University Defence Research Collaboration (UDRC)

Engineering and Physical Sciences Research Council & Defence Science and Technology Laboratory

Loughborough, Surrey, Strathclyde and Cardiff (LSSC) Consortium

"Signal Processing Solutions for the Networked Battlespace"

First Year Progress Report

March 2014

Director: Professor Jonathon Chambers FREng

Deputy Director: Professor John Soraghan

Contents

Executive Summary

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. However, it is envisioned that UK forces will have a suite of networked sensor systems available to them. This suite of sensors will be a heterogeneous mix of modern and legacy systems including a small number of highly capable but expensive systems and a larger number of less expensive but less capable systems. In addition there will be a certain amount of processing power heterogeneously distributed amongst the various sensor systems.

Within this environment, there will be a need to:

- maximize the amount of information on enemy activity by the use of the most appropriate sensors;
- transport this information to the people who need to have it;
- take due notice of the amount of communications bandwidth available;
- cope with the possibility of a high density of signals;
- cope with novel signals that are hard to detect or classify;
- reduce the work load of the operators and interact with coalition forces;
- be adaptable to cope with signals as yet unknown;
- be able to execute all the operations in the shortest possible time;

To address these requirements the following **ten research themes** were identified by the EPSRC and Dstl in the call for the UDRC consortia:

T1: Weak signal detection in high volume of clutter; T2: Signal processing in high dimension feature space; T3: Signal processing in high uncertainty; T4: Signal processing for sparse or fleeting signals; T5: Signal processing to support sparse sampling of highly non-stationary signals; T6: Extraction/separation of multiple overlapping/interwoven signals; T7: Statistical anomaly detection; T8: Distributed/decentralised signal processing; T9: Algorithms to support dramatic reduction in computation; T10: Accreditable machine learning or data-driven techniques.

The LSSC consortium therefore carefully designed a coherent programme of work on the basis of five strongly ***interlinked work packages (L_WPs)***, each supported by a lead industrial partner(s) from amongst: the Mathworks, Prismtech, QinetiQ, Selex-ES, Texas Instruments, and Thales; and this report details the progress in these WPs between 1st April 2013 and 31st March 2014. Our consortium comprises four internationally recognised academic-based signal processing groups and provides unique capability from across the UK in the field of signal processing;

particularly in *mathematically rigorous methods for statistical anomaly detection and classification in high dimensions (AD), handling uncertainty and incorporating domain knowledge (HU), signal separation including beamforming and compressive sensing/sparsity (SS), MIMO and distributed sensing (MDS) and their efficient implementation (EI)*.

The following ***connectivity matrix*** therefore maps our consortium's five primary expertise areas to the ten themes:-

Theme:	[T1]	[T2]	[T3]	[T4]	[T5]	[T6]	[T7]	[T8]	[T9]	[T10]
AD	X	X					X		X	X
HU			X		X				X	
SS	X	X		X	X	X		X	X	
MDS	X		X		X			X	X	
EI	X	X	X	X	X	X	X	X	X	X

Note: Light grey crosses emphasize that research in efficient implementation and supporting dramatic reduction in computational complexity is interwoven with all other planned technical activities.

Technical Challenges: Our activity moreover impacts upon the following technical challenges provided by Dstl, on the basis of the short descriptions provided on the UDRC website as at 25th June 2012:-

Linkage Matrix Showing Work Package to Dstl Technical Challenge Mapping

CHG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
AD		X	X	X							X					X		X			X		X		X		X			X			X	X		X	X	
HU	X	X	X			X				X	X					X			X												X		X	X				X
SS	X						X		X				X	X	X	X							X	X							X	X	X	X				X
MDS	X				X				X					X						X						X							X					
EI	X	X	X	X	X	X	X		X	X	X		X	X	X	X		X	X	X	X		X	X	X	X	X		X	X	X	X	X	X		X	X	X

In summary, over the first year eight postdoctoral RAs have been recruited and seven affiliated PhD students have started their studies. Overall technical leadership and management of the LSSC consortium have been achieved through three-monthly consortium management team (CMT) and consortium steering group (CSG) meetings held at all the four university sites together with regular reporting (two weekly (RAs) and four weekly (PhD students)). The consortium has enjoyed the input of independent experts as part of the CSG and provided three-monthly written progress reports to Dstl.

The five workpackages have each been led by two senior academics and supported by a lead and other industrial supporters. An important achievement during the first year has been to identify technical contacts within Dstl for all of the workpackages who are now serving as knowledge transfer agents between the consortium and Dstl. These contacts together with the industrial supporters are contributing significantly in defining problem contexts and evaluation datasets.

The following five reports are structured in a common style: listing staff involved; original targets; progress and achievements; further technical detail; future work for year two, together with references and outputs (journals and conference works are marked with "*" to aid in identifying these works). Please note that the referencing style varies slightly between the reports.

The LSSC consortium has contributed to the first theme day on source separation and sparsity; the UDRC launch event in December 2013; led the IET's first conference on Intelligent Signal Processing held immediately before the UDRC launch event, thereby engaging the wider UK community; and organised a special session on Sensor Signal Processing for Defence at the IEEE International Symposium on Communications, Control and Signal Processing, to be held in Athens in May 2014.

In conclusion, we believe that the foundations are now in place for the LSSC consortium to work with all partners in the UDRC and provide new signal processing solutions for the networked battlespace.

Acknowledgement

All members of the LSSC consortium wish to express their considerable thanks to Professor Andrew Baird, Paul Thomas, Bob Elsley and Ros Knowles Dstl and Drs Liam Blackwell and Matthew Lodge EPSRC for their considerable help over the last year in realising the LSSC Consortium as part of the new UDRC.

Selected Innovations in Five Workpackages

L_WP1: new anomaly detection system concept; delta surprise measure; anomaly based network intrusion detection system with automatic data labelling and metric selection; anomaly detection for video surveillance with online segmentation

L_WP2: GMTI radar-based vehicle tracking incorporating domain knowledge; new interactive model particle filtering framework; game theory based distributed resource allocation for MIMO radar network; achieves Nash equilibrium

L_WP3: polynomial matrix methods for convolutive source separation; multimodal and sparsity based approaches for source separation; emerging application in underwater systems; circulant embedding and bootstrapping

L_WP4: radar waveform design based on the fractional Fourier transform; strong waveform quality and reuse properties; passive bi-static micro-Doppler based target identification; cadence velocity diagram

L_WP5: efficient MATLAB implementation and fast converging matrix polynomial decompostions; graph theory and implementation of Bayesian belief networks; fractal beamformer inspired by Pearl’s algorithm

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

1.1 Staffing

Work Package Leaders:	Prof David Parish (LU) and Prof Josef Kittler (SU)
Other Academics:	Dr Yulia Hicks (CU), Prof. Jonathon Chambers (LU)
Research Associates:	Ms Cemre Zor (SU), Mr Francisco Aparicio-Navarro (LU), Dr Ioannis Kaloskampis (CU)
Affiliated Research Stud.	Pengming Feng (LU)
Lead Project Partner:	Mr Angus Johnson (Thales)
Other Project Partners:	Mr John Griffin and Mr George Matich (Selex-ES)
Dstl contacts:	Drs Gavin Pearson and Jacob Suresh

1.2 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 anomaly detection methodology that is not only effective and computationally efficient, but can also provide insight into the nature and statistical characteristics of the detected anomalies.

The fundamental philosophy is to model normality, i.e. “normal” behaviour and “normal” data characteristics in order to provide an acceptable balance between false positive / negative detections. To ensure the models of normality are not corrupted by unreliable and ambiguous data, data quality and ambiguity measures are to be taken into account.

1.3 Available Datasets

Currently we have access to the following data sets

- Simulated network communication data (LU)
- Surveillance video data (CU)
- Portsmouth harbour shipping data made available by Thales
- Discussions have been held with John Mitchell (UCL) and Miguel Rio (UCL) regarding access to data for the problem of network monitoring and anomaly detection.
- Via the ITA project, initial discussions are to take place with Alessandra Russo (Imperial College) regarding distributed anomaly detection for networks

1.4 Outline of Research Approach

Anomaly detection is classically formulated as an outlier detection problem in statistical hypothesis testing. Our thesis is that anomaly detection in complex systems should involve additional mechanisms that would enhance the efficiency of anomaly detection, but most importantly, allow various types of anomaly and their nuances to be identified and distinguished.

A schematic diagram of the proposed overall anomaly detection system is shown in Figure 1.1. The system is adjunct to the main operational system, which in our example is a machine perception system interpreting input sensor data in a hierarchical manner by engaging non-contextual and contextual labelling processes. (For other scenarios, such as multimodal experts, the operational system would have to be suitably adapted.) The sensor data to be interpreted first feeds into a discriminative object / primitive classification system. The output of the non-contextual decision making system is then channelled to a contextual classifier.

In a conventional approach, both non-contextual and contextual decision making systems would have associated outlier detectors, and any outlier would signal anomaly. In the proposed architecture there are additional mechanisms to gain more detailed information about the nature of anomaly. First of all, there is a classifier incongruence detector, which compares the outputs of the two decision-making systems. In normal circumstances the classifiers should mutually reinforce each other. Any incongruence between the classifier outputs could be indicative of some sort of anomaly and therefore its detection is very important. It is also important to recognise that the notion of normality applies only to scenarios where sensor data quality is comparable. Thus another important mechanism is data quality assessment, which for sensor data of degraded quality would switch off the anomaly detection system. Other important mechanisms are decision confidence gauging to avoid anomaly flagging in ambiguous situations and long term statistical data analysis and monitoring to detect a model drift.

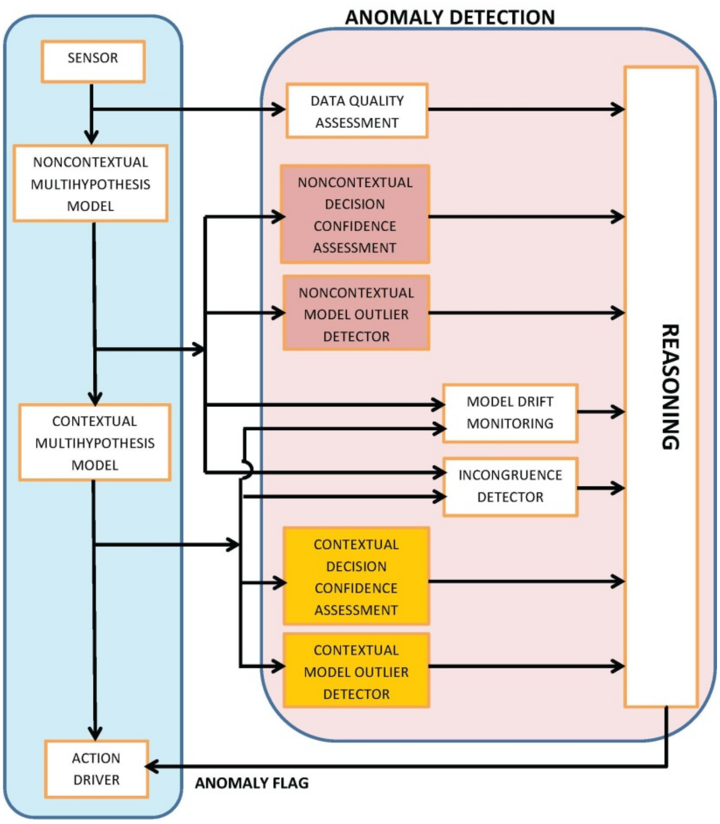

Figure 1.1 Domain Anomaly Detection System Architecture

Thus, we propose a comprehensive methodology for anomaly detection, which builds on the above mechanisms and jointly reasons about the findings of the respective data analysis tools.

The methodological advances in anomaly detection offered by the proposed anomaly detection system architecture will be validated on diverse applications. An example includes network anomaly detection with the aim to increase the efficiency of flagging network intrusion. Another domain is 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:-

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

L_WP1 relates to the other work packages in terms of the following issues:

- WP2: Usage of mechanisms to reduce uncertainty. Input to approaches dealing with large volumes of data or data loss.
- WP4: Application to non-IP, i.e. non-“Cyber” signals.
- WP4: Information / Data Fusion approaches.
- WP5: User of viable implementation strategies. Provider of exemplar algorithms for evaluation.

1.5 Overview of Technical Progress in L_WP1

The work to date has concentrated on Task 1.2-3 concerned with incongruence detection and on the development of baseline systems for two applications of anomaly detection as part of Task 1.1-1. Initial investigation of data quality modelling and assessment (Task 1.2-2) has been carried out in the context of anomaly detection in communication networks (LU). In particular:

- A novel anomaly detection system architecture has been proposed which includes several distinct mechanisms to detect anomalous events and facilitates their characterisation. In addition to the conventional distribution outlier detection, the mechanisms include classifier incongruence detection, data quality assessment, classifier confidence gauging, model-drift detection. The outputs of these processes feed into a reasoning engine, which draws conclusions about the presence of anomaly and its nature. The details of the detection system architecture have been presented in (Kittler, et al., 2013).

- The focus of the activities in the first year was on the problem of classifier incongruence detection, which has been addressed as one of the key anomaly detection mechanisms. A novel surprise measure, which is bounded to a finite interval has been proposed and investigated. A theoretical analysis of the proposed measure and its error sensitivity has been carried out for scenarios representative of expert decision congruence and incongruence.
  Guidelines for surprise measure thresholding have been developed based on comprehensive simulation studies involving different input expert probability distributions, and estimation noise characteristics.

- As an application of anomaly detection based on network anomaly, methods have been developed to increase the efficiency of an anomaly based Intruder Detection System (IDS). Work has been undertaken to automatically label a data set and also to select automatically a set of metrics to be used in the anomaly detection process. These mechanisms can be used together to allow, for example, an anomaly detection operation to be tuned to optimise performance towards a specific requirement. Examples would include minimising False Positives (FPs), or maximising the Detection Ratio (DR). A paper discussing these aspects of the work has been approved by DSTL and submitted for publication (Aparico-Navarro, Parish, & Kyriakopoulos, 2014).

- The core of the anomaly detection system for surveillance videos, namely video segmentation based on evolving mixture models, has been developed by specializing on spatial video segmentation, which aims to divide each frame into meaningful area segments.
  More specifically, the first year contribution in this subject is an online video segmentation algorithm, which allows for consistent segmentation of consecutive video frames using an evolving mixture model. Efficient handling of computer memory and storage and automatic adjustment of the model's parameters to cater for abrupt changes between consecutive frames are the main features of the method. The latest findings are to be presented in (Kaloskampis & Hicks, Estimating adaptive coefficients of evolving GMMs for online video segmentation, 2014).

1.6 Technical Details

1.6.1 Anomaly Detection Mechanisms (L_WP1.2-3)

In the reporting period the theoretical research focused on the incongruence detection.

The detection of anomaly in sensor data processed by a complex decision making system, such as a contextual or multimodal decision making mechanism as given in Figure 1.1 can be aided by detecting incongruence of the outputs of different subsystems voicing independent opinions about the strengths of various data interpretation hypotheses.

Detecting incongruence can be formulated as a problem of statistical hypothesis testing. This typically involves some proposition, referred to as a null hypothesis and a test statistics. If the outcome of the test statistics is consistent with its known distribution model, then the null hypothesis is accepted. An outlier of that distribution would lead to the hypothesis rejection. An observation is considered an outlier at a given level of significance, i.e. if the test statistics value exceeds a threshold corresponding to some vestigial probability, such as 5% or 1%.

Accordingly, the proposition in incongruence detection is that two classifier outputs are congruent. A test statistics is applied, and if it exceeds a threshold corresponding to the required level of significance the hypothesis is rejected, that is the classifier outputs are deemed incongruent.

Given two decision making experts, their incongruence can be detected by measuring the Kulback-Leibler divergence between their respective class probability distributions, by considering the a posteriori class probability distribution output by one of the experts as a reference. This measure is referred to as the Bayesian Surprise (Δ_{BS}) (Itti & Baldi, 2005). When Δ_{BS} is high, it means there is a high difference in the a posteriori probability distributions, leading to incongruence between the classifier outputs.

Δ_{BS} can be interpreted as a measure of similarity between two discrete probability distributions functions. However, there are a few issues related to it:

- It goes to infinity in the case of having the a posteriori distribution of an expert in the vicinity of zero for any class.
- It is not symmetric in terms of selecting different experts as reference.
- It can produce the same value for completely different scenarios.
- It accumulates contributions from all classes, including those that can be interpreted as noise, and therefore is strongly affected by estimation errors.

In order to overcome these problems, we have proposed a new measure, namely Δ_{avg}. Let $\widetilde{P}(\omega_j|x)$ and $P(\omega_j|x)$; $j = 1, \dots, m$ denote the a posteriori probabilities associated with the hypothesis that model ω_j explains the input data, which have been estimated by the two experts. Assuming that these a posteriori probabilities will be estimated subject to estimation errors, the proposed surprise measure Δ_{avg} can be expressed as:

$$\begin{aligned}\Delta_{avg} = \frac{1}{4}\{&\left|P(\mu|x) - \widetilde{P}(\mu|x) + \eta_\mu(x) - \tilde{\eta}_\mu(x)\right| + \delta(\mu,\tilde{\mu})\left|\widetilde{P}(\tilde{\mu}|x) - \widetilde{P}(\mu|x) + \tilde{\eta}_{\tilde{\mu}}(x) - \tilde{\eta}_\mu(x)\right| \\ &+ \left|\widetilde{P}(\tilde{\mu}|x) - P(\tilde{\mu}|x) + \tilde{\eta}_{\tilde{\mu}}(x) - \eta_{\tilde{\mu}}(x)\right| + \delta(\mu,\tilde{\mu})\left|P(\mu|x) - P(\tilde{\mu}|x) + \eta_\mu(x) - \eta_{\tilde{\mu}}(x)\right|\}\end{aligned} \tag{1.1}$$

where $\tilde{\mu} = \arg\max_\omega \widetilde{P}(\omega|x)$ and $\mu = \arg\max_\omega P(\omega|x)$, i.e. the dominant hypotheses flagged by the two experts; and $\tilde{\eta}_\omega$ and η_ω are the noise terms associated with the two experts for class ω. The delta function (δ) is defined as equal to 0 if $\tilde{\mu} = \mu$ and 1 otherwise. The terms including the delta function are needed in order to magnify the surprise value if the two classifiers support distinct hypotheses.

This measure has many advantages over the Bayes surprise such as the fact that it is symmetric as it does not depend on the choice of an expert as a reference. The noise associated with non-dominant classes is masked, and the measurement values do not diverge as they are confined to interval (0, 1).

It should be mentioned that the estimation errors have to satisfy the condition of summing up to one, and being smaller than 1 when added on top of an a posteriori probability for any given class by any expert. Therefore, although the assumption of a normal distribution with zero mean has been made for all estimation errors, the distribution gets distorted for the a posteriori probabilities close to the boundaries of 0 and 1. The distorted distributions are in the shapes of folded normal distributions.

Within the analysis of the surprise measure for different pairs of expert probability (a posteriori) distributions, the following cases have been analysed for surprise value thresholding to account for incongruence detection:

Case 1: Both classifiers produce identical probability distributions

Case 2: Both classifiers agree on the most probable hypotheses

Case 3: Classifiers disagree on the most probable hypotheses

Note that these are the scenarios before the effects of the additive estimation noise, and that noise can cause label change on the (most probable) hypothesis.

Comprehensive experimental analysis has been performed by evaluating cases, which are parameterized by the error free surprise values defined in terms of expert probability distributions, the occurrence of label switching, and estimation noise distribution.

