ARGUS II DARP

ARGUS II DARP: Final Report

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Executive Summary

ARGUS II was an industry-led, university based, DARP programme on the applications of agent-based information fusion, which started in May 2003 and concluded in May 2008. The academic partners and their respective research backgrounds were: the University of Oxford (Information Fusion) and the University of Southampton (Multi-Agent Systems). The industrial partners and their specific application interests in the context of ARGUS II were: Rolls-Royce (Shop Visit Planning), BAE Systems (Decentralised Air Traffic Control), and QinetiQ (Wide Area Surveillance).

ARGUS II achieved significant breakthroughs in agent-based information fusion – the result of combining two hitherto disparate subject areas. This involved extending single actor information fusion techniques into a multi-actor environment in which different stakeholders are present, and extending multi-agent system techniques into domains where there is significant uncertainty. The research outputs were integrated and captured in “academic demonstrators”, which showed how they could be used to track targets reliably under uncertainty and coordinate limited sensing and communication resources in a decentralised sensor network.

ARGUS II also achieved successful industrial demonstrations of agent-based information fusion. Rolls-Royce demonstrated how agent negotiation methods could be exploited to set robust scheduling strategies in the aerospace services domain. BAE Systems demonstrated how a probabilistic multi-agent framework could be exploited to develop “Free Flight” algorithms required for future air traffic control concepts. QinetiQ demonstrated how information fusion and agent-based methods could be exploited for wide-area surveillance when operating in a resource-limited network of disparate sensors.

The project delivered 28 technical publications and was instrumental in organising a number of special sessions at international conferences, such as NIPS and Fusion. Genuine research advances were made and these have been recognised within the scientific community, with particular highlights being:

- bounded Covariance Inflation – a new algorithm for robust and reliable data fusion;
- decentralised algorithms for static and dynamic coalition formation;
- novel application of computational mechanism design to sensor networks;
- novel decentralised coordination mechanisms based on the max-sum algorithm.

ARGUS II was presented with the Engineer Award for Large Industry and University Collaboration in 2007. The partnering element of ARGUS II was particularly strong and
resulted in a number of joint scientific papers, secondments and recruitment of university researchers into industry, and sharing of software. The five year duration of the DARP allowed time for teams to form, gel, and transition the research into exploitation.

The project held two conferences in 2007 and 2008 at the BERR Conference Centre in London. These showcased the ARGUS II technology and its applications to audiences in excess of sixty people at each event, drawn from academia, industry, and government. The events were very successful as a means of promoting the technology and for engaging potential end users.

Finally, ARGUS II has contributed directly to a number of new initiatives between the partners that will continue beyond the end of the project. BAE Systems, Southampton and Oxford are engaged in the ALADDIN project (value £5.5m over 5 years), which will build on the ARGUS II research and apply it to the disaster management domain. Rolls Royce, with Southampton University, has won an EPSRC grant (value £150k) to undertake a feasibility study of decentralised scheduling and coordination within the setting of engine overhaul and maintenance. QinetiQ aims to use the output from ARGUS II to underpin development of MOD’s Base Protection CCD project.

In summary, motivated by an increasing requirement for decentralised solutions in networked systems, ARGUS II has made significant contributions to the emerging field of agent-based information fusion. The practical exploitation of these contributions has been demonstrated successfully in three diverse industrial application areas. The work undertaken in ARGUS II has promoted a number of follow-on activities involving the project partners. This will ensure further development of the technology and investigation of its broad application potential in the defence, civilian, and aerospace sectors.

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### Rationale

#### 1. Describe need for the original research programme

The ARGUS II research programme was established to meet the need of an increasingly network-centric world in which computational costs were falling, and pervasive sensing and communication were enabling data to be gathered and disseminated on a massive scale. In particular, the perceived need was to filter, fuse, and interpret this data in support of timely and effective decision-making.

This broad requirement appeals to a diverse range of disciplines, from aerospace and defence applications, to medical, manufacturing and business process engineering. The specific requirement of the ARGUS II programme was to understand how data filtering, fusion, and decision-making can be effective in systems where:

- There are multiple sources of intrinsically uncertain and ambiguous data
- There are multiple decision makers and each may have a different goal
- Data sources and decision makers are spatially distributed and networked
- Fault-tolerance, scalability, and adaptability, are desired system attributes
- System resources (e.g. sensing and communication bandwidth) are limited

This need had only been partially addressed before the start of the ARGUS II programme. There was no complete and integrated framework for distributed data fusion and decision-making on the large scale. ARGUS II was proposed to fill this gap.

