking using airborne GMTI with geographic information”, to appear in *Aerospace Science and Technology*.
3. M. Khan, M. Yu, P. Feng, L. Wang and J. Chambers, “An Unsupervised Acoustic Fall Detection System Using Source Separation for Sound Interference Suppression”, *Signal Processing*, Vol. 110, pp. 199-201, 2015.
4. R. Ding, M. Yu and WH Chen, “*A Multiple Target Tracking Strategy Using Moving Horizon Estimation Approach*”, *24th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Gothenburg, Sweden, 2015.
5. P. Feng, M. Yu, S. Naqvi, W. Wang and J. Chambers, “A Robust Student’s-t Distribution PHD Filter with OCSVM Updating for Multiple Human Tracking”, *23rd European Signal Processing Conference (EUSIPCO)*, Nice, France, 2015.
6. A. Panoui, S. Lambotharan and J.A. Chambers, “Game Theoretic Distributed Waveform Design for Multistatic Radar Networks,” to appear in IEEE Transactions on Aerospace and Electronic Systems, 2016.
7. A. Deligiannis, S. Lambotharan, and J.A. Chambers, “Game Theoretic Analysis for MIMO Radars with Multiple Targets,” IEEE Transactions on Aerospace and Electronic Systems, under second revision, Feb. 2016.
8. A. Deligiannis, A. Panoui, S. Lambotharan, and J.A. Chambers, “Game Theoretic Power Allocation and the Nash Equilibrium Analysis for a Multistatic MIMO Radar Network,” IEEE Transactions on Signal Processing, to be submitted, March 2016.
9. A. Daniyan, Y. Gong, P. Feng, J.A. Chambers, and S. Lambotharan, “Kalman-Gain Aided Particle PHD Filter for Multitarget Tracking,” IEEE Transactions on Aerospace and Electronic Systems, Submitted Nov. 2015.
10. A. Daniyan and S. Lambotharan “Game Theoretic Data Association for Multi-target Tracking with Varying Number of Targets,” IEEE Radar Conference, Philadelphia, May 2016.
11. A. Deligiannis, G. Rossetti, A. Panoui and S. Lambotharan, and J.A. Chambers, “Power Allocation Game Between a Radar Network and Multiple Jammers,” IEEE Radar Conference, Philadelphia, May 2016.

12. G. Rossetti, A. Deligiannis and S. Lambotharan, "Waveform Design and Receiver Filter Optimization for Multistatic Cognitive Radar," IEEE Radar Conference, Philadelphia, May 2016.

Two journal papers are in preparation:

1. M. Yu, H. Oh, WH. Chen and J.A. Chambers, "A GMTI Manoeuvring Ground Vehicle Tracking Method Aided by Geographic Information", plan to submit to *IEEE Transactions on Aerospace and Electronic Systems*.
2. R. Ding, M. Yu, H. Oh, and WH. Chen, "New Multiple Target Tracking Strategy Using Contextual Information and Optimisation Method", plan to submit to *IEEE Transactions on Systems, Man, and Cybernetics: Systems*.

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[R3] G. Bang, I. Kweon, "Multi-target tracking using social force model in discrete continuous optimisation scheme", *Electronic letters*, vol. 49, no. 21, pp. 1331–1333, 2013.

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[R5] W. Farrell. "Tracking of a ballistic missile with a-priori information", *IEEE Transactions on Aerospace and Electronic Systems*, 44(2):418–426, 2008.

[R6] J. Jung and D. Hwang. The novel impact point prediction of a ballistic target with interacting multiple models. In *13th International Conference on Control, Automation and Systems, Gwangju, Korea*, 2013.

L_WP3: (SS) Signal Separation and Broadband Distributed Beamforming

3.1 Staffing

Work Package Leaders: Dr Wenwu Wang (SU) and Prof John McWhirter (CU)
Other Academics Involved: Prof. Ian Proudler, Prof. Jonathon Chambers, Dr. Philip Jackson, Prof. Josef Kittler, Dr. Stephan Weiss, Dr. Yulia Hicks, and Dr Syed Mohsen Naqvi
Research Associates: Dr Mark Barnard
Research students: Mr Luca Remaggi (SU), Miss Jing Dong (SU), Mr Zeliang Wang (CU), Waqas Rafique (NU), Pengming Feng (NU), Mingyang Chen (SU)
Lead Project Partner: Macleod Malcolm (QinetiQ), and Richard Brind (Atlas Electronik)
Dstl contact: Julian Deeks (Naval Systems Dept), Nick Goddard (Naval Systems Dept), and Alan Johnson (Sensors & Countermeasures Dept)

3.2 Aims and Introduction

This work package concerns with the development of low-complexity robust algorithms for underdetermined and convolutive signal separation, broadband distributed beamforming, facilitated by low-rank and sparse representations, and their fast implementations, and the application of these techniques to the defence related problems, especially for processing underwater acoustic and sonar data, such as for signal denoising, source localisation, separation, extraction and tracking.

We aim at proposing novel methods to address the challenges in source separation in dense signal environment. This include extracting signals of interest and suppression of interference from corrupted sensor measurements, e.g. for the problems of convolutive mixing (i.e. multipath signal propagation), underdetermined mixing (i.e. more sources than sensors), and unknown number of target signals. This work package links to L_WP1 in weak signal detection; L_WP2 in unknown number of targets and order selection; L_WP4 in MIMO signal detection; and L_WP5 in data reduction.

L_WP3.1 is devoted to the problem of multichannel convolutive source separation and broadband distributed beamforming, with a focus on polynomial matrix decomposition techniques and their variants. L_WP3.2 focus on reverberant, underdetermined and noisy source separation, with a focus on the techniques such as robust statistics and bootstrapping, time-frequency masking, sparse representation, and Bayesian estimation. Both L_WP3.1 and L_WP3.2 have focussed on the underwater acoustic data e.g. the Portland 3 sonar datasets, with additional data including SAR image data and video datasets.

3.3 Available Datasets

Currently we have access to the following datasets:

- Portland 3 dataset
- An underwater acoustic channel simulator
- Surrey’s BRIR (Binaural Room Impulse Response) datasets
- Surrey’s RIR (Room Impulse Response) datasets
- CAVIAR (Context Aware Vision using Image-based Active Recognition) datasets
- PETS (Performance Evaluation of Tracking and Surveillance) 2009 datasets
- TUD datasets

3.4 Overview of Technical Progress

We have made a number of progresses in the past year, which are summarized as follows.

- We have developed an improved version of the SBR2 algorithm, i.e. MS-SBR2 (Wang et al. 2015b), for calculating the PEVD of polynomial matrices. The improved algorithm can provide much faster convergence than SBR2 when dealing with high dimensional polynomial matrices. In other words, the diagonalization of bigger MIMO channel matrices can be implemented faster than that of using the SBR2 algorithm. We have also developed a method to limit the redundant polynomial order growth for the resulting para-Hermitian matrix and the paraunitary matrix when performing the PEVD process using the MS-SBR2 algorithm. This method introduces a new time-shift strategy which keeps all the row (column) shifts in the same direction at each iteration.
- We have applied a recently proposed adaptive sparse sequential Bayesian approach for direction of arrival (DOA) estimation and denoising of underwater acoustic sources. This sparse reconstruction method is an extension of the classic Bayesian approach to a sequential Maximum a Posterior (MAP) estimation of the signal over time. A sparsity constraint is enforced through the use of a Laplacian like prior at each time step. An adaptively weighted LASSO cost function is sequentially minimised using the new measurement received at each time step. This algorithm was tested on the very challenging Portland03 dataset and presented in (Barnard and Wang, 2015).
- In collaboration with Atlas Electronik Ltd, we have studied sparse array configuration for robust underwater acoustic localisation and tracking. The sparse array technique has the potential to overcome the limitation that the maximum sensor spacing must be half of the wave length, in order to avoid spatial aliasing, allowing us to have arrays with larger apertures whilst having fewer sensors. This also potentially allows us to develop array configurations that are robust to the loss of one or more sensor, a very common problem with underwater hydrophone arrays. Several simulation studies have been performed including the changes of array response and array gain with respect to sparsity and noise levels.
- We applied the sparse analysis model based dictionary learning algorithm, i.e. Analysis SimCO which we proposed earlier, to the problem of multiplicative noise removal. Multiplicative noise, also known as speckle noise, often occurs in e.g. synthetic aperture radar (SAR) and sonar (SAS) images, due to the interference introduced in the data acquisition process. We developed two algorithms (Dong et al. 2015, 2016), for multiplicative noise removal, based on a data fitting model regularised by a term defined on the sparse analysis dictionary learned from data and another term enforcing smoothness of the signal. The algorithms have been evaluated on real SAR image data and show state-of-the-art performance as compared with several other baseline methods proposed recently.
- We have introduced a new mixed source prior to be used in both the independent vector analysis (IVA) and the fast fixed point IVA (FastIVA) algorithms. The proposed source prior is a mixture of multivariate super Gaussian and multivariate Student's t distributions for the IVA algorithm. The multivariate Student's t distribution has heavier tails which can be useful in modelling high amplitude components in voiced signals (Rafique et al., 2015). At the same time, the dependent super Gaussian distribution can be used to model the rest of the signals.
- We proposed a new analysis dictionary learning algorithm named Analysis SimCO (Dong et al., 2014) and also an extended version Incoherent Analysis SimCO by incorporating incoherent constraint. In these algorithms, the idea of simultaneous codeword optimisation used in the synthesis model dictionary learning has been adapted and applied to the analysis model. The algorithm iterates between the two steps: analysis sparse coding and dictionary updates, until it converges based on an error performance cost function. The Analysis SimCO algorithm has also been used for image denoising, SAR image despeckling and audio super-resolution.
- A new independent vector analysis method based on multivariate Student's t distribution has been introduced, where the Student's t distribution is used to model the dependencies between the frequency bins of frequency domain blind source separation. The advantage of the

Student's t distribution has been exploited in both the IVA and the FastIVA algorithms by changing the source prior from a multivariate Gaussian distribution to a multivariate Student's t distribution. The weight of the distributions in the mixed source prior is adapted according to the energy of the measured speech mixture signals according to the observed mixture signal.

- To improve source separation performance, we have also considered the use of the information from the data acquisation environment such as the locations of acoustic reflectors. To this end, we have studied several different acoustic reflector localisation methods, and also proposed new algorithms for acoustic reflector localisation, including image reversion based methods and time difference of arrival techniques (Remaggi et al., 2015a, 2015b, 2016a, and 2016b). We have evaluated the proposed methods and the baseline techniques on four real acoustic impulse response datasets collected in different rooms in University of Surrey.
- We have developed several methods to improve the performance of source tracking based on PHD filter including the use of Student's-t distribution in the prediction step of the particle PHD filter instead of the commonly used Gaussian distribution, which is then employed to build the joint distribution of the state model and the measurement noise in the particle PHD filter. In measurement model, a one class support vector machine (OCSVM) and a deep belief network are used to calculate weights for particles, in this way, the environmental noise from background subtraction step is mitigated. We have also used a social force model based MCMC resampling step to make the prediction step of the particle PHD filter more robust. In social force model, the interaction of targets with other targets and environment is considered, after calculating the social force for each particle, an energy function is created to represent the social force. The details about the methods and results can be found in (Feng et al. 2015a, 2015b, 2015c, 2016).

3.5 Technical Details

3.5.1 MS-SBR2 Algorithms

1) MS-SBR2 Algorithm in Broadband Optical MIMO Systems

In broadband MIMO systems, the channel is characterized by frequency-selective fading. In order to recover the transmitted data sequence corrupted by channel interference (CI), polynomial matrix singular value decomposition (PSVD) can be used to remove the CI by decomposing the frequency-selective MIMO channel into a number of independent frequency-selective SISO channels (Ta and Weiss, 2007), and the remaining inter-symbol interference (ISI) for each SISO channel can be eliminated by further equalization techniques, such as zero-forcing (ZF) equalization or maximum likelihood sequence estimations (MLSE).

One way for calculating the PSVD is based on the polynomial matrix eigen-value decomposition (PEVD) method, which is analogous to how the scalar matrix EVD can be used to generate the SVD of a matrix. In terms of this method, the second order sequential best rotation (SBR2) algorithm has been used in most of the existing literature. However, we have recently developed an improved version of the SBR2 algorithm, i.e. MS-SBR2 (Wang et al. 2015b), for calculating the PEVD of polynomial matrices. The improved algorithm can provide much faster convergence than SBR2 when dealing with high dimensional polynomial matrices. In other words, the diagonalization of bigger MIMO channel matrices can be implemented faster than that of using the SBR2 algorithm. Another motivation of introducing the multiple shift idea into the SBR2 algorithm is that it permits us to minimize the order growth of para-Hermitian matrices by making all row (column) shifts in the same direction (Wang et al., 2016a). However, this factor is currently being investigated and has not been taken into consideration in this work. Further details regarding this algorithm, including numerical examples and comparison of convergence, can be found in (Wang et al. 2015b).

In this work, we aim to examine how this improved SBR2 algorithm, i.e. MS-SBR2, can be exploited to solve the channel equalization problem for a broadband MIMO system. A conference paper (Wang et al., 2016a) has been written to summarise the key findings and it is currently under review. To demonstrate the proposed PSVD method, we applied it to a measured 2×2 broadband optical MIMO system in which the BER qualities are evaluated over a range of signal-to-noise ratios (SNRs). In addition, different transmission modes for each layer (each SISO channel) are analysed under a fixed spectral efficiency of 8 bit/s/Hz in order to see which transmission mode can achieve the best BER performance. In addition, this work has been conducted under the collaboration with Prof. Andreas Ahrens from University of Wismar, Germany. As another outcome of this collaboration, a conference paper (Ahrens et al., 2015) has been published in the 2nd IET conference on Intelligent Signal Processing.

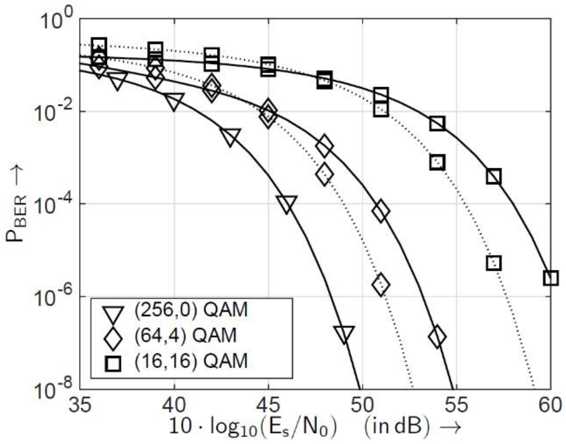


Fig. 3.1. BER with power allocation (dotted line) and without power allocation (solid line) by applying the PSVD method and zero-forcing equalization scheme, showing the comparisons among different transmission modes when transmitting over the optical 2×2 MIMO channel. Note that no power allocation scheme is needed for the (256,0) QAM transmission mode. Simulation results have shown that the activation of all transmission layers does not necessarily lead to the best BER performance. On the contrary, the (256, 0) QAM seems to achieve the best performance in the studied example.

2) Order-Controlled MS-SBR2 Algorithm for PEVD

Following on the development of the MS-SBR2 algorithm, we have found a new method which can limit the redundant polynomial order growth for the resulting para-Hermitian matrix and the paraunitary matrix when performing the PEVD process using the MS-SBR2 algorithm. This method introduces a new time-shift strategy which keeps all the row (column) shifts in the same direction at each iteration. Therefore it gives us the flexibility to remove the exact zero-valued outer polynomial coefficient matrices. A paper (Wang et al., 2016b) is currently being prepared regarding this work, and it will be submitted to the IEEE SAM 2016 conference very soon. Apart from that, further research activities have been conducted in terms of the multichannel spectral factorization using PEVD. The row-shift corrected truncation method (Corr et al., 2015) has been utilized to shorten the order of the spectral factor, and it has been compared against the conventional truncation method. This part of research has been published in the ACSSC 2015 conference (Wang et al., 2015a).

3.5.2 Adaptive Sparse Bayesian Algorithm for Source Localisation and Signal De-noising

We have evaluated a recently proposed adaptive sparse sequential Bayesian approach for *direction of arrival* (DOA) estimation and signal de-noising by Mecklenbruker et al (2013). This approach extends sparse reconstruction

methods to sequential data. This is achieved by extending the classic Bayesian approach to a sequential *Maximum a Posterior* (MAP) estimation of the signal over time. A sparsity constraint is enforced through the use of a Laplacian like prior at each time step. An adaptively weighted LASSO cost function is sequentially minimised using the new measurement received at each time step. This algorithm was tested on the very challenging Portland03 dataset. This dataset was collected at Portland harbour in the UK using two linear hydrophone arrays laid on the sea floor. The target, a small fishing boat, then performed a number of transits in the harbour in various directions. This dataset is particularly challenging with a lot of noise from both natural and man-made sources. Therefore an effective method is required for de-noising and localisation on this dataset.

In estimating the DOA of underwater acoustic sources we have the following linear model at time step *k*.

$$\mathbf{y}_k = \mathbf{A}\mathbf{x}_k + \mathbf{n}_k$$

where $\boldsymbol{y_k}$ is the signal from the sensor array, $\mathbf{A}$ is a matrix of steering vectors for each possible DOA, $\boldsymbol{x_k}$ is the sparse signal representation and $\boldsymbol{n_k}$ is additive noise. We wish to find the *Maximum a Posteriori* (MAP) estimate of $\boldsymbol{x_k}$, thus providing an estimate of the DOA for a number of sources at each time step *k*.

A weighted LASSO cost function is sequentially minimised using the new measurement received at each time *k*.

$$\zeta_k(\mathbf{x}_k) = \frac{\|(\mathbf{y}_k - \mathbf{A}\mathbf{x}_k)\|_2^2}{\sigma^2} + \mu \sum_{m=1}^{M} w_{km}|x_{km}|$$

where *M* is the number of possible DOA angles, σ^2 is the noise variance, $\boldsymbol{w_k}$ is a vector of weights on the DOA, μ is a parameter that controls the level of sparsity of the estimates $\boldsymbol{x_k}$. Full details of the algorithm can be found in (Mecklenbruker et al., 2013) and (Panahi and Viberg, 2012).