Below are representative results obtained for Case 2 and Case 3 in a three class-labelling problem. In the simulation experiments, various combinations of expert a posteriori probability distributions yielding a given / fixed surprise value are identified. After the addition of estimation noise on each realization, different surprise value distributions are obtained (Note that $\sigma = 0.15$ for the estimation noise). The results contain all possible scenarios including noise induced label switching.

Figure 1.2 (a) shows the distribution of surprise measure values induced by estimation errors for the initial noise free surprise value of 0.2. Setting the threshold around 0.3 would identify the majority of cases as “congruent”. However, the results are illustrative of the effect of estimation errors and how they can lead to false positive detection. Figure 1.2 (b) on the other hand depicts the distribution of the surprise value equal to 0.5 corresponding to the noise free case of expert disagreement. The threshold of value 0.3 again would yield a satisfactory outcome, labelling most cases as “incongruence”. In both cases shown in Figure 1.2 (a) and (b), 99% of the outlier areas beyond the proposed threshold are induced by label change caused by the estimation noise.

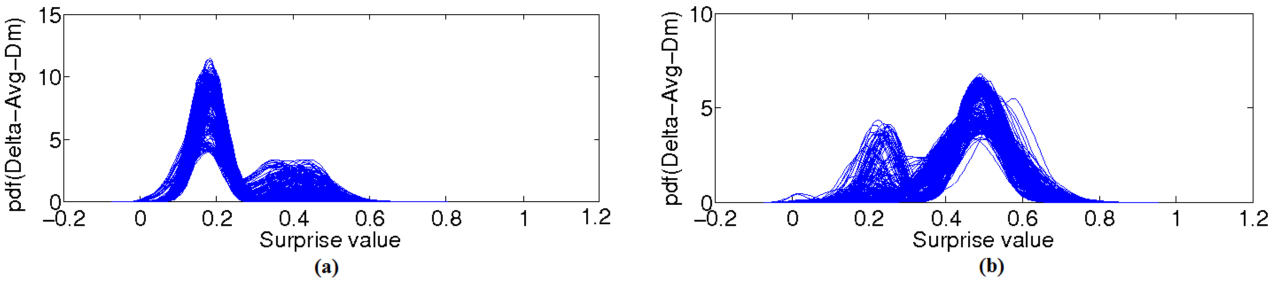

Figure 1.2 (a) Pdf. of Surprise Val.=0.2 for Expert Agreement (b) Pdf. of Surprise Val.=0.5 for Expert Disagreement

Note the area under the surprise distribution curves beyond the threshold is smaller in the disagreement scenario than in the case of agreement. This difference would be reflected in the relative proportion of false positive and false negative detection.

1.6.2 Application: Network Anomaly Detection (L_WP1.2)

As an initial application of anomaly detection, L_WP1 has concentrated on developing methods to increase the efficiency of an anomaly based Intrusion Detection System (IDS). For this, a technique that allows the automatic labelling of instances of an unlabelled dataset has been developed. Note that this methodology is studied as a part of the 'Data Quality Assessment' module, defined in the proposed anomaly detection system given in Figure 1. The definition of the term 'data quality' may be very broad, changing according to the specific area to which it is applied. In the area of statistical anomaly detection in communication networks, the definition of good data quality refers to characteristics of the information that allows the proposed anomaly detection system to identify efficiently the presence of anomalies. The better the data quality, the more efficient will be the generated anomaly detection results.

Correctly labelled datasets are commonly required, especially while using supervised IDSs, evaluating the efficiency of the IDSs for detecting intrusions, using feature selection techniques. In normal conditions, real network traffic is not labelled. Collecting labelled datasets from real networks is highly complicated, and in many cases impossible. Currently, datasets are mainly labelled by implementing previous off-line forensic analysis. This is highly resource and time consuming, and does not allow real-time implementation. The novel approach developed by LU automatically generates labelled network traffic datasets using an unsupervised anomaly based IDS. The resulting labelled datasets are subsets of the original unlabelled datasets.

Initially, supervised IDSs tend to generate better attack detection results than unsupervised IDSs. But, in order to use them, these systems require labelled training datasets to operate. The resulting outcome of the developed approach can be used as training datasets to train supervised IDSs. The proposed approach also benefits the efficient evaluation of the IDSs. Traditionally, the Detection Rate (DR), False Positive Rate (FPr), and False Negative Rate (FNr) have been the parameters used to evaluate the efficiency of IDSs. These parameters provide quantifiable evidence of how effective the IDSs are at making correct detections. In order to be evaluated in terms of DR, FPR and FNr an IDS needs to know the real nature of the analysed information. The instances that compose the analysed information have to be labelled as normal or malicious. The proposed approach is able to provide a correctly labelled dataset that can also be employed in task of IDS efficiency evaluation.

Our detection system provides three levels of belief, for each analysed instance. These are belief in *Normal*, which indicates how strong the belief is in the hypothesis that the current analysed frame is non-malicious, belief in *Attack*, which indicates how strong the belief is in the hypothesis that the current analysed frame is malicious, and belief in *Uncertainty*, which indicates how doubtful the system is regarding whether the current analysed frame is malicious or non-malicious. The difference between the belief in *Normal* and the belief in *Attack* plays an important role in the correct detection of the attacks. Therefore, if an appropriate threshold defining the boundary between strong and weak belief results could be found, misclassified instances could be discarded from the automatically labelled dataset.

The instances with differences above this threshold would be included in the labelled dataset, whereas the instances with belief results differences below this threshold would not be included. The used methodology defines the boundary threshold, based on the mean (μ) and standard deviation (σ) values, as: $\gamma = \mu_{total} - 2\sigma_{total}$. Statistically, the labelled dataset contains 95.44% of the original dataset and only correctly labelled instances are included in the new dataset.

Selecting the particular set of metrics that allows the IDS to generate the best intrusion detection results is also part of 'Data Quality Assessment' module. This is achieved using feature selection techniques. The use of feature selection is currently inappropriate for unsupervised IDSs, especially if the IDSs perform their detection in real-time. One of the reasons for this is because feature selection works only if the records in the datasets have been previously labelled. A similar need for correctly labelled datasets arises when feature selection techniques are utilised. A Genetic Algorithm (GA) based approach has been developed to perform the task of feature selection. The GA is a stochastic search technique that has been implemented to automatically provide the set of metrics that generate the most appropriate intrusion detection results. The GA could reduce the computational demand in situations in which a great number of metrics is considered. The GA follows a 6-steps process and uses the concept of chromosomes. A chromosome is a binary representation of solution vectors, a fixed length array with sequences of bits {0, 1}. The chromosomes evolve through successive iterations or generations. The fitness function value ($f_{fitness}$) is a quality measurement that indicates how well each individual chromosome fits the design requirements. It is expected that after successive generations, the chromosomes with higher $f_{fitness}$ prosper while those with lower $f_{fitness}$ disappear. In the implemented experiments, the used fitness function is $f_{fitness} = \mathrm{DR} + (100 - \mathrm{FPr}) + (Metrics_{Total} - Metrics_{Selected})$.

There is limited work in this area. One of the few recent papers that target the automatic generation of labelled network traffic datasets (Gargiulo, Mazzariello, & Sansone, 2012) also proposes the use of an unsupervised anomaly IDS to label packet datasets. However, there are notable differences in the implementation between both approaches. For instance, the authors of this paper define a guard region and the packets that fall in the guard region are not included in the labelled dataset. This approach needs to execute the algorithm multiple times, in order to find the appropriate guard region. In contrast, in our approach, only a single boundary threshold is defined. In addition, in our approach, the boundary threshold is defined only once for the whole dataset. The outcome of the GA based approach has experimentally shown that it is possible to implement an automatic feature selection approach using the labelled dataset, and the efficiency of the use of the automatically generated dataset.

In a new stage of the research, LU has focused on the simulation of networked battlespace scenarios. Conducting experiments in real battlespace networks is not always a feasible option. In addition to the lack of network traffic datasets, we come across multiple confidentiality issues and the risk of compromising sensitive information. These simulations provide a virtual testbed in which to apply and evaluate the statistical anomaly detection algorithms, as well as experimenting with different network attack tools without the risk of compromising sensitive information. A basic representation of a battlespace network has been created, using two particular network simulation tools, OMNET++ (Omnetpp, 2014) and OPNET (Opnet, 2014). This network replicates one of the topologies for networked battlespace communications included in a set of slides that we received from Gavin Patterson at DSTL. Initial network traffic activity has been monitored and parameters such as throughput have been measured. A number of PowerPoint slides, including the diagram of the network topology, diagrams of the exchanged messages and measurements have been sent to DSTL for further advice on whether the simulated network is representative of a real networked battlespace scenario, or whether we need to address the simulation differently.

Initial research has also been conducted into how contextual information could be included into the intrusion detection process, as part of our efforts to improve the efficiency of the detection system.

1.6.3 Application: Anomaly Detection in Video

As another application of anomaly detection, L_WP1 specializes on anomaly in surveillance videos. Based on the general framework for anomaly detection given in Figure 1.1, a system for anomaly detection in video has been developed as depicted in Figure 1.3. The core of the system is a video segmentation algorithm which is based on evolving mixture models.

Anomaly detection is handled as follows. Low level features (e.g. colour, texture, motion etc.) are first extracted from each video frame; these features are then clustered using a mixture of Gaussians. Each mixture component corresponds to a region of the image which encompasses pixels with similar characteristics. The spatial video segmentation part of the system tracks the evolution of the mixture components over time. Anomaly is defined as an abrupt change in the mixture, indicated by either a significant change in the characteristics of one or more of its components or a change in the mixture's composition (e.g. appearance of a new component or disappearance of an old one).

As the first year's contribution, a new video segmentation algorithm, which builds on the idea of varying the parameters of the model used for segmentation according to difference from frame to frame has been developed. The novelty of the proposed algorithm is in automatically adjusting the contribution of old and new information in the evolving model according to the measured difference between consecutive frames. Experimental results showed that the proposed method offers more uniform segmentation results in scenes featuring significant changes.

In summary, our video segmentation algorithm works as follows. First, as in a standard approach to segment an image using a mixture model, a feature vector is extracted for each pixel in the video frame. The pdf. of these vectors is modelled using a Gaussian mixture model (GMM). It is assumed that each Gaussian in the mixture corresponds to a segment of the frame. To segment an image each pixel in the frame is attributed to a segment according to its probability as estimated with the pdf.

When expanding to online video segmentation, the parameters of the GMMs representing segments, including the number of Gaussians, should change over time according to changes in the video leading to an evolving GMM. Our algorithm achieves this update by merging the evolving GMM with a temporary GMM trained on the current frame. After merging, the temporary GMM and all data related to it (image, extracted features) are discarded as the algorithm only requires the parameters of the evolving GMM for the next step; this results in efficient handling of computer memory and storage. The contribution of the evolving GMM and the temporary GMM is determined by an adaptive coefficient.

Keeping this coefficient constant throughout the image sequence as in (Charron & Hicks, 2010) proves sufficient when the difference from frame to frame is not significant. To improve segmentation accuracy in videos featuring important changes from frame to frame, our algorithm detects them and adjusts the coefficient according to the significance of these changes.

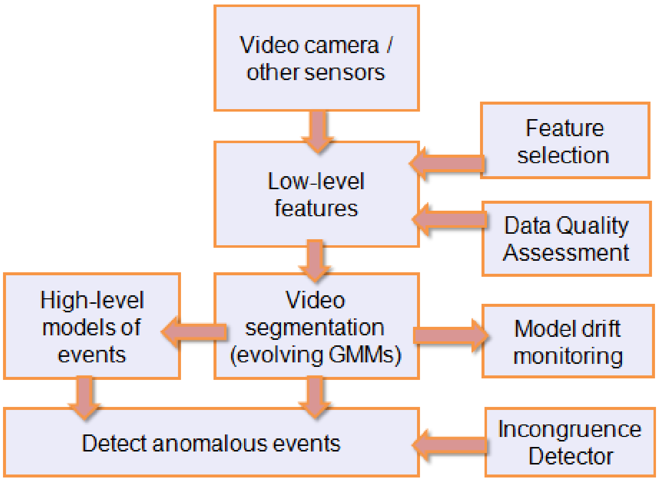

Figure 1.3 The proposed system for anomaly detection in video

We tested the algorithm using (a) publicly available videos for benchmarking purposes (b) videos featuring defence related content.

(a) Publicly available video
The segmentation results of the proposed method are compared against those obtained by the method described in (Charron & Hicks, 2010). Both methods are used to segment the publicly available Flower video sequence (Xiph.Org Foundation, 2013). Application of video segmentation on this video is challenging, as it is captured using a moving camera, which results in new objects entering the scene.

The contribution of old and new information in the evolving model is adjusted automatically according to the fluctuation of the adaptive coefficient c, which represents the importance of change in the scene from frame to frame (Figure 1.4). Lower values of c indicate more significant changes.

We compare our method's segmentation performance qualitatively against that of the algorithm presented in (Charron & Hicks, 2010). Both algorithms handle the important change detected in frame 182 sufficiently. There are no noticeable differences between the segmentation results of the two algorithms in these frames. This is due to the fact that the algorithm of (Charron & Hicks, 2010) uses a constant value for its adaptive coefficient which is close to the estimated value of our algorithm in this interval. However, as shown in Figure 1.5 there is noticeable loss of accuracy of (Charron & Hicks, 2010) compared to our method in later frames, where a lower value for the adaptive coefficient is required for accurate segmentation.

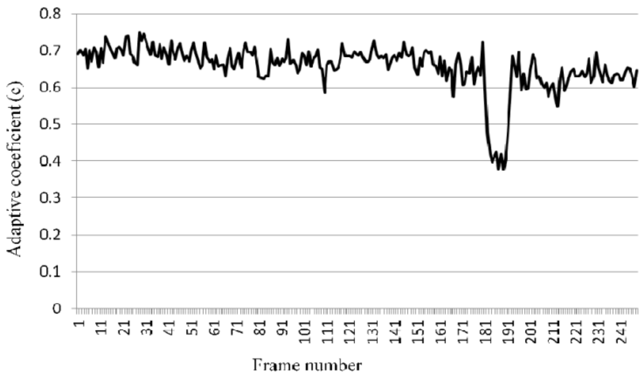

Figure 1.4 Fluctuation of the adaptive coefficient (c) within the flower video sequence

(b) Defence related video
We also investigate our method's applicability to defence related videos. The "Chopper" clip (Military videos collection, 2014) was chosen, captured in the field with non-optimal equipment. Our method succeeds in segmenting the frames of this video with good accuracy.

As reported in (Zabih & Kolmogorov, 2004) inclusion of pixel coordinates in the feature vectors sometimes causes large, uniform areas to split into two or more parts. To solve this problem, we currently develop an energy function which imposes a penalty in the case when neighbouring segments have different labels. Unlike (Zabih & Kolmogorov, 2004) where such a function is defined at pixel level, our method works at cluster level. The algorithm was tested in the flower sequence (Xiph.Org Foundation, 2013) significant improvements were noted in frames which were over-segmented by the previous version of our algorithm.

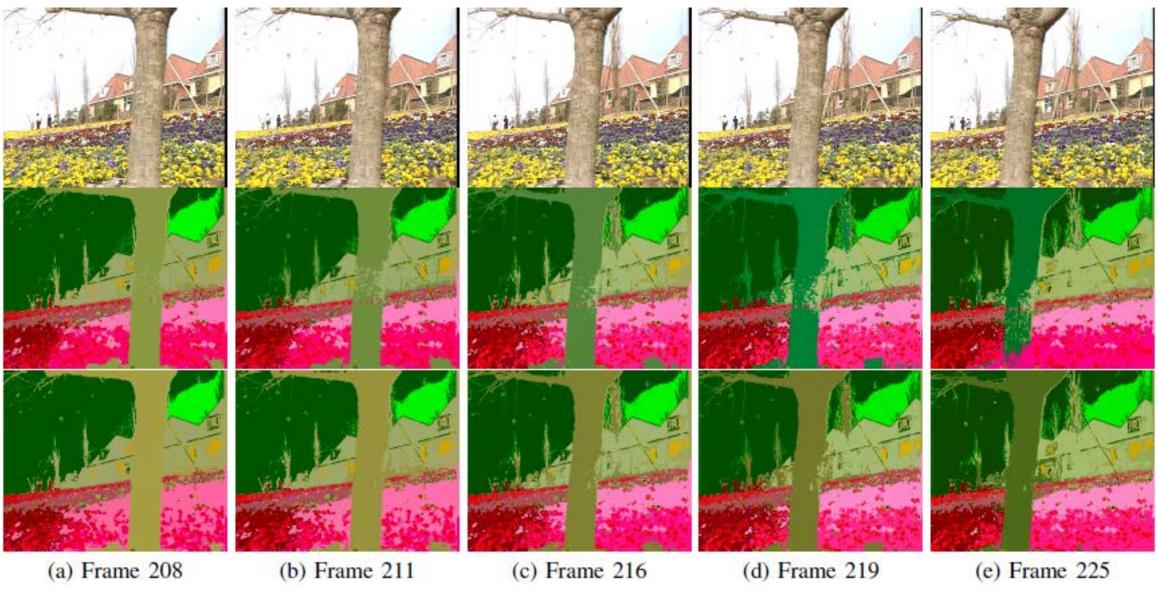

Figure 1.5 Segmentation results. Top row: original image; middle row: algorithm (Charron & Hicks, 2010)**; bottom row: our method.**

1.6 Future Work

As a part of the anomaly detection methodology development, the plan is to:

- Extend the incongruence detection study to multiclass problems. We shall also investigate the effect of modelling estimation error using more realistic distributions such as the Poisson distribution. The results of the study will be written up and submitted for publication.
- Develop data quality estimation techniques for the communication network anomaly detection problem.
- Develop solutions for dealing with missing data.
- Develop anomaly detection system reasoning engine based on Dempster-Shafer theory of evidence combination. Future work for anomaly detection in communication networks aims to incorporate domain and contextual information and extend the concept of anomaly to include unexpected changes in performance**.**

The above methodology will be applied to the problem of anomaly detection in the two application domains investigated at LU and CU respectively. In the case of intrusion detection, based on the contextual information, an IDS could modify its detection capabilities and take decisions accordingly. We identify three main sources of information, mission-oriented, situational and behavioural information. Mission-oriented information could be understood as the commander's intent in standard military operational orders or the alert states. Based on this information, similar measurements may have different interpretation. Situational information could be envisioned as the actual network traffic information monitored. This information provides constant knowledge of the current status of the network. The situational information would allow the detection system to adjust and adapt the network to unforeseen circumstances, according to this information. Different devices may share information to increase the situational knowledge about the monitored environment status. Finally, the behavioural information could be obtained directly from the network users. Users could indicate present and future behaviour intentions or actions. In a battlespace scenario, independent units may deliberately change the actions established by commander's intent, these changes may be indicated and the detection capabilities of the IDS changed accordingly. An IDS could determine if the monitored actions correlate with the correct behaviour information indicated by the user and the detection could be more accurate.

We will investigate approaches to incorporate the described contextual information into the IDS. One feasible technique to steer the network intrusion detection, based on the contextual information, is Weighted Dempster-Shafer (D-S). Normally, in tasks of data fusion, different measuring sensors receive similar level of trust. Weighted D-S allows one to quantitatively provide different level of trustworthiness to different measuring sensors. The approach that LU is currently considering is to modify the detection capabilities of the IDS, not only based on the trustworthiness to different measuring sensors, but also based on the contextual information. For instance, focusing in our current IDS, different alert status may increase of reduce the different levels of belief.

Effort has been directed towards establishing a simulation environment for a networked battlespace scenario. This will allow further advances to networked anomaly detection in the networked battlespace to be investigated, including the incorporation of domain or context related information.