#### 2. Describe research challenges as implied by need statement

The main research challenges addressed by ARGUS II were:

- **Data Fusion.** *How to model uncertain data sources and combine them in a mathematically principled way when their degree of correlation and reliability may only be partially known.*

  In particular, within a large-scale sensor network, a data fusion processing node may be presented with the same data multiple times via different routes through a complex communication network. If it is repeatedly fused under an independence assumption, the data fusion node will generate an inconsistent estimate that could create further inconsistency at other nodes, potentially leading to catastrophic failure of the system.

- **Decision Making.** *How to coordinate local decisions to achieve good system-wide behaviour when the decision-makers may have different goals and operate in a dynamic and uncertain environment.*

  For example, in a large-scale sensor network, local decision-makers (sensors) may act upon selfish decisions (what to observe) in an attempt to maximise their own reward (information gain). This can have negative performance implications for the system as a whole. The challenge is therefore to develop decision-making methods...
that result in coordinated actions that are best for the overall system.

- **Decentralised Systems.** *How to develop decentralised data fusion and decision-making methods that are modular, scalable and robust.*

In a large-scale decentralised sensor network system, rather than having to rely on a single centralised data fusion and decision-making node, there are multiple nodes. These should be constructed and programmed in a modular fashion. The system should be free from computing and communication bottlenecks as it is increased in size. It should also be capable of surviving on-line loss (or addition) of sensor nodes and dynamic changes in the network structure.

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### 3. Describe the research direction taken in the programme and how this addresses the need. Summarise why this approach was taken, over alternatives

The research direction taken by ARGUS II was to integrate two different subject areas: Bayesian probabilistic inference (BPI) and Multi-Agent Systems (MAS). This direction was motivated by the desire to develop a mathematically rigorous and overarching framework for multi-agent decision-making under uncertainty, from which pragmatic solutions could be derived by approximation for a wide ranging set of applications.

- BPI was selected for the ARGUS II programme because it provides a mathematically principled and consistent framework for reasoning under uncertainty, and a multitude of techniques that address the need to model, filter and fuse, uncertain data. The opportunity for new research was identified to generalise BPI to a multi-agent environment and develop methods to handle correlated and corrupt information.

- MAS was selected for the ARGUS II programme because it provides mechanisms and protocols, underpinned by Game Theory, that address the need for coordinated decisions in a decentralised system comprising multiple interacting decision-makers. The opportunity for new research was identified to incorporate uncertain information into the MAS domain and to develop efficient decentralised optimisation algorithms.

This research direction was taken because it built on a core of theory and results that already existed in the BPI and MAS subject areas. It was also recognised that the strengths of BPI and MAS were complementary and that their synergistic combination potentially could open up new applications, particularly in the sensor and communication-rich, network-centric, world.

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### 4. Describe organisational approach: the way in which challenges were addressed.
ARGUS II was an industry-led, university-based, programme involving five partners in total: the University of Oxford, the University of Southampton, BAE Systems, Rolls-Royce, and QinetiQ. The role of the university partners was to pursue fundamental research under the guidance of the industrial partners. The role of the industrial partners was to provide the application focus and exploitation routes for the research.

The programme was organised around technology demonstration activities. In the early phase of the programme (years 1-2) the university partners developed research prototype demonstrations in the form of Java simulations. Specifically, agent-based information fusion methods were applied to a simulation of decentralised target tracking and sensor management in a bandwidth-limited, large-scale, sensor network.

The research demonstrations served as a focus to bring together the university partners and develop their understanding of each others subject area, its theoretical basis and assumptions, terminology and language, and overlaps – advancing the field beyond that which was available from an international perspective.

In the second phase of the programme (years 3-5), the industrial partners exploited the technology building blocks developed by the universities to construct three application-focused demonstrations:

- **Decentralised Air Traffic Control (BAE Systems)**. This exploited a probabilistic representation of uncertainty and agent negotiation methods to demonstrate conflict resolution among aircraft in future air-traffic scenarios.

- **Wide Area Surveillance (QinetiQ)**. This exploited distributed data fusion and agent-based coalition formation methods to demonstrate wide area surveillance systems based on a resource-limited network of disparate sensors.