Here we present results on the Portland03 dataset. The sequence shown is of a small vessel moving beam on to a linear hydrophone array. The left figure shows the results of using traditional beamforming method, the right figure shows results of the method described above. More comprehensive results can be found in Barnard and Wang (2015). We have demonstrated that an adaptive Bayesian sparse representation can be used to accurately estimate and track the DOA of underwater acoustic sources. The results of these experiments show that imposing a sparsity constraint on the DOA can greatly reduce the amount of unwanted noise in the final result.

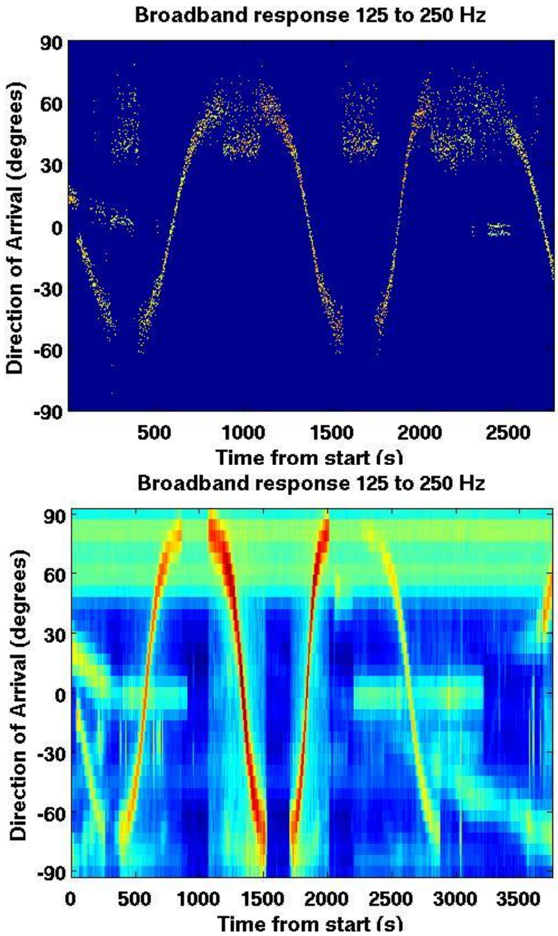


Fig. 3.2. DoAs estimated using the sparse Bayesian algorithm and with conventional delay-sum-beamformer.

3.5.3 Sparse Array Design

Here we investigate sparse array configuration for robust underwater acoustic tracking. This helps us overcome the limitation that the maximum sensor spacing must be half of the wave length, in order to avoid spatial aliasing. This allows us to have arrays with larger apertures whilst having fewer sensors. This also potentially allows us to develop array configurations that are robust to the loss of one or more sensor, a very common problem with underwater hydrophone arrays.

In order to create a sparse sensor configuration we employ a weighting vector $\boldsymbol{w}$ of length N for the sensors in the array. Using simulated data we perform a convex optimisation to ensure a minimum error in the array response whilst ensuring sparsity in $\boldsymbol{w}$. This convex optimisation is formulated as follows:

$$\min |\boldsymbol{w}|_1 \; subject\ to \; ||\boldsymbol{p_r} - \boldsymbol{w^H}\mathrm{A}||_2 \leq \alpha$$

where $|\boldsymbol{w}|_1$ is the l_1 norm of $\boldsymbol{w}$, $\boldsymbol{p_r}$ is the vector holding the desired beam response at a particular frequency Ω and DOA angle θ, A is the matrix composed of the steering vectors at the corresponding frequency Ω and DOA and α places a limit on the error between the desired and the designed responses. This minimisation was implemented using the CVX toolbox in Matlab.

We tested our proposed approach on simulated data. The results below show the response to a source simulated beam on (θ = 0 degrees) to the array. The simulated array was composed of 50 elements with an inter-element spacing of 2.5 metres. The upper two plots show the desired response and the response using the sparse vector $\boldsymbol{w}$, generated in the optimisation process. It can be seen that the response of the sparsely weighted vector is almost identical to the desired response. To increase the level of sparsity in $\boldsymbol{w}$ we select only the sensors corresponding to the peak values in $\boldsymbol{w}$, and this is shown in the lower plot. It can be seen that while some of the side lobes have increased the main beam is still approximately 5dB above the nearest side lobe.

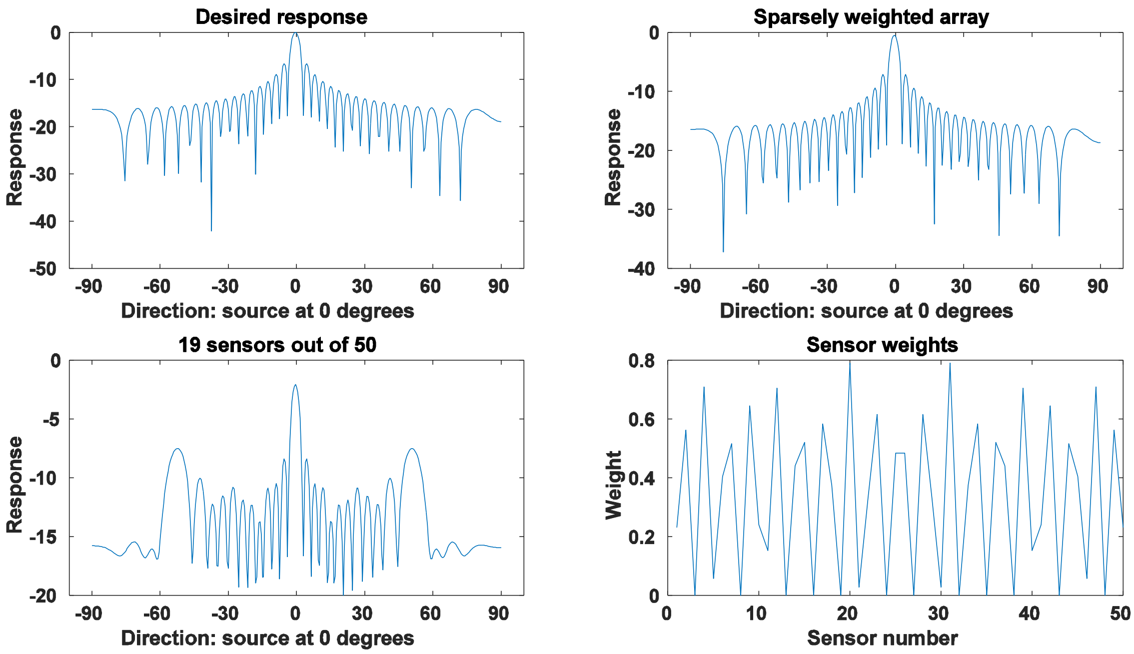


Fig. 3.3. Sparse array design example. Top left: desired response. Top right: sparse array response. Bottom left: array response with the increase level of sparsity. Bottom right: sensor weights.

We further investigated the effect of sparse array configuration on the array gain. Array gain is the ratio of the SNR of the array output and the SNR of a single hydrophone element, given by

$$AG = \frac{|\boldsymbol{w^H}\mathrm{A}|^2}{\boldsymbol{w^H} N_c \boldsymbol{w}}$$

where N_c is the noise coherence function, which we use to simulate a coherent noise source beam on to the array (θ = 0 degrees). The plots below show the array gain with the array steered to -50 degrees and 0 degrees. The effect of the noise source at 0 degrees can clearly be seen in the reduced array gain in that direction.

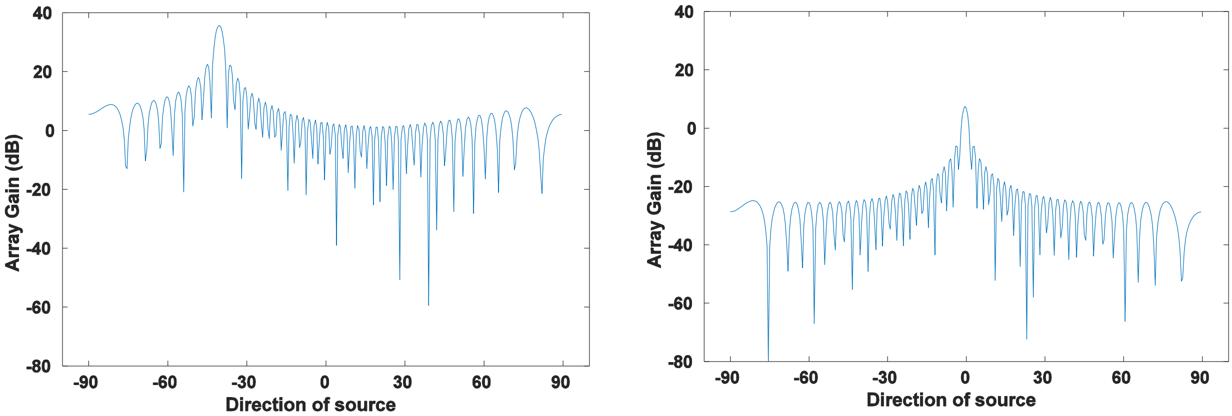


Fig. 3.4. Array gain with the array steered to -50 degrees and 0 degrees.

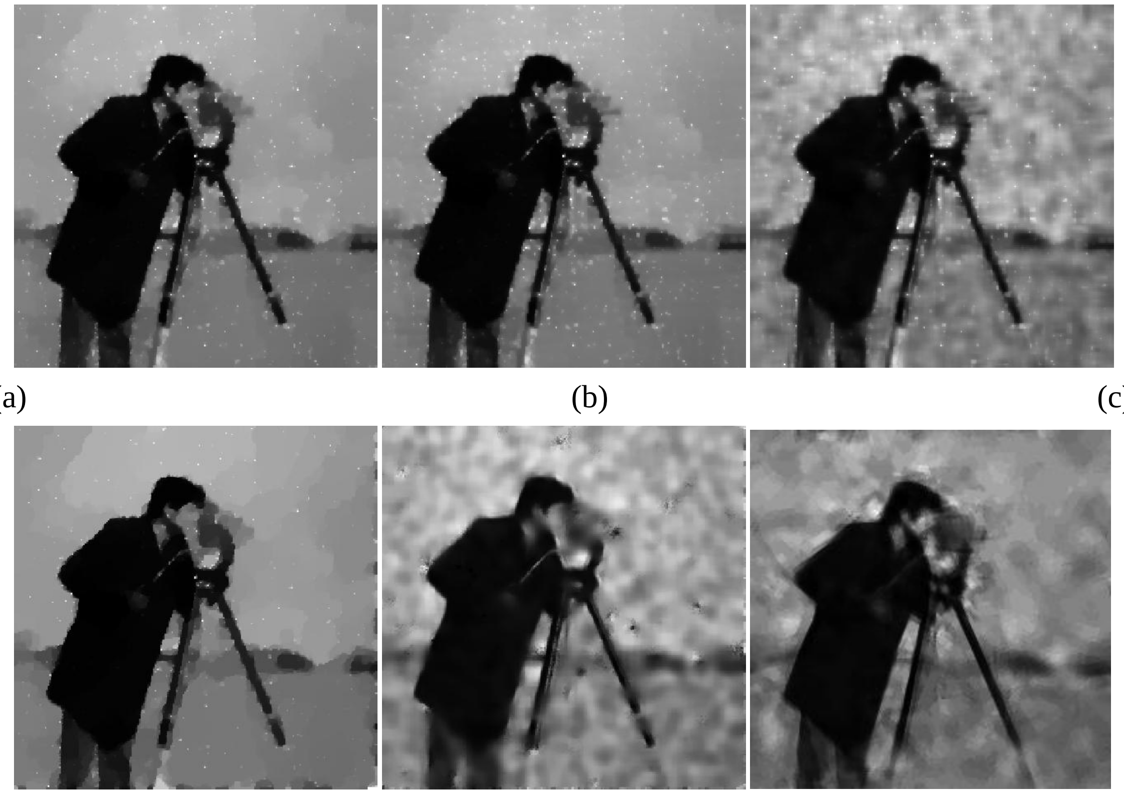
3.5.4 Removing Speckle Noise based on Regularised sparse analysis model

Multiplicative noise, also known as speckle noise, arises in many images, such as synthetic aperture radar (SAR) and sonar (SAS) images, which can be regarded as an effect of the interference phenomena in their acquisition processes. Compared to additive Gaussian noise often assumed in traditional image denoising, removing speckle noise is deemed to be more difficult for two reasons. First, the noise is multiplied with (rather than added to) the original image, which results in a non-linear relationship between observed and noise-free images. Besides, the widely used Gaussian distribution in image denoising is not suitable for characterizing the statistical property of the noise while the Gamma distribution is commonly employed instead, and thus the data fidelity term derived from the noise model is not quadratic, raising difficulties for optimization. Based on our previous work on analysis dictionary learning and its application to reducing additive Gaussian noise, we propose to remove multiplicative noise using analysis dictionary learning. In particular, two algorithms (Dong et al. 2015, 2016), for multiplicative noise removal have been proposed, which will be introduced in detail as follows.

The first algorithm is referred to as removing speckle noise by analysis dictionary learning (RSN-ADL). In general, RSN-ADL consists of two stages: analysis dictionary learning and image recovery. In the first stage, an analysis dictionary is learned from some image data using Analysis SimCO algorithm (Dong et al. 2016a). dictionary. This regularized optimization problem is solved with the alternating direction method of multipliers (ADMM). Experimental results on synthetic speckled images and real SAR images demonstrate the promising performance of the proposed algorithm. This work has been published in SSPD2015 (Dong et al. 2015).

According to our experiments, our proposed RSN-ADL is able to preserve details while reducing multiplicative noise, but the smooth regions are not well-recovered. Thus, we extended the reconstruction formulation in the RSN-ADL algorithm by introducing a smoothness regularizer. Since the dictionaries are usually well adapted to textures but not good as smooth areas, the employment of the smoothness regularizer has the potential to overcome this issue. This algorithm is referred to as MNR-ADL-SR (Dong et al. 2016b) and is going to be submitted to IEEE Transactions on Signal Processing. Specifically, the new reconstruction model is proposed which consists of a data fidelity term, a sparse analysis model based regularizer and a smoothness regularizer. The data fidelity term is derived from the log-likelihood function of the noisy image. The sparse analysis model based regularizer is constructed with an analysis dictionary learned via the Analysis SimCO algorithm (Dong et al. 2016a), and the smoothness regularizer is formed using the discrete derivatives in the horizontal and vertical directions. For the smoothness regularizer, two cases controlled by the power parameter of the term have been discussed, which are named as MNR-ADL-SR_1 and MNR-ADL-SR_2 respectively. For the optimization of the proposed model, two auxiliary variables are introduced to convert the unconstrained optimization problem to an equality-constrained problem, aiming to split the variables in the objective function. ADMM is carefully adapted to address the equality-constrained problem by constructing its augmented Lagrangian and updating the variables alternatively.

Experiments with synthetic images and SAR images have been performed to compare our proposed algorithms and several baseline algorithms including RSN-ADL. For the synthetic images, the denoising performance is evaluated with three quantities: Peak Signal to Noise Ratio (PSNR), Mean Absolute-deviation Error (MAE), and the Mean Structural SIMilarity Index (MSSIM). The denoising results found in one test for the “Cameraman” image are shown in Fig. 3.5. The average results over the 30 random realizations measured in PSNR, MAE and MSSIM are demonstrated in Fig. 3.6. The denoising results for a real SAR image are shown in Fig. 3.7. It can be seen, from the denoised images in Fig. 3.5, that the visual appearance of the results obtained by MNR-ADL-$SR_1$and MNR-ADL-SR_2 are better than those of RSN-ADL. MNR-ADL-SR_1 and MNR-ADL-SR_2 can preserve image details as well as RSN-ADL, but reconstruct the relatively smooth areas much better than RSN-ADL (see the background of the Cameraman image). This demonstrates the benefit of introducing the smoothness regularizer. When the noise level is relatively high, as shown in Fig. 3.6, our proposed algorithms obtain the best results for most cases in terms of the performance metrics, which indicates their superiority in removing a high level multiplicative noise compared with the baseline algorithms.



(f)

Fig. 3.5. Results for Cameraman (L=1). (a) MNR-ADL-SR$_1$ (PSNR=20.97 dB). (b)MNR-ADL-SR$_2$ (PSNR=20.89 dB). (c) RSN-ADL (20.62 dB). (d) MIDAL (20.86 dB). (e) MNR-DL-TV-2 (19.69 dB). (f) DNF (19.44 dB).

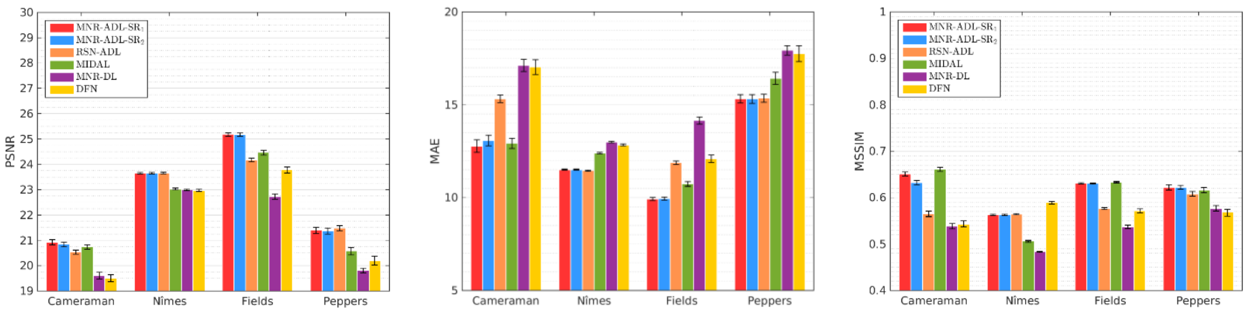


Fig. 3.6. Denoising results in PSNR, MAE and MSSIM based on 30 noisy realizations for the synthetic speckled images, with the noise level L=1.