As for future work for anomaly detection in surveillance videos, the focus is going to be on further developing the incremental learning of statistical models (GMMs) of video features. We have already made progress by adding an energy function to our algorithm which handles the problem of over-segmentation of large uniform areas. Testing and optimisation of this method are currently carried out.

Furthermore, the evolution of the statistical mixture model over time will be tracked; anomalies will be detected as significant changes in the characteristics of one or more of the mixture's components or a change in the mixture's composition.

Another research direction will be to combine the low-level statistical models of video features learned from our method with high-level event models (e.g. hierarchical graphical models (Kaloskampis, Hicks , & Marshall, Automatic analysis of composite activities in video sequences using key action discovery and hierarchical graphical models, 2011)) for the purpose of analysing complex behaviour in video.

Finally, we will investigate the applicability of our methodology to other application areas. In particular we shall consider several defence-related datasets, including video streams from UAVs and the thermal imaging videos from the UDRC website (University Defence Research Collaboration in Signal Processing, 'Thermal imaging videos, 2014). We shall also consider the Portsmouth shipping data from Thales. The aim is to identify at least one data set, which could act as a vehicle for collaborative research engaging the complementary expertise of the three partners working in L_WP1. To extend the anomaly detection activity into the healthcare sector, the affiliated PhD student at LU is building upon work in fall detection (Yu. M., and Chambers, J.A, et al., 2012, 2013) which also requires tracking and links to L_WP2, and is focused upon exploiting deep learning (Feng., P., and Chambers, J.A., et al., 2014).

1.7 References

Xiph.Org Foundation. (2013). Retrieved from http://media.xiph.org/.

Military videos collection. (2014). Retrieved from http://www.militaryvideos.net.

Omnetpp. (2014). Retrieved from http://www.omnetpp.org.

Opnet. (2014). Retrieved *from* http://www.opnet.com.

University Defence Research Collaboration in Signal Processing, 'Thermal imaging videos. (2014). Retrieved from http://www.see.ed.ac.uk/drupal/udrc/data-centre/.

* Aparico-Navarro, F., Parish, D., & Kyriakopoulos, K. (2014). Automatic dataset labelling and feature selection for intrusion detection systems. *MILCOM .* Submitted.

Charron, C., & Hicks, Y. (2010). An evolving MoG for online image sequence segmentation. *17th IEEE International Conference on Image Processing (ICIP)*, (pp. 2189–2192).

* Feng, P., Yu, M., Naqvi, S.M., and Chambers, J.A., (2014), Deep Learning for posture analysis in fall detection, submitted to DSP 2014, Hong Kong.

Gargiulo, F., Mazzariello, C., & Sansone, C. (2012). Automatically building datasets of labelled IP traffic traces: A self-training approach. *Applied Soft Computing*, 12(6), 1640-1649.

Itti, L., & Baldi, P. (2005). A princincipled approach to detecting surprising events in video. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, (pp. 631-637).

* Kaloskampis , I., & Hicks, Y. (2014). Estimating adaptive coefficients of evolving GMMs for online video segmentation. *6th IEEE International Symposium on Communications, Control, and Signal Processing (ISCCSP 2014).* To Appear.

Kaloskampis, I., Hicks , Y., & Marshall, D. (2011). Automatic analysis of composite activities in video sequences using key action discovery and hierarchical graphical models. *2nd IEEE Workshop on Analysis and Retrieval of Tracked Events and Motion in Imagery Streams (IEEE ARTEMIS 2011)*, (pp. 890–897).

* Kittler, J., Christmas, W., de Campos, T., Windridge, D., Yan, F., Illingworth, J., & Osman, M. (2013). Domain Anomaly Detection in Machine Perception: A System Architecture and Taxonomy. to appear in *IEEE Transactions on Pattern Analysis and Machine Intelligence*.

Lezama, J., Alahari, K., Sivic, J., & Laptev, I. (2011). Track to the future: Spatiotemporal video segmentation with long-range motion cues. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR).*

Yu, M., Rhuma, A., Naqvi, S.M., Wang, L. and Chambers, J.A., (2013) “An unsupervised online support vector machine based person-specific fall detection system for monitoring an elderly individual in a room environment”, *IEEE Trans. on Info. Technology in Biomedicine*, Vol. 17(6), pp. 1002-1014.

Yu, M., Rhuma, A., Naqvi, S.M. Wang, L. and Chambers, J.A., (2012) “Posture recognition based fall detection system for monitoring an elderly person in a smart home environment”, *IEEE Trans. on Info. Technology in Biomedicine*, Vol. 16, No. 6, pp. 1274-1286.

Zabih, R., & Kolmogorov, V. (2004). Spatially coherent clustering using graph cuts. *IEEE Conference on Computer Vision and Pattern Recognition*, (pp. 437-444).

L_WP2 (HU) Handling uncertainty and incorporating domain knowledge

2.1. Staffing

Work Package Leaders:	Prof Lambotharan (LU) and Prof Wen-Hua Chen (LU)
Research Associates:	Dr Anastasia Panoui (LU), Dr Miao Yu (LU)
UDRC Research Student:	Mr Tasos Deligiannis (LU)
Affiliated Research Student:	Mr Pengming Feng (LU)
Lead Project Partner:	Mr Angus Johnson (Thales)
Dstl Contacts:	Dr Marcel Hernandez, Dr Jordi Barr.

2.2. 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 L_WP1 through domain knowledge; and L_WP3 & L_WP4 in handling incomplete sensor information & achieving robustness to jamming.*

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).

L_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.

L_WP2.2: Robust signal processing techniques under uncertainty, modelling uncertainty with stochastic dynamic processes, and characterization of uncertainty with a game theoretic framework [PDRA3/PS2]

Robust signal processing techniques based on convex optimizations will be developed to tackle uncertainty. Mathematical models and approximation techniques will be developed to model an uncertainty region as a convex hull so that low complexity algorithms can be developed. Robust techniques based on both a probabilistic approach and worst case optimizations will be developed. The application scenario will include distributed/networked beamformer design under manifold uncertainty, imperfect sensor measurements and radar clutters. Instead of treating uncertainty as caused by a static collection of events and associated relationship, the uncertainty will be investigated within the framework of dynamically evolving phenomena.

In this framework, uncertainty will be considered as caused by dynamic entities having states and transitions from one state to another resulting from actions in the battlespace. Both hidden Markov model and Bayesian networks will be used to characterise uncertainty. To enhance characterization of uncertainty and to understand the underlying mechanisms further, this WP will consider uncertainty as caused by dynamically varying actions created by various players in the battlespace, e.g. coalitional forces and enemies. Hence a game theoretical framework will be developed. The work will start with a non-cooperative game theoretical framework and will be extended to Bayesian games to account for incomplete information. The framework will then be extended to stochastic games (Markov games) to model dynamically changing actions and evolution of uncertainty. The possible battlespace scenarios that will be considered within this framework will include air formation to ground attack-defence system, defence against jamming in radars (linked to WP 4.1) and counteracting uncertainty created by deception by enemies, for example fake RF signal injection.

2.3 Progress made in the first year in addressing the original objectives

2.3.1 Overview

The original aim of this work package was “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 the development of signal processing algorithms for handling uncertainties by incorporating domain knowledge and game theoretic methods. Two postdoctoral research associates and one PhD student work on this work package.

2.3.2 Engagement with partners

The leading industrial partner for this work package is Thales. We have had a number of meetings with Mr Angus Johnson. Discussions have been made in terms of technical support and way of engagements.

There are a few changes in terms of Dstl technical contact for this work package. The current technical contacts for WP2.1 and WP2.2 are Dr Marcel Hernandez from the Advanced Signal Processing & Fusion Team and Dr Jordi Barr from the Sensors & Countermeasures Department, respectively. Both Dr Hernandez and Dr Barr are experienced signal processing experts and have provided a number of very insightful comments and suggestions to this work package.

2.3.3 Review of progress

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

1. **Identify the limits of the current generic Bayesian inference approaches when incorporating domain knowledge in signal processing particularly in a battlespace environment**. In many cases, the domain knowledge or other information could be represented as various (hard or soft) constraints in a statistic way. This leads to a much reduced solution space hence ambiguity and level of uncertainty could be significantly reduced. However, in all the current Bayesian filtering approaches of incorporating domain knowledge, constraints are directly applied on the system states in modelling and consequently algorithm development. But in reality, the constraints (knowledge) actually affect the distribution and the evolvement of underlying system dynamics (i.e. interaction between the physical system and its operational environment). We aim to investigate new modelling approaches and develop a new generic Bayesian framework by taking into account the fact that the distribution of the future controls/input is actually affected by the domain knowledge (e.g. a driver is more likely to move the vehicle to the middle of the road if a vehicle is now quite close to the edge of a road).

2. **Compare different implementations of generic Bayesian frameworks, particularly particle filtering and Gaussian mixture algorithms.** Although Bayesian theory provides a rigorous framework in developing algorithms for incorporating domain knowledge in signal processing, it is difficult to implement and, in general, not computationally tractable. Most notably, the incorporation of the knowledge significantly distorts the statistic distribution even if the distribution for the dynamic systems without constraints is Gaussian. Particle filtering and Gaussian mixture algorithms are two popular numerical implementations of the generic Bayesian framework. A detailed study on a GMTI radar tracking benchmark consisting of Doppler blindness zone, missed detection and multiple manoeuvring modes of the moving object (i.e. constant velocity, acceleration, and stop) has been carried out. Our research has shown that *the IMMPF (Interactive Multiple Model Particle Filtering) yields much better tracking performance (in particular when the vehicle is stationary) than the latest multiple model Gaussian mixture methods with acceptable computational burden*.

3. **Investigate how to incorporate different types of domain knowledge into the state-of-the-art algorithms**. For a tracking example, we investigate how to incorporate domain knowledge, not only where a moving object shall be or is more likely to be, but also where the moving object is unlikely or impossible to be. Geographic Information Systems (GIS) are used to extract available domain knowledge, and advanced multiple model particle algorithms are developed where measurements and particle swarm optimisation algorithms are exploited to improve particle samplings and the algorithm efficiency.

4. **Development of game theoretic power allocation algorithm for statistical MIMO radars**. When multiple radars operate simultaneously, they may interfere with each other unless there is a proper coordination among these radars in terms of waveform selection and power allocation. However, in a battlefield environment, it

may be impossible or infeasible to have proper communication and coordination between radars; hence they need to have intelligence to optimise their transmission parameters such as power and waveforms in order to achieve certain target performance. We have shown that the game theoretic method has the ability to control and minimise the transmission powers of radars in order to achieve a target signal to disturbance ratio (SDR) for all radars. This method does not require any communication between radars. The mathematical proof for the convergence of this algorithm is currently under investigation.

2.4 Technical details

2.4.1 L_WP2.1

Modelling and algorithm development for constrained dynamics systems affected by knowledge/environment

It is well known that the movement of an object is significantly affected or constrained by its operational environment. When a signal processing algorithm is developed to process sensor measurements, its performance may be dramatically improved by taking into account background knowledge and the information of the operational environment. Consider a dynamic system described by

$$x_k = f(x_{k-1},\ m_{k-1},\ w_{k-1}) \tag{2.1}$$

with the sensor observation model

$$z_k = h(x_k,\ v_k) \tag{2.2}$$

where x_k is the system state at time k, w_k the driving noise or system random input, m_k the mode of system dynamics at time instant k, z_k the measurement, and v_k the measurement noise. When prior information such as the knowledge about the operational environment is available, quite often it can be represented as (soft or hard) constraints,and thereby used to shape the probabilistic density distribution. In most of the current Bayesian filtering framework, such information is represented as (equality or inequality) constraints on the ***system states***, e.g. non-positive

$$x \leq 0 \tag{2.3}$$

The current modelling approach is to deal with the system dynamics and the constraints separately. That is, system (2.1) evolves with time itself and then the constraints (2.3) are applied to system (2.1). Various ways have been proposed to deal with the case when the constraints (2.3) are violated; for example, forcing the system state to stay in the region defined by (2.3) (this implies that it is more likely the state is on the boundary of the set defined by (2.3)), or rejecting any state trajectory outside the region defined by (2.3) and regenerating state trajectories by randomly generating input sequences w_k based on their prescribed distribution. These methods cannot truly represent the physical process between the system dynamics and the environment, and the interaction between the input/control action and the environmental constraints. For example, if a vehicle is quite close to the edge of a road, the driver is more likely to control the vehicle to move away from the edge. Therefore, although the driver's behaviour is still random from an observer point of view, it is generated from a distribution heavily affected by the environment knowledge.

We have proposed to directly model the domain knowledge on the *input w*, rather than the state *x* as in (2.3). Consequently, a different Bayesian framework and corresponding algorithms have to be developed on the basis of this new modelling approach. This also affects how to design simulation methods to make the simulation closer to real world scenarios so as to be able to better assess different Bayesian algorithms for incorporating domain knowledge.

Benchmark study on the comparison of IMMPF (Interactive multiple model particle filtering) and Gaussian mixture algorithms: GMTI radar tracking with a Doppler blindness constraint

In this work, the state-of-the-art IMMPF algorithm is applied and modified to incorporate the Doppler blindness constraint information in GMTI tracking. Particular attention has been given to compare another quite promising solution -- Gaussian mixture algorithm (Clark et al.). The IMMPF algorithm applies the particle filtering scheme to implement the recursive Bayesian filtering for a stochastic hybrid system, in which multiple state models are concerned. Furthermore, due to the nature of the particle filtering, IMMPF can efficiently deal with the non-linear property of the GMTI radar measurement model.

The case study scenarios are taken from (Clark et al.) and all the results shown in Tables 2.1 and 2.2 except for the IMMPF are taken from (Clark et al.) for the sake of comparison. The scenarios are defined with three key parameters:

MDV: the minimum detectable velocity;
$P_{d:}$ the detection rate of the GMTI radar when a vehicle is moving above the minimum detectable velocity;
$\delta_{r:}$ Standard deviation of the range rate noise.

All the parameters and simulation setting are the same as in (Clark et al.). A number of the existing solutions for this problem have been investigated in (Clark et al.) as shown in Tables 2.1 and 2.2. The most relevant one is the noise related Doppler blind mixture filter with multiple models (NRDB-MM) developed in (Clark et al.) based on the latest Gaussian mixture approach. In the first IMMPF algorithm, the same multiple models as in NRDB-MM are used, while in the second IMMPF algorithms, three models are used for each x axis and y axis so nine models result from the assumption that the movement in x and y axes are independent in the vehicle models.

Results in Tables 2.1 and 2.2 show that

1. Compared with all the other methods including Gaussian mixture approaches, a *substantially* improved performance is obtained by the IMMPF where the Doppler blindness constraint information is incorporated to deal with no recorded measurements.

2. Even better tracking performance is obtained by using more maneuvering models to describe the vehicle’s movement in a more accurate way.

Scenario	I	II	III	IV	V	VI	VII	VIII
P_d	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
$\sigma_{\dot{r}}(m/sec)$	1.5	1.0	0.75	0.6	1.5	1.0	0.75	0.6
$MDV/\sigma_{\dot{r}}$	2	3	4	5	2	3	4	5
EKF	420.89	418.08	462.27	388.71	254.06	308.98	246.96	265.07
SDPD	241.84	220.54	280.94	214.27	51.32	60.38	43.37	46.80
NRDB	197.41	168.31	219.81	162.76	44.26	49.00	34.65	36.96
SIR-PF	198.78	163.47	221.05	163.50	43.92	48.93	33.28	37.65
EKF-MM	56.29	55.64	59.76	44.01	25.99	33.99	25.61	30.33
NRDB-MM	56.32	56.77	61.92	45.22	25.59	33.90	24.66	29.73
IMMPF (three models)	29.06	24.04	23.67	24.66	20.59	15.46	14.73	15.47
IMMPF (nine models)	20.47	14.89	12.90	12.01	16.07	9.15	8.29	7.53

Table 2.1 Blind zone performance assessment: The time-averaged RMSE errors (in meters) in x-coordinate

One of the concerns of the particle filtering implementation is related to computational time. Similar to (Clark et al.) for SIR-PF, 5000 particles are used for each movement type in our IMMPF. The algorithms are implemented on a PC with 3.00 GHz processing speed and 2.00 GB memory using Matlab 2012(a). For the case of three state models, the IMMPF based method is approximately 0.14 s. For the nine state models case, it takes 0.42s to execute the improved IMMPF algorithm. For this case study, as indicated in (Clark et al.), the sampling time is 5 seconds. Therefore we believe there is no major concern about the computational time for this quite complicated particle filtering algorithm.

Scenario	I	II	III	IV	V	VI	VII	VIII
P_d	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
$\sigma_{\dot{r}}(m/sec)$	1.5	1.0	0.75	0.6	1.5	1.0	0.75	0.6
$MDV/\sigma_{\dot{r}}$	2	3	4	5	2	3	4	5
EKF	105.57	118.52	126.08	126.02	81.54	102.53	120.93	106.85
SDPD	101.10	113.63	123.61	122.97	79.97	99.97	119.02	104.75
NRDB	101.82	114.80	123.31	123.09	80.21	100.53	119.23	104.93
SIR-PF	121.64	122.12	133.55	154.76	84.47	116.18	140.61	112.03
EKF-MM	34.02	36.73	39.49	37.44	27.56	31.97	33.15	31.18
NRDB-MM	40.17	49.01	53.35	49.09	38.78	45.29	57.48	47.41
IMMPF (three models)	24.88	29.92	32.08	24.96	23.23	24.18	28.72	22.51
IMMPF (nine models)	11.55	10.87	10.96	10.20	11.43	9.90	10.92	10.16

Table 2.2 Blind zone performance assessment: The time-averaged RMSE errors (in meters) in y-coordinate

GIS information aided ground vehicle tracking

In this work, we exploited more information in Geographic Information System (GIS) for vehicle tracking with different movement types. The geographic information could be easily acquired from the on-line dataset. When the vehicle moves off-road, its movement is constrained by inaccessible areas such as woods, buildings and high slope regions as the vehicle could not move into these regions. When the vehicle moves on-road, the vehicle's movement follows the road and should always be within the road boundary. But we also consider the vehicle may move to off-road from on-road or vice versa.

A multiple model particle filtering algorithm is applied in this work, considering the vehicle could move on/off road with different movement types. Most notably, the MMPF algorithm is improved by incorporating a particle swarm optimization step in sampling, which makes the samples converge into the high likelihood region of the measurement by maximizing the measurement likelihood function. This new particle filter is referred to as **MM-PSO-PF.**

The simulation is performed on a real scenario in Lindifferon, St. Andrews. A UAV is simulated to cruise at an altitude of 200m to monitor this area, the circle radius is 100m and the angle speed of the UAV is ($\pi/20$). A vehicle is simulated as in Figure 2.1 to move on the ground, it can both move on road and off road; it is also able to move in different movement types—stop, moving in a constant velocity and manoeuvre.