- **Shop Visit Planning (Rolls-Royce)**. This exploited agent negotiation methods to demonstrate robust scheduling strategies for the aerospace services support domain.

The organisation of the ARGUS II programme into these demonstration activities was designed to provide a vehicle for university/industry collaboration that maximised the probability of early exploitation of the technology. Other potential demonstrations covering different industrial application areas are discussed later.

### Objectives

**5. Describe primary objective of project**

The primary objective of ARGUS II was to develop and promote UK capability in decentralised data fusion and decision-making, to enable UK defence and aerospace industries to address future challenges resulting from the proliferation of sensors, networks and computation. Associated with this was the need to advance the technical field beyond that which existed at the start of the programme.
## Specific Partner Objectives:

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<tr>
<th>Lead Partner:</th>
<th>BAE Systems</th>
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<tr>
<td><strong>Primary Objective:</strong></td>
<td>Exploit agent-based information fusion technology to demonstrate improved safety and efficiency performance in the future air-traffic control application context - a decentralised, dynamic, and uncertain domain, in which aircraft will be granted increasing autonomy to plan their own routes through the airspace. (The background to this objective was focussed primarily on UAVs, but recognising the more general applicability in the longer term to possible ATC requirements once the concepts in the approach had been established and proven.)</td>
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### Extent Achieved:

- Probabilistic methods were successfully exploited to represent uncertainty in the domain arising from factors such as: wind buffeting the aircraft, dynamic modelling errors, imprecise execution of actions by pilots
- Agent-based negotiation methods were successfully exploited to resolve conflicts among multiple aircrafts flight plans and ensure coordinated plans were executed
- The probabilistic and agent-based methods were successfully combined to provide an integrated framework for distributed optimisation of aircraft routing decisions
- A simulation-based demonstration of the technology was achieved and used to demonstrate improved performance with respect to an alternative technology (Rule-Based Collision Avoidance) for a standard set of benchmark conflict resolution scenarios

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<th>Partner 1:</th>
<th>QinetiQ</th>
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<td><strong>Primary Objective:</strong></td>
<td>Exploit agent-based information fusion technology to demonstrate improvements in situational awareness over current capability, threat detection, and sensor management, in a Wide Area Surveillance context.</td>
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### Extent Achieved:

A demonstration system was produced that was able to achieve this objective through the novel combination of agent-based coalition-formation and distributed data fusion architectures.

<p>| Partner 1: | Rolls-Royce |</p>
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<th>Primary Objective:</th>
<th>Exploit agent-based information fusion technology for the assessment of composite whole-engine reliability modelling and use it to design robust scheduling strategies for the aerospace services domain.</th>
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| Extent Achieved: | • Estimation of whole-engine reliability was achieved through a study of Weibull mixture models (WMM). WMM is a novel approach for estimating time to disruption in service by combining an engine’s failure modes without reliance on the normal assumption of independence among the different modes.  
• Agent-based negotiation to schedule shop visit appointments by satisfying engine life-driven and margin-driven requirements, and optimizing risk-revenue trade-off  
• Adaptive re-scheduling to mitigate unforeseen circumstances such as in-service events, forced changes to aircraft usage patterns, repair delays, maintenance staff unavailability, etc. |
| Partner 1: | University of Southampton |
| Primary Objective: | Develop novel techniques for controlling and managing decentralised multi-stakeholder systems in which there is a significant degree of uncertainty. Apply these techniques, based on Game Theory, in realistic and industrially relevant settings. |
| Extent Achieved: | Significant theoretical progress in the areas of computational mechanism design and decentralised coordination of multi-sensor networks was made. The results obtained were presented in a number of academic papers and implemented within the two academic demonstrators.  
• Performed foundational work on computational mechanism design and applied it for the first time within sensor network settings in which information and estimates, rather than physical goods and tasks, are traded.  
• Applied computational mechanism design to novel task allocation problems, including those involving capacity constrained suppliers, in the presence of uncertainty and unreliable reporting.  
• Performed novel analysis of discrete bid auctions; an area of the auction literature that had previously received little attention but is critical to actually deploying auctions and mechanism design within a computational setting. |
• Developed a decentralised multi-hop routing algorithm for sensor networks that maximises the lifetime of the overall sensor network through local decision making.