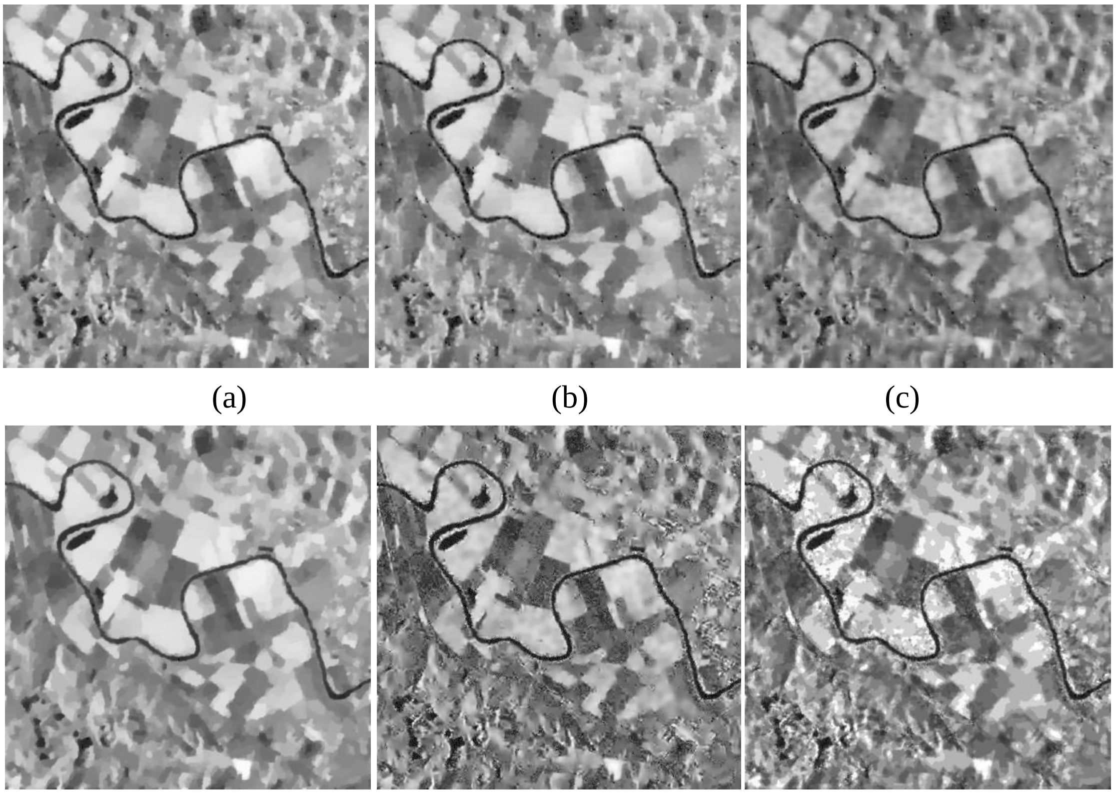


Fig. 3.7. Denoising results for a real SAR image. (a) MNR-ADL-SR_1. (b) MNR-ADL-SR_2. (c) RSN-ADL. (d) MIDAL. (e) MNR-DL-TV-2. (f) DNF.

9 3.5.5 Convolutive Blind Source Separation

Earlier work in blind source separation (BSS) has focussed on instantaneous mixtures, e.g. under the framework of independent component analysis (ICA) (Jutten and Herault, 1991; Haykin and Chen, 2005; Cichocki and Amari, 2002). In practical applications, such as in a so-called cocktail party environment (Cherry, 1953), a convolutive mixing model is often considered, leading to the convolutive BSS (CBSS) problem (Pedersen et al., 2007). Time domain methods for CBSS are generally computationally complex (Bingham and Hyvarinen, 2000). Therefore frequency domain (FD) methods are preferred (Parra and Spence, 2000). Although this approach reduces the computational cost, it introduces the permutation problem across the frequency bins. In recent years, independent vector analysis (IVA) was introduced as an extension of the ICA algorithm. The IVA algorithm can theoretically avoid the permutation ambiguity by using a dependent multivariate source prior instead of independent univariate source prior as in the case of the ICA algorithm (Kim et al., 2007). By using a dependent multivariate source prior, the dependency between different frequency bins of each source can be retained, whilst the independence between each source vector can be maximised. Recently, selecting the appropriate multivariate source prior to improve the separation performance of the IVA algorithm has become a research focus.

1) Multivariate mixed source prior

The separation performance of the IVA algorithm depends on the nonlinear score function which is used to preserve the inter-frequency dependency. We have introduced a new mixed source prior to be used in both the IVA and the fast fixed point IVA (FastIVA) algorithm. The proposed source prior is a mixture of multivariate super Gaussian and multivariate Student's t distributions for the IVA algorithm. The multivariate Student's t distribution has heavier tails which can be useful in modelling high amplitude components in speech signals, such as in voiced signals (Rafique et al., 2015). At the same time, the dependent super Gaussian distribution can be used to model the rest of the signals. Furthermore, the IVA and the Fast IVA algorithms using the mixed source prior are tested with real binaural room impulse responses and results are shown in the Figure 3.8. This work was presented in IET Intelligent Signal Processing conference, London, UK 2015 and in IEEE Sensor Array and Multichannel Signal Processing Workshop, Rio de Janerio, Brazil, 2016.

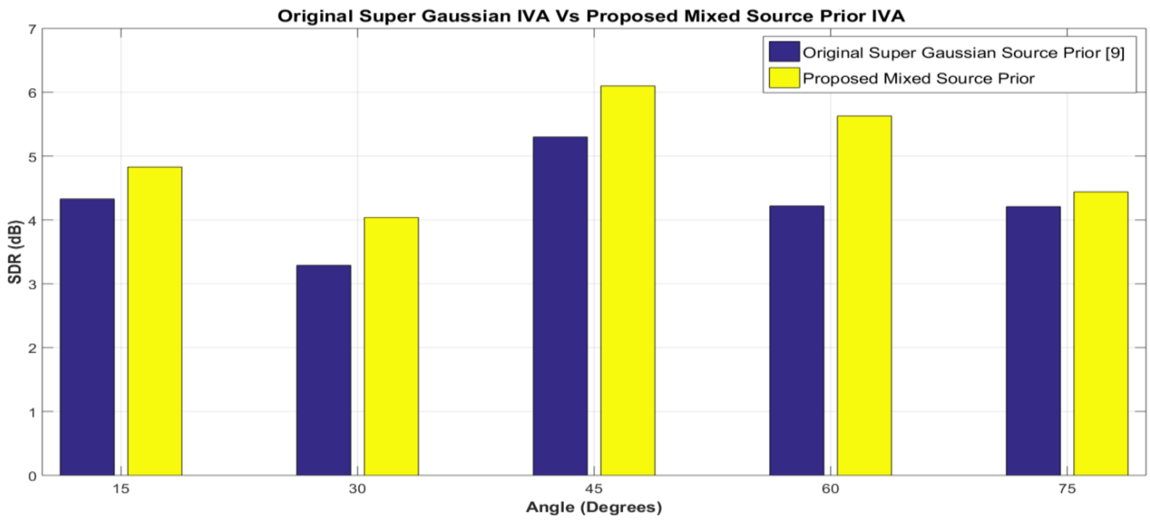


Fig. 3.8. The bar graph provides SDR (dB) for original IVA and proposed mixed source prior IVA for five different angles. Results are averaged over six random speech mixtures. The position of the source was varied in steps of 15◦ between 15◦ to 75◦. Real BRIRs were used. Our proposed mixed source prior yields a considerable improvement at all separation angles.

2) Energy driven multivariate mixed source prior

In order to further improve the separation performance of the IVA algorithm, the weight of both distributions in the mixed source prior should be automatically adapted according to the energy of the measured speech mixture signals and the source prior should adapt according to the observed mixture signal. Importantly, the method is found to be successful only with access to the mixtures not the original sources. Again, the separation performance of the IVA algorithm is evaluated in different realistic scenario with very high reverberation time and results are shown in Figures 3.9 and 3.10. This work is already submitted for review in EUSIPCO 2016.

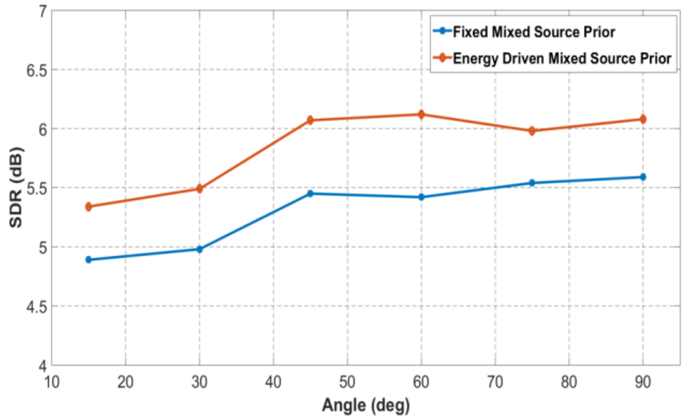


Fig. 3.9. The graph shows the results at different room types. Real BRIRs were used. Results were averaged over twelve mixtures at each angle.

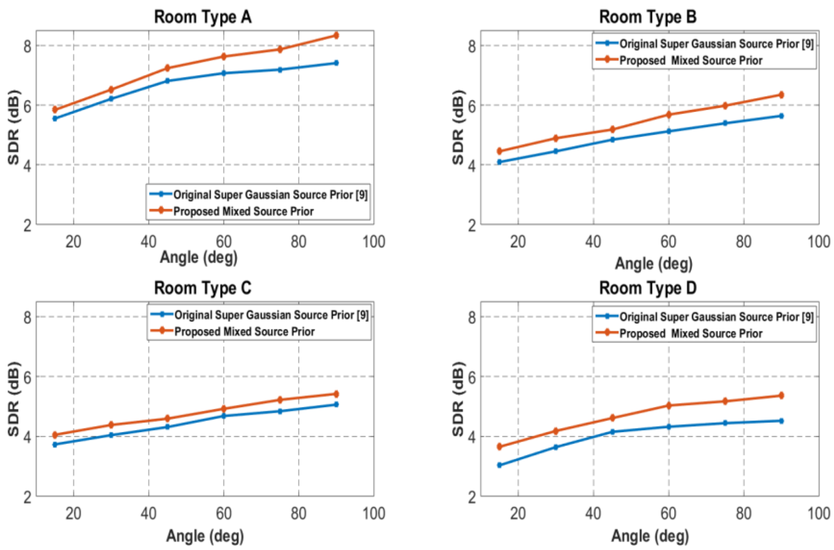


Fig. 3.10. The graph shows the performance of the fixed and energy driven source prior using BRIRs. Results were averaged over twelve mixtures at each angle.

10 3.5.6 Reflector Estimation

The work has been mainly focused on the comparison among different acoustic reflector localisation methods including state-of-the-art and proposed ones, in order to find the best performed method. The output has been used to start developing a source separation model, aiming to improve the results given by the source separation algorithm by Mandel et al. (2010). An additional work has also been done, implementing methods able to graphically visualize the information carried by multichannel room impulse responses (MC-RIRs), an important way to better understand wave-fields.
Starting with this last research topic, we presented at the 139th International AES Convention (Remaggi et al. 2015) the multiple MC-RIR datasets recorded in diverse rooms, using up to 60 loudspeaker positions and various uniform compact microphone arrays. Two data

parameter groups have been analysed: “raw data and direction of arrival (DOA)-time energy analysis” and “reflection and reflector localization”. Relatively to the first one, we presented a technique to visualize the DOA of acoustic energy over time. It is a visualization similar to (Melchior et al. 2010), achieved by steering a super-directive beamformer in each azimuth direction with a resolution of one degree. This representation can be considered as an evolution of (Hulsebos, 2004), where the author plotted the raw signals adjacent to one another in the time domain. These two types of visualization are reported in Figure 3.11. The second group of techniques (i.e. the “reflection and reflector localization”) aims to visualize the reflections and the reflecting surfaces. The first model is based on image sources. To localize the image sources, time of arrivals (TOAs) and direction of arrivals (DOAs) are utilized. The related reflector is drawn as the plane perpendicular to the line generated by the image source and the loudspeaker and passing through its mid-point. The position of the reflection is given by the intersection of the reflector and the line between the microphone array centre and the image source. In Figure 3.12, this visualization is shown.

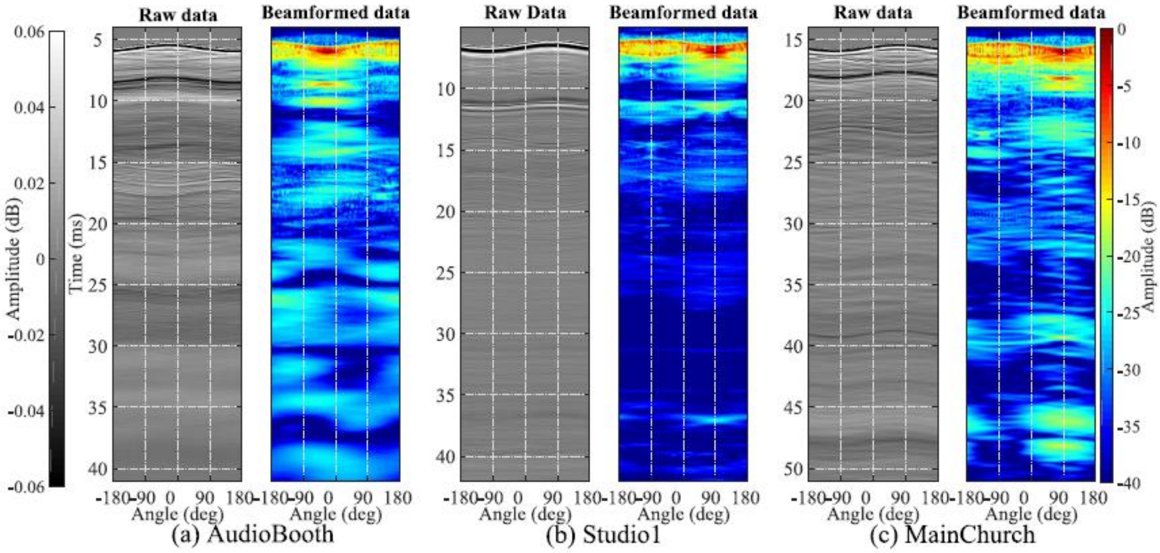
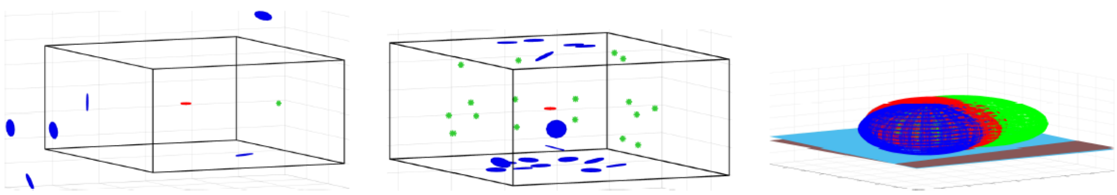


Fig. 3.11. Raw data and DOA-time energy (beamformed data) visualizations compared using three datasets.



(a) Six reflections (blue), one loudspeaker (green), UCA (red). **(b)** First reflection (blue) for every loudspeaker (green), UCA (red). **(c)** Ellipsoids, estimated plane (brown) and groundtruth (blue).

Fig. 3.12. Reflection and reflector visualizations.

Within the second part of this report, the main output of this year of research is presented. Through a journal paper (that is going to be submitted in the incoming weeks to the IEEE/ACM Transactions on Audio Speech and Signal Processing), three main contributions have been presented. The first one is an epoch detector, the clustered dynamic programming projected phase-slope algorithm (C-DYPSA), utilized to directly extract TOAs from MC-RIRs. The second contribution is given by the point based model (POM), which is a novel reflector localization technique based on firstly localizing the image source and then estimating the reflector position. In addition, four variants have been also developed, which are expanding the information exploited, using multiple loudspeakers. They have been named as: RANSAC-POM (R-POM), median-POM (M-POM), average-POM (AVG-POM), and least-square-POM (LS-POM). The third contribution is on the evaluation of the proposed novel reflector localization techniques, with respect to the performance of the quadratic surface based model (QSUM) that we have previously presented (Remaggi et al., 2015b), and two baselines (Tervo and Tossavainen, 2012), (Dokmanić et al., 2013). The results of this analysis are reported in Table 3.1 and Table 3.2. Since (Tervo and Tossavainen, 2012), (Dokmanić et al., 2013) used two image source locator algorithms which are different from our proposed in POM, in Table 3.1, the root mean square error (RMSE) is calculated considering the distance between the estimated images and their relative ground truth. Setting a threshold of 50cm, only fine errors are exploited for the RMSE calculation. The localization rate (LR) is the percentage of fine errors over the total of estimated images. The experiments have been performed over four datasets. Results show our image locator used in POM to be the best, compared to the state-of-the-art techniques.

	Localization rate (%)					**Root mean square error (mm)**				
	AudioBooth	Studio1	VML	Vislab	AVG	AudioBooth	Studio1	VML	Vislab	AVG
Tervo et al.	32	34	11	30	27	353±6	350±6	367±13	348±4	350±1
Dokmanic et al.	81	94	0	74	66	300±37	309±14	--	288±29	299±5
POM	**100**	**100**	**31**	**100**	**82**	**208±23**	**232±36**	**352±33**	**251±0**	**230±11**

Table 3.1. Performance comparison among image locator algorithms.

In Table 3.2, the comparison among the full reflector localization models considered is presented, showing our QSUM (Remaggi et al. 2015b) to be the best.