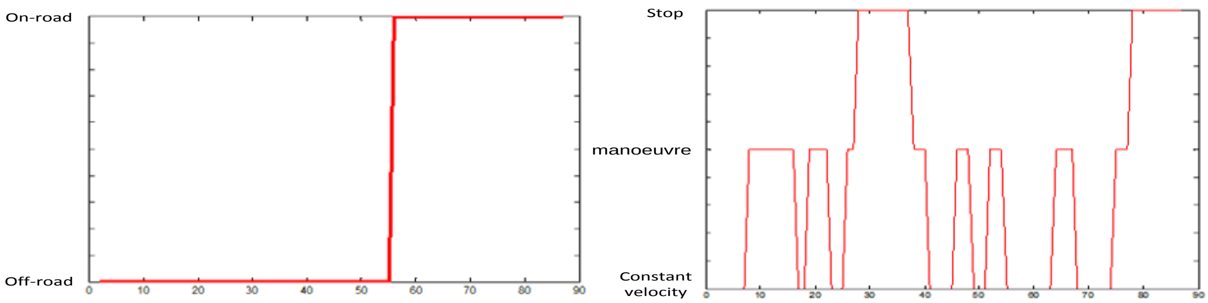

Fig. 2.1 Off-road and on-road intervals and profiles of vehicle movement types: ordinate units seconds

The importance of incorporating the GIS information is evaluated. We can see more accurate tracking result with smaller RMSE could be obtained by the aid of the GIS information as shown in Table 2.3. 30 trials of Monte Carlo simulations for each situation are performed and the statistics of the RMSEs for tracking with/without domain knowledge are analysed, the results are presented in the following table. It is clearly evident that better tracking performance could be obtained with the aid of the GIS information.

	No. of successful tracks	Mean of RMSE (m)	Standard deviation (m)
Tracking without GIS	20/30	24.57	17.06
Tracking with GIS	30/30	9.35	2.62

Table 2.3 Performance assessment of the MM-PSO-PF algorithm with or without GIS information

We also compare the proposed MM-PSO-PF algorithm with other different algorithms, including the standard multiple model particle filter (MM-PF), multiple model auxiliary particle filter (MM-APF) and the multiple models version of the differential evolution Monte Carlo based particle filter (MM-DEMC-PF). Table 2.4 clearly shows the proposed MM-PSO-PF algorithm outperforms all the other MM algorithms due to its feature in maximising the likelihood function based on the measurements, which makes the sampling much more efficient.

	No. of successful tracks	Mean of the RMSE (m)	Standard deviation(m)
MM-PF	20/30	14.99	5.17
MM-APF	26/30	16.02	3.99
MM-DEMC-PF	30/30	14.58	4.90
MM-PSO-PF	30/30	9.35	2.62

Table 2.4 Performance comparison of a number of different multiple model particle filter algorithms

2.4.2 L_WP2.2

Convex Optimization and Game Theoretic Techniques

Many problems faced in a networked battlefield require optimization of certain criteria such as detection probability of targets or signal to noise plus interference ratio of sensor measurements under various practical constraints such as transmission power, available bandwidth, false alarm rate and delay. The convex optimization techniques have the ability to handle these problems and to provide mathematically tractable solutions. We exploit this in our distributed optimization of transmission power in a MIMO radar environment as discussed below. The game theory is a mathematical tool for modelling strategic interaction of various rational players or entities. There are many emerging applications of game theoretic methods in a networked battlefield such as distributed resource allocations in radar and sensor networks, tracking intelligent targets and electronic counter measures. The particular case of interest to this work package is the uncertainty created by deception of enemies in a network battlefield. This includes cases of deliberate RF signal injection and jamming by intelligent targets. Therefore, interaction of intelligent targets is considered in the waveform design of radars. Game theory naturally fits well into understanding and modelling mathematically the interaction of radars and jammers and to develop techniques for waveform design that is robust to jamming.

Another area of interest for game theoretic methods is on guidance law for interceptors within the context of ballistic missiles (BM). Normally, a BM's flight path includes three phases namely early phase, mid phase and final phase. Due to reasonable opportunity and time to detect, pursue and interact, a ballistic missile is normally intercepted and disabled in the mid phase. However, in the mid phase, in order to confuse the interceptor, a BM would release multiple decoys and possibly multiple warheads. The conventional guidance law for the interceptor is based on proportional navigation which assumes the flight path and the velocity for the BM is defined and optimal control theory is used to minimise the distance between the BM and the interceptor. However, it is not impossible that future BMs may have intelligence and flexibility to manoeuvre (change of direction and acceleration), so that the guidance law for the interceptor should be an optimal control strategy against the optimal control strategy of the BM. This can be characterised by differential game theoretic methods and will be of interest to this work package.

Distributed resource allocation for statistical MIMO radar network using game theory

While the overarching aim remains the development of signal processing algorithms for tackling uncertainties created by intelligent targets within a radar environment as discussed above, as a preliminary work on the potential of game theory and convex optimization, we have proposed an intelligent distributed resource allocation technique for a statistical MIMO radar environment. The ultimate aim is to extend this work to distributed MIMO waveform design that is robust to jamming using this game theoretic framework.

We investigated the possibility of placing multiple low power radars distributively in a geographical area for surveillance without requiring any significant coordination between them while the whole radar network aims to achieve a common goal, for example certain probability of detection. When multiple radars operate in the same frequency bands, they may interfere with each other and it is important that their waveforms and the corresponding powers should be optimised. However, in many situations, coordination between radars is neither feasible nor attractive. Hence, we proposed a non-cooperative resource allocation technique for a radar network. We considered a set of clusters of radars as shown in Figure 2.3 and assumed no coordination between the radars in various clusters; however, radars in each cluster have coordination. The radars in each cluster are expected to determine appropriate transmission power so that target return signal at each radar attains a certain signal to disturbance (noise plus clutter return) ratio (SDR). Importantly, each radar aims to use minimum possible transmission power to attain a certain target SDR. Accordingly, radars in each cluster communicate to determine a set of orthogonal waveforms and the corresponding minimum possible transmission power, while assuming no communication between radars in various clusters. We solved this using a non-cooperative game theoretic framework which offers the freedom to every MIMO radar group to act independently, and taking into account the actions of the other radar groups, to adjust the power in order to achieve a certain target SDR.

The game theoretic results showed that the clusters of MIMO radars have the ability to act in a decentralised manner to allocate transmission power to its radars. Simulation results described below verified that the algorithm has the ability to allocate powers to radars in various clusters distributively while achieving a target SDR without requiring any coordination. The power allocation algorithm converges to a unique equilibrium known as Nash equilibrium. Existence and uniqueness of the Nash equilibrium are two important features of game theoretic algorithms to ensure desirable convergence. Even though we have seen stable convergence in the simulation studies, we are currently investigating how to establish this mathematically.

For the simulation study, we considered a network of four radars, which is partitioned into two clusters of size two as shown in Figure 2.3. At every time step, upon receiving a number of signal samples, each radar updates its power in such a way that the overall power of the MIMO cluster is minimized until equilibrium is reached.

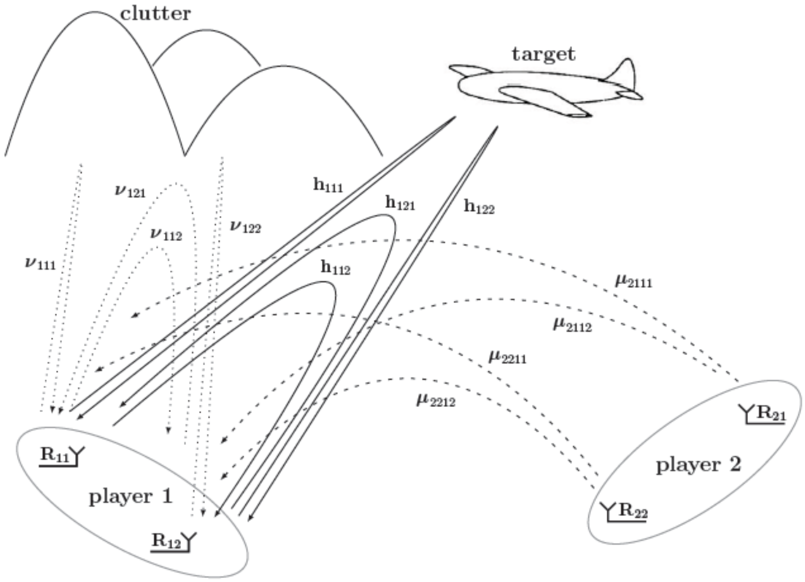

Figure 2.3: A radar network with two MIMO radars for each cluster of size two.

All the channel gains from each transmitting radar to receiver radar and the channel gain corresponding to the clutter paths and the cross channel gain between radars in various clusters were modelled using magnitude square of zero mean complex Gaussian random variables. We have set the desirable target SDR for the return signal for each radar to be 3.76 dB. We have set the maximum power that each radar in any cluster could use to three different values as 1W, 0.15w and 0.12W. The actual transmission power used by the two radars in each cluster and the total transmission power of radars in each cluster is shown in Table 2.5. When the maximum possible transmission power for each radar is very high or when there are no constraints on the maximum transmission power, only one of the radars in each cluster aims to illuminate signals which can be used by the peer radars in the same cluster as a signal of opportunity for detection. This keeps the overall interference in the network low. However, when there is a limit on the maximum possible transmission power of each radar, the radars in each cluster aim to share the transmission power in order to achieve a desired signal-to-disturbance ratio.

	maximum power	$\overline{p}_{ki} = 1$	$\overline{p}_{ki} = 0.15$	$\overline{p}_{ki} = 0.12$
Custer 1	(p_{11}^*, p_{12}^*)	(0, 0.1744)	(0.0408, 0.15)	(0.0927, 0.12)
	total power	0.1744	0.1908	0.2127
Custer 2	(p_{21}^*, p_{22}^*)	(0.1593, 0)	(0.15, 0.0151)	(0.12, 0.0634)
	total power	0.1593	0.1651	0.1834

Table 2.5: The allocated power for radars in each cluster for different upper limit on the transmission power (1W, 0.15W and 0.12W)

Currently we are investigating methods to allocate waveforms and beamformers in addition to power allocation using these non-cooperative game theoretic methods.

2.5 Future Plans

For L_WP2.1, the focus is to

1. develop the idea of the new modelling approach for the interaction of a physical system and the influence of its behaviour due to its operational environment or other relevant information, develop new Bayesian algorithms based on this new modelling approach. Furthermore, new simulation methods will be developed based on the new modelling approach to assess the new algorithms and existing ones in more realistic scenario. Pengming Feng (LU) will be helping with this task and linking with L_WP1.

2. incorporate different types of knowledge or constraints which have not been fully taken into account or are difficult to cope with by the existing algorithms. For example, most of the current particle filtering algorithms are only able to efficiently deal with convex constraints or convex sets. For infeasible constraints/sets (i.e., a physical system must be not within the sets, rather than within the sets), it is hard to convert them into convex sets.

3. further investigate the advantages and shortcomings of different numerical implementations of signal processing algorithms taking into account domain knowledge developed based on the Bayesian framework.

For L_WP2.2, the focus is to

4. establish existence and uniqueness of Nash equilibrium for the distributed power allocation techniques proposed for the statistical MIMO radar network. The current approach is based on proving the best response function for updating the transmission power is a standard function (Lasaulce et al.).

5. extend the game theoretic algorithm developed for power allocation to waveform and power allocation techniques for statistical MIMO radar network. The aim is to introduce intelligence to radars in various clusters to automatically adapt their waveform and transmission power to reduce interference in the network while achieving a target performance.

6. investigate interaction of smart targets and radars and propose non-cooperative game theoretic techniques for MIMO radar waveform design that is robust jamming.

2.6 Outputs

Two conference articles have been accepted for publication:

1. * A. Panoui, S. Lambotharan and J.A. Chambers, “Game Theoretic Power Allocation Techniques for a MIMO Radar,”, IEEE International Symposium on

Communications, Control and Signal Processing (ISCCSP), Athens, May 2014.

2. * M. Yu, C. Liu, W.-H. Chen and J. A. Chambers. An improved ground vehicle tracking algorithm by integrating Bayesian tracking framework with an auxiliary particle filter, "Signal Processing, Sensor/Information Fusion, and Target Recognition XXIII" conference, in SPIE Defense + Security, 5-9 May 2014, Baltimore, Maryland USA.

Two journal papers are under preparation for IEEE journals:

1. * M. Yu, C. Liu, B. Li and W-H Chen. GMTI Radar Tracking Based on Interactive Multiple Models Particle Filter.

2. * M Yu, D. Yu and W-H Chen. Geographic Information Systems aided Manoeuvring Ground Vehicle Tracking.

2.7 References:

Clark, J., Kountouriotis, P., and Vinter, R. (2009). A new Gaussian mixture algorithm for GMTI tracking under a minimum detectable velocity constraint. *Automatic Control, IEEE Transactions on*, 54(12), 2745–2756, Dec. 2009.

Lasaulce, S. Debbah, M., and Altman, E., “Methodologies for Analyzing Equilbria in Wireless Games,” IEEE Signal Processing Magazine, pp. 41-52, Sept. 2009.

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:	Prof. Ian Proudler, Prof. Jonathon Chambers, Dr. Philip Jackson, Prof. Josef Kittler, Dr. Stephan Weiss, Dr. Yulia Hicks
Research Associates:	Dr Swati Chandna (SU)
UDRC Research students:	Mr Luca Remaggi (SU), Miss Jing Dong (SU), Mr Zeliang Wang (CU), Mr Waqas Rafique (LU)
Lead Project Partner:	Prof. Macleod Malcolm (QinetiQ)
Dstl Contacts:	Drs Julian Deeks, Alan Johnson, Nick Goddard

3.2 Aims and the lists of the original L_WP3 in the case for support:

To develop low-complexity robust algorithms for underdetermined and convolutive signal separation, broadband distributed beamforming, facilitated by low-rank and sparse representations, and their fast implementations. Links to L_WP1 in weak signal detection; L_WP2 in unknown number of targets and order selection; L_WP4 in MIMO signal detection; & L_WP5 in data reduction.

Extracting signals of interest and suppression of interference from corrupted sensor measurements remain as fundamental challenges in many networked battlespace applications. We aim to propose novel methods to address these challenges, 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.

L_WP3.1: Multichannel convolutive source separation, broadband distributed beamforming

We will focus on the development of algorithms using low-rank algebra and optimisation particularly based on advanced polynomial matrix (PM) techniques [1,2]. The PM eigenvalue decomposition (PEVD) provides a powerful tool for multichannel convolutive mixing and broadband sensor arrays and has the great advantage of only requiring second order statistics, thus avoiding the much greater computational loads and sample sizes associated with higher order statistics. In this WP, we will use the PEVD to design algorithms for source separation from multichannel convolutive mixtures. Potentials of using the PEVD to identify subspaces in space-time will be exploited in tasks such as broadband angle-of-arrival estimation, beamforming, and distributed systems. Facilitated by the work in L_WP3.2, we will study the potential of extending our dictionary learning algorithm [14] from memoryless to convolutive signals using the PM model [1]. Sparseness constraints on the PEVD model will be considered for addressing the underdetermined source separation problem. Domain knowledge, as discussed in L_WP2, such as the prior information on approximate bearing, expected periodicity, and array geometry, will be incorporated into the algorithm design, leading to a family of semi-blind or softly constrained algorithms that are expected to provide robust performance for target signal extraction and interference cancellation in noisy environment or under array imperfections. Fast and low-cost implementations of PM techniques will be addressed as part of WP5.

L_WP3.2: Underdetermined signal separation with unknown number of target signals

We will consider fundamental study of sparsity-motivated techniques. We recently showed that source separation can be re-formulated as a signal recovery problem in compressed sensing by sparsifying the sensor signals using a dictionary [14], and then reconstruct the sources from the dictionary atoms using sparse coding algorithms e.g. subspace pursuit. The dictionary learnt from training data has the potential to perform better for noisy mixtures than a predefined one e.g. the discrete cosine transform (DCT), and hence will be considered here. Adaptive methods, which aim to mitigate the need of training data, will be developed to perform source estimation and dictionary update jointly in an alternating manner. Multi-level hierarchical representations of the dictionary will be designed to improve the computational efficiency of these algorithms and to facilitate their fast implementation in

L_WP5. Convolutive mixtures will be addressed in the time-frequency (T-F) domain with the dictionary learnt from convolutive signals (as in L_WP3.1). These methods will be compared to the probabilistic T-F masking techniques [7,21], where the T-F masks are formed according to the probability of each T-F point in the mixture being dominated by each source, which is estimated by evaluating the statistical, spatial, temporal and/or frequency cues from the mixtures. The noise variance will be exploited to improve the reliability of the cues evaluated from noisy mixtures and weak signals. A variational Bayesian approach will be used to model each T-F point as a variational mixture of Gaussian distributions, thanks to its robustness to initialisations and its advantage in dealing with the unknown number of target signals (a model uncertainty challenge discussed in L_WP2), as compared to maximum likelihood based expectation maximisation approaches. The above algorithms will also be extended for multimodal signal separation via the cross-modal coherence of multi-modalities.

3.3 Progress made in the first year in addressing the original objectives

3.3.1 Progress of L_WP3.1

The work undertaken in CU has been mainly on L_WP3.1 where the aim is to develop polynomial matrix decompositions for various source separation problems in particular, for convolutive source separation. The RA planned in the original proposal for L_WP3.1 has been re-allocated to L_WP1. Therefore, a PhD student, Mr Zeliang Wang, has been recruited to work on this WP, who started in October 2013, six months after the project officially started. He has been studying the literature of polynomial matrix decomposition and its application to multichannel spectral factorizations.

3.3.2 Progress of L_WP3.2

The work undertaken in SU has been mainly on L_WP3.2 where we aim to develop sparsity-motivated techniques for source separation in noisy and reverberant environments, possibly with missing data or highly corrupted sensor measurements. The mixing system can be underdetermined with an unknown number of sources that is greater than the number of sensors. To this end, we have been studying in the following sub-areas in the first year.

- The focus of Dr Swati Chandna was the use of the bootstrap technique to improve the performance of the time-frequency masking based source separation techniques in a highly reverberant acoustic environment. The basic idea of this method is to generate multiple random copies of the sensor measurements using a technique called circulant embedding, and then estimate the acoustic cues and the time-frequency masks from each copy based on an expectation maximisation algorithm. These individual copies are then averaged to obtain the final estimate which is then used for the separation of source from the acoustic mixtures. We have tested the proposed algorithm for real room mixtures recorded at the University Surrey and the results show that source separation performance can be further improved by the bootstrap technique. The preliminary results of this work have been presented in a manuscript which we have submitted to the 2014 IEEE Statistical Signal Processing Workshop. We are also now testing the algorithm for underwater acoustic data provided by Alan John (Dstl). More details can be found in the technical description below and the papers listed at the end of the WP.

- The work of Miss Jing Dong has been on the development of the analysis model based dictionary learning algorithms for sparse representations, and their application to signal denoising and separation problems. In particular, our effort has been on extending the synthesis model based Simultaneous Codeword Optimisation (SimCO) algorithm to the case of analysis model. So far, we have developed two algorithms. The first algorithm is called analysis SimCO, which has been shown to provide good performance for the recovery of dictionary atoms and signal denoising, and the preliminary results of this work have been summarised in a paper that has been accepted for the IEEE ICASSP 2014 Conference in Florence, Italy, and Jing Dong has also won an IEEE Signal

Processing Society Travel Grant to present this work. The second algorithm is a Nestov gradient based algorithm which we have applied to SAR image despeckling and the work has been accepted to be present in the IEEE ISCCSP 2014 conference to be held in Greece. More details can be found in the technical description below and the papers at the end of the WP.

- The direction of Mr Luca Remaggi has been on informed source separation by considering some prior information that could be gained from practical systems for improving source separation performance. Luca officially studied his PhD in January 2014. Therefore, he has been mainly focusing on the study of the background of acoustic source separation in both room environments and underwater acoustic environment. For example, he has focused on the implementation of three algorithms for room acoustic modelling and sound source localisation. The first algorithm implemented is to detect peaks giving a room impulse response as input. The second is the MUSIC algorithm, having some impulse responses relative to a source and a linear microphone array that are used to calculate the direction of arrival. The third one is an algorithm based on Antonacci's ellipses method, which will be useful to estimate the geometry of a room giving some impulse responses. The FDTD model will generate a graphical representation of the sound propagation in a room.