• Developed efficient algorithms for coalition structure generation, particularly in the novel case where coalitions can overlap, and applied them to the novel problem of coordinating sensors. These algorithms were applied within the QinetiQ industrial demonstrator.

• Developed a decentralised coordination mechanism based upon the max-sum algorithm. The mechanism allows individual agents to decide on actions that maximise the sum of their utilities through local computation and communication. The mechanism was demonstrated in the joint universities research prototype demonstrator and has been exploited by both BAE and QinetiQ in their respective industry demonstrations.

• Produced 13 conference papers and 5 scientific journal papers.

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<th>Partner 1: University of Oxford</th>
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<td><strong>Primary Objective:</strong></td>
<td>Develop innovative mathematical techniques for multi-sensor information-fusion and detection in uncertain decentralised environments that are constrained by bandwidth. Applied these techniques in realistic, industrially relevant settings.</td>
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<td><strong>Extent Achieved:</strong></td>
<td>Significant theoretical progress was made in the areas of: inference when there is an unknown (or bounded) degree of data incest, efficient decentralised information sharing in multi-sensor networks, fault analysis with incomplete data, and decentralised coalition formation. All these methods were successfully applied to a wide range of industrial problems.</td>
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<td>• Developed a novel algorithm (called Bounded Covariance Inflation) for efficient communication and fusion of estimates in decentralised sensor networks. The approach has been successfully applied to a multi-agent map building application and exploited by QinetiQ, for multi-sensor data fusion, in the context of Wide Area Surveillance</td>
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<td>• Developed novel decentralised algorithms for static and dynamic coalition formation, for effective sensor-target allocations in sensor networks. These algorithms were applied to target identification and localisation. They have been exploited by QinetiQ, for sensor management, in the context of Wide Area Surveillance</td>
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<td>• Contributed to mixture-model theory with an emphasis on fault analysis, in particular through the Weibull mixture model. This</td>
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work has been exploited by Rolls-Royce, for estimation of whole engine reliability, in the context of Aero Repair and Overhaul.

- Developed methods to determine bounds on the efficiency of nonlinear estimators. The research was performed in collaboration with BAE Systems in response to a specific problem in their application area of Air Traffic Control.

- Developed a currency for information which allowed efficient allocation of communication bandwidth within selfish multi-agent systems. This work was done in conjunction with the University of Southampton and formed part of the joint university demonstration activity.

- Produced a total of 12 scientific publications

## Evaluation of Objectives

### 6. How well did the project meet its original objectives? In areas which were not achieved, what were the reasons and what was achieved in their place?

The project’s original objectives fell into five main categories: technical, partnering, training, exploitation, and dissemination. All key objectives have been met by the project as indicated by the following measures of success:

- **Technical**

  The project sought to investigate the theoretical connections between Bayesian Probabilistic Inference (BPI) and Multi-Agent Systems (MAS), and to develop novel algorithms resulting from these connections. Ground-breaking work was done by the university partners and transformed into successful demonstrations by the industrial partners. The project exposed parallels and synergies between BPI and MAS that had hitherto been obscured because of their different conceptual underpinnings and terminology. Moreover, these synergies led to algorithmic breakthroughs and innovations with respect to decentralised data fusion and decision-making in resource-limit systems.

  A measure of the technical success of the project was its publication record. A total of 18 conference and 7 journal papers were produced. These report novel work in the areas of: computational mechanism design, design of online auction mechanisms, efficient algorithms for coalition structure generation, decentralised coordination of agent systems, algorithms for efficient fusion and communication in decentralised sensor systems, contributions to mixture model theory using Weibull distributions, and development of principled information metrics for agent systems. These publications have advanced the field to a level that increasing numbers of citations to the work undertaken are being noted.

- **Partnering**

  The partnering aspect of ARGUS II was a particular strength of the project. The
university partners were unknown to each other at the start of the project, but succeeded in building a strong and mutually beneficial collaboration that will continue at a technical level beyond ARGUS II. The university partners met on a regular basis throughout the project to exchange information with each other in their respective subjects, leading to a common understanding that formed the basis for joint research. Their strong partnership is evident in the production of 6 joint research papers as well as the joint university demonstrator system which required significant team working and which gained much praise from feedback following the conference in February 08.