	Average RMSE + confidence interval (mm)				
	AudioBooth	Studio1	VML	Vislab	AVG
POM	86±5	46±9	148±14	47±16	82±24
R-POM	26±3	48±4	249±37	44±3	92±53
M-POM	92±8	54±5	120±4	70±3	84±14
AVG-POM	56±3	49±4	127±5	59±1	73±1

LS-POM	22±2	48±4	158±14	56±2	71±30
QSUM	**21±1**	**17±3**	**82±6**	**30±0**	**38±15**

Table 3.2. Comparison of reflector localization algorithms.

The last part of this work done during the last year has been starting to incorporate QSUM into a source separation technique. The method by Mandel et al. (2010) has been selected as the baseline, and, during the incoming months, a new probabilistic way to create separation masks will be proposed.

11 3.5.7 Source Tracking

The focus of this work is mainly on the social force model based MCMC-OVSCM particle PHD filter for multiple human tracking. This method is briefly summarised below.

After the prediction step of the particle PHD filter, the weights for each particle are calculated by the energy based social force model, which contains energy function for distance $E_{k,d}^{m,i}$, energy function for changing of angle $E_{k,\varphi}^{m,i}$, energy function for changing of velocity $E_{k,U}$ and energy function for changing of destination $E_{k,W}$:

$$E_{k,d}^{m,i}(n) = e^{\frac{||p_k^{m,i}+tv_k^{m,i}-p_k^n-tv_k^n||}{2\sigma_d^2}} \quad E_{k,\varphi}^{m,i}(n) = (1+\frac{(v_k^{m,i})^T v_k^n}{||v_k^{m,i}||\cdot||v_k^n||})^\beta$$

$$E_{k,U}(m,i) = e^{-\frac{||v_k^{m,i}-u^m||}{2\sigma_v^2}} \quad E_{k,W}(m,i) = e^{-\frac{\frac{(p_k^{m,i}-p_0^m)^T v_k^{m,i}}{||p_k^{m,i}-p_0^m||\cdot||v_k^{m,i}||}}{2\sigma_W^2}}$$

then the energy based social force for each particle is calculated as:

$$s_k^{m,i} = \prod_{n\neq m} E_{k,d}^{m,i}(n)E_{k,\varphi}^{m,i}(n)E_{k,U}(m,i)E_{k,W}(m,i)$$

After calculating the social force for each particle, all particles are fed into an MCMC resampling step to achieve more accurate prediction. In measurement model, the OCSVM classifier is employed to calculate the likelihood for particles, which is also aided by background subtraction. At last, the weights for the particles are updated by the update step of the particle PHD filter, and resampled in order to avoid the computational complexity growing exponentially. The proposed system is evaluated on the selected sequences from the CAVIAR, PETS2009 and TUD datasets. Results are presented in Figure 3.13 which shows that the proposed method improves the tracking performance.

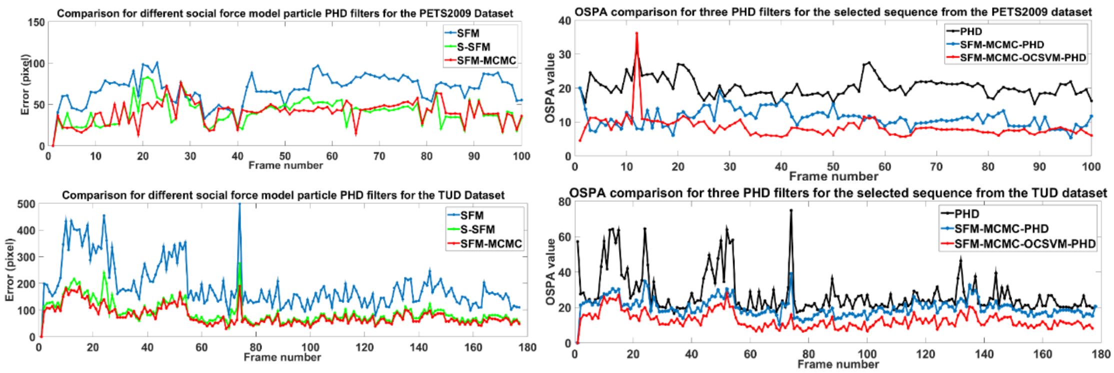


Fig. 3.13. Tracking performance of the proposed social force model based MCMC-OVSCM particle PHD filter as compared with baseline methods including PHD and SFM-MCMC-PHD.

3.6 Future Plans

- We will continue to improve the MS-SBR2 algorithm, and perform comprehensive testing for the MS-SBR2 algorithm to thoroughly evaluate its performance. Different types of dataset will be used to test the algorithm, such as large size random matrices, simulated MIMO data, and defence related data such as Portland 03 dataset.
- Based on the sparse array algorithms that we already developed, more simulations will be performed to evaluate its behaviour in a variety of situations including the sidelobe, array gain, and SNR. We intend to develop a joint sparsity model where the spatial sparsity is exploited together with the array sparsity. This work is currently undertaken by a new PhD student Mr Mingyang Chen who started his PhD at University of Surrey in January 2016. The performance of these algorithms will be evaluated both synthetically, as well as using real underwater acoustic data e.g. Portland 03 dataset.
- To further enhance the separation performance of the IVA algorithm, we are developing a new framework for the IVA algorithm by using the expectation maximization (EM) algorithm. We are evaluating this new framework by using the mixture of Gaussians as a source prior. By using the EM algorithm, weight of distributions in the Gaussian mixture can be adapted according to different speech signals, which can potentially improve the separation performance of the IVA algorithm. Furthermore we are planning to test the EM framework for the IVA algorithm by using other suitable statistical distributions that can better model the speech signals and improve the separation performance in the realistic scenarios.
- We will use the information of acoustic reflectors estimated by the proposed algorithms such as POM and QSUM to improve source separation performance. Informed source separation algorithms will be developed based on probabilistic time-frequency masking and EM algorithm. We will evaluate how much improvements could be achieved with the geometrical information obtained in the sensor operating environment. The methods could be also applied in a harbour environment for underwater acoustic application scenario.
- We intend to continue using the social force model to predict the dynamic model for targets, in order to make more robust measurement model and reduce the computational complexity. The method of sparse representation will be employed to calculate the weight for particles. A dictionary will be built in the optimization step of the sparse representation, in this way, more observation information can be utilized, hence improve the results of the tracking system.

3.7 Selected Activities and Engagements

Engagement with industry partners and Dstl:

- Atlas Electronik has been acting as a partner for the work package L_WP3.
- A joint project (of seven months) under the MoD MarCE scheme between Atlas and Surrey has started in September 2015 and is still ongoing. The project is titled "Array processing exploiting sparsity for submarine hull mounted arrays". Simulations have been performed for studying the performance of an array in terms of array gain and SNR under sparse array configuration.
- Julian Deeks and Wood Gary visited Surrey on 10th December. Wenwu Wang organised the showcase of the work done in Surrey including source separation, dictionary learning and sparse recovery. We have discussed the potential links of these work with Dstl's interest, in particular, on sonar imaging.

Engagement between partners:

- Joint work between Surrey University and Newcastle University has been conducted on sparse analysis model based dictionary learning and its use for signal recovery from noisy signals e.g. for image denoising and audio super-resolution.
- Discussion has been initiated between Surrey and Cardiff on developing joint polynomial dictionary learning method based on polynomial matrix decomposition techniques.

3.8 Outputs

During the past year, we have generated the following publications.

Published/accepted:

- Z. Wang, J. G. McWhirter, and S. Weiss (2015a), "Multichannel Spectral Factorization Algorithm Using Polynomial Matrix Eigenvalue Decomposition," in 49th Asilomar Conference on Signals, Systems and Computers, CA, USA, 2015.
- A. Ahrens, A. Sandmann, S. Lochmann, and Z. Wang (2015), "Decomposition of Optical MIMO Systems using Polynomial Matrix Factorization," in 2nd IET Int. Conf. on Intelligent Signal Processing, London, UK, 2015.
- Z. Wang, J. G. McWhirter, J. Corr, and S. Weiss (2015b), "Multiple shift second order sequential best rotation algorithm for polynomial matrix EVD," in EUSIPCO 2015, Nice, France, pp. 844-848.
- M. Barnard and W. Wang (2015), "Adaptive Bayesian Representation for Underwater Acoustic Signal De-noising", in Proc. 2nd IET International Conference on Intelligent Signal Processing (ISP 2015), London, UK.
- J. Dong, W. Wang, W. Dai, M. D. Plumbley, Z. Han, and J. Chambers (2016a), "Analysis SimCO algorithms for sparse analysis model based dictionary learning", IEEE Trans. Signal Process., vol. 64, no. 2, pp. 417-431, 2016.
- J. Dong, W. Wang, and J. Chambers (2015), "Removing speckle noise by analysis dictionary learning", in Proc. Sensor Signal Processing for Defence Conf., pp. 7193-7197, 2015.
- W. Rafique, S.M. Naqvi, P.J.B. Jackson and J.A Chambers (2015), "Independent vector analysis with multivariate Student's t distribution source prior for speech separation in real room environments,"IEEE ICASSP, Brisbane, Australia, pp. 474-478, 2015.

- L. Remaggi, P.J.B Jackson, P. Coleman, and J. Francombe (2015a), “Visualization of compact microphone array room impulse responses”, in Proc. of the 139th AES Convention (e-brief), New York, USA, 2015.
- L. Remaggi, P. J. B. Jackson, W. Wang, and J. A. Chambers (2015b), “A 3D model for room boundary estimation”, in Proc. of the ICASSP, Brisbane, Australia, 2015.
- P. Feng, W. Wang, S.M. Naqvi and J. A. Chambers (2015a), ‘‘A robust PHD filter with deep learning updating for multiple human tracking,’’ in Proc. IEEE International Conference on Digital Signal Processing (DSP), pp. 1227-1231, 2015.
- P. Feng, M, Yu, S. M. Naqvi, W. Wang and J. A. Chambers (2015b), “A robust Student’s-t distribution PHD filter with OCSVM updating for multiple human tracking,” in Proc. European Signal Processing Conference (EUSIPCO), pp. 2396-2400, 2015.
- P. Feng, W. Wang, S.M. Naqvi and J. A. Chambers (2015c), ‘‘Variational Bayesian PHD Filter with Deep Learning Network Updating for Multiple Human Tracking,’’ in Proc. Sensor Signal Processing for Defence (SSPD), pp. 1-5, 2015.
- P. Feng, W. Wang, S. M. Naqvi, S. Dlay and J. A. Chambers (2016), ‘‘Social force model aided robust particle PHD filter for multiple human tracking,’’ accepted by International Conference of Acoustics, Speech and Signal Processing (ICASSP), pp. 1-5, 2016.

Submitted/under review/under preparation:

- Z. Wang, A. Sandmann, J. G. McWhirter, and A. Ahrens (2016a), "Multiple Shift SBR2 Algorithm for Calculating the SVD of Broadband Optical MIMO Systems," in 39th Int. Conf. on Telecommunications and Signal Processing, Vienna, Austria, 2016. (under review)
- Z. Wang, J. G. McWhirter, J. Corr, and S. Weiss (2016b), "Order-Controlled Multiple Shift SBR2 Algorithm for Para-Hermitian Polynomial Matrices," 9th IEEE Sensor Array and Multichannel Signal Processing Workshop, Rio de Janeiro, Brazil, 2016. (under preparation)
- J. Dong, Z.-F. Han, Y. Zhao, W. Wang, and J. Chambers (2016b), “Sparse analysis model based multiplicative noise removal with a smoothness regularizer”, to be submitted to IEEE Trans. Signal Process.
- P. Feng, W. Wang, S. Dlay, S. M. Naqvi and J. A. Chambers (2015d), “Social force model based MCMC-OCSVM particle PHD filter for multiple human tracking,’’ submitted to IEEE Transactions on Multi-Media in December, 2015.

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L_WP4: MIMO and Distributed Sensing
End of Year report April 2015– Mar 2016.

Staffing
Work Package Leaders: Prof. John J. Soraghan (ST) and Prof. Ian K. Proudler (LU)
Other Academics Involved: Dr. Stephan Weiss, Prof.Sangarapillai Lambotharan
Research Associates: Dr Carmine Clemente (PDRA6- ST)
UDRC Research students: Mr Domenico Gaglione (PS6- ST), Mr Christos Ilioudis (PS5- ST)
Affiliated Research Students: Mr Jianlin Cao (ST), MrYixin Chen (ST), Mr Adriano Rosario Persico.
Lead Project Partner: Selex ES, Edinburgh
Dstl contact: Stephen Moore (Sensors & Countermeasures Dept), Brian Barber (Sensors & Countermeasures Dept)

Aims and the lists of the original L_WP4 in the case for support:
To develop novel paradigms for Distributed MIMO Radar Systems (DMRS).Links to L_WP1 & L_WP2 through anomalies; L_WP3 through exploiting sparsity and L_WP5 for decentralised processing. Advanced signal processing methods for active/passive DMRS will be investigated. The approaches aim to improve performance, reduce system requirements with the result of producing a set of algorithms suitable for robust applications in a cluttered networked battlespace. (T1,T3,T5,T8)

Progress made in the second year in addressing the original objectives

Staffing

In October 2015 Mr Alessio Izzo joined the group as a UDRC affiliated PhD researcher. He is currently researching advanced signal processing for echo-cancellation and micro-Doppler for quality assessment of loud-speakers. The Electronic Support Measures of Selex ES co-sponsored a PhD studentship that will start in October 2016. The student will be working on Fine-Time Resolution of Passive RF imaging.
UDRC affiliated PhD researcher, Mr Adriano Rosario Persico, has been invited by the Fraunhofer Institute in Germany for a 6-month internship. Mr Persico will be in Germany until August 2016. Mr Persico will continue the research on advanced signal processing algorithms for ballistic missile classification.

L_WP4.1 progress
The work developed at ST on WP4.1 focuses on the development of novel signal processing techniques, paradigms and systems for high performance distributed sensing. The work includes the development of new cognitive radars that are able to fuse together intelligently different radar technologies and information sources in a distributed sensing framework.
To this end, the work has concentrated in the following sub-areas during the third year.

- Dr Clemente led the research dealing with the development of a novel concept of multi-functional radar able to perform the communication and radar sub tasks at the same time with reduced additional resource requirements. Dr Clemente, Mr Gaglione, Mr Ilioudis and Mr Persico worked on the development of the novel concept of communicating radar using fractional order division multiplexing. The novel modulation scheme and the required processing have been developed by the team at Strathclyde. The proof of concept has been funded through a CDE project on Persistent Surveillance from the Air. Currently the hardware in the look validation of the concept has been successful. Future work will deal with the testing on field performing target ranging/micro-Doppler evaluation and data link. This work led to a conference paper at the IEEE Radar Conference 2016 [1] **L_WP 4.1-1**.

- The focus of UDRC PhD student Mr Ilioudis (PS5) has been on developing a novel framework for the evaluation of the ambiguity function in distributed MIMO environments. The novel ambiguity function provides a tool for the design of MIMO radar systems with low computational cost. The novel ambiguity function model will be presented at the IEEE Radar Conference 2016 [2] **L_WP 4.1-4**.

- The focus of UDRC affiliated PhD student Mr Jianlin Cao is on the design of femto-satellites to realize satellite swarms in the space. He has investigated technical challenges and constraints typical of this family of novel systems. In particular, he has assessed the performance of his design under various conditions, including errors on the localization of each satellite. Furthermore, the capability of the proposed system to generate SAR images has been assessed providing a quantification of the potential vs costs of the novel technology. This work led to a paper presented at the IAC conference [3] and has been presented to the SET for Britain competition 2016. **L_WP 4.1-2, 4.1-5**.

- The focus of affiliated PhD student Mr Yixin Chen has been the development of a novel equalization scheme for under water acoustic communication. The novel scheme introduces the Partial Fractional Fourier Transform concept to deal with double-dispersive channels. The outcome of this work has been published to SSPD 2016 [4] **L_WP4.1-1, L_WP4.1-2**.

L_WP4.2

The work developed at ST on L_WP4.2 focuses on the development of novel signal processing techniques and algorithms for distributed systems. To this end, we have concentrated in the following sub-areas in the third year.

- For L_WP4.2 Dr Clemente has focussed on the investigation of novel algorithms Automatic Target Recognition from SAR images and micro-Doppler signatures. A low computational cost algorithm exploiting Krawtchouk moments has been developed. The novel algorithm has been compared with the Pseudo-Zernike based algorithm previously developed in this work-package and has shown higher classification accuracy with smaller computational cost. This work led to a journal paper [5] and to a conference paper published at the IEEE Radar conference 2016 [6], **L_WP4.2-1, 4.2-4**.

- In collaboration with the University of California Los Angeles, Mr Ilioudis developed a novel algorithm for Edge detection from SAR images. The algorithm exploits phase stretch transform and allow multi-scale edge detection. This work was presented at the ISP conference 2015 [7], **L_WP4.2-2, 4.2-4**.

- Dr Clemente has investigated the benefits of distributed MIMO configurations for the specific application of border control using micro-Doppler information. This work, in collaboration with TOBB University in Ankara led to the submission of a paper to EURAD 2016 conference [8], **L_WP4.2-5, 4.2-3**;

- Dr Clemente (PDRA6) investigated the design of a polarimetric decomposition framework for Synthetic Aperture Radar images. This work, developed in collaboration with the University of

Naples led to the submission to a IEEE Transaction on Geoscience and Remote Sensing [9], **L_WP4.2-2.**

- Dr Clemente worked also on impact of the algorithms developed in this work package on other application areas. In particular, the benefit of micro-Doppler analysis and classification for assisted living applications has been evaluated. The work has been developed in collaboration with the University of Cranfield and TOBB University in Ankara and led to a Journal paper [8]. Furthermore, the application of the novel micro-Doppler classification algorithms has been also investigated in the automotive domain. It is anticipated that this work will lead to a conference paper.
  Additionally, a feasibility study has been developed in collaboration with the Centre for Ultrasonic Engineering of the University of Strathclyde aimed to investigate the application of micro-Doppler for high-speed non-destructive evaluation. This work is currently evaluated by the Research Centre on Non Destructive Evaluation for further financial support.
  Finally, applications of array processing and micro-Doppler for public address systems and loud-speakers quality assessment has been investigated in collaboration with Tannoy LTD. The PhD student Alessio Izzo has started working on this topic, co-funded by the University of Strathclyde and Tannoy LTD.