- The activity of Mr Waqas Rafique at LU has been on independent vector analysis based source separation. More specifically, he has been studying the use of Student t's distribution for the modelling of spectral dependency in independent vector analysis.

3.4 Technical details

Polynomial matrix decoposition

Based on the established polynomial matrix factorization techniques, especially SBR2 algorithms [1], two different ways to implement the SBR2 algorithms have been proposed. One is the 2-D array implementation of SBR2 algorithm, and the other is called SBR2 algorithm with the positive search strategy. We evaluated the performance of the 2-D array method by comparing it with the original 3-D SBR2 algorithms. The 2-D version shows some advantages in computational efficiency, and the time elapsed in MATLAB simulation has been reduced almost by a half. In the positive search SBR2 algorithm, the dominant element in the coefficient matrices is searched only in the positive coefficient planes instead of searching the upper triangular matrices through all the coefficient planes (i.e. the searching starts from zero-lag plane to positive coefficient plane). Both search strategies of the dominant element have shown the same simulation results. In addition, we tried to apply the anti-delay matrix to the original SBR2 algorithm. This operation only affects the H matrix (Paraunitary polynomial matrix), but not the final diagonalized matrix (ParaHermitian polynomial matrix). The purpose of doing this is to use the delay matrix indeterminacy to manipulate the H matrix such that there are no negative coefficient planes in the H matrix. We are also studying multichannel spectral factorization algorithms [2], and developing novel algorithms based on the SBR2 algorithm.

Bootstrap technique based underdetermined convolutive source separation

Our work focuses on the problem of convolutive blind source separation (BSS) for under determined mixtures. We study the problem of simultaneously separating I sound sources from M mixtures acquired in a reverberant environment. If the number of sources exceed the number of sensors, i.e. $I > M$, the problem is underdetermined, and traditional matrix inversion de-mixing as in the exact or over-determined case ($I \leq M$) do not apply. In the underdetermined case, BSS is often achieved by assuming a statistical model for a chosen set of cues. For example, interaural cues such as the interaural level and phase difference as well as the mixing vector cue have been used in the literature to perform source separation for speech mixtures which are known to satisfy a sparsity condition in the time-frequency domain. Such techniques proceed by assuming an appropriate statistical model for such cues with their parameters depending on unobserved source signals. The expectation-maximization (EM) algorithm is used to obtain maximum likelihood estimates of these unknown parameters. A useful by-product of the EM algorithm is that it allows a probabilistic classification of each time-frequency point as being dominated by the source signals. With T and W denoting the number of time and frequency bins, for each source index i = 1,..,I, we have a W x T matrix of weights which gives the probability that source i is dominant at the W x T time-frequency points. This matrix of weights, known as the T-F mask allows separation of the sources via a simple inverse short-time-frequency transform.

We note that the cues of interest, which comprise the 'observed data' in a typical EM estimation problem, are estimated from the given reverberant mixture and therefore, have reverberation effects built into them. Due to the diffuse character of reverberation, data points/cues with high reverberation may not fit a source model particularly well and as a result lead to poor parameter estimates. Since T-F masks are derived from these parameter estimates, this can lead to poor performance of the source separation algorithm, especially when mixtures are acquired under high reverberation. We observe this interdependency between the parameter estimates and the T-F mask, which means that for improved performance, maximum likelihood parameter estimates derived from such reverberant cues should be comparable to the ground-truth parameter estimates, i.e. estimates that would be obtained when only the source signals of interest were observed at the sensors.

Secondly, from an inference point of view, we note that the T-F mask that is used for source separation is derived from one length-N sample of the mixture signal. In a controlled environment, such as in a room with low reverberation, there may not be a large variation in the estimates over different observations of the speech mixture, however, with data recorded in other environments such as underwater acoustic data, one would expect the estimates to be very sensitive to the underlying measurements. Thus, the T-F mask estimated from just one length-N recording may not be very reliable.

With this in mind, we have proposed the technique of bootstrap averaging to obtain better separation results for highly reverberant mixtures [3]. The technique of bootstrap averaging also known as bagging was first suggested in the area of machine learning by Brieman [4]. Although, commonly used in statistical classification and regression problems, it has never been used in the area of blind source separation. Let $y = [y_1, \ldots, y_p]$ denote a p-variate process with a probability distribution denoted by Fy(.). Let $Y \equiv [y_1, \ldots, y_N] \in C^{Nxp}$ denote a sample obtained from y, by independently drawing N samples from the probability distribution Fy. Let $\hat{\theta}(Y) \equiv \hat{\theta}$ denote the statistic of interest derived from Y, then bootstrap averaging relies on the result that the aggregated estimator

$$\hat{\theta}_A(B) = \frac{(\hat{\theta}_1 + \ldots.. + \hat{\theta}_B)}{B} \tag{3.1}$$

obtained by generating B samples $Y_1, \ldots.., Y_B$ from Fy, and computing $\hat{\theta}_J$ from Y_j has a smaller mean squared error than $\hat{\theta}$. Since in practice, the underlying distribution of the given sample is unknown, the aggregated estimator can be constructed by bootstrapping the given sample Y to obtain, $Y_1^o, \ldots\ldots, Y_B^o$ from which the corresponding bootstrap estimates $\hat{\theta}_1^o, \ldots.. \hat{\theta}_B^o$ can be derived. Then, we define the bootstrap sample version of the aggregated estimator given above as

$$\hat{\theta}_A^o(B) = \frac{(\hat{\theta}_1^o + \ldots\ldots \hat{\theta}_B^o)}{B}. \tag{3.2}$$

In our work, we bootstrap the given mixture and use the bootstrap averaged maximum likelihood parameter estimates and the corresponding T-F mask to perform source separation using one of the model-based source separation algorithms. We used a recently proposed technique [5] based on circulant embedding to generate statistically similar samples of the given mixture. This simulation methodology generates samples from non-parametric spectral estimates of the given sample via circulant embedding. The spectral density estimate captures the second order statistics of the data set and the circulant embedding approach based on circulant matrices makes it a very fast re-sampling technique.

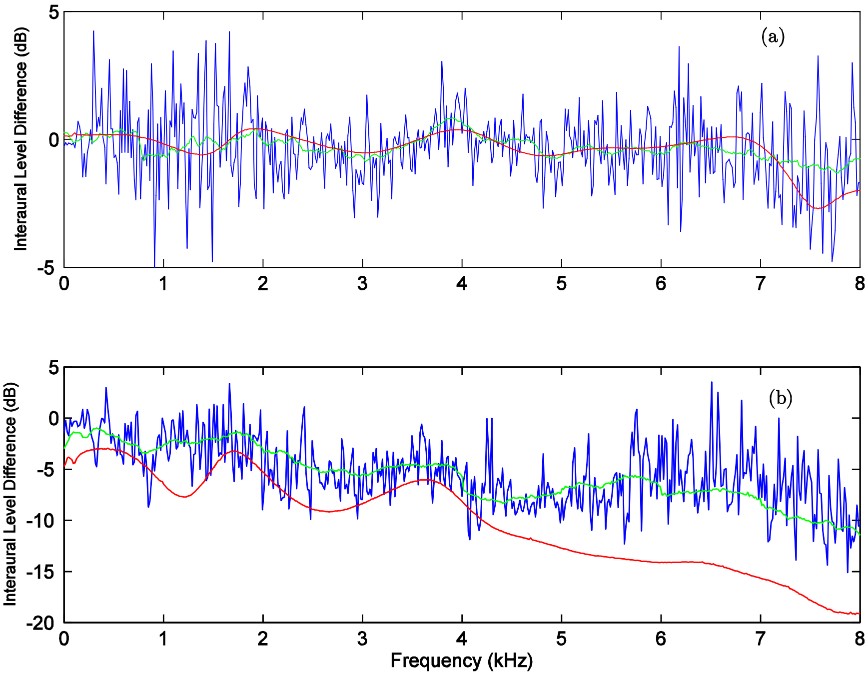

Fig 3.1. Estimates of mean ILD (dB) from a given mixture with source s1 placed at 0◦ in (a) and s2 at 30◦ in (b). In each graph, the perfectly smooth line (red) shows the ground-truth direct-path ILD from sources measured in isolation, the graph with slightly jagged edges (green) shows the boot strap averaged mean ILD estimate and the serrated graph with large deviations (blue) is the estimate from the combined method of [7].

One of the key assumptions for this simulation methodology to work is the stationarity of samples. Since speech signals are highly non-stationary, this technique is not directly applicable. However, a fairly reasonable assumption for speech signals is that blocks of length 30 ms are stationary. Consecutive blocks of length corresponding to 30ms are bootstrapped and then joined together to get a bootstrap sample of the entire signal. The technique discussed above is implemented using these bootstrapped versions of the mixture signal. A comparison of the bootstrap averaged mean interaural level difference estimate with the ground-truth direct path interaural level difference shows that our estimates are very smooth as compared to the estimate obtained from the original source-separation algorithm, as shown in Figure 3.1.

We performed source separation using the corresponding bootstrapped average T-F mask; we see a significant increase in the average Signal-to-Distortion Ratio (SDR) for different experimental set-up configurations. This confirms that our method can be used to improve the performance of model-based source separation algorithms.

Dictionary learning based signal denoising and SAR despeckling

Dictionary design is an important problem in sparse representation. Recent studies have shown that dictionaries learned from a set of training signals have the potential to fit the signals better than the analytical dictionaries [8,9]. Many dictionary learning algorithms are established on the synthesis model, where a signal is represented as a linear combination of a few atoms (signal components) from the dictionary. Learning dictionaries with an analysis model where the product of the dictionary and the signal is sparse, however, has received less attention, with only a few activities emerging recently, such as [9-13]. We consider the dictionary learning problem for the analysis model based sparse representation and its applications to image denoising and synthetic aperture radar (SAR) image despeckling.

A novel algorithm is proposed by adapting the synthesis model based simultaneous codeword optimisation (SimCO) algorithm [14] to the analysis model, and this algorithm is referred to as Analysis SimCO [15]. Analysis SimCO assumes that the analysis dictionary contains unit l_2-norm atoms. The optimization consists of two stages: analysis sparse coding and dictionary update. In the analysis sparse coding stage, the sparse representations of the signals based on a fixed dictionary is estimated with applying hard thresholding to the products between the dictionary and the signals. In the dictionary update stage, the atoms of the dictionary are updated by the optimization on manifolds, which is adapted from SimCO. This framework allows one to update multiple dictionary atoms in each iteration, leading to a computationally efficient optimisation process. Experimental results on synthetic data show that the proposed algorithm is competitive in recovering the ground-truth dictionary and learning a dictionary that leads to sparse representations of the signals, as compared with three baseline algorithms, Analysis K-SVD [9], analysis operator learning (AOL) [10] and learning overcomplete sparsifying transforms (LOST) [12]. The proposed algorithm is also applied to denoising the images with additive white Gaussian noise (AWGN). For each noisy image, an analysis dictionary is learned with the patches extracted from the image and then OBG [8] is used to recover the original image. Experimental results demonstrate the effectiveness of Analysis SimCO in image denoising problem, especially when the noise level is high.

We also introduce a new analysis dictionary learning algorithm based on Nesterov's gradient method [16]. Nesterov's gradient method improves the gradient-based methods by achieving the optimal convergence rate $O(\frac{1}{t^2})$ with t being the iteration number, and has been applied to many problems, such as nonnegative matrix factorization [18] and image deblurring [19]. In our proposed algorithm, the dictionary learning process is formulated as an optimisation problem with the cosparsity and unit l_2-norm constraints of the atoms in the dictionary, which is the same as the objective function of Analysis SimCO [16]. The algorithm iteratively solves this problem by alternating between analysis sparse coding and dictionary update. The dictionary update stage is realized with Nesterov's gradient method followed by the normalization of the rows of the dictionary. Experimental results on synthetic data demonstrated the promising performance in recovery rate and average cosparsity. We apply the proposed algorithm to the despeckling of SAR images and the results show that it works well for this problem. An example of despeckling based on Analysis SimCO as compared with baseline algorithms is shown in Figure 3.2. The noisy image was generated by adding a signal-dependent term to the original speckle-free image. We compare our proposed algorithm with PPB [24] and Analysis K-SVD [8]. The PSNR of the despeckle images are 27.65 (PPB), 27.43 (Analysis K-SVD) and 27.46 (Analysis SimCO) respectively. According to this measurement, Analysis SimCO offers slightly better result than Analysis K-SVD. Even though the despeckled image obtained by PPB has the highest PSNR, some details of the despeckled image (e.g. the texture part on the lower right corner) are overly smoothed, as can be seen in Figure 3.2.

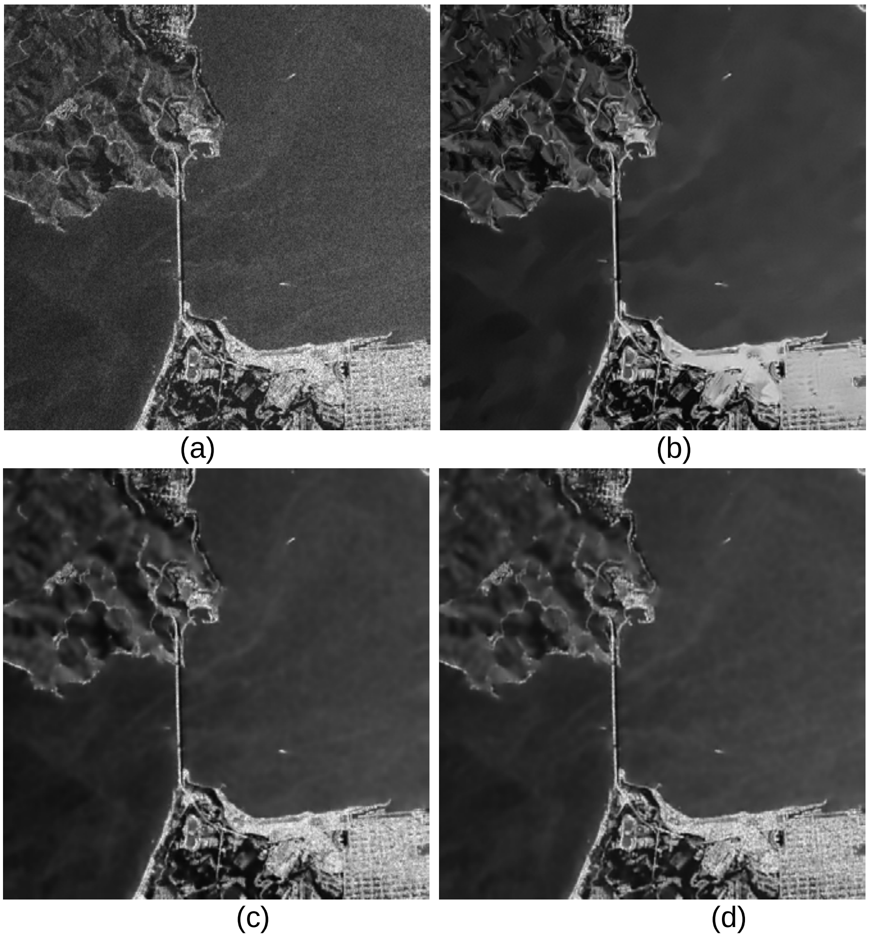

Fig. 3.2. Noisy image and despekled images. (a) Noisy image, (b) PPB, (c) Analysis K-SVD, and (d) Analysis SimCO.

Independent Vector Analysis based Source Separation

Amongst research in signal processing, independent component analysis (ICA) is the central tool for the BSS problem. For the basic ICA model, the mixtures are assumed to be instantaneous, which means that there is no transmission delay between the sources and microphone array. However, for a practical speech separation problem in a real room environment, a convolutive BSS problem results due to the reflections from the ceiling, floor and walls. Traditional time domain methods will have huge computational cost because real room impulse responses are typically on the order of thousands of samples in length. Thus, many frequency domain methods have been proposed to reduce the computational complexity as convolution in the time domain corresponds to multiplication in the frequency domain. However, the classical permutation problem is magnified in the frequency domain due to the potential misalignment of the separated sources at different frequency bins.

The independent vector analysis (IVA) algorithm can theoretically avoid the permutation problem in frequency domain blind source separation byusing a multivariate source prior to retain the dependency between different frequency bins of each source vector. An appropriate dependency structure which can better preserve the dependency within the source vector is still needed for improving the separation performance. Therefore a super-Gaussian multivariate Student's t-distribution was adopted as the source prior to model the spectrum of speech signals and to mitigate imprecise variance knowledge as is commonplace in non-stationary signal processing. This approach improved the source separation performance [20].

The time-frequency (TF) masking is another technique used for source separation motivated both in computational auditory scene analysis (CASA) and BSS which relies on the assumption of signal sparseness i.e., the majority of the TF samples of each signal are almost zero and thus the sources rarely overlap. The TF approach can therefore, unlike conventional BSS algorithms handle the under-determined problem where the number of sources is greater than the number of sensors. Gaussian mixtures modelling are commonly used for clustering and density estimation for TF masking to achieve the blind separation of a mixture of speech signals. The use of non-Gaussian modelling represented by the Student's t-distribution can enhance the model-based expectation maximization source separation and localization. This heavy tailed distribution as compared to the Gaussian distribution can better capture the outlier values especially when the sources are in close proximity and the accurate representation of the tail behaviour appears to lead to improve the separation. Therefore Student's t-distribution was adopted to model the interaural level difference (ILD), interaural time difference (ITD) to enhance source segregation [21,22].

3.5 Future Plans

To further apply our algorithms to defence related data

We will make further effort in linking our proposed algorithms with defence related applications and datasets. We have already started such efforts. For example, the work by Jing Dong is now linked with SAR image despeckling, which appears to be a good match to the image denoising application she strives to explore. Both Swati Chandna and Luca Remaggi have already begun their study on an unclassified passive sonar dataset given to us by Dr Alan Johnson (Dstl) which was originally provided by Dr Richard Brind (Atlas). The dataset contains hydrophone element recordings (time series) from two static arrays which were deployed on the seabed in Portland harbour in shallow water. Each array comprised 32 synchronised hydrophone sensors which were nominally deployed in a line at 3m intervals. Analysis indicates that one of the arrays was deployed in a slight curve while the second array was close to straight. The two arrays were not physically connected and were not synchronised (i.e. the two arrays cannot be processed coherently without some clever combining). The arrays were deployed approximately parallel to each other at a spacing of ~920m. A small work boat acted as a directional source of acoustic energy during the datasets. The work boat performed a number of tracks past the arrays in the presence of other unknown sources of noise (such as docked boats, and transiting shipping). The positions of the workboat are known but not the other sources. The Portland dataset includes some interesting issues: high side-lobe levels when processed with a conventional beamformer, high bearing rate contacts, signals at low and high signal-to-noise ratios, non-linear arrays with uncertain sensor positions. In addition, the arrays contain multiple sensors which may be suitable for investigating compressive sensing, sparse array or signal decomposition methods. However there is limited ground truth and controlled signals were not transmitted from a source during the Portland tests. We will investigate the potential of using this dataset to benchmark the performance of the algorithms we are developing. However, further interactions with Dstl and Atlas are required in order to better understand the dataset.

To complete the evaluation of the proposed algorithms and writing up the journal papers

Our future work on the bootstrap approach is not just limited to improving source separation but shall also extend to allow statistical inference on source separation based on T-F masks.