Similarly, there was strong partnering between the university and industry partners. This took the form of regular meetings, workshops, secondments (university into industry and vice versa), sharing of software, and collaborative papers. Of the 25 ARGUS II publications, 5 are joint publications between university and industry. This close level of partnership particularly helped to facilitate the insertion of technologies developed by the universities into the industrial demonstration systems.

The strong partnering element of the ARGUS II project was recognised by the UK engineering community in 2007 when it won The Engineer Technology and Innovation Award for Large Company and University Collaboration.

• Training

For the university personnel who worked full time on the ARGUS II programme: lead Rezek (Oxford) and Alex Rogers (Southampton) were awarded lectureship positions at UK universities as a consequence of their contributions to the programme; Raj Dash (Southampton) was awarded a PhD and the BCS Distinguished Dissertation award; Viet Dung Dang (Southampton) was recruited to an industrial position, applying the knowledge gained on agent technology in commercial settings; Partha Dutta (Southampton) was recruited by Rolls-Royce as a Technologist; Steven Reece (Oxford) completed a three month secondment with BAE Systems.

For the industrial personnel who worked on the ARGUS II programme: Mark Briers (QinetiQ) and Armin Stranjak (Rolls-Royce) were both awarded PhDs; David Nicholson (BAE Systems) was appointed to a Theme Lead position on the ALADDIN project, to promote further exploitation of agent-based information fusion within industry.

• Exploitation

The industrial partners have actively promoted the exploitation of ARGUS II technology within their businesses:

BAE Systems has formed a Strategic Capability Partnership with the University of Southampton in Distributed Data and Information Systems (DDIS). A current activity within DDIS is the Autonomous Learning Agents for Decentralised Data and Information Networks (ALADDIN) project. This involves three of the ARGUS II partners (BAE Systems, Southampton and Oxford) as well as other UK universities.

Rolls-Royce has promoted the exploitation potential of agent-based information fusion technology to manage and optimise the services that the company provides in the aerospace engine overhaul and repair business. Work will continue with Southampton, beyond ARGUS II, to explore this opportunity.

QinetiQ has had dialogue with several UK commercial organisations that hope to
procure QinetiQ’s current real-time surveillance capability. QinetiQ’s technology roadmap has identified ARGUS II technology as enhancing their future capability demonstrators, and hence real-time surveillance products. Similarly, MOD’s Base Protection CCD project has shown significant interest in ARGUS II real-time surveillance technology, and should utilise it in future spirals of this program.

- **Dissemination**

Toward the end of its final year (February 2008), the project held a conference at the BERR Conference Centre in London and attracted an audience of 65 people outside the project, from government, industry, and academia. A previous ARGUS conference and a Workshop had also been held, ensuring good visibility of the project and positive feedback throughout its duration.

The main research elements of ARGUS II have been disseminated in the form of presentations and papers at major international conferences in the subject areas of information fusion and agents, including NIPS, Fusion, and AAMAS. The project has also been instrumental in organising workshops at these conferences, for example a NIPS workshop on *Game Theory and Reasoning Under Uncertainty* and a Fusion Conference workshop on *Agent Based Sensor Fusion*.

The industrial partners have disseminated ARGUS II outputs within their businesses and customer communities. BAE Systems has presented ARGUS II demonstrations to air traffic control domain experts at the National Air Transport Services (NATS), Eurocontrol, and NLR. QinetiQ has presented to stakeholder representatives for real-time surveillance capability from MOD and commercial organisations.

### 7. What was the nature and level of the innovations created by the project, particularly their novelty and originality (as measured by patents for example)?

The main innovations generated by ARGUS II were a result of bringing together two disparate fields of research, and advancing and extending their respective domains of applicability. Specifically, ARGUS II has shown how Bayesian probabilistic inference can be extended into a multi-agent environment, where there are multiple stakeholders and a significant level of uncertainty. The novel outcome of ARGUS II has thus been a principled framework for agent-based information fusion, from which a number of original algorithms and applications were produced. This framework has undoubtedly established a new and continuing capability in the UK with which to influence other new and demanding application areas.

In the area of Bayesian probabilistic inference and information fusion:

- A new method known as Bounded Covariance Inflation (BCI) was developed for mitigating the problem of rumour propagation inherent in peer-to-peer systems. This is important because rumour propagation can give rise to severely inconsistent estimates, possibly resulting in unsafe actions where safety is critical. Rumour propagation causes multiple estimates to become correlated and the existing solution (Covariance Intersection) assumes complete ignorance about the level of correlation that it induces. BCI relaxes this assumption to include upper and lower bounds on correlation when they are known. Incorporation of the bounds results in considerably more accurate fused estimates for example, in applications...
such as decentralised tracking and self-localisation (SLAM).