- UDRC PhD student Mr Domenico Gaglione (PS6) worked on the development of an algorithm for Krawtchouk moments based target recognition from SAR images. This research led to a journal paper [5]. Mr Gaglione has also worked on the extension of his sparse representation algorithm for helicopter classification to the multi-target scenario and to the general rigid body target scenario, including ballistic missiles **L_WP4.2-1, 4.2-4, 4.1-2, 4.1-3**.

- The focus of affiliated PhD student Mr Adriano Rosario Persico has been the development of a Krawtchouk based algorithm micro-Doppler based classification of ballistic missiles. This work led to a conference publication [6]. Additionally, he reviewed the literature in the field of sparse representation and compressed sensing algorithms for ballistic missiles imaging and space situation awareness. From February 2016 Mr Persico is with the Fraunhofer Institute in Germany for a 6-month internship **L_WP4.2-1, 4.2-4**.

Technical Highlight

Ambiguity Function for Distributed MIMO Radar Systems

In recentyears multiple-input and multiple-output (MIMO) radar systems have attracted the interest of the research community due to their potential to increase significantly their performance compared to traditional phased array radars. Generally, MIMO radar systems are classifies into two categories: distributed and collocated, depending on how the antennas of each system are placed. The collocated configuration is similar to the phased array systems with all the antennas placed in a close proximity. This orientation offers superior parameter identification, direct applicability of
adaptive non-parametric techniques for parameter estimation, enhanced performance of parametric algorithms and flexibility of transmitted beampattern designs. In the distributed or statistical structure the antennas are widely scattered in a large area. This configuration allows spatial diversity in terms of independent target observations and enhanced target localization and detection performance.
The Ambiguity Function (AF) is one of most common tools used to evaluate the performance of a radar system providing information regarding the resolution, estimation accuracy, probability of detection and false alarm etc. In the case of mono-static radar systems the AF is defined as the response of a filter matched to the transmitted signal for different time

delays and Doppler shifts in the received signal. However, the application of the same concept is not sufficient to evaluate a MIMO radar system since parameters such as the geometry of the system and the degree of orthogonality (cross-correlation) between the operating waveforms play significant role in the overall performance

of the system. In recent years various formulations of AF for multi-static radars have been proposed. In our work a

definition based on the maximum likelihood (ML) parameter estimation and on the concept of information theory is used. In this work a mathematical analysis has been undertaken in order to extract the AF in terms of signal-to-noise ratios (SNRs) and matched filter output

The performance anaysis of the proposed multistatic AF was performed for different scenarios.

Firstly a 4x4 MIMO sensor system was examined for varying and constant energy parameter in a medium SNR scenario. In the second scenario the same analysis was conducted for high SNR . In the thrd scenario the system is examined for

a varying transmitting power between the transmitters. For all the cases the carrier frequency is set at 2 GHzand a 30x30 square meters surveillance is examined. Additionally all the antennas are considered omnidirectional with unitary gain and the non-free space losses are set to 0.

The sequences used in the system are a set of quasi-orthogonal linear frequency modulated (LFM) waveforms. Specifically, typical full up and full down chirps are used together with a two-third up and one-thirds down chirp and a one-thirds up and two-third down chirp. The reason for this design is to achieve low the cross-correlation between all the waveforms in a simultaneous transition while ocupyiing all the available bandwidth. In this case the maximum crosscorrelation level is -27 dB which is close to the inverse of the time-bandwidth product.

For the geometry of the system, the transmitters and receivers are placed in pairs on a circle with 5 m radius centred at the center of the surveillance area. The geometry of the described system is illustrated in Figure 1.

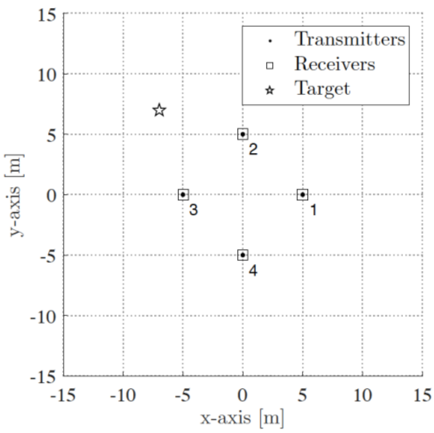

Figure 13 Sensors and Target geometry in the surveillance area

Scenario 1

In the first scenario the system is examined for varying and constant energy parameter. Additionally all transmittershave the same transmitting power. Figure 2 illustrates the AF of the examined system for varying and constant SNRon a logarithmic scale.

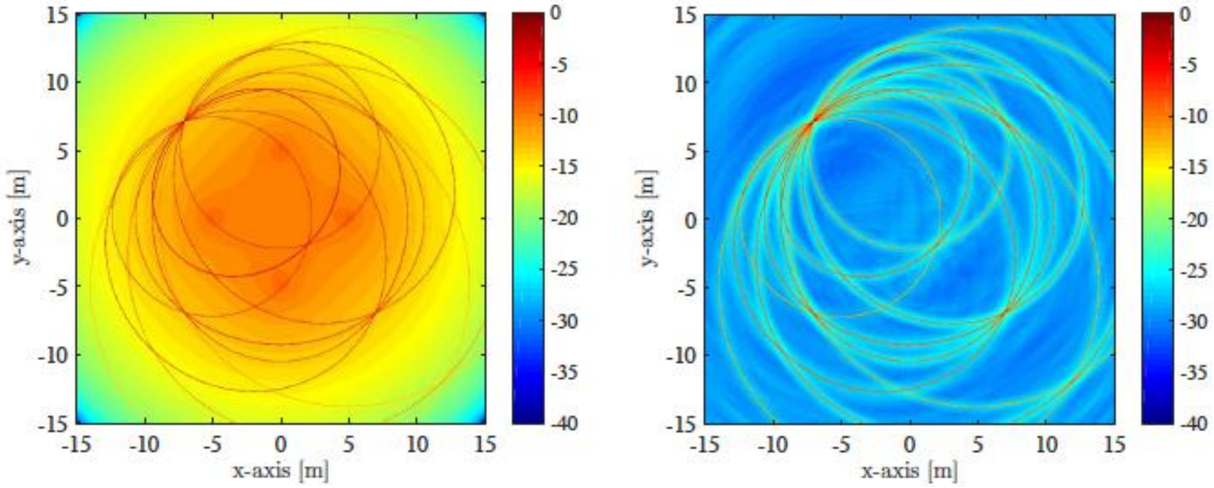

Figure 14 Multi-static AF of the system described in Scenario 1 with (left) varying and (right) constant energy parameter

The value of the SNR in the constant case was set equal to 28.7 dB which in the average of the varying case. Comparing the two sub-plots in Figure 2 it can be observed that the AF for varying energy parameter has significantly higher floor level and side lobe levels (SLL) (see sub-figure (left)) compared to the case where the energy parameter was constant (see sub-figure (right)). This phenomenon is very significant in a multi-static system as each pair of sensors experiences different SNR that depends on the systems geometry and the targets position. It is therefore very important to choose the correct model when evaluating a system.

B. Scenario 2

For the second scenario the same design as the first is considered , however with a higher SNR.

The sub-figure (left) in Figure 3 illustrates the AF for varying energy parameter and average SNR = 58.7 dB. Comparing these results with those in Figure 2 it can be seen that the difference between AFs of varying and constant energy parameters is less noticeable for higher SNRs.

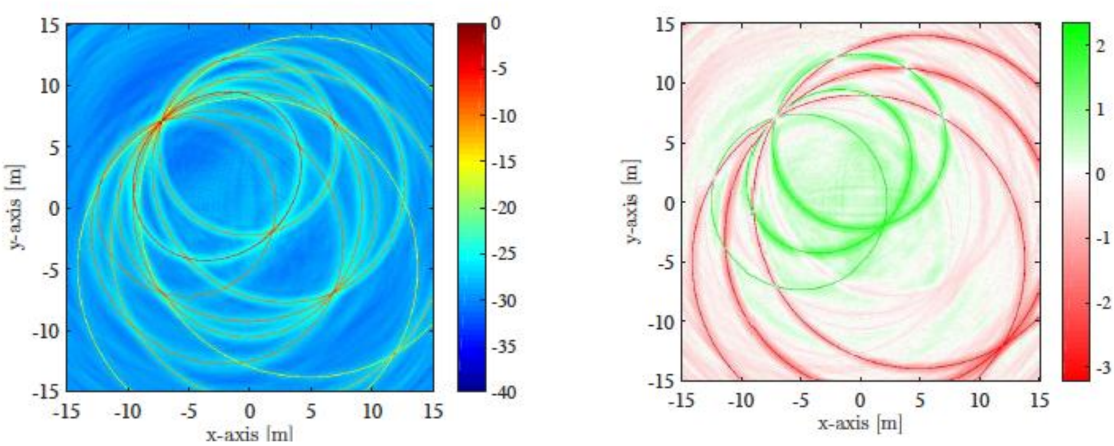

Figure 15 (left) Multi-static AF of the system described in Scenario 2 with varying energy parameter, and (right) its ratio after dividing each elements with those of an AF with constant energy parameter

Additionally sub-figure (right) in Figure 3 illustrates the result in logarithmic scale after dividing the AF in sub-figure (left) by the elements of an AF with constant energy parameter and SNR equal to the average of the varying case. To better evaluate the results it should be considered that in an AF lower values outside the target's resolution bin can be translated to better detection/resolution performance. Therefore positive values (see green color in sub-figure (right)) indicate areas where the system performs better assuming constant energy parameter while negative values indicate areas where the system performs better under the assumption of varying energy parameter. In the examined case this difference can higher than 3 dB.

C. Scenario 3

In the third scenario the system with varying energy parameter presented in Scenario 1 is examined with the transmitted power also varying in each transmitter.

Figure 4 illustrates the ratio between the elements of an AF with uniform transmitting power and one with non-uniform.

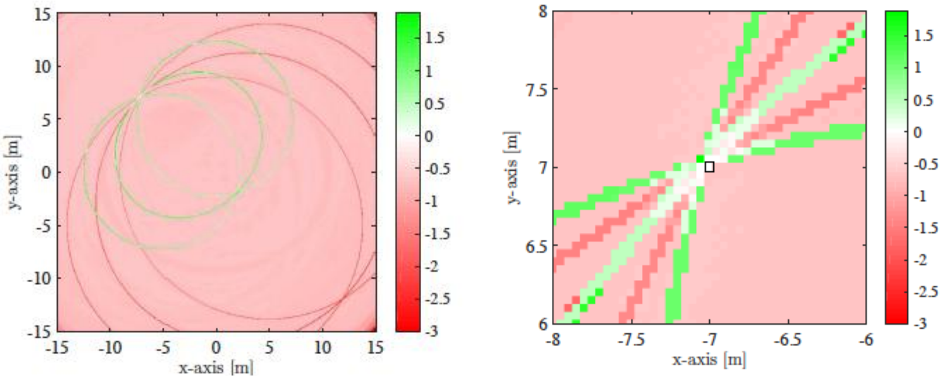

Figure 16 (a) Ratio between AF with uniform and non-uniform power allocation as described in Scenario 2, and (b) zoomed region close to the area of the target denoted by the black square.

In the non-uniform case transmitters 1 and 4 are using 50% more power than the uniform case while transmitters 2 and 3 are using 50% less. Therefore the total power consumption is the same in both cases. From the results it can be seen there is a trade off in performance between side-lobes occurring from the mono-static and bi-static configurations of pairs 1 and 4 , and those occurring from 2 and 3 . Inspecting the area close to the target (Figure 2(b)) it can also be observed that by increasing the power of the distant transmitters it is possible to decease the intensity at the range bins close to the target. This can increase the resolution in areas close to the target whith however increasingthe side lobe levels in distant areas.

In summary a novel multi-static AF basedon a distributed MIMO radar systems framework and the Kullback directed divergence was developed. The novel approach provides a powerful design tool with limited computational cost. Theoretical analysis showed that the AF is maximally stretched between 0 and 1 while also being flexible for various system assumptions. Simulation results showed the importance of making the correct assumptions and the impact that they have in the performance of the system. Finally a scenario of varying power allocation was examined, showing how increased resolution can be achieved by trading with higher side-lobe level.

Fractional Fourier Based Waveform for a Joint Radar-Communication System

The increasing demand of spectrum resources and the need to keep the size, weight and power consumption of modern radars as low as possible, has led to the development of solutions like joint radar-communication systems. In this sub task a novel Fractional Fourier Transform (FrFT) based waveform design was developed for joint radar-communication system (Co-Radar), which can generally be employed whenever there is the need to perform radar operations and send information to one or multiple receivers.
Conventional OFDM uses the Fast Fourier Transform (FFT) to map the in-phase and quadrature (IQ) samples to different frequency shifted sub-carriers. In our FrFT based OFDM system the FrFT based multiplexer maps the IQ symbols to different chirp sub-carriers. Its block diagram, together with the de-multiplexer, is shown in Figure 5.

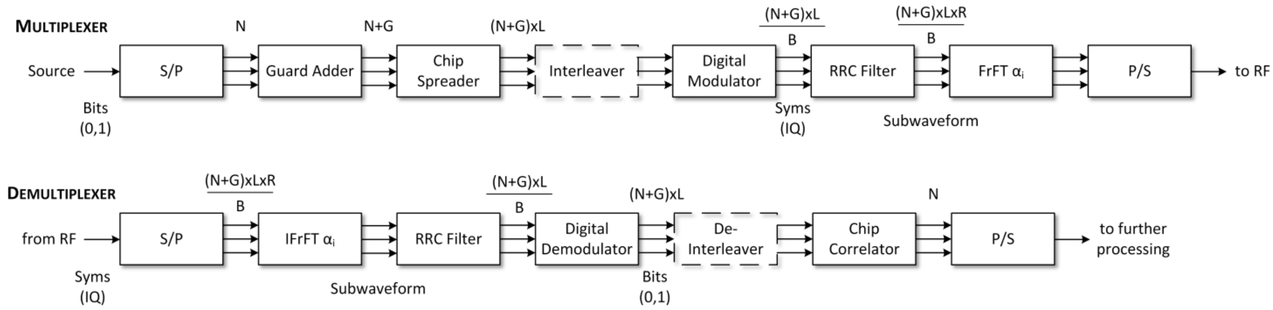

Figure 5. Block diagram of the (top) Multiplexer and (bottom) De-Multiplexer of the developed Co-Radar waveform design framework.

Serial-to-Parallel, guard adder, chip spreader, interleaver (optional), digital modulator and multi-rate Root Raised Cosine (RRC) filter blocks are common for a generic multiplexing scheme. The FrFT block is the key stage, which facilitates the generateion of a waveform with uniformly spaced chirp sub-carriers as shown in Figure 6a.

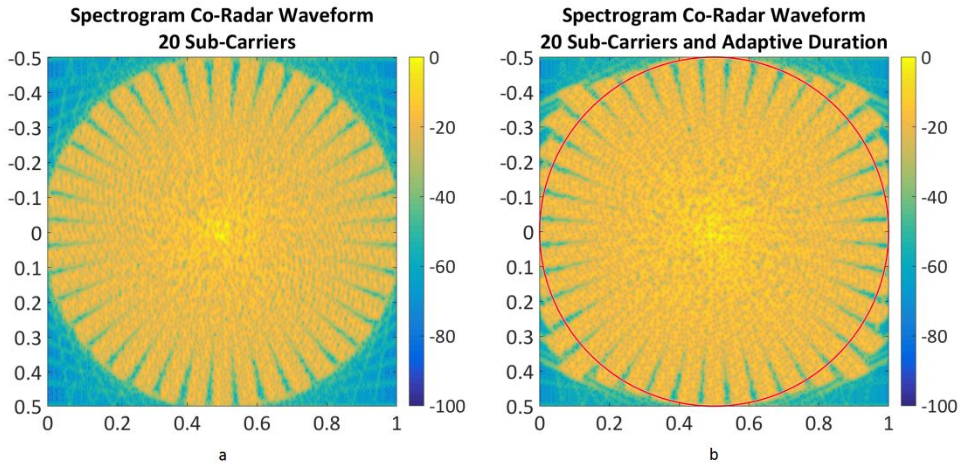

Figure 6. Spectrogram of a FrFT Based Co-Radar Waveform with 20 sub-carriers, (a) without and (b) with the implementation of the adaptive duration.

Different approaches were also proposed in order to better exploit the available bandwidth, such as the use of chirp sub-waveforms with adaptive duration (Figure 6b), and to mitigate the Inter-Carrier Interference (ICI), such as, for example, the employment of an interleaver.
The Co-Radar waveform was shown to have radar performance comparable to the most common Linear Frequency Modulated (LFM) pulse, as shown in Table I. Although it is outperformed in all the parameters except the zero-Delay cut SSL, the developed modulation

scheme can still provide acceptable performance taken into account its additional capability to send information.

Table I. Radar Performance Parameter.

	Co-Radar	LFM
Doppler Resolution	$86.8\ kHz$	$60.4\ kHz$
Range Resolution	$44.4\ cm$	$28.5\ cm$
Bandwidth ($-3dB$)	$183.7\ MHz$	$265.4\ MHz$
Zero-Delay Cut SSL (MAX)	$-7.15\ dB$	$-6.65\ dB$
Zero-Doppler Cut SSL (MAX)	$-8.05\ dB$	$-13.0\ dB$

The communication results are shown in Figure 7. The Bit Error Ratio (BER) are seen to be lower than 10^{-3} and 10^{-2} when 10 and 20 sub-carriers are used, respectively, in the worst scenario, that is the Lognormal-Rice channel, which simulates a communication channel with Line-of-Sight (LOS) and bad weather conditions.