As mentioned earlier, source separation for data/mixtures recorded in acoustic environments which cannot be physically controlled to avoid randomness to any extent, directly relies on the measurement made starting at a chosen time point. Note that the T-F mask derived from this measurement is only an ‘estimate’ of a property of the true underlying mixing process, precisely, the probability with which each source dominates a given time-frequency point. And source separation techniques rely on this T-F mask estimate derived from the measurement to isolate the sources of interest. We suspect that T-F mask estimate obtained from a data set measured under high reverberation could be more unreliable, or in other words, sensitive to the underlying measurement. To this respect, we aim to study confidence intervals for T-F masks corresponding to different reverberation times. In addition to statistical inference, this would also provide an insight into when exactly we’d expect the bootstrap averaging approach to work. Since, one of the objectives of this work package is to develop low-complexity algorithms, we’d ideally like to develop a more efficient bootstrap technique to identify stationary blocks of time series from the given non-stationary signal. To this end, we’ve been studying a new framework known as SLEX which provides efficient and accurate identification of stationary blocks. However, further work needs to be done to extend our bootstrap technique using this framework and is added to our list of future work.

We will further study some technique details of the Analysis SimCO algorithm. For example, we will explore the possibility to replace the hard thresholding with other thresholding methods. The convergence of the Analysis SimCO algorithm will also be studied. More experiments with synthetic data will be conducted to present the performances of our proposed algorithm and the baseline algorithm more reliably. We will further look into the speckle noise model of SAR images and apply the Analysis SimCO algorithm to the SAR image despeckling problem

To study source separation and denoising under incomplete and/or highly noisy sensor measurememts

Incomplete data sets are a common problem in real-world measurements. This may occur, for example, due to failure in one or more sensors in an array of sensors used for recording underwater acoustic data for the entire time duration of the experiment, or, only for a short time-duration. Some commonly employed methods for dealing with missing data include ignoring the unknown observations; filling-in each missing observation with the last value observed (last observation carried forward) or simply using a single imputation, for example, using the mean of the observed data to fill-in all unknown missing observations. As we’d expect, such techniques may lead to significant bias in our inference and therefore sophisticated techniques need to be used. We plan to use statistically principled methods in order to achieve this, by for example, using a statistical model for the full data set including a model for the missing mechanism. Other well-known methods such as multiple imputation, i.e. generating imputed values for missing observations from an appropriate probability distribution shall also be studied. Another way to deal with incomplete data set could be to model it as an irregular time series, i.e. thinking of it as a scenario where data was not observed at equally spaced time points. Extensive literature can be found on irregularly spaced time series and a literature survey shall allow us to explore how it may be used for source separation.

To Study Multichannel Spectral Factorization Algorithms

We will further study the multichannel spectral factorization algorithms, and our plan is to develop a novel spectral factorization algorithm based on the SBR2 algorithm. The rationale behind this is to take advantage of the properties of paraunitary polynomial matrix and the diagonalized polynomial matrix in SBR2 algorithms. Once the new algorithm has been tested, we are going to write a paper and submit it for publication.

Independent Vector Analysis and Dependency Modelling

The research on improved probabilistic models for CASA based source separation and variants of IVA are the focus of future plans. We will investigate various heavy-tailed dependent statistical models and consider EM and variational Bayesian methods for parameter inference. We will apply the approaches on various datasets including the under water passive dataset from Portland Harbour. The PhD student involved will also benefit from various training courses provided by the his host university, as will the other students involved in the LSSC consortium.

International Collaborations

We have also collaborated with Professor Christian Jutten and his team from the Gipsa Lab in Grenoble, France on multimodal source separation which has led to a joint publication in the IEEE Signal Processing Magazine which is part of a leading special issue in the field [23].

3.6 References and Outputs:

[1] J. G. McWhirter, P. D. Baxter, T. Cooper, S. Redif, and J. Foster, "An EVD algorithm for para-Hermitian polynomial matrices," Signal Processing, IEEE Transactions on, vol. 55, pp. 2158-2169, 2007.

[2] G. Janashia, E. Lagvilava, and L. Ephremidze, "A new method of matrix spectral factorization," IEEE Transactions on Information Theory, vol. 57, pp. 2318-2326, 2011.

* [3] S. Chandna and W. Wang, "Improving Model-Based Convolutive Blind Source Separation Techniques via Bootstrap", submitted to IEEE Statistical Signal Processing Workshop, 2014.

[4] L. Breiman, "Bagging predictors," Machine learning, vol. 24, no. 2, pp. 123–140, 1996.

[5] S. Chandna and A. Walden, "Simulation methodology for inference on physical parameters of complex vector-valued signals," IEEE Transactions on Signal Processing , vol. 61, pp. 5260–5269, 2013.

* [6] S. Chandna and W. Wang, "A Bootstrap-Based Improvement for Model-Based Convolutive Blind Source Separation" (work in progress)

[7] A. Alinaghi, W. Wang, and P. J. B. Jackson, "Integrating binaural cues and blind source separation method for separating reverberant speech mixtures," in IEEE International Conference on Acoustics, Speech and Signal Processing, pp. 209–212, 2011.

[8] M. Aharon, M. Elad, and A. Bruckstein, "K-SVD: An algorithm for designing overcomplete dictionaries for sparse representation," IEEE Trans. Signal Process., vol. 54, no. 11, pp. 4311–4322, 2006.

[9] R. Rubinstein, T. Peleg, and M. Elad, "Analysis K-SVD: A dictionary-learning algorithm for the analysis sparse model," IEEE Trans. Signal Process., vol. 61, no. 3, pp. 661–677, 2013.

[10] M. Yaghoobi, S. Nam, R. Gribonval, and M.E. Davies, "Constrained overcomplete analysis operator learning for cosparse signal modelling," IEEE Trans. Signal Process., vol. 61, no. 9, pp. 2341–2355, 2013.

[11] S. Hawe, M. Kleinsteuber, and K. Diepold, "Analysis operator learning and its application to image reconstruction," IEEE Trans. Image Process., vol. 22, no. 6, pp. 2138–2150, 2013.

[12] S. Ravishankar and Y. Bresler, "Learning overcompletesparsifying transforms for signal processing," in Proc. IEEE Int. Conf. on Acoust., Speech, and Signal Processing, 2013, pp. 3088–3092.

[13] S. Ravishankar and Y. Bresler, "Learning sparsifying transforms," IEEE Trans. Signal Process., vol. 61, no. 5, pp. 1072–1086, 2013.

[14] W. Dai, T. Xu, and W. Wang, "Simultaneous codeword optimization (SimCO) for dictionary update and learning," IEEE Trans. Signal Process., vol. 60, no. 12, pp. 6340–6353, 2012.

* [15] J. Dong, W. Wang, and W. Dai, “Analysis SimCO: a new algorithm for analysis dictionary learning”, accepted by IEEE Int. Conf. on Acoust., Speech, and Signal Processing, 2014.
[16] J. Dong and W. Wang, “Analysis dictionary learning based on Nesterov’s gradient with application to SAR image despeckling”, accepted by 6th Int. Symposium on Communications, Contral and Signal Processing, 2014.
[17] Y. Nesterov, “A method of solving a convex programming problem with convergence rate O(1=k2),” Soviet Mathematics Doklady, vol. 27, no. 2, pp. 372–376, 1983.
[18] N. Guan, D. Tao, Z. Luo, and B. Yuan, “NeNMF: an optimal gradient method for nonnegative matrix factorization,” IEEE Trans. Signal Process., vol. 60, no. 6, pp. 2882–2898, 2012.
[19] A. Beck and M. Teboulle, “A fast iterative shrinkage thresholding algorithm for linear inverse problems,” SIAM J. Imaging Sci., vol. 2, no. 1, pp. 183–202, 2009.
* [20] Y. Liang, G. Chen, S. M. Naqvi, and J. A. Chambers, Independent vector analysis with multivariate student's t-distribution source prior for speech separation, Electronics Letters, vol. 49, issue 16, August 2013
* [21] M. S. Khan, S. M. Naqvi, A. Rehman, W. Wang and J. A. Chambers, Video-aided model-based source separation in real reverberant rooms, IEEE Trans. Audio, Speech and Language Processing, vol. 21, no. 9, pp. 1900-1912, September 2013.
* [22] Z. Zohny, S.M. Naqvi, and J.A. Chambers, “'Enhancing the MESSL algorithm with robust clustering based on the Student's t-distribution”, accepted for IEE Electronics Letters, 2014.
* [23] B. Rivet, W. Wang, S.M. Naqvi, and J.A. Chambers, "Audio-Visual Speech Source Separation", IEEE Signal Processing Magazine, 2014. (in press)
[24] C. Deledalle, L. Denis and F. Tupin, “Iterative Weighted Maximum Likelihood Denoising With Probabilistic Patch-Based Weights,” IEEE Trans. Image Process., vol.18, no.12, pp.2661-2672, 2009.
[25] J. Foster, J.G. McWhirter, M.R.Davies, and J.A. Chambers, “An Algorithm for Calculating the QR and Singular Value Decompositions of Polynomial Matrices”, IEEE Trans. Signal Processing, Vol 58(3) pp 1263-1274, 2010.

L_WP4: MIMO and Distributed Sensing

4.1 Staffing

Work Package Leaders:	Prof. John J. Soraghan (ST) and Prof. Ian K. Proudler (LU)
Other Academics Involved:	Dr. Stephan Weiss (ST), Prof. Sangarapillai Lambotharan (LU)
Research Associates:	Dr Carmine Clemente (ST)
UDRC Research students:	Mr Domenico Gaglione (ST), Mr Christos Ilioudis (ST)
Affiliated Research Students:	Mr Jianlin Cao (ST), Mr Yixin Chen (ST)
Lead Project Partner:	Selex ES, Edinburgh
Dstl contact:	Stephen Moore, Brian Barber

4.2 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 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.
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.

L_WP4.1 DMRS: waveform design, application of compressed sensing, passive systems [PDRA6/PS5]

Inspired by major benefits gained from MIMO communications, coherent and incoherent DMRS will allow dramatic increase in detection, tracking and classification performance only if an optimal set of signal processing techniques are applied. In [1] our Linear Canonical Transform (LCT) methods using the Fractional Fourier Transform (FrFT) have been successfully developed for a range of monostatic radar applications. An analysis of alternative waveform designs for DMRS will be conducted. Novel waveform design approaches such as the FrFT and Fractional Cosine Transform based orthogonal chirp division multiplexing will be investigated. The use of these LCT based transmission schemes will make the system more robust with respect to fading and dispersion particularly in the case of double-dispersive channel where the time and frequency dispersion can be reduced by the use of the FrFT. Airborne based sensing is an example of an environment with double dispersive channel that is still an open problem for MIMO radar [2]. A study of sparse signal representations in the DMRS using LCT based waveforms with application to multichannel systems will be carried out. The work will use the fact that targets of interest in the DMRS will possess a sparse representation in the appropriate LCT domain. Compressed sensing techniques such as Complex Approximate Message Passing [3] will be investigated for reduction of (i) bandwidth requirements, (ii) processing requirements, (iii) memory storage requirements, and for performance improvements. Passive systems are useful to increase the covertness while reducing costs. Possible illuminators of opportunities (DVB-T, Wi-fi, Wi-Max, GNSS. etc) will be investigated for the realization of a passive distributed radar system for cheap and covert border control applications. Ambiguity function models, direct signal removal techniques, Kalman filtering, and constant false alarm rate (CFAR) detectors are some of the techniques that will be investigated.

L_WP4.2 DMRS: anti-clutter/jamming, information fusion, advanced ATR systems [PDRA6/PS6]

It is known that DMRS offers enhanced anti-clutter and anti-jamming potentials. Novel signal processing methods for jamming and clutter mitigation in high cluttered and distributed environments will be developed.

Our anti-jamming and clutter reduction techniques [2] developed for monostatic radars involving empirical mode decomposition (EMD) and LCT filtering techniques will be used as a basis for methods for distributed MIMO monopulse radar systems. Other methods that will be considered include SVD and Space Time Adaptive Processing. DMRS offers significant enhanced automatic target recognition (ATR) [4]. We will build on our recent work in bistatic radars [5] to derive new multidimensional micro-Doppler signatures and target reflectivity profiles in DMRS. As there will be a set of micro-Doppler signatures for a target with different azimuth the angular dependence of the micro-Doppler shift will be removed thus creating a unique signature. The work will investigate the formation of 3D profiles of targets. DOA techniques will also be developed for overall performance improvement. These features will be merged together in an information fusion framework that will be exploited for target identification, classification and tracking. Both coherent and incoherent MIMO regimes will be considered, and information fusion will be exploited to obtain a high confidence ATR system. The challenge of information sharing between the sensors and the associated decentralised processing will be considered throughout WP4 in collaboration with researchers in WP5.

4.3 Progress made in the first year in addressing the original objectives

Staffing

In April 2013 Dr Carmine Clemente was appointed as research associate (PDRA6) to work on L_WP4. He was supported on aspects of L_WP4 by undergraduate, post graduate project students and a visiting research student and Dr Tony Kinghorn's Group within Selex-ES, Edinburgh. Two UDRC PhDs were appointed in Jan 2014. Mr Christos Ilioudis (PS5) began a PhD program focussing on L_WP4.1 while Mr Domenico Gaglione (PS6) focusses on L_WP4.2. There a further two affiliated UDRC PhDs working on research related to WP4 started in Oct 2013. Mr Yixin Chen works on MDS for Sonar and underwater applications while Mr Jianlin Cao works on ChipSat designs. In Jan 2014 three visiting professors were appointed to the University of Strathclyde who will help in guiding the evolution of UDRC activities within Strathclyde and the LSSC. These are Professor Chris Baker, Ohio State University, Professor Antonio De Maio, University of Naples, and Brian Barber, Dstl.

4.3.1 L_WP4.1 progress

The work developed at ST on WP4.1 focusses on the development of novel signal processing techniques, paradigms and systems for high performance distributed sensing. To this end, we have been studying in the following sub-areas in the first year.

- In L_WP4.1 Dr Clemente (PDRA6) has focussed on the investigation of novel waveform design based on the use of the fractional Fourier transform to obtain novel libraries to be exploited in MIMO radar systems. The models and the performance have been analysed providing positive results in terms of waveform quality parameters and reuse properties. The results of this work have been submitted and accepted for presentation at the IEEE Radar Conference 2014 in Cincinnati [6] and to the 6th ISCCSP 2014 conference in Athens [7].

  Dr Clemente has also concentrated on the development of a prototype passive bistatic radar for micro-Doppler based classification. The prototype was to act as a proof of concept introduced by Clemente and Soraghan in [8]. Currently an MEng Group of students are working on the hardware development of the prototype that is currently in its final stage of construction.

Furthermore the procurement and the initial deployment of 8 Ku band (24 GHz) commercial radar was part of the work of Dr Clemente on this area of research. The equipment will contribute to the setup of experiments that will be helpful for algorithm testing for most of the LSSC consortium outputs.

- The focus of UDRC PhD student Mr Ilioudis (PS5) has been on familiarising with RADAR systems in general and obtaining a strong background on the techniques used in waveform generation and signal processing. Furthermore a study on the applications of MIMO systems methodology on radars is being carried out in order to investigate the advantages and disadvantages that they have compared to the traditional RADAR systems and the advantages and disadvantages that MIMO Radar systems have compared with the traditional radars. He is focussing on some novel signal processing subjects such as the fractional based waveform libraries and anamorphic stretch transform [9].

  He has also started working on the definition of a constant envelope framework to be used to force constant envelope to the novel fractional waveform libraries. It is expected that this work will be submitted to the SSPD Conference 2014.

- The focus of UDRC affiliated PhD student Mr Jianlin Cao is on the design of femto-satellites to realize satellite swarms in space. He has investigated technical challenges and constraints typical of this family of novel systems. These systems would be able to provide low cost large aperture in the space. Mr Cao has been investigating possible signal processing challenge rising from the random array nature of the swarm of femto-satellites in the space.

4.3.2 L_WP4.2

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

- For L_WP4.2 Dr Clemente has focussed on the investigation of novel algorithms and approaches for micro-Doppler based automatic target recognition, providing different properties applicable to both traditional and nonconventional distributed/MIMO sensors. The outlier rejection problem was addressed by the application of Robust PCA, this work was presented at the IMA Mathematics for Defence conference 2013 [10], while the multi-feature integration challenge was investigated and presented at the ISP 2013 conference [11]. In collaboration with a visiting research student, Luca Pallotta, from the University of Naples a novel framework based on the use of the Pseudo-Zernike moments providing scale, translational and rotational invariant features was developed providing high micro-Doppler classification capabilities, this work led to paper accepted for presentation to the IEEE Radar Conference 2014 in Cincinnati and to a Journal Paper submitted to the IEEE Transactions on Aerospace and Electronic Systems [12-13]. All the micro-Doppler related works have been tested with real datasets in Ku and X bands (the latter provided by Selex ES, Edinburgh).

  A multi-channel distributed algorithm for automatic target recognition with identification capabilities from SAR has also been developed exploiting the Pseudo-Zernike moments discriminating capabilities, the multi-look clutter mitigation provided by the multi-channel approach and the spatial diversity provided by different angular observations. The developed algorithm has been tested with the Gotcha 3D volumetric dataset and led to the submission of a paper to the International Radar Conference 2014 in Lille [14] and to the preparation of a journal paper to be submitted to IET Radar Sonar and Navigation or to IEEE Transactions on Aerospace and Electronic Systems.

- UDRC PhD student Mr Domenico Gaglione (PS6) has reviewed basics of radar systems and the essential processing which concerns the radar signal. He also concentrated on signal processing techniques such as the Fractional Fourier Transform and Compressed Sensing to investigate their applications for micro-Doppler based ATR. Furthermore he is also studying the basics of the micro-Doppler effects in radar and started working on the development of a full polarimetric version of the ATR algorithm [14] exploiting the Krogager decomposition which is expected to lead to a submission to the SSPD Conference 2014.

- The focus of affiliated PhD student Mr Yixin Chen is broadband beamforming and array processing for underwater applications. Mr Chen is conducting a critical literature review in the subject area. The central aim of Mr Chen's work is to investigate the use of linear canonical transforms and micro-Doppler signature extraction in an underwater environment for sensing and communications. This work will involve developing novel signal waveform and distributed MIMO designs.

4.4 Technical Details

Fractional Waveform Libraries

In the modern battlefield scenario radar systems typically operate in a congested electromagnetic environment and with severe constraints in terms of interference mitigation, frequency occupancy, security and performance. The coexistence of different systems for different applications, high accuracy in target detection, tracking and recognition, low probability of intercept, jamming and MIMO radar are all examples where a hostile environment, from an electromagnetic point of view can cause dramatic consequences to the overall performance. In this scenario the selection of the most suitable waveform can play an important role. Fixed and adaptive radar waveform design have been widely investigated in the literature, providing waveforms that can suit different applications. However each of them present trade-offs between characteristics such as range resolution versus side lobe levels. The ability to form novel libraries of waveforms that are able to maintain the same or higher level of performance is of interest to the radar community and other related disciplines
.

In WP4 we investigate the use of fractional Fourier Transform (FrFT) based phase coded waveforms to generate new families of waveform libraries. The FrFT is a generalization of the Fourier transform and has already been applied in radar signal processing [15] and OFDM modulation [16] demonstrating the potential of this signal processing tool for various applications. In our approach for the generation of novel radar waveform libraries the FrFT is applied to the waveforms (e.g. the code sequence). The analytical formulation of the novel waveform libraries and the relationship between the ambiguity functions of the original waveforms and their fractional version were derived. Analysis of the waveform quality parameters was performed. In [6] the performance in terms of ambiguity function was analysed showing interesting and potentially powerful properties of the novel libraries, while the reuse capabilities of the library were investigated in [7] demonstrating that the proposed approach is able to provide several waveforms applicable in MIMO and Low Probability of Intercept Radars.