- A new lower bound on the performance of nonlinear estimators was established. The formulation of such bounds is important because they provide a theoretical benchmark for evaluating the performance of practical estimation algorithms. ARGUS II developed tighter bounds than had previously been calculated. This result is of significant interest to the estimation community and is frequently cited.

- Weibull mixture models were formulated to compensate for certain forms of dependence in a set of data points. In addition, a literature review revealed a shortcoming in papers related to the computation and visualization of the uncertainty in the model parameters.

In the area of decentralised decision making agents and resource allocation:

- A novel method was developed for leveraging forecasts of dynamic environments in order to form stable coalitions of agents. This solves an outstanding issue in sensor management. Other applications include scheduling, operations research, and software agents.

- Decentralised coordination algorithms were developed that will now allow agents within a decentralised system to select actions that will optimise a global utility through entirely local computation and communication.

- Work on computational mechanism design extended the application of these techniques into novel areas, particularly their use within sensor systems to allocate constrained resources, and their use with task allocation systems. Both areas have been picked up by other researchers within the community and developed further.

Regarding the industrial applications of ARGUS II technology:

- Solutions to conflict resolution in the airspace domain are traditionally the remit of air traffic controllers. However, inspired by technology developments in navigation, surveillance and communications systems, there is a shift toward empowering the actual aircraft to make decisions themselves. While some decentralised decision-making techniques have been proposed, they lack rigour, do not scale, or are unable to deal with uncertainty. The ARGUS II solution to the problem uniquely provides all of these benefits.

- All real-time surveillance products (deployable and capable) in current use are manpower intensive. The ARGUS II project was able to develop novel capability to reduce operator workload by automating the management of sensors and provide an improved situational awareness picture by fusing the observations from multiple sensors to reduce uncertainty and improve track quality.

The innovative technical work carried out in ARGUS II has been recognised by the publication of 25 papers in high-quality peer-reviewed journals (e.g. ACM and IEEE Transaction) and conference publications (e.g. AAMAS), a BCS distinguished dissertation award, new collaborations, and new projects (e.g. ALADDIN, SEAS DTC).

The original applications pursued in ARGUS II by the industrial partners have been recognised by internal company awards (Rolls-Royce won an R&T Directors award for best idea, BAE Systems was nominated for a Chairman’s Award for Innovation), new
8. How have the consortium members been strengthened by involvement in the project in terms of skills, resources and experience. Include details of staff training and careers progression aided by the project?

The ARGUS II project has carried out multi-disciplinary research in support of diverse applications. As a result, it has exposed all the consortium members to new technical areas and their surrounding practical concerns. This has expanded the skills of everyone on the project and contributed to various staff training and career progression highlights.

- **Academic Partners**

  The two academic partners have forged a very strong collaboration as a result of their introduction through the ARGUS II project. They have become skilled in each other’s technical area and in collaboration they have developed and advanced the theoretical connections between the different disciplines.

  Through working closely with industry, the academic partners have gained skills communicating their research ideas and results to non-academic collaborators in the project and to a mainly industrial audience at the project conferences. They have also been exposed to some of the practical implementation issues associated with applying their fundamental research ideas in ‘real world’ situations.

  As a result of their strong research profiles on the ARGUS II project, Dr. Iead Rezek (Oxford) and Dr. Alex Rogers (Southampton) were appointed to lectureship positions at UK universities. Dr. Mark Ebden (Oxford) has also been appointed as an RA on the ALADDIN project to continue his research on dynamic coalitions.

  Dr. Viet Dung Dang (Southampton) has moved to a position in industry, joining a company that is currently working with one of the industrial partners to apply multi-agent systems technology in a commercial setting.

  Dr. Krishnen Vytelingum (Southampton) carried out formative research in decentralised task allocation and scheduling. He is now employed on an EPSRC grant to perform a feasibility study to further demonstrate the application of this technology in the Rolls-Royce application area.

- **Industrial Partners**

  As a result of working closely with university researchers, the industrial partners have gained skills communicating their application requirements and constraints to non-industrial collaborators. They have been exposed to unfamiliar technology and gained an appreciation of its capabilities, performance, assumptions, and maturity.