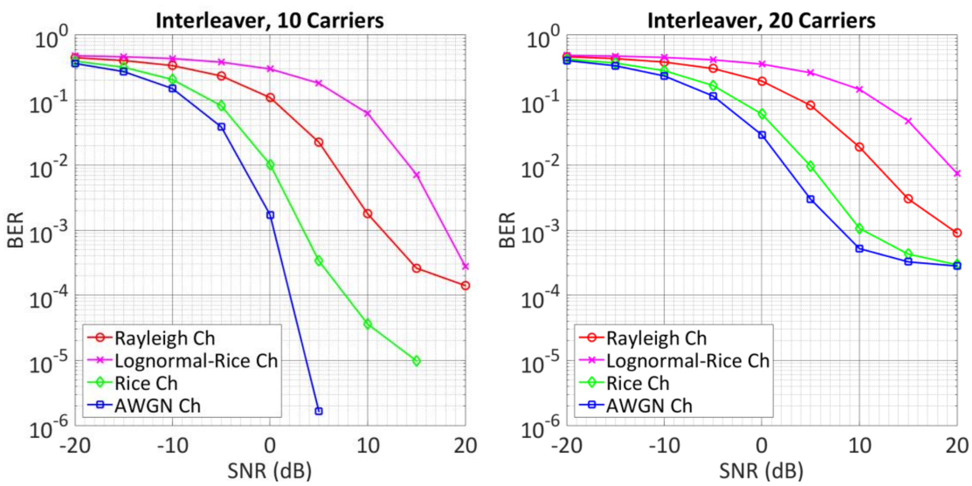

Figure 7. Communication Performance when (left) 10 sub-carriers and (right) 20 sub-carriers are used.

Krawtchouk Moments for SAR based ATR

Target recognition of military vehicles is a topic of increasing interest and demanding requirements.The knowledge of the vehicles deployed in a specific area of interest is fundamental to the understanding of the threat that exists (e.g: Small Intercontinental Ballistic Missile launcher rather than a theatre missile launcher). Furthermore it also allows a better understanding the activities in a specific site. Currently there is a growing interest in the ability to increase the level of knowledge of the identification or characterization stage, where the actual capabilities of the vehicle/object can be better understood. Many current ATR algorithms for vehicles require the ability to identify small differences among targets like a specific configuration of a multirole vehicle.
To address this challenge we have developed an algorithm for ATR based on Krawtchouk moments. The characterization capability, reliability and low computational cost

requirements of the new method have been investigated. A common issue of most families of image moments, is the level of discretization error and poor robustness in low Signal to Noise Ratio (SNR) conditions. This error builds up as the order increases, limiting the accuracy of the computed moments. This drawback results in target recognition algorithms with less accuracy in discriminating between targets that differ in small components, than would be possible if only robust higher order moments are used. Krawtchouk moments have some peculiar characteristics, in particular they are discretely defined, thus there is no requirement of spatial normalization and the discretization error is nonexistent. This translates into a relaxation on the amount of resources required to represent and store the polynomials. Moreover, the computational cost is reduced due to the orthogonality property of Krawtchouk polynomials that relaxes the requirements of feature selection to mitigate overfitting. These characteristics, together with the capability to pre-compute the polynomials, makes this family of image moments compatible with SWAP systems.

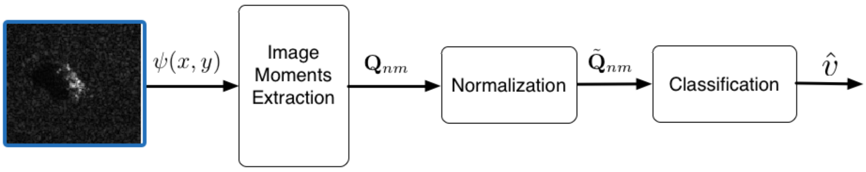

Figure 8 Functional block of the Krawtchouk Moments based ATR algorithm

In Figure 8 the functional block of the developed algorithm is shown. Starting from a chip image containing the target the Krawtchouk moments are extracted and normalized. Then a standard classifier (e.g.: SVM or KNN) can be applied to obtain the target class declaration.

The performance of the proposed algorithm has been assessed on real data. The MSTAR Dataset is a collection of SAR images of 14 different military targets, that represents a useful test-bench for ATR algorithms.

This dataset can be used for the different levels of target classification. According to the NATO AAP-6 Glossary Terms and Definitions, with “recognition” is meant the classification of the type/category of target; “identification” regards the capability to assign the target to a subclass; “characterization” takes into account the class variants. Following this definition the images are supposed to cover the full 360 azimuth angle. However, due to missing images in the dataset, the total number of observations does not always cover each aspect angle. Moreover, different targets have different number of images. In the performance analysis 191 samples are used as the minimal number of images available for all the targets. The training images are selected randomly and the same number of images for each target from the set of images acquired at 15 degrees of depression angle is considered. Moreover, a total of 100 Monte Carlo runs are performed for each analysis in order to be able to draw randomly a wider set of training and test images for the targets with more than 191 images available.

In order to investigate the capabilities and the robustness of the proposed approach, the results of the new algorithm are compared to those obtained using the pseudo-Zernike moments. In the experiments a k -NN classifier with k = 3.

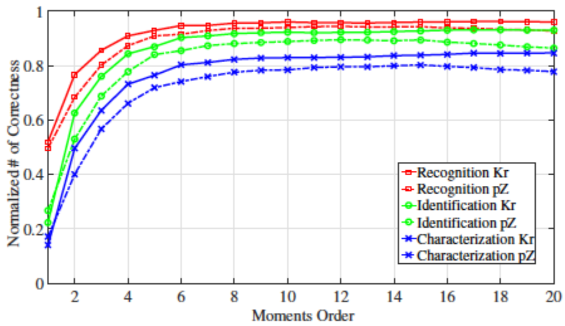

Figure 9 Performance on the MSTAR Dataset

Figure 9 the normalized average number of correct Recognition, Identification and Characterization obtained for both Krawtchouk and pseudo-Zernike approaches. In the analysis all the moments available up to a selected order are considered.
From Figure 9 it is seen that the Krawtchouk based algorithm is superior to the pseudo-Zernike based algorithm for all three levels of target discrimination. For example, considering moments of order up to 20 (441 features) the percentage of correct target recognition reaches 96.02% using the proposed algorithm while is 92.64% for the pseudo-Zernike algorithm. A similar trend is seen for the target identification case with performance going from 92.97% to 86.42% of correct identi fication when switching from Krawtchouk to pseudo-Zernike approach. This performance difference is confirmed in the target characterization case with correct target characterization of 84.58% using Krawtchouk versus the 77.74% obtained with the pseudo-Zernike. The identification and characterization results, with 6.55% and 6.89% of improvements in performance respectively, confirms the capability of Krawtchouk moments to represent with higher fidelity smaller details of the targets.
To demonstrate the higher robustness to noise of the Krawtchouk based approach, a stress analysis under different noise conditions has been performed. In the experiments additive and multiplicative noise are added to the dataset that are assumed to initially contain noise free images
The confusion matrices showing the percentage of correct recognition obtained using moments up to order
10 (121 features) with SNR of 0 dB (additive noise) are reported in Tables II and III, for Krawtchouk and pseudo-Zernike approaches respectively.

	BMP2 9563	BMP2 9566	BMP2 C21	T72 132	T72 812	T72 S7	2S1	T62	ZSU	BTR70 C71	BTR60	ZIL131	BRDM	D7
BMP2 9563	65.06%	11.38%	18.62%	0.20%	1.00%	0.45%	1.12%	0.27%	0.33%	0.16%	0.06%	0.06%	0.27%	1.00%
BMP2 9566	23.38%	59.69%	11.37%	0.25%	1.08%	1.12%	0.28%	0.42%	0.59%	1.31%	0.21%	0.22%	0.09%	0.00%
BMP2 C21	30.97%	14.91%	48.58%	0.91%	0.92%	0.55%	1.29%	0.29%	0.19%	0.84%	0.02%	0.20%	0.24%	0.12%
T72 132	0.58%	0.53%	1.38%	84.75%	4.20%	5.13%	0.08%	0.54%	2.13%	0.02%	0.04%	0.43%	0.03%	0.17%
T72 812	0.44%	0.69%	0.93%	3.89%	76.90%	13.79%	0.22%	0.97%	1.61%	0.22%	0.03%	0.29%	0.00%	0.02%
T72 S7	0.48%	1.40%	0.79%	9.04%	14.23%	70.76%	0.12%	0.52%	0.91%	0.32%	0.51%	0.80%	0.02%	0.08%
2S1	1.16%	2.08%	2.64%	0.41%	0.84%	0.15%	85.96%	0.28%	0.28%	3.75%	0.48%	0.81%	0.45%	0.71%
T62	2.14%	1.67%	3.00%	2.86%	1.98%	2.04%	2.93%	77.15%	2.90%	0.66%	0.48%	1.01%	0.82%	0.35%
ZSU	1.13%	0.55%	1.37%	1.47%	0.04%	0.20%	0.47%	2.67%	89.03%	0.85%	0.14%	0.02%	0.45%	1.61%
BTR70 C71	0.25%	0.29%	0.74%	0.28%	0.48%	0.06%	0.70%	0.09%	0.01%	92.75%	2.30%	1.00%	1.04%	0.00%
BTR60	0.68%	0.37%	1.53%	0.21%	0.14%	1.14%	0.29%	0.83%	1.09%	3.42%	88.13%	0.49%	1.35%	0.34%
ZIL131	2.15%	0.87%	1.69%	0.95%	0.86%	1.40%	5.08%	0.90%	0.32%	2.59%	0.51%	79.22%	2.90%	0.57%
BRDM	1.31%	2.15%	1.65%	0.84%	0.47%	0.94%	3.17%	1.65%	3.27%	3.39%	1.11%	0.98%	78.13%	0.95%
D7	0.26%	0.54%	0.72%	0.08%	0.00%	0.05%	0.12%	0.08%	0.32%	0.00%	0.32%	0.01%	0.59%	96.91%

Table II Performance in Additive Noise for Krawtchouk approach

	BMP2 9563	BMP2 9566	BMP2 C21	T72 132	T72 812	T72 S7	2S1	T62	ZSU	BTR70 C71	BTR60	ZIL131	BRDM	D7
BMP2 9563	49.06%	15.43%	22.36%	1.54%	0.80%	1.38%	1.91%	0.79%	0.29%	2.60%	0.61%	1.34%	1.53%	0.35%
BMP2 9566	24.53%	42.68%	18.41%	1.82%	1.29%	2.38%	1.78%	0.73%	0.33%	2.90%	0.71%	1.13%	1.20%	0.11%
BMP2 C21	28.45%	18.47%	39.30%	0.99%	1.07%	2.37%	2.24%	1.31%	0.41%	2.06%	0.61%	0.85%	1.20%	0.66%
T72 132	2.85%	3.05%	3.04%	65.09%	6.29%	10.04%	0.79%	2.79%	1.45%	0.51%	1.09%	1.73%	0.53%	0.74%
T72 812	2.57%	2.77%	2.06%	7.25%	55.82%	19.74%	1.36%	2.43%	1.62%	0.79%	1.13%	1.55%	0.20%	0.72%
T72 S7	2.08%	3.46%	2.67%	9.93%	10.66%	60.46%	0.74%	1.68%	1.64%	1.37%	0.94%	2.35%	0.48%	1.54%
2S1	1.90%	5.91%	3.64%	1.30%	1.44%	2.26%	60.06%	2.31%	2.93%	10.78%	0.70%	4.49%	0.83%	1.46%
T62	5.51%	4.55%	8.71%	4.34%	3.29%	4.75%	4.62%	49.85%	2.88%	2.98%	2.30%	1.83%	2.20%	2.20%
ZSU	0.84%	0.89%	1.17%	1.47%	0.39%	0.95%	0.77%	7.06%	77.18%	0.02%	0.61%	0.31%	0.98%	7.35%
BTR70 C71	2.47%	2.36%	2.32%	0.27%	0.11%	0.12%	1.68%	0.70%	0.02%	85.52%	1.16%	0.95%	2.27%	0.05%
BTR60	1.43%	1.96%	2.02%	1.27%	0.36%	1.76%	0.99%	1.59%	0.86%	8.46%	75.01%	1.05%	2.70%	0.54%
ZIL131	1.83%	2.34%	3.76%	2.60%	1.76%	1.36%	6.47%	2.85%	0.58%	6.73%	3.43%	63.84%	1.66%	0.79%
BRDM	1.70%	2.92%	1.23%	0.72%	0.44%	1.04%	3.30%	1.75%	1.94%	4.30%	3.31%	0.85%	74.72%	1.78%
D7	1.84%	0.71%	1.79%	1.16%	0.40%	2.17%	1.45%	2.22%	5.18%	0.15%	0.44%	0.40%	0.70%	81.38%

Table III Performance in Additive Noise for pseudo-Zernike approach

A figure of merit for the overall performance of a target recognition algorithm considers the ratio of the sum of the values appearing in the diagonal of the confusion matrix to the sum of all the other values. This should have a value as high as possible, which is infinite for a perfect algorithm.

This figure of merit results to be 3.65 and 1.69 from Tables II and III respectively.

Moreover, the tables show that in the presence of different configurations of the same vehicle (like BMP2 and T72), the capability of target characterization of the Krawtchouk based algorithm is superior compared to pseudo-Zernike. For example, considering the two 3x3 top left matrices of the confusion matrices relative to the BMP2 and T72 targets, and marked in red and blue for clarity, it is seen that both exhibit a more "diagonal" behaviour in the Krawtchouk case than in the pseudo-Zernike one. In particular the figure of merit is 1.56 and 1.02 when the red matrices are considered and 4.62 and 2.83 for the blue matrices in the Krawtchouk and pseudo-Zernike cases respectively. These latest results demonstrate the capability of Krawtchouk moments to maintain a good representation of details in presence of noise.

The proposed approach was shown to provide a more reliable solution to the automatic target recognition challenge from SAR images with higher capabilities in discriminating between different sub-classes of targets and in noisy environments. This approach is, thus, particularly suitable for SWAP systems and appealing to be used on SAR images acquired with low cost sensors mounted on UAVs.

Other activities

- The PhD student Lars Wurtz Jokumsen from Aalborg University-Terma AS visited the group from September to November 2015. Lars worked on target classification using random forest from maritime surveillance radar data;
- The MSc student Annachiara Amideo from the University of Naples "Federico II" visited the group from September 2015 to February 2016. Annachiara worked on novel polarimetric decompositions for SAR images from single and multi-frequency images;
- A CDE project responding at the call "Persistent Surveillance from the air" has been granted and was developed between October 2015 and March 2016;
- 4 Multi-octave horn antennae have been acquired to provide experimental capabilities to gather data and test algorithms;
- Prof. Soraghan, Dr Clemente, Mr Gaglione, Mr Ilioudis, Mr Cao, Mr Persico and Mr Chen attended the SSPD 2016 Conference. Moreover 3 papers were presented at the conference;
- The IEEE Radar Conference 2015 in Cincinnati was attended by Mr Gaglione and Mr Ilioudis where 3 papers were presented;
- Mr Gaglione was awarded the first prize for the best student paper competition at the IEEE Radar Conference 2015.
- Mr Ilioudis was awarded the third prize for the best student paper competition at the IEEE Radar Conference 2015.

- Mr Ilioudis and Mr Gaglione have visited the Ohio State University and delivered a technical presentation of the research activities of the group at the US Air Force Research Laboratories in May 2015;
- The Intelligent Signal Processing 2015 in London was attended by Mr Ilioudis;
- The IAC conference 2015 in Jerusalem was attended by Mr Cao where he presented 1 paper;
- Knowledge exchange meetings with Selex ES - ESM, NXP Freescale, Telespazio Vega and Airbus took place to investigate possible collaborative opportunities;
- The Radar and MIMO Signal Processing themed meeting was organized in collaboration with the Edinburgh consortium.
- Professor Chris Baker from the Ohio State University (now with Aveillant LTD) and Professor Antonio De Maio from the University of Naples visited the group for two days in May 2015;
- Dr Clemente attended the "Vectors In Radar Technology" event in London (December 2015) organized by Professor Hugh Griffiths.
- Dr Clemente attended the NATO specialist meeting on "Radar Imaging for Automatic Target Recognition", where he presented a paper.
- Dr Clemente attended two meetings of the UK Defence Solution Centre related to the CDE awarded in 2015.

Plan for the fourth year

Field Validation of the communicating radar concept

Additional hardware and further experimental campaigns will be developed during the 4th year. The aim is to develop a demonstrator to be used in public events (e.g.: CDE marketplace) and exploited to attract industrial interest in the innovation.

Micro-Doppler enhanced Tracking

Exploiting micro-Doppler information, enhanced tracking techniques will be possible, for instance the case of manoeuvring targets is one of the cases where additional information provided by the micro-Doppler signatures can lead to enhanced tracking capabilities.

Investigation of solution for Enhanced Space Situation Awareness

The research topic of Space Situation Awareness will be expanded during year 4. In particular solutions able to provide enhanced capabilities for SSA will be investigated, including high-resolution imaging and enhanced sensor systems. Dr Clemente has already applied for funds to the UK Space Agency for a feasibility study on a Passive Bistatic Radar system on CubeSats for Space Debris monitoring.

Investigation of novel signal processing techniques

Recently introduced signal processing techniques such as Partial Fast Fourier Transform, Random Fractional Fourier transform, stochastic differential equation, and image moments appears to be very interesting and their potential in the network battlespace will be investigated.