In Figure 4.1 an example of the cross-correlation maps obtained for different Fractional Fourier Transform orders applied to a Barker and P4 sequence is shown, from the maps the reuse factor within a library can be obtained, for the shown cases a reuse factor 5 and 10 is achievable respectively.

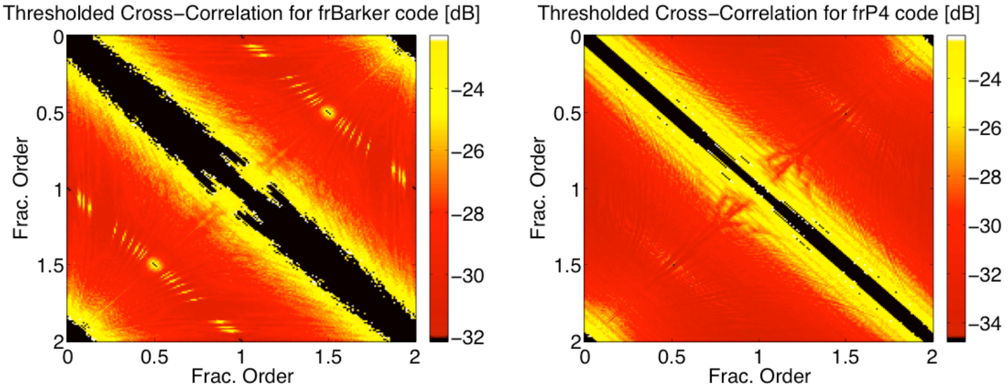

Figure 4.6 Orthogonality Map for the Fractional Barker and P4 libraries, reuse factor 5 and 10.

Moreover preliminary analysis on the constant envelope constraint on the novel libraries demonstrated that the performance is not affected by the use of this requirement common to most radar system.

Passive Bistatic Radar (PBR) For Micro-Doppler based Target Identification

The PBR follows the work developed during UDRC Phase 1 [8]. A proof of concept hardware for the analysis of the micro Doppler effect in a passive bistatic GPS radar system to determine the characteristics of a helicopter's rotor blades in currently under development. Useful applications for such a project could be the detection of helicopters in a military environment, however in theory such a system could be calibrated for other objects, such as humans or radio wave absorbing stealth objects, enabling the detection of objects otherwise hidden to conventional radar. This system could be used to detect helicopters that fly below altitudes that can be detected by conventional radar. Another benefit is that because the receivers are relatively cheap - as they don't have to transmit high power signals - a series of receivers can be deployed across a boundary without fear of a major loss of investment.

Due to the low received power of the GPS signals, it will be necessary to carry out significant noise cancellation, and maximise received power gain through the use of high quality receiver and a high gain GPS antenna. It will also be necessary to investigate the properties of GPS signals, including coarse/acquisition (C/A) decoding, in order to successfully track signals. The system is now under test and should be able to provide the first results shortly to be presented to one of the CMT/CSG meetings.

Robust Micro-Doppler Classification

The problem of micro-Doppler classification in the presence of outliers is addressed by exploiting robust statistics. When dealing with real data it is likely that it will exhibit the presence of unexpected observations within the data which can affect the correct reduction of the representative features of a target signature. For the specific case of micro-Doppler based classification this problem can appear in the feature selection stage. To address this problem Robust PCA based on the Minimum Covariance Determinant (MCD) estimator was developed.

The use of principal component analysis for feature dimensionality reduction is a common approach in machine learning and has been adopted in the framework for micro-Doppler classification. However dealing with real data that are likely to exhibit the presence of unexpected observations (outliers), the PCA can fail in reducing effectively the representative features of the signature. This causes an incorrect projection of the data along the principal components, which then results in an incorrect de-correlation of the different features.
To address this problem PCA is replaced by Robust PCA based on the MCD estimator. The proposed approach is tested using three algorithms that were developed to perform feature extraction from m-D signals. Features produced by each of these algorithms were used for classification of real X-band radar data containing micro-Doppler of six classes of human and animal motions, in all the cases it was demonstrated how the use of the MCD estimator to obtain the covariance matrix estimation was able to provide significant advantages on the final classification stage.

Multi-Feature integration for micro-Doppler Classification
In this task the effect of feature fusion has been investigated. In particular three novel micro-Doppler feature extraction algorithms are presented and applied to a dataset containing real X-band radar data of moving ground targets. In each case data dimensional reduction was carried out using principal component analysis and incorporated into the feature extraction process. Extracted features are classified using a support vector machine (SVM) classifier. It was found that all three algorithms were able to produce classification accuracies in excess of 90%. The performance of the different algorithms was shown to depend on the method used and the degree of dimensionality reduction imposed at the PCA stage.
The Spectrogram Frequency Profile (SFP) algorithm generates features based on the projection of a spectrogram, gained through Time Frequency Analysis (TFA) of the micro-Doppler signal, onto its frequency axis. The Cadence Velocity Diagram Frequency Profile (CVDFP) algorithm generates features which benefit from the localisation in time of TFA by projecting a Cadence Velocity Diagram (CVD), which is formed from the spectrogram, onto its cadence frequency axis.
A third novel algorithm combines SFP and CVDFP features, using PCA to remove redundancy between the two. Features produced by each of these algorithms were used for classification of real X-band radar data containing micro-Doppler of six classes of human and animal motions. These data were collected in an outdoor scenario with the influence of clutter and noise providing a realistic test-bench for the algorithms.
In conjunction with each feature extraction algorithm, a feature dimensionality reduction stage was applied as part of the feature extraction process. This stage exploits the minimum covariance determinant method to robustly reduce the feature vector dimensions using a Robust PCA algorithm
It was found that all three algorithms performed favourably when compared to the TFDDF benchmark algorithm, and were able to produce classification accuracies greater than 90%. However the third algorithm, with the benefits of the multi-feature integration was able to perform better than the others with a maximum value of percentage of correct classification of 94.9%.

Pseudo-Zernike Based micro-Doppler Classification
In this task a completely different approach for micro-Doppler classification was

developed. The approach exploits the orthogonal basis provided by the pseudo-Zernike polynomials to represent the Cadence Velocity Diagram obtained from a micro-Doppler signature. The family of geometric moments represented by Hu, [17], Zernike, [18], and pseudo-Zernike, [19], have been widely used in image processing for pattern recognition and image reconstruction. These moments can provide interesting characteristics such as position, scale, and rotational invariance. Zernike moments, unlike Hu moments, are obtained using a set of orthogonal polynomials, namely Zernike polynomials, obtaining independent moments. This is an important property as independent moments permit more information to be obtained considering the same number of coefficients. Pseudo-Zernike moments introduced by Bhatia in [19] improve Zernike moments reducing the noise sensitivity compared to Zernike moments and increasing the number of moments available for a given order of the polynomial. For these reasons the pseudo-Zernike moments were selected as features to discriminate different micro-Doppler signatures, in the proposed approach.
The proposed algorithm exploits the properties of the pseudo-Zernike moments to extract robust features with a limited number of values. The moments are applied to the Cadence Velocity Diagram of the micro-Doppler signature in order to minimize the feature acquisition dependence. Moreover the invariant properties of the novel feature, together with the opportunity to extract a desired accuracy from the data, open to many ATR applications. Scale, rotational and translational invariance can be easily obtained with the pseudo-Zernike based approach providing robust features, for example the micro-Doppler feature obtained from data acquired with an X-band radar can be used as reference in a Ku-band based system, or monostatic training data can be used in a multistatic scenario; another example is that signature relative to target with the same behaviour but different bulk velocities would appear with the same feature vectors (e.g.: two humans running with slightly different velocities).
Moreover, the novel features have been tested on real micro-Doppler data in Ku and X bands, producing high classification accuracy.

Distributed multi-Channel ATR

In the modern battlefield scenarios the availability of multiple sources of information, such as spatial, temporal or other diversities, allows improvements in sensor performance and capabilities. In particular, the modern radar scenario involves different diversities, some provided by the sensor position in the space-time plane: spatial diversity given by multiple platforms observing from different positions and temporal diversity provided by multiple passes over the same area from the same platform, and their combinations; and others given by different sensor characteristics: frequency, waveform and polarization diversity. Of particular interest is the combination of these two categories of diversities that can be described as a Distributed Multiple-Input Multiple-Output Radar Sensor Network (DMRS). We investigated the possibility of exploiting this information for improving the performance compared to that possible from a classic Single-Input Single-Output system. Other important aspects include the ability of achieving high performance with low cost algorithms and the capability to summarize the discriminating information thereby reducing the communication overload between sensors.

A particular application is ATR and its lower level tasks (identification, characterization and fingerprinting) from Synthetic Aperture Radar (SAR) data. Moreover, the way in which targets scatter signals of different polarizations also

contains information that can be exploited in target recognition, so the use of full-polarization SAR data can lead to improved ATR performance and for this reason is also of particular interest.
In this task an algorithm for ATR, with target identification capabilities, from multiple spatially separated full-polarimetric SAR data was developed. The algorithm exploits full-polarimetric information and, at low computational cost, extracts reliable and easy-to-share discriminating features based on the pseudo-Zernike moments and applies an information fusion approach to increase the target classification performance. The algorithm is applied to real full polarimetric X-band SAR data. The dataset used in this analysis is the "Gotcha Volumetric SAR Data Set V1.0" [20], consisting of SAR phase history from a sensor with carrier frequency of 9.6 GHz and 640 MHz bandwidth, full azimuth coverage and 8 different elevation angles. The imaging scene consists of numerous civilian vehicles and calibration targets.
The analysis is performed using 1, 2 and 3 test data images to characterize the benefits of the multi-sensor framework and the classification fusion stage. In Figure 4.2 an example of the considered configuration and results achieved considering 1, 2 or 3 passes are shown.

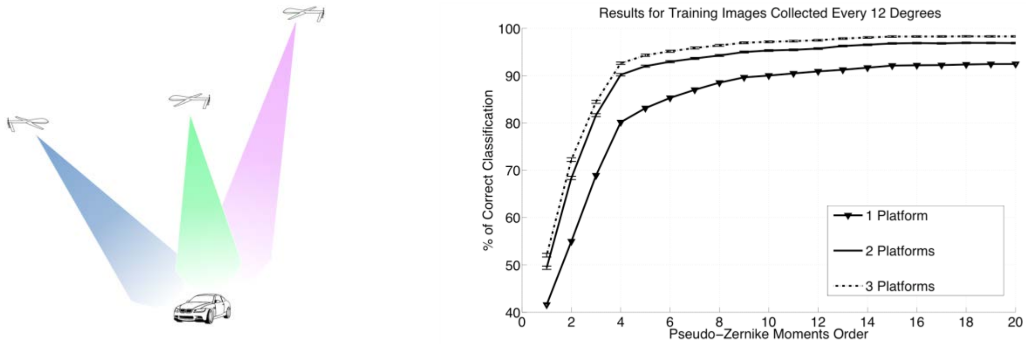

Figure 4.7 Example of acquisition and results considering 1, 2 or 3 passes for a training dataset collected with 12 degrees of Azimuth spacing

The benefit of using multiple passes is evident and can be quantified to be on the order of 10% for both the 2 and 3 platforms cases. For example performance on the order of 98% of correct target identification were obtained considering three independent observations of a target from three different azimuth angles with training samples separated of 12 azimuth degrees.
The proposed algorithm appeared to have multiple advantages: reliable target identification, multi-observation fusion capabilities without the requirement of a multi-platform training set, ability to provide good automatic target identification performances with a limited set of target observations as training, the capability to identify target observed from an angle different from those used for training. The pseudo-Zernike moments properties such as translation and rotation independence makes the algorithm robust with respect to the relative target orientation in the image plane and not registered images between different.

4.5 Future Work

Analysis of the novel waveform libraries in a realistic MIMO environment

The analysis of the performance of the Fractional waveform libraries will be completed with the application in a MIMO environment with multiple Tx/Rx. The analysis will be performed against other existing approaches.

Application of sparse representation for micro-Doppler based ATR

Sparse representation and allows to develop compressed sensing and dictionary learning techniques that have been proven to provide relevant advantages in terms of accuracy, resolutions and classification. The application of such a framework to micro-Doppler data (in different configurations) will be investigated during the next year.

Realization of multi-carrier multi-angle micro-Doppler database

In order to provide data of interest to test algorithms a database of micro-Doppler data with multiple observation angle, carrier frequencies and configurations will be acquired and made available for the testing of algorithms.

Detection and Classification in Foliage Penetration SAR

From discussions with Brian Barber from Dstl rose that analysis of Foliage Penetration SAR images is still a complex challenge due to the very particular nature of the dataset. In the next year techniques to mitigate the clutter effect for both detection and target classification will be investigated.

Investigation of novel signal processing techniques

Recently introduced signal processing techniques such as the anamorphic stretch transform and dual parameter fractional Fourier transform appears to be very interesting and their potential benefits in the network battlespace will be investigated.

4.6 References and Outputs:

[1] A.S. Amein, and J.J. Soraghan, Fractional chirp scaling algorithm: mathematical model, IEEE Trans. Signal Processing, 55(8), pp. 4162-4172, 2007.

[2] S.A. Elgamel, and J.J. Soraghan, Using EMDFrFT filtering to mitigate very high power interference in chirp tracking radars, IEEE Signal Process. Letters, 18(4), pp. 263-266, 2011.

[3] D.L. Donoho, et al., Message passing algorithms for compressed sensing. Proc. Natl. Acad. Sci., 106(45), pp.18914-18919, 2009.

[4] Y. Luo, et al., Three-dimensional micro-Doppler signature extraction in MIMO radar, in Proc. Int. Conf. Signal Process. Systems, pp. V2-1-V2-4, 2010.

[5] C. Clemente, and J.J. Soraghan ,“Vibrating Target Micro-Doppler Signature in Bistatic SAR with a Fixed Receiver”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 50, no. 8, pp. 3219-3227, August 2012.

* [6] C. Clemente, I. Shorokhov, I. Proudler, and J.J. Soraghan, “Radar Waveform Libraries Using Fractional Fourier Transform”, IEEE Radar Conference 2014, Cincinnati, USA, 19-23 May 2014.

* [7] C. Clemente, C. Ilioudis, D. Gaglione, K. Thompson, S. Weiss, I. Proudler, and

J.J. Soraghan, “Reuse of Fractional Waveform Libraries for MIMO Radar and Electronic Countermeasures”, 6th International Symposium on Communications, Control, and Signal Processing (ISCCSP 2014), Athens, Greece,
21-23 May 2014.
* [8] C. Clemente, and J.J. Soraghan, “GNSS Based Passive Bistatic Radar for micro-Doppler analysis of helicopter rotor blades”, IEEE Transactions on Aerospace and Electronic Systems, Vol. 50, issue 1, January 2014.
[9] M. H. Asghari and B. Jalali, "Anamorphic transformation and its application to time-bandwidth compression", Applied Optics, Vol. 52, pp. 6735-6743 (2013).
* [10] C. Clemente, A. Miller, J. J. Soraghan, “Robust Principal Component Analysis for micro-Doppler based automatic target recognition” , 3rd IMA conference on Mathematics in Defence, 24- October 2013,
Malvern (UK).
* [11] A. Miller, C. Clemente, J. J. Soraghan, “Micro-Doppler based target classification using multi-feature integration” , Intelligent Signal Processing (ISP) Conference, 2-3 December 2013, London (UK).
* [12] L. Pallotta, C. Clemente, A. De Maio, J.J. Soraghan, and A. Farina, “Pseudo-Zernike Moments Based RadarMicro-Doppler Classification”, IEEE Radar Conference 2014, Cincinnati, USA, 19-23 May 2014.
* [13] C. Clemente, L. Pallotta, A. De Maio, J.J. Soraghan, and A. Farina, “A Novel Algorithm for Radar Classification based on Doppler Characteristics Exploiting Orthogonal Pseudo-Zernike Polynomials”, submitted to IEEE Transactions on Aerospace and Electronic Systems.
* [14] C. Clemente, L. Pallotta, I. Proudler, A. De Maio, J.J. Soraghan, and A. Farina, “Multi-Sensor Full-Polarimetric SAR Automatic Target Recognition Using Pseudo Zernike-Moments”, Submitted to the International Radar Conference 2014, Lille.
[15] C. Clemente and J.J. Soraghan, “Range Doppler and chirp scaling processing of synthetic aperture radar data using the fractional Fourier transform,” Signal Processing, IET, vol. 6, no. 5, pp. 503–510, 2012.
[16] A.A.A. Solyman, S. Weiss, and J.J. Soraghan, “Low complexity LSMR equalisation of FrFT-based multicarrier systems in doubly dispersive channels,” in Signal Processing and Information Technology (ISSPIT), 2011 IEEE International Symposium on, 2011, pp. 461–465.
[17] M. K. Hu, “Visual Pattern Recognition by Moment Invariants”, IRE Trans. on Information Theory, Vol. 8, No. 2, pp. 179-187, February 1962.
[18] M. Teague, “Image Analysis via the General Theory of Moments”, Optical Society Am., Vol. 70, No. 8, August 1980.
[19] A. B. Bhatia and E. Wolf, “On the Circle Polynomials of Zernike and Related Orthogonal Sets”, Mathematical Proc. Of the Cambridge Philosophical Society, Vol. 50, No. 1, pp. 40-48, 1954.
[20] E. Ertin, C. D. Austin, S. Sharma, O. L. Moses, and L. C. Potter, “GOTCHA Experience Report: Three-Dimensional SAR Imaging with Complete Circular Apertures,” in SPIE Proceedings Vol. 6568, 2007

L_WP5 (EI): Low Complexity Algorithms and Efficient Implementation

5.1. 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.
Affiliated PhD Students:	Jamie Corr (ST), Jethro Dowell (ST)
Project Partners:	Mathworks, Texas Instruments, and PrismTech
Dstl Contacts:	Dr David Nethercott and Dr George Jacob

5.2. Aims and the lists of the original L_WP5 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, Prism Tech, and Steepest Ascent, 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.

5.3. Progress made in the first year in addressing the original objectives

Our focus has main been on L_WP5.1, considering numerically efficient implementations for key algorithms developed by the consortium, where a number of ideas has been generated and are supported by outputs. The work on L_WP5.2 has been performed in terms of familiarisation with computations platforms, particularly multi-core systems with industrial partner Texas Instruments, and FPGA implementations with industrial partner Mathworks (formerly Steepest Ascent Ltd).

Progress of L_WP5.1 (Data Reduction and Distributed Processing)

- The focus of Dr Keith Thompson has been on researching the use of statistical signal processing methods for mapping algorithms to distributed processors. In particular the use of Probabilistic Graphical Models (PGMs) is under investigation as potentially powerful tool of representing different algorithms in a compact probabilistic structure. Of greatest interest is the use of approximate inference methods that can allow the numerical efficiency of complex probabilistic models to be increased significantly. Furthermore, research is being conducted into alternative methods of approximating probability distributions based on deterministic, scalable methods rather than statistical sampling methods such as MCMC. Another important part of this initial period of the project has been to conduct a broad search of interesting methods that would be worth exploring in WP5. This effort has been in response to our Dstl contacts who have recognised that the broad umbrella of 'Efficient Implementations' allows the potential for a large number of research areas to be targeted in greater depth. Keith has also shared his focus with developing capability for WP5.2 Hardware Realisations. In order to support this work a number of initial algorithms have been identified and developed to support hardware development training. In particular, developments made in PEVD methods are to be used along with some classification algorithms (SVMs and GP classifiers). An initial idea on distributed array processing using deterministic metrics (or the mean of pdf only) has been published in IET Intelligent Signal Processing [Karagiannakis 2013].