  As a result of their strong contributions to the ARGUS II project, Armin Stranjak (Rolls-Royce) was promoted to the Specialist Role for Information Engineering; David Nicholson (BAE Systems) was appointed Technology Transfer Theme Lead on the ALADDIN project; and Mark Briers (QinetiQ) was promoted to (cross-project) technical
leader position in QinetiQ’s Data Fusion and ISTAR technology capability group.

Rolls-Royce recruited Partha Dutta (Southampton) as a Technologist. BAE Systems hosted Steven Reece (Oxford) on a 3-month secondment to work on Bounded Covariance Inflation and apply it to a BAE Systems problem case: multi-robot self-localisation and map-building in a GPS-denied environment.

Two of the industrial partners, QinetiQ and BAE Systems, have commenced a joint programme of research for MOD, that builds on knowledge and experience gained from the ARGUS II project in the area of distributed data fusion.

Rolls-Royce is looking to apply the techniques from ARGUS II to enhance its internal capability for scheduling engine maintenance in its civil aerospace operations.

**Outlook**

9. Summarise remaining research and exploitation challenges (those that were identified at beginning of programme, those that have become apparent during the course of the programme) – both what they are and why they are important.

**Research challenges:**

The detailed integration of Game Theory and Machine Learning, which provides a unified theoretic basis for agent-based information fusion, requires further research to explore its full potential. Even though significant progress was made in the ARGUS II project, some of the connections between these two disciplines will need to be investigated in greater detail to explore their full theoretical and practical implications.

For example, novel decentralised optimisation algorithms were one of the main research outputs from the ARGUS II project. The performance of these algorithms was investigated for specific problem cases, motivated by the industrial applications. Further research is required to determine their general performance characteristics on a wider front and provide bounds on the behaviour and quality of their solutions.

A further research challenge is to develop more efficient versions of the ARGUS II algorithms, such as dynamic coalition formation. The research would focus on how to structure and represent the problem space, so approximations could be made that reduce computational cost but incur minimal performance loss.

Other more specific research challenges, related to the industrial applications, are the subject of ongoing discussion between the partners. Rolls-Royce and Oxford are discussing opportunities to research and apply conditional fault analysis with respect to whole-engine risk analysis. Rolls-Royce and Southampton are continuing to investigate the application of decentralised scheduling for engine repair and overhaul in dynamic environments, funded by EPSRC. QinetiQ and Oxford are discussing how to improve the efficiency of dynamic coalition formation algorithms applied to (real-time) wide area surveillance in both commercial and defence contexts. BAE Systems, Oxford, and Southampton, are engaged in the ALADDIN project, continuing to address research challenges in agent-based information fusion and transferring them into industrial applications.

**Exploitation challenges:**
ARGUS II has demonstrated the potential of agent-based information fusion in three relevant industrial applications. The remaining exploitation challenges are to mature the technology and develop strategies for inserting it into each application domain. This will require a smooth phased transition from current deployed systems to the ‘ARGUS-equipped’ systems of the future. Key to this is early engagement with end users to build their trust and confidence in the technology.

For Rolls-Royce, the main exploitation challenge is to integrate the engine scheduling tool developed in ARGUS II with current practices and deployment strategies.

For BAE Systems, the main exploitation challenge is to further develop the probabilistic and decentralised decision-making framework, developed in ARGUS II, in the context of its future Autonomy business products and systems.

For QinetiQ, the main exploitation challenge is to mature the enhanced situation awareness and reduced operator workload capability, developed in ARGUS II, for potential insertion in a future mobile surveillance and security product.

10. Describe extent to which remaining challenges could be addressed by knowledge generated within programme. Identify any capability gaps.

- **Research challenges:**

ARGUS II has generated a well-founded core knowledge base for solving problems relating to reasoning and acting under uncertainty in a multi-agent environment. The remaining challenges could be addressed by maturing the contents of this knowledge base. For example, while ARGUS II technology may be able to solve a relevant problem in theory, issues such as finite computational and communication resources may limit its application in practice. One key capability gap is to realise efficient practical solutions to certain multi-agent inference and decision-making problems, in particular where there is a large state and/or action space. This could be tackled by researching how to exploit structure or context in these problems, to reduce the size of the state-action space.