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36- S. Z. Gurbuz, C. Clemente, A. Balleri, J. Soraghan , "Micro-Doppler Based In-Home Aided and Unaided Walking Recognition with Multiple Radar and Sonar Systems" , IET Radar Sonar and Navigation

37- C. Clemente, L. Pallotta, D. Gaglione, A. De Maio, J. J. Soraghan , "Automatic Recognition of Military Vehicles with Krawtchouk Moments" , IEEE Transactions on Aerospace and Electronic Systems

38-L. Pallotta, C. Clemente, A. De Maio, J. J. Soraghan , "Detecting Covariance Symmetries for Classification of Polarimetric SAR Images" , IEEE Transactions on Aerospace and Electronic Systems

39- A.R. Persico, C. Clemente, D. Gaglione, C. Ilioudis, J. Cao, L. Pallotta, A. De Maio, I. Proudler and J. Soraghan , "On Model and Algorithms for Micro-Doppler based Recognition of Ballistic Targets" , IEEE Transactions on Aerospace and Electronic Systems

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41- M. Bugra Ozcan, A. R. Persico, C. Clemente, S. Zubeyde Gurbuz, J. Soraghan , "Performance Analysis of Co-Located and Distributed MIMO Radar for Micro-Doppler Classification" , European Radar Conference 2016, EuRAD 2016 , London, United Kingdom, 5-7 October 2016

PhD projects Titles:

Mr Domenico Gaglione (PS6- ST) -***Automatic Target Recognition and Tracking from Radar***
Mr Christos Ilioudis (PS5- ST)– ***Distributed MIMO Radar Systems***

Mr Jianlin Cao (ST)-***Spacecraft-on-a-chip concepts with application to Earth remote sensing***
Mr Yixin Chen (ST)-***Underwater acoustic Communication based on Multicarrier Scenario***
Mr Adriano Rosario Persico (ST)-***Radar signal processing for defence against airborne threats and space situation awareness***
Mr Alessio Izzo (ST)- ***Acoustic MIMO Array Echo Cancellation Algorithms and Radar Technology based Audio Speakers Characterization***

L_WP5 (EI): Low Complexity Algorithms and Efficient Implementation

1. Staffing

Work Package Leaders: Prof. Ian Proudler (LU), Dr. Stephan Weiss (ST)
Other Academics involved: Prof. John McWhirter (CU)
Research Associate: Dr. Keith Thompson (ST)
Other Research Associates: eventually all other PDRAs (LU, SU, CU and ST) will be involved.
Contributing PhD Students: Jamie Corr (ST), Fraser Coutts (ST), Mohamed Alrmah (ST), and Ahmed Alzin (ST)
Project Partners: Mathworks and Texas Instruments,
Research Themes: T8 and T9
[dstl] Contacts: Dr David Nethercott, Dr George Jacob, and Dr Nick Goddard

2. Aims and Objectives of L_WP5

2.1 Lists of original aims in the case for support

To develop novel paradigms and implementation strategies for a range of complex signal processing algorithms operating in a networked environment. Links to L_WP1-L_WP4. (Relates to all themes)
Low complexity algorithms will be targeted by both generic efficient approaches to common themes across the consortium, such as high-dimensional array data, and application-specific low-cost implementations through collaborative research and active engagement with all other WPs.

L_WP5.1 Data reduction and distributed processing

Lower dimensional representation of data can lead to significant cost reduction, including data-independent techniques such as frequency domain, sub-band or subspace-based processing and thinning of sensor data. This work will exploit a combination of data dependent and independent techniques to achieve a significant data reduction, and will demonstrate how this can be exploited in low-cost algorithms. Due to operating in a networked environment, the efficient organisation of algorithms across a distributed processing platform will be considered. This work will explore algorithms and applications from across all work packages. Areas of study include (i) Polynomial decompositions leading to sparse representations through data-dependent optimal transformations (e.g. Karhunen-Loeve transform (KLT)), for dimensionality reduction in beamformers (ii) Parallel implementations of linear algebra functions and distributed processing methods (e.g. systolic array design, IP core implementations, vector-codebook methods) to minimise the communications bandwidth between processing nodes and (iii) Statistical signal processing problems will be utilised to map algorithms to distributed processors, whereby constraints on the communication bandwidth between nodes need to be set (e.g. Bayesian belief network (BBN) structures).

L_WP5.2 Hardware Realisations

Collaborating with Texas Instruments, PrismTech, and Steepest Ascent (now Mathworks), numerically efficient schemes are to be derived, with mappings onto suitable processing platforms to be investigated that demonstrate real-time algorithms in suitable test scenarios. Multi-core GPU-based platforms and programming environments such as CUDA are an enabling technology for massively parallel processing of data (facilitating real-time applications at low cost, but potentially high power consumption). In contrast, micro-controllers, DSP and FPGA based processing platforms are perfect candidates for low power, inexpensive sensor processing units. In collaboration with industrial partners, state-of-the-art Multicore DSP/FPGA embedded solutions are to emerge that are capable of matching the power performance-price constraints posed by the range of specific problems arising within all work packages of the consortium.

2.2 Year Mid-Term Review - Objectives & Progress Update

In the recently conducted project mid-term review, L_WP5 objectives, sub-tasks and progress points were updated to the following:

Objectives

- L_WP5.1) Exploit recently developed spatio-temporal techniques based on polynomial matrix decompositions to generate sparse representations of broadband signals to aid in distributed signal detection and separation
- L_WP5.2) Propose computationally efficient realizations based on parallel implementation

Overall Progress against Objective

The aim of WP5 is to develop novel paradigms and implementation strategies for complex signal processing algorithms in a networked environment. With a focus on polynomial matrix methods, we have made significant progress in terms of algorithm enhancement, exploiting numerical efficiencies, and created a unique Matlab toolbox that supports a range of applications where we have demonstrated the method's benefits. We now are fully equipped in terms of hardware processing platforms to undertake implementations and lend assistance to other WPs. In the second phase, WP5 will further enhance the polynomial methods and their applications, but also expand to networked and distributed algorithms, and work towards a closer interaction with other WPs regarding hardware realisations.

Progress against Sub-Tasks

L_WP5.1) Data reduction and distributed processing

- *Element completed* - A Matlab toolbox on polynomial matrix decomposition has been created and made available to the public with support from MathWorks. In the area of polynomial matrix decompositions fast converging algorithms have been developed. Numerical speed-up of implementations have been achieved using e.g. Jacobi sweeps instead of an eigenvalue decomposition (polynomial matrix methods were adopted as an example implementation and area of focus at the 2nd quarterly LSSC meeting).
- *Ongoing* - Review of Bayesian belief networks; further development of polynomial matrix methods, with applications to beamforming and sonar.
- *Future* - Activities will be directed towards distributed beamforming, the application of polynomial matrix methods to the Portland sonar dataset via internship at Thales; general assistance with numerical optimisation for WP1-4.

L_WP5.2) Hardware realisations

- *Element completed* - Hardware kits for FPGA, multicore DSP and CPU processing have been acquired, with an FPGA implementation of a wideband transceiver completed; attendance of TI training courses.

- *Ongoing* - Development of sample implementations for all three platforms; and hardware implementation of a polynomial matrix decomposition algorithm are currently undertaken.
- *Future* - Assistance to WP1-4 for hardware realisation of workpackage-specific solutions.

In the following sections of this report more details are included to elaborate on the technical progress made.

3. Progress made in the 3rd year in addressing the original objectives

In the 3rd year of the project L_WP5.1 has further driven the progress of numerically efficient algorithms of interest to the consortium. In depth analysis of the performance and computational efficiency of recently devised Polynomial Eigenvalue Decomposition (PEVD) algorithms has been the main focus of the work. This further analysis has been important to consolidate the great progress made in the first two years of the project, and now begin to demonstrate the greater resultant benefits of the new algorithms in terms of deployment. These developments continue to be added to augment the performance of the publically available PEVD Matlab toolbox released in the previous year of the project. Further lower level research has been carried out into modelling distributed processing systems using graphical model techniques and approximations.

In L_WP5.2 (Hardware Realisations) the focus is to grow capability in the implementation of a variety of complex algorithms with the view to supporting the wider consortium with hardware and expertise. New hardware covering FPGA, DSP, and GPU computing platforms have been acquired together with supporting materials. Further example implementations using these new facilities are currently in progress. In tandem with L_WP5.1, hardware implementation of some the latest developments in PEVD algorithms is in progress.

3.1 Progress of L_WP5.1 (Efficient Algorithms, Data Reduction and Distributed Processing)

In L_WP5.1 the focus of Keith Thompson has been leading the research into the use of statistical Probabilistic Graphical Models (PGMs) for the purposes of modeling distributed systems, and also mapping sequential algorithms to distributed processors. PGMs such as Bayesian Networks or Markov Random Fields, are powerful frameworks for representing probabilistic relationships between different variables and thus offer the potential to re-imagine algorithms in a compact probabilistic structure. As relationships between variables are captured by a graph structure (composed of nodes, edges), it is intuitive to re-imagine the variables, and relationships encoded, as a distributed system. Furthermore, in the established field of Distributed Algorithms various message-passing algorithms exist to share (traverse) information between processes across a communication graph, whereas for PGMs message-passing algorithms (such as Belief Propagation) update probabilities of individual nodes. Overall, there are overlaps between the two areas, but the overall utility of the methods are not directly comparable. As a result, research effort has been made to attempt to reconcile the two is producing interesting results. Keith is also involved in the ongoing development of PEVD algorithms through the co-supervision, with Dr. Stephan Weiss, of PhD students Jamie Corr and Fraser Coutts, and provides support in maintaining the PEVD Matlab Toolbox. Keith has also shared his focus with developing capability for WP5.2 Hardware Realisations (see below).

The focus of Stephan Weiss has been particularly in the context of L_WP5.1, with the aim of exploring, characterising and applying polynomial matrix decomposition techniques. A number of different iterative polynomial matrix eigenvalue decomposition (PEVD) algorithms have been developed and assessed w.r.t. various performance characteristics such as computational cost, order of polynomial matrix factors, diagonalisation etc.. The majority of these algorithms, together with a representative number of demonstrations, are contained in the PEVD Matlab toolbox.
A number of applications have been pursued to demonstrate the use of polynomial matrix formulations and PEVD algorithms. This includes broadband angle of arrival estimation as well as broadband beamforming, where advantages for arbitrary array configurations, off-broadside constraints, and computational complexity have been established in simulation examples.

3.1 Progress of L_WP5.2 (Hardware Implementations)

The focus of Dr. Keith Thompson has been on further developing capability of implementing complex algorithms across a range of different computing platforms and devices. To support this objective some new hardware development options have been acquired by the group in Strathclyde to complement our existing DSP and FPGA hardware. A stated objective of WP5 is to propose computationally efficient realizations based on parallel implementation. Therefore, an underlying consideration when sourcing new hardware options is to ensure that a variety of different computer architectures can be made available to the consortium. Not all algorithms are suitable for full implementation in hardware (either in FPGA or ASIC), therefore different options for developing solutions with suitable hardware/software partitions are desirable.

- Xilinx Kintex-7 FPGA, Digilent Genesys2 (50,950 logic slices, 16mb BRAM, 840 DSP slices, 1Gb DDR3)

  http://www.digilentinc.com/Products/Detail.cfm?NavPath=2,719,1488&Prod=GENESYS2

- Xilinx Zync-7000-based Zedboard (Dual-Core ARM Cortex A9, 13300 logic slices, 512mb DDR3, 220 DSP slices)
  http://www.xilinx.com/support/university/boards-portfolio/xup-boards/XUPZedBoard.html
- TI Multicore DSP 66AK2L06 (2x ARM Cortex A15, 4x C66x DSP cores, 2x FFT Co-processor,2GB DDR3)
  http://www.ti.com/tool/xevmk2lx
- GPU Laptop – Quad-core Intel i7, Nvidia GTX 970M with 1280 CUDA Cores, 3Gb DDR5
  http://www.geforce.co.uk/hardware/notebook-gpus/geforce-gtx-970m/specifications

The newly released FPGA development board from Digilient, employs a Xilinx Kintex-7 (28nm) architecture marketed as the company's best performance/pound solution and has considerable logic resources and on-board memory. The board design also has a numerous on-board I/O ports and peripherals (e.g. onboard ADC) allowing it to be used for general signal and video processing applications. The device can be configured for use as a standalone processing solution or utilised alongside a host-PC as a co-processor for accelerated computation. Through interactions with Xilinx, the potential to organise loans of even more capable (Virtex 7) devices was made clear. Before doing so, such algorithm

implementations should be designed, simulated and synthesised using the appropriate vendor tools to mitigate any risk that a suitable outcome can indeed be realised.
The consideration for hardware/software co-design and partitioning drove the selection of the other development kits recently brought to market from Xilinx and Texas Instruments. In the case of Xilinx, the Zync architecture combines an application-capable ARM RISC processor core with FPGA-style programmable logic in a hybrid System-on-chip (SoC) architecture. From Texas Instruments, the high-end multicore ARM + DSP device offers provides a multitude of options for hardware/software co-design. Furthermore, the board from TI has further hardware FFT co-processors implemented on the device to allow repeated high-speed computation of frequency domain based operations. This device has been marketed by TI as particularly suitable for SAR applications.

Lastly, a powerful GPU equipped laptop has been procured with a view to providing support in identifying and exploiting parallelism in higher level programming languages and software. Retaining algorithm development within high level environments such as Matlab is advantageous in terms of productivity and gaining instant feedback on modifications. However such developments remain predominantly sequential in nature, excepting array processsing (vectorised) BLAS routines enabled in Matlab using a CPU's floating-point unit vector registers and SIMD instructions, and functions enabled to auto-detect and exploit multiple CPU cores. Further parallelisation can be exploited on a developer's PC if a suitable Graphics Card (GPU) can be installed and suitably targeted in software. Matlab's Parallel Processing Toolbox has been designed to take advantage of the growth of such hardware in general purpose PCs/workstations, and Nvidia's C-based CUDA programming tools can also be leveraged for further performance gains. Therefore, with this facility we are to provide support to other WPs in accelerating their code for the general purpose of improved code implementation and also increase simulation productivity. Furthermore, by identifying such potential parallelism in earlier algorithm development stages may have further downstream benefits in determining pathways toward more lower-level hardware implementation (RTL level). Current implementation work is focused on implementation of Polynomial EVD algorithms (see later section) onto FPGA hardware, building on expertise gained in last year's development of a broadband Television White-Space (TVWS) transceiver design onto a FPGA [ref].

4. Technical Details

4.1 L_WP5.1 Polynomial EVD Theory, Implementations and Applications

Focus on Polynomial Matrix Techniques

As outlined in previous reports, at the 2nd quarterly meeting in Surrey in 2013, the consortium took the decision that WP5 should initially focus on one particular algorithm implementation. Due to its wide use across particularly WP3 and WP5, its degree of novelty and uniqueness to the consortium, and an encouraging application by Dstl in the sonar domain, much effort has therefore been dedicated to polynomial EVD (PEVD) algorithms. Our effort has however not just contributed to a direct implementation, but we have taken a wider approach to consider the theoretical foundations, numerical efficiency, and a number of sample applications in addition to providing a stable implemented platform for others to use.

PEVD Existence and Uniqueness

The polynomial eigenvalue decomposition of a parahermitian matrix – which describes the structure and symmetry of a space-time covariance matrix – was found to be ambiguous w.r.t. the paraunitary or lossless matrix factors that afford the decomposition. This has been exploited for a potential order reduction of paraunitary matrices [Corr 2015a], which also led to a novel approach to trimming the paraunitary matrices in PEVD algorithms [Corr 2015b]. Particular for SBR2-type algorithms, this order reduction can be substantial, and has been incorporated to good effect into the work of Zeliang Wang and John McWhirter in WP3 [Wang 2015].

PEVD Algorithm Speed-Up

While the order reduction of paraunitary matrices has a direct impact on the cost of applying e.g. a subspace projection once the PEVD is calculated, the computational cost of iterative PEVD algorithms has also been under scrutiny. Previously, our focus had been on eliminating more energy per iteration step in the SMD algorithm[Corr 2014a, Corr 2014b, Corr 2015c], an approach that has now also been adopted in WP3 for the SBR2 algorithm [Wang 2015]. We have investigated two different approaches for further reduction of algorithmic cost: by limiting the search space of off-diagonal elements to lag values close to zero lag, fewer norms have to be calculated, searches are performed over a reduced space, and – most importantly – the order growth per iteration of both the parahermitian and paraunitary matrix factors are curbed. The later increases the speed of the algorithm, and in turn also leads to lower-order decompositions while suffering only an insignificant decrease in diagonalisation performance [Corr 2015d, Corr 2015e].

Recent work has focussed on memory and computational savings that exploit the symmetry conditions inside a parahermitian matrix, reducing is storage requirements and arithmetic operations by 50% [Coutts 2016], which also contributes to a faster execution of iterative SBR2 and SMD algorithms.

PEVD Algorithm Performance Characterisation

The uniqueness of the PEVD is also reflected in potential ambiguities of iterative algorithms for its computation. We have particularly investigated the impact of source model conditioning on the diagonalisation performance of algorithms. For example, if convolutive mixed sources are not initially spectrally majorised, PEVD algorithm such as SBR2 and SMD will aim to produce a spectrally majorised diagonal parahermitian matrix. However, non-differentiable points in the power spectra cause high orders in the parahermitian cross-spectral density matrices and potentially infinite order in the paraunitary matrix factors [Corr 2015c].

PEVD Implementations and Matlab Toolbox

A Matlab PEVD toolbox containing polynomial matrix decomposition algorithms was released in 2014 [Weiss 2014] at http://pevd-toolbox.eee.strath.ac.uk/. We have continued to maintain this toolbox, and updated it with a number of demonstrations and examples. To support the adoption of polynomial matrix EVD tools, Stephan Weiss and John McWhirter will be presenting a PEVD tutorial at the IEEE Sensor Array and Multichannel Signal Processing Conferences (SAM 2016) in Rio de Janeiro in July 2016.