- The focus of Dr Stephan Weiss has been to support the efforts of exploring a new family of matrix diagonalisation algorithms, and any potential benefits --- in terms of diagonalisation performance but also computational complexity – that can be obtained. A substantial assessment of sequential matrix diagonalisation, with an emphasis on the computational advantages that can be derived from its calculated paraunitary matrix, has been submitted to IEEE Transactions on Signal Processing in January 2014 [Redif 2014]. Links between the polynomial matrix EVD and coherent signal subspace methods --- use for e.g. subspace-based methods such as MUSIC but also data reduction as desired for L_WP5.1--- have been investigated. The latter is a well- established technique that had been developed by Prof Mos Kaveh (University of Minnesota at Minneapolis) three decades earlier. In a noise-free environment, both approaches perform the same, but polynomial matrix EVDs are less robust in noise, where the covariance matrix with estimation errors will be diagonalised and the noise pushed in the paraunitary matrices that define the signal subspace. An initial assessment of this has been published in the IEEE Workshop on Computational Advances in Multi-Sensor Adaptive Processing 2013 [Weiss 2013].

- The focus of Mr Jamie Corr, supported by Drs Thompson and Weiss and Profs McWhirter and Proudler has been the analysis of the computational complexity of the sequential best rotation algorithm, and the development of multiple-shift versions of the sequential matrix diagonalisation family of iterative polynomial EVD algorithms. This has been submitted to the IEEE Workshop on Statistical Signal Processing 2014 [Corr 2014a], with a causally-constrained versions under review for the European Signal Processing Conference 2014 [Corr 2014b].

- The focus of Mr Jethro Dowell has been on multi-channel prediction of wind speed and direction. The data has been modelled as a multi-variate complex time series, whereby the processing of complex-valued data has advantages compared to a real-valued mutli-variate representation with a higher dimension. This work is performed as UDRC-affiliation, but the nature of the work, as discussed during the 2nd LSSC quarterly meeting at the University of Surrey, has direct impact on the consortium, and the implementation of algorithms. Therefore, the work published in Wind Energy [Dowell 2014a] has been extended in collaboration with Dr Chandna (SU) to address augmented processing of complex data, which has been submitted to the IEEE International Workshop on Statistical Signal Processing 2014 [Dowell 2104b].

Progress of L_WP5.2 (Hardware Implementations)

- The focus of Dr Keith Thompson was driven by a decision in the early stages of L_WP5 that L_WP5.2 should be progressed in parallel with L_WP5.1. As a stated objective of WP5 is to be available to support the implementation requirements of the other WPs, the need to develop greater experience and expertise in the latest hardware development tools early in the project was deemed necessary. From a short term perspective in terms of gaining good experience in mapping algorithms on to hardware, we are to focus on looking at efficient implementations of some well-established methods. Ideally, these are to be kept useful and relevant to other WPs, and also relevant to some of the challenges outlined by Dstl that reference the use of subspace methods. Hardware outcomes currently in development are:
    - FPGA Implementation of PEVD methods including SBR2 and ME-SMD
    - GPU accelerated Support Vector Machine and Gaussian Process Classifiers

5.4. Technical Details

Technical Details for L_WP5.1

Matlab implementation efficiency of polynomial matrix decompositions

As an example for a unique advanced signal processing algorithm that is emerging from within the consortium, the second order sequential best rotation (SBR2) algorithm has been investigated with respect to potential savings in computations and cost reductions. Firstly, the aim was to eliminate redundancies or exploit best practice in Matlab programming in order to speed up SBR2 without any loss in performance and accuracy. For this, SBR2 has been investigated using Matlab's profiler, which highlights the relative processing time that various commands and functions require during the execution of an algorithm. Interesting, it was found that the search for the maximum element, which SBR2 delays and rotates onto the diagonal in every step, posed a significant bottleneck. This was removed by re-organising how data was stored in arrays, and the subsequent search over a one-dimensional array eliminated the problem and speed up the algorithm by approximately a factor of three for the size of matrices that were considered. Although a very simple trick by itself, this has subsequently resulted in a significant decrease in simulation time for any processing based on SBR2, such as for [Redif 2014, Corr 2014a & b].

Fast converging polynomial matrix decompositions

Based on an idea by John McWhirter and in direct collaboration with L_WP3, a new family of iterative polynomial EVD algorithms has been designed and investigated. Different from SBR2 [McWhirter 2007], where at every iteration only the maximum off-diagonal element is eliminated, the sequential matrix diagonalisation (SMD) algorithm eliminates all off-diagonal elements on the zero-lag slice of the space-time covariance matrix, thus zeroing all instantaneous cross-correlation terms at every iteration. The elimination does not just involve the maximum element as in the case of SBR2, but in SMD, the maximum off-diagonal column is identified and shifted to the zero-lag matrix, where it is eliminated together with the corresponding row due to the parahermitian property of the space-time covariance matrix. SMD has been proven to converge [Redif 2014], and, by transfering more energy per iteration step, diagonalises a parahermitian matrix in significantly less number of iterations than SBR2.

The SMD algorithm can achieve levels of diagonalisation that are unattainable with SBR2; however this comes at a significant increase in computational complexity, even for a lower cost SMD version, which only searches for the maximum element (ME) and therefore termed ME-SMD rather than the maximum off-diagonal column norm. Important in the context of L_WP5.1 is the fact that SMD and ME-SMD, though costly to calculate, achieve the diagonalisation with a lower order of paraunitary matrices, therefore making the decompositions achieved with SMD and ME-SMD less costly to apply when compared to SBR2 [Redif 2014]. Thus, e.g. the paraunitary matrices that would perform a subspace decomposition for e.g. broadband angle of arrival estimation [Weiss 2013] have a much lower complexity than with SBR2.

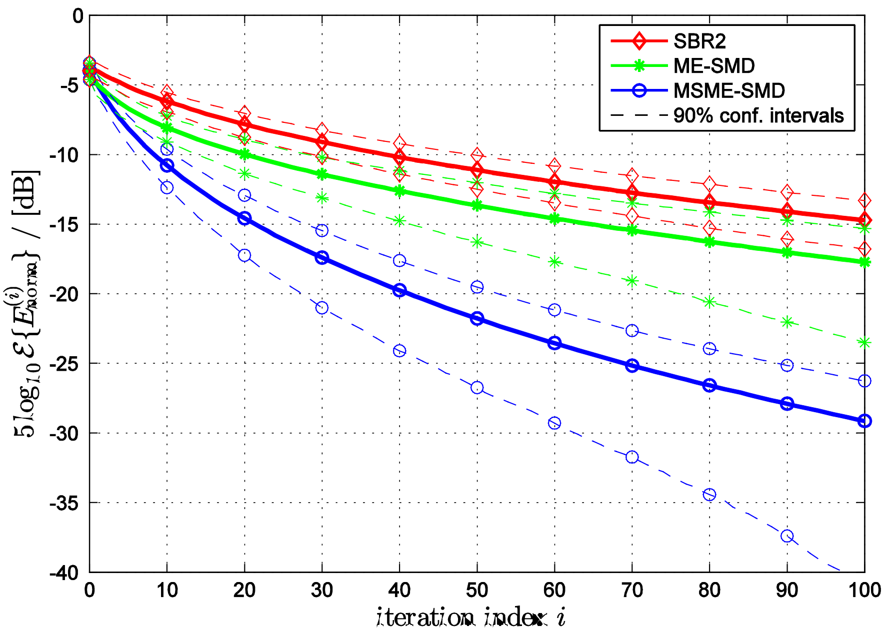

Fig. 5.1 Remaining off-diagonal energy in dependency of iterations for MSMD-SMD algorithm compared to benchmarks.

Recently, we have expanded the idea of SMD and ME-SMD by shifting even more energy onto the lag-zero slice in very iteration, here it is then transferred onto the diagonal by means of an ordered EVD. This is achieved by shifting extra columns and rows at every iteration, leading to an even faster diagonalisation than with SMD and ME-SMD as shown in Figure 5.1. This algorithm is referred to as multiple-shift maximum element SMD (MSME-SMD) algorithm [Corr 2014a]. The determination of shifts is non-trivial, and a maximum number of shifts has been obtained in [Corr 2014a] by restricting the search space where maximum columns can be identified. This selection leads to shifts that may be causal or anti-causal at every iteration, such that overall a non-causal paraunitary matrix emerges. By restructuring and further restricting the search space, a causal paraunitary matrix can be extracted instead. The reduction in search space is compensated by a lower growth in polynomial order, such that overall a causality-constrained MSME-SMD algorithm can be implemented without performance loss compared to MSME-SMD [Corr 2014b].

Linkages between polynomial EVD and other numerical techniques for broadband array and multichannel signal processing

The polynomial EVD as approximated by SBR2 and SMD algorithms can be used for broadband subspace decomposition, which in turn enables L_WP5.1-relevant parameter and data reduction techniques in addition to many other applications such as broadband angle of arrival estimation [Weiss 2013]. A suitable benchmark for the PEVD as a polynomial subspace technique are coherent signal subspace methods developed by Mos Kaveh's group over the last three decades at the University of Minnesota at Minneapolis. Coherent signal subspace techniques average across frequency bins, whereby the covariance matrix in each bin is “focussed”. In the simplest interpretation, this amounts to pre-steering the direction of interest to appear at broadside, such that narrowband processing techniques suffice for angle of arrival estimation or signal extraction. We have shown that the PEVD approach to subspace decomposition is identical to the coherent signal subspace approach in a noise-free environment. However, if noise or estimation errors corrupt the space-time covariance matrix, the PEVD will diagonalise regardless and thus push the noise into the paraunitary matrices, where the identification of subspaces is therefore less robust to noise than with the coherent signal subspace approach. The important understanding [Weiss 2013] set some of our aims for future work.

Multi-channel prediction using complex valued representation

For a multichannel prediction problem involving complex-valued time series, we have developed a cyclo-stationary Wiener filter [Dowell 2014a]. Motivated by the prediction of wind speed and direction at several geographically separated sites, we have modelled wind speed and direction as magnitude and phase of a complex random process. The situation has diurnal and seasons cycles, necessitating the cyclo-stationary approach. The method fills a gap in two respects: there exist sophisticated complex-valued approaches which however only consider the single-channel case; for multi-channel systems, often only speed, not direction, is considered which impacts on the causality of the scenario. The derived system has been shown to outperform existing benchmarks [Dowell 2014a]. This has been extended in collaboration with Dr Swati Chandna (SU) to design an augmented Wiener predictor. This system has an added,widely linear component, which can be justified by performing statistical tests on the dependence or independence or real and imaginary part of the time series to establish the properness of a complex valued random variable [Dowell 2014b].

Distributed processing

Prof Ian Proudler [Proudler 2007] proposed to use “loopy” graphs to implement statistical methods using a Bayesian belief network. This idea has been extended to use “loopyness” to create iterative signal processing algorithms. Pearl’s algorithm as an implementation of a Bayesian belief network is not guaranteed to converge, yet many powerful signal processing algorithms are based on the principle of iteratively approaching a solution. The idea is also that this implementation principle could perhaps be applied to deterministic problems, where just the mean instead of probability density function is propagated. As a by-product, a deterministic problem may find a distributed implementation offered by the graph nature of Pearl’s algorithm.

We have not progressed very far on the generalisation of these ideas, yet Pearl’s algorithm has inspired two related works --- the distributed calculation of a large fractal beamformer [Karagiannakis 2013], where local processing ensures that the processing in any one node does not exceed set limits, and that local calibration information about nodes is only required locally. Also, Pearl’s algorithm has been implemented in a generic and scalable form, and used to optimise the station assignment in a heterogeneous network, where the Bayesian belief propagation idea with levels of uncertainty, e.g. for the gain of a link, can be taken into account and be replaced by concrete evidence if available [McGuire 2014]. The solution obtained with this approach has been confirmed and verified against a previous deterministic, exhaustive search optimisation [McGuire 2013].

Technical Details for L_WP5.2

Hardware Platforms
Dr Thompson has completed a training course in FPGA development, and is now working towards implementing PEVD methods (especially the SBR2 algorithm) on a suitable FPGA device, whereby a Xilinx Spartan 8 that has been provided by Steepest Ascent / Mathworks. Optimised Matlab code for SBR2 implementations has been transferred from Matlab to Simulink in order to utilise Xilinx System Generator and the ISE package.
In terms of graphical processor units (GPUs) a low-end Nvidia GPU has been acquired and is being used to explore the use of CUDA tools and Matlab Parallel Processing toolbox.

5.5. Linkages with Dstl and Industry

Regular contact has been maintained with the L_WP5 designated Dstl contacts David Nethercott and George Jacob, both to update Dstl on the progress of WP5 and to seek feedback on relevance to Dstl. On several occasions, Dstl staff highlighted the desire to address beamforming-type problems both in the acoustic and RF frequency ranges in order to cover both sonar and radar applications. Significant engagement has taken place with partners from Mathworks (formerly Steepest Ascent) in terms of providing FPGA development training materials. We have also had discussions with Mathworks related to general programming techniques that could address computational bottlenecks in simulating algorithms within the consortium, by e.g. making use of Matlab's parallel processing loops (forvar).
Representatives from Mathworks, Texas Instruments and Prismtech have all been invited to attend the Show & Tell event to be held in conjunction with the CSG meeting in Strathclyde on April 7th and 8th 2014, and the industry day in June 2014 as part of the UDRC summer school at Heriot Watt University. The objective of these events is to further develop links and engage these industrial partners to further the objectives of the consortium and seek feedback on the relevance of the consortium's research. In November 2013, Prof J. Soraghan and Dr K.Thompson visited Texas Instruments in Freising for several days to hold an extended discussion on the LSSC Consortium objectives with representatives from TI’s University Program. This event also provided a showcase of some of TI’s latest technology developments, particularly with respect to embedded processing and multi-core systems.

5.6. Future Plans

To develop an efficiently implemented Matlab Toolbox for polynomial matrix decomposition algorithms.
The aim is to extend Jamie Corr's work on polynomial matrix decomposition algorithms to produce a toolbox of highly efficient implementations of the sequential best rotation algorithm a well as a new and emerging family of sequential matrix diagonalisation methods. The efficiency will be achieved through a combination of approximations and efficiency-tricks in Matlab. Approximations include to e.g. express a full EVD by a limited number of Given rotations to achieve diagonalisations with a precision that is commensurate to the level of off-diagonal

energy at which an SBR2 or SMD algorithm stops its iteration. The parallel for-loop in Matlab, and conversion of multi-dimensional arrays to cleverly-indexed one-dimensional arrays over which searches for e.g. maximum elements can be conducted much faster, will be exploited.

To develop fast converging, low-cost polynomial matrix decompositions
Sequential matrix diagonalisation algorithms are costly in terms of diagonalisation of a parahermitian matrix. However, the level of decomposition that can be reached with respect to SBR2 is significantly improved, and if comparable decompositions can be reached by both SBR2 and SMD, the latter bears a significant advantage in terms of the required order of paraunitary matrices to achieve such decompositions. Therefore, although SMD algorithms are more expensive to diagonalise a matrix, they yield processor matrices that are significantly less computationally expensive than their SBR2 counterparts. To realise this further, we will investigate ideas on “optimal” multiple-shift algorithms that can maximise the diagonalisation per step and hopefully create SMD algorithm versions that are yet more powerful in obtaining low-cost paraunitary processing systems.

To establish linkages with coherent signal-subspace methods
Extend collaboration with Prof Mostafa Kaveh (University of Minnesota) to establish links with his coherent signal subspace techniques for broadband array processing, in order (i) to better understand the link of this well-established benchmark technique with polynomial matrix approaches, and (ii) to potentially derive any computational advantages from understanding these links.

To develop distributed approaches for signal processing, with an emphasis on beamforming
Bayesian belief networks have been shown to implement statistical signal processing algorithms such as the turbo equalisers [McEliece 1998], and the aim will be to see if a generic mapping of signal processing algorithms will be possible. The complexity of the algorithm will depend on e.g. the resolution with which probability density functions are represented in Pearl’s algorithm, and perhaps approximations by polynomial methods may be a possibility, such that a simple trade-off between complexity and algorithm accuracy can be achieved.

To establish a hardware suite with sample implementations
Based on the understanding of FPGA and multi-core systems, an aim for th 2nd year will be to have a hardware suite set up at the UDRC/LSSC laboratory in Strathclyde, where sample algorithms can be implemented in hardware, supported by the software tools donated by industrial partners Texas Instruments (Code Composer Studio) and Mathworks, where automatic code generation tools for FPGAs such as Matlab Coder and HDL Coder will be explored. Based on comments from Dstl but also discussions with industrial partner Selex ES, computational complexity alone should not be the metric of merit, but memory requirements of algorithmic implementations must also be considered.

5.6. Outputs

* [Weiss 2013] S. Weiss, M. Alrmah, S. Lambotharan, J.G. McWhirter, M. Kaveh: "Broadband Angle of Arrival Estimation Methods in a Polynomial Matrix Decomposition Framework," 5th IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing, St. Martin, December 2013.

* [Redif 2014] S. Redif, S. Weiss, and J.G. McWhirter: "Sequential Matrix Diagonalisation Algorithms for Polynomial EVD of Parahermitian Matrices," submitted to IEEE Transactions on Signal Processing, January 2014.

* [Corr 2014a] J. Corr, K. Thompson, S. Weiss, J.G. McWhirter, S. Redif and I.K. Proudler: "Maximum Element -- Maximum Energy Sequential Matrix Diagonalisation for Parahermitian Matrices," submitted to IEEE Statistical Signal Processing Workshop, Gold Coast, Australia, June/July 2014.

* [Dowell 2014b] J. Dowell, S. Weiss, D. Infield and S. Chandna: "A Widely Linear Multichannel Wiener Filter for Wind Prediction", submitted to IEEE Statistical Signal Processing Workshop, Gold Coast, Australia, June/July 2014.

5.7. References

[Corr 2014b] J. Corr, K. Thompson, S. Weiss, J.G. McWhirter and I.K. Proudler: "Causal Multiple Shift Maximum Element Sequential Matrix Diagonalisation for Parahermitian Matrices," submitted to European Signal Processing Conference, Lisbon,Portugal, September 2014.

[Dowell 2014a] J. Dowell, S. Weiss, D. Hill, and D. Infield: "Short-term spatio-temporal prediction of wind speed and direction, "Wind Energy, published online 2013, to appear in print 2014.

[Karagiannakis 2013] P. Karagiannakis, K. Thompson,J.Corr, I.K. Proudler and S.Weiss: "Distributed Processing for a Fractal Array Beamformer," IET Intelligent Signal Processing, London, UK December 2013.

[McEliece 1998] R.J. McEliece, D.J.C. Mackay, and J-F. Cheng: "Turbo Decoding as an Instance of Pearl's 'Belief Propagation' Algorithm," IEEE Journal on Selected Areas in Communications, 16(2):140-152, 1998.

[McGuire 2013] C. McGuire and S. Weiss: "Power-Optimised Multi-Radio Network under Varying Throughput Constraints for Rural Broadband Access," 21st European Signal Processing Conference, Marrakech, Morocco, September 2013.

[McGuire 2013] C. McGuire and S. Weiss: "Multi-Radio Network Optimisation Using Bayesian Belief Propagation" submitted to 22ndf European Signal Processing Conference, Lisbon, Portugal, September 2014.

[McWhirter 2007] J.G. McWhirter, P.D. Baxter, T. Cooper, S. Redif, and J. Foster: "An EVD Algorithm for Para-Hermitian Polynomial Matrices," IEEE Transactions on Signal Processing, 55(5):2158-2169, 2007.

[Proudler 2007] I.K. Proudler, S. Roberts, S. Reece, and I. Rezek: “An Iterative Signal Detection Algorithm Based on Bayesian Belief Propagation Ideas,” 15th International Conference on Signal Processing, 2007.