PEVD Applications and Linkages

Two application areas have been addressed using polynomial matrix formulations and decompositions: (I) broadband angle of arrival (AoA) estimation and (ii) broadband beamforming. Broadband AoA has been investigated previously and reported in e.g. [Alrmah

2013a; Weiss 2013], where a polynomial subspace implementation enables a broadband extension of the MUSIC algorithm. Performance enhancements have been accomplished by using the SMD family of algorithms over SBR2 with their enhanced diagonalisation performance, thus defining subspaces more accurately [Alrmah 2014]. In the area of broadband beamforming, previously the problem formulation in the framework of polynomial matrices has led to interesting aspects [Weiss 2015]. On one hand, polynomial steering vectors as defined in e.g. [Alrmah 2013b; Alrmah 2013c] enable an easy definition of constraints off broadside, resulting in a much lower distortion in look direction than achievable with standard time-domain broadband beamformer. On the other hand, the use of a polynomial quiescent vector and blocking matrix in the Generalised Sidelobe Canceller algorithm decouples the complexity of this preprocessing step from a multichannel adaptive filter performing interference suppression, thus enabling a significant reduction in complexity for adaptive broadband beamformers with arbitrary look direction.
Over the past year, work on broadband beamforming has particularly exploited the simple polynomial notation to address awkward problems such as arrays with arbitrary 3-dimensional geometry, with good performance for adaptive broadband beamformers demonstrated in [Alzin 2015].

Algorithmic Links to Distributed Processing

Previously we had considered distributed solutions to large-scale beamformers [Karagiannakis 2013b; Karagiannakis 2013c; Punzo 2014], with a distributed calculation within such a beamformer proposed in [Karagiannakis 2013a]. Pearl's algorithm – as covered in the original UDRC proposal – has been implemented in a generic and scalable form, and used to optimise the station assignment in a heterogeneous network. In this work, the Bayesian belief propagation idea with levels of uncertainty, as it e.g. may arise for the gain of a link, can be taken into account and be replaced by exact evidence [McGuire 2014]. The solution obtained with this approach had been confirmed against a previous deterministic, exhaustive optimisation in [McGuire 2013].
We have started to pursue some ideas on distributed broadband beamforming. For this purpose. Jamie Corr is currently on secondment at Professor Marc Moonen's group in KU Leuven.

Radio Transceiver Hardware Implementation

A radio transceiver implementation on an FPGA capable of up- and down-converting 320MHz wide bands had previously been discussed and has now been written up and archived [Elliot 2016]. Given the networked aspect of the battlespace theme in the UDRC, this radio transceiver work appeared very useful, and has over the past year extended to a further design [Elliot 2015], which is less costly than [Elliot 2016] but has to have a wider mix of sampling rates within each system block --- this addresses the problem that otherwise the RF signal consists of components with sampling rates in excess of what an FPGA can handle at its interface. The proposed solution therefore multiplexes and subdivides the input signal into a number polyphase signals that each run at a realisable sampling rate.

4.2 L_WP5.2 Technical Details for WP5.2 - Implementation of PEVD Algorithms (Technical Highlight)

In this technical highlight we describe the design work currently in progress on adapting Polynomial EVD algorithms towards implementation on FPGA hardware. In the first two years of the UDRC project further development of Polynomial EVD algorithms has received great attention, with numerous improvements targeted at improving the computational efficiency reported. In order to capitalise on this algorithm development WP5 is now focused on implementing some of these developments on a suitable hardware device. Currently, the PEVD toolbox code is defined in Matlab and exploits the array processing capability of this development environment. The original SBR2 algorithm has been implemented on FPGA architecture in an existing recent publication [Kasap et al. 2014], where computational performance reported compared favourably to Matlab floating point implementation (~2 orders of magnitude faster execution). In our work we investigate the implementation of the newer generation of SMD algorithms to leverage their proven greater diagonalisation and improvements in hardware efficiency.

The SMD family of algorithms allow para-Hermitian matrices that result from the calculation of a Space-Time covariance matrix to be diagonalized to a much greater degree. This is achieved by transferring more energy per iteration from the off-diagonal elements of the para-Hermitian matrix to the diagonal of the zero-lag slice. This has been shown to lead to a significant increase in performance of the algorithm in terms of convergence. In addition to greater diagonalization performance, the SMD algorithms allow the order of the defined paraunitary matrices to be constrained relative to the original SBR2 algorithm. This is important from the perspective of hardware implementation, as the PEVD algorithm ultimately defines an All-Pass FIR-type filter-bank. For the SMD algorithms, the product of Para-unitary matrices can be significantly shorter in length leading to a more efficient implementation consisting of fewer multiply-and-accumulate MAC operations. Further work has also been successful in defining suitable trimming constraints that have led to even more hardware efficient implementations.

Post-PEVD Stage

In reporting developments to stakeholders [dstl] and industrial partners, important feedback has been received on how best to exploit the improved diagonalisation performance of the new algorithms. In particular, how may the more accurate PEVD estimated by the new algorithms be related to performance of subsequent processing stages where the diagonalised matrix is to be exploited. Therefore, our work is to take a more 'systems' perspective on the implementation of PEVD algorithms by integrating the PEVD computation within an architecture to also compute direction of arrival (DoA) estimates, see Figure 1. To perform this post-PEVD stage, a Polynomial MUSIC (Multiple Signal Classification) algorithm [Weiss et al. 2013] is also implemented to analyze the noise and signal subspaces created by the PEVD algorithm. Due to the increased diagonalisation performance of the new SMD algorithms, direction estimates of a greater accuracy may be realized. Of particular interest in our work is to further develop applications for the algorithmic improvements, and provide performance indicators that are a level of abstraction above the diagonalisation measures previously published.

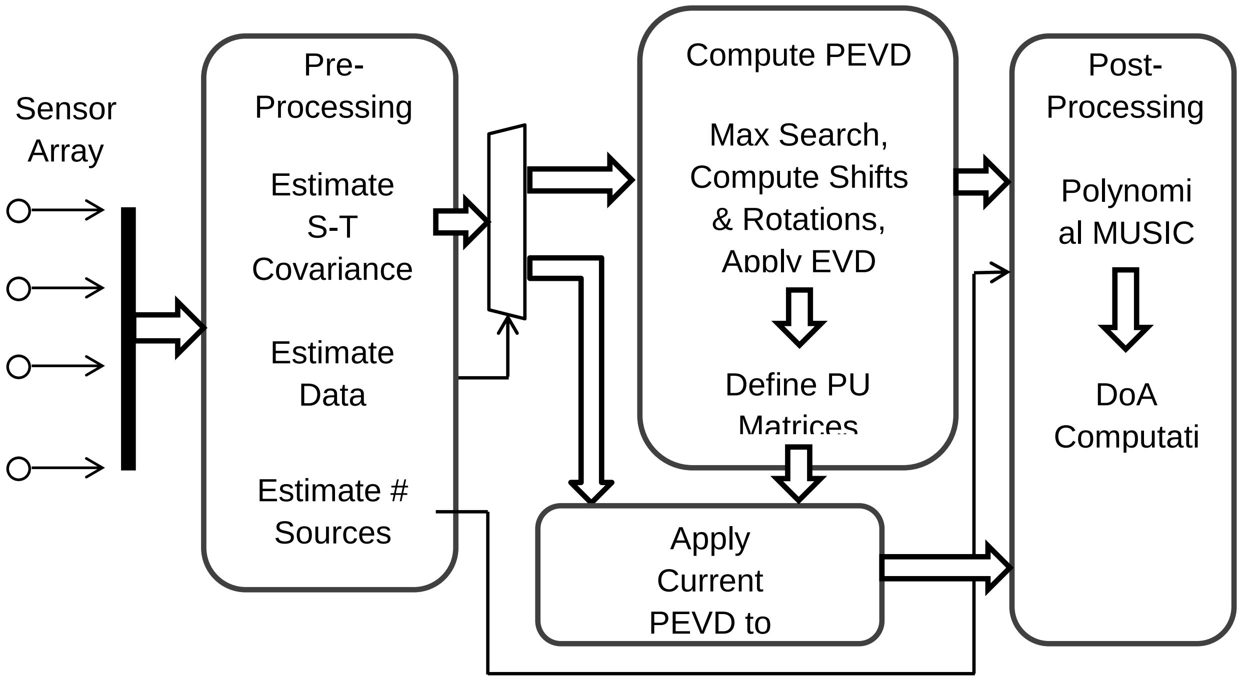

Figure 1 – Overall System Diagram for PEVD-based DoA system

The PEVD algorithm will result in a solution (a product of Paraunitary Matrices) that may realised as common FIR filterbank architecture, such that the implementation of the result on FPGA architecture can be achieved readily. Such a solution can then be applied to further incoming sensor array data to provide updated decompositions. However, if the stationarity of incoming data does not hold, an updated PEVD decomposition must then be computed efficiently and subsequently applied. Such an arrangement is depicted by the de-multiplexor arrangement shown in Figure X. Therefore, an architecture that provides the facility for designing an adaptable filter is the objective. Such a filter design system must be adaptable in both in terms of coefficients and filter length as each PEVD computed may be different dependent on the incoming data. As a result the reconfigurable nature of the FPGA-based design architecture is appropriate. Furthermore, the obtained FIR filterbank implementation can also be realised in a number of different ways to exploit parallelism, as discussed in [Parhi].

Pre-PEVD Stage

Along with examining the post-PEVD stage, a pre-processing stage must also be considered carefully. PEVD algorithms are defined to decompose the Space-Time covariance matrix that is Parahermitian in form. However, in the development conducted so far, this initial ‘data layer’ where the Space-Time covariance matrix must first be estimated has received less attention. At present, the PEVD algorithms have been developed and tested using a source model generating a matrix from independent Gaussian sources combined with innovation filters and a convolutive mixing matrix, see [Redif 2015]. This matrix and its conjugate form are then convolved to generate the Space-Time covariance matrix to which the PEVD algorithms are applied. Therefore, in considering the estimation of the Space-Time covariance matrix the algorithms are to be decoupled from the current source model and adapted to data would be incoming from a true sensor array, and how to implement the covariance matrix estimation. Of further significance when considering the system as a whole, is whether this covariance matrix can be estimated in parallel fashion. Estimation of such a 3 Dimensional data structure may be seen to be a computational intensive step in the overall system if a large array is to be deployed as the size of array may be directly related to the dimensions of the resultant covariance matrix. Parallel covariance matrix estimation techniques have been investigated in other literature, see [Parhi 1999], where duplicate mathematical operations are eliminated leading to performance benefits.

Furthermore, parallel estimation of the covariance matrix has potential implications for the rest of the implementation and algorithm itself. As hardware is inherently parallel (using different physical circuit components to perform different operations), most benefit in terms of concurrency can be obtained if data and computations may be processed in independent parallel threads/streams. Utilising stream processing is very much favourable for FPGA hardware, where a number of sequential operations based on individual elements or sub-partitions of the data are processed on independent hardware. This means data can be potentially stored more locally to the actual relevant operations, further facilitates pipelining of different algorithm stages, and potentially reduces accesses to off-chip memory that are likely to cause Memory Bandwidth issues (e.g. Cache misses). Fundamentally, the benefit of being able to process the data in such a way will need to be examined against the current sequentially processed PEVD algorithm where the entire matrix is stored, and made available as a search space to identify off-diagonal energy. Sub-matrices may indeed be searched more efficiently, but will result in local maxima being identified, thus fundamentally compromising the convergence properties of the underlying algorithm. Nevertheless, it may be possible to incorporate certain operations (such as performing a local search for maximal elements) that could be used to accelerate a further global search strategy. Lastly, the need to continuously estimate the covariance matrix as new input vector arrives from the sensor array is relevant. For example, would a recursive strategy that updates the covariance matrix be preferable to processing a matrix individually, then collecting a whole new independent covariance matrix into a buffer to be processed subsequently.

Development Process

This work is being carried out using Xilinx development tools: Vivado and System Generator (Matlab-to-HDL code generation). Matlab code defined in the PEVD Toolbox has been reconfigured into appropriate user defined Simulink blocks, together with IP cores made available by Xilinx. Although it is now possible to generate HDL code directly from Matlab script m files, employing Simulink has the benefits in terms of understanding the flow of data through the system, akin to providing more of a Signal Flow Graph type of perspective and description. Conversion from the default Matlab floating point double precision to Fixed-point numerical representation is a necessary step to limit logic utilisation by individual operations. Finite State Machines (FSM) are employed to control the sequential (clocked) processing of the individual algorithm steps. Hand-coded VHDL design code is utilised to glue together generated HDL code along with algorithmic tweaks. The primary device targeted in this implementation work is a Xilinx Kintex-7 (XC7K325T) FPGA device.

At present the algorithm is implementation is designed so that it may be operated on the FPGA as a standalone system (not as co-processor with host-PC), with individual modules defined, simulated and implemented. Once correct operation is verified against floating point equivalent results, modules are then to be combined and tested. A detailed analysis of the resources consumed along with accuracy and timing analysis will be published in a forthcoming paper (to be submitted to IEEE Transactions on Circuits and Systems journal). Furthermore, further implementation work is to investigate scaling of the algorithm onto devices with greater resources available (e.g. Virtex-7) to examine how such capability could be leveraged. Furthermore, potential exists to modify the architecture to employ a 'partial reconfigurable' strategy where the configuration of a portion of the FPGA logic resources maybe reloaded with an alternative circuit (with potential implications for latency).

5. Linkages With Industry

Dstl

L_WP5 has maintained regular contact with David Nethercott, George Jacob, Nick Goddard at Dstl.

In the early 2015, L_WP5 was supplied by [dstl] with a table outlining the intersection of various techniques with applications of interest, with the broad objective of examining the complexity of various methods and potential for approximation. Following initial discussions the need to more closely define suitable achievable objectives was identified, and [dstl] project lead Paul Thomas has indicated that we should revisit this in the near future.

Mathworks

L_WP5 has benefited greatly from continued excellent support from our industrial partner Mathworks from contacts at both Mathworks Cambridge (Dr. Marc Willerton) and Mathworks Glasgow (Dr Garry Rice). Both contacts have provided useful technical advice regarding the latest Mathworks tools in helping prepare, release and update the PEVD Toolbox. Furthermore, both have been supportive in providing information sessions at UDRC events on Parallel Processing Toolbox (April 2015 at Strathclyde CSG meeting) and HDL Code Generation tools (Hardware Theme Day at Strathclyde Nov 2015).

Texas Instruments

In November 2015 Dr Keith Thompson attended the biannual Texas Instruments Academic Symposium in Germany to interact with TI's University Program delegates and find out more information from product engineers on the latest hardware options and developments on the market. A useful observation from this visit has been to appreciate how this major industry player is seemingly reducing focus on developing ever more capable DSP processors. Instead, significant focus and development has now shifted more toward the analog domain, especially (low) power management and control systems, complemented with Op-amp ICs, and microcontroller endeavours.

Kaon Ltd

Stephan Weiss consulted to Kaon Ltd (Guildford) on broadband beamforming implementations. A frequency-invariant design was implemented for a sonar application which will be delivered to one of Kaon's clients.

Thales/Dstl

A path has been established for Jamie Corr to work with the Portland Data set, applying PEVD methods. The internship will be supported by Dstl (Nick Goddard) but be hosted at Thales Underwater Sustems (Sam Somasundaram), likely from April or May 2016 onwards.

6. Future Plans

Plans for 4th Year

Uniqueness and Order Reduction of Polynomial Matrix Factors

Knowing that the PEVD factorisation is not unique due to ambiguities in at least the paraunitary matrices [Corr 2015a], we will investigate the area further. Spurious manipulations can include diagonal all-pass sections, as well a quadrature-mirror filter arrangements with perfect frequency characteristics. Inclusion of such spurious terms will increase the order of paraunitary matrices; therefore a better understanding of ambiguities in the representation may also lead to a better exploitation of any redundancies of parauntary matrices in the decomposition and therefore assist in attaining a lower complexity of either the algorithm or the subspace decomposition that it affords.

Polynomial Subspace Metrics

Since different iterative PEVD algorithms return different paraunitary matrices, the characterisation of similarity or dissimilarity of subspaces is important. Over the next year, we would like to obtain a metric that might e.g. extend narrowband subspace angles to the polynomial case, capable of assessing the distance between polynomial subspaced. This will require manipulation tools such as common rootfinding or perhaps the expression of polynomial matrices and vectors in Groebner bases to eliminate spurious terms and identify potential equivalences. Subspace angles for subspaces of more than a single dimension in the narrowband case require an SVD, and alternative for the polynomial case will have to be found.

Broadband Beamforming

Based on the extension of the MVDR polynomial broadband beamformer in [Weiss 2015] and its extension to 3-d arbitrary array configurations, the next step will include the investigation of a polynomial Capon beamformer to which adaptive versions in [Weiss 2015; Alzin 2015] should be expected to converge.

PEVD Toolbox Evolution

We will aim to include the various fast-converging versions of the SBR2 and SMD algorithm families. As an interim step to an FPGA implementation, mex files for SMR2 and SMD could be considered, ideally exploiting many of the redundancies established in [Coutts 2016].

Distributed Processing

The link to Colin McGuire at MathWorks and access to his knowledge on Bayesian Belief Network remains. In addition, we anticipate to take ideas from Jamie Corr's visit to KU Leuven (Belgium) onward, where he is currently visiting the group of Marc Moonen, which is world leading in distributed adaptive filtering.

Application and Working With Real Data

A visit to Thales Underwater Systems supported by Dstl is planned for around April/May 2016 for Jamie Corr. Jamie would be expected to apply enhanced PEVD algorithms to the Portland Harbour data set. The data set contains non-stationary data, and a number of real-world challenges are likely to appear when processing this data set with the PEVD.

7. Academic Outputs

UDRC Output with Dstl Clearance: Journal and Conference Publications

[Alrmah 2014] M. Alrmah, J. Corr, A. Alzin, K. Thompson, and S. Weiss. Polynomial subspace decomposition for broadband angle of arrival estimation. In *Sensor Signal Processing for Defence*, pages 1–5, Edinburgh, Scotland, Sept. 2014.

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Software Output:

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Related Output (without Dstl Clearance):

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