Follow-on work to improve algorithm efficiency is planned for the dynamic coalition formation and decentralised scheduling algorithms. This work will seek to close a gap left by ARGUS II, i.e. the provision of guarantees or bounds on performance. Although ARGUS II developed useful point solutions for these algorithms, a capability to ‘predict’ performance, given a general problem specification, would be very valuable.

- **Exploitation challenges:**

The knowledge generated during the ARGUS II programme resulted in proof-of-principle demonstrators in three industrial application areas. These provided an initial platform for pursuing the remaining exploitation challenges, through wider engagement with application domain experts, system engineers, and end users.

Many of the exploitation challenges are common to all three applications. Given the technology base and application requirements generated across ARGUS II, it should be possible to further close the exploitation gap by maturing the demonstrations (exposing them to more realistic, real-world factors) in parallel with improving the
technology components (making them better, faster, more accurate).

For example, the sensing requirement for the wide-area surveillance application implies a vast quantity of data, from which information needs to be extracted, summarised, and subjected to pattern-of-life analysis. Such analysis would help to warn operators of potential threats through the automated flagging of suspicious behaviour. Similarly, for archived data, an automated meta-data tagging capability would ensure large volumes of data and information would be able to be searched ("mined") more efficiently.

11. Identify other technologies that could be used to address these gaps, and their maturity.

The main gap is computational. ARGUS II technology is computationally intensive to exploit in general since it appeals to large-scale combinatorial problems, such as sensor allocation and fusion. However, being agent-based, much of the computation lends itself to being distributed over multiple processing nodes. High throughput, brute force parallel computing is one way to address the computational challenge posed by ARGUS II. For example, Grid Computing is a special type of parallel computing that is being used to solve other “grand challenge” problems in astronomy, genomics, and meteorology. Distributed or Grid Computing is a relatively short-term solution and is expected to yield moderate gains in performance. Conversely, Quantum Computing is a longer-term solution that has the potential to bring enormous computational gains. It is the view of the research team that the limitations of any current computational capability will, over the next five to ten years, not be a major issue as advances made in current research worldwide come to fruition.

12. Recommend further research and development activities that may be necessary to address these capability gaps.

- Research activities:

  A detailed theoretical analysis of the ARGUS II algorithms is necessary to set bounds on their performance given a problem specification, e.g. the number of agents, the sensor noise distribution, the social welfare function, etc.

  A research study into approximate inference and decision-making methods is necessary to investigate whether the efficiency of the ARGUS II algorithms can be improved and what the approximations imply in terms of performance.

  Prediction is a fundamental element of the ARGUS II algorithms. For example, predicting a sequence of sensing actions to maximise expected information gain with respect to some objective. Research into Gaussian Processes may be necessary to provide sufficiently accurate predictions over multiple time steps.

  Continued research is necessary into the parallels between loopy belief propagation in Bayesian networks and the use of the max-sum algorithm in multi-agent systems to coordinate actions. More generally there are many parallels, among Machine Learning, Game Theory, and Statistical Physics, still to be researched with a view to exploiting
practically useful relationships and synergy.

- **Development activities:**

Further development work is necessary in all three application areas to further address the capability gaps: For example, there is a need:

- in the shop visit planning application, to investigate the challenges of performing engine service scheduling in a decentralised manner by considering the business policies of various stakeholders in the aerospace industry.

- in the air traffic control application domain, to consider sequence and merging of aircraft on approach to airports, landing slot assignment and ground operations, performance metrics and validation & certification.

- in the wide-area surveillance application, to consider automated pattern-of-life analysis for distributed information sources, and efficient representation of uncertainty associated with meta-data tagging of multiple sources of complementary data and information.

### Market opportunity

**13. What are the possible applications of the innovations the project has created?**

- **General:**

  The project has created innovations that appeal primarily to applications in which: uncertainty is endemic; estimation and decision-making processes have to be distributed for reasons of fault-tolerance, modularity, or scalability; multiple stakeholders may be present; and where resources are limited. As such, ARGUS II is particularly applicable to large-scale information systems operating in an open, dynamic, and uncertain environment.

  Recent step changes in the availability and cost of sensing and communication devices have opened up the potential for many applications that fit this description. In the defence sector, this is being driven by the requirements for network-enabled capability and autonomy in support of improved mission effectiveness and situation awareness. Applications include Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR), and cooperative control of UAV fleets. Elsewhere, critical scientific and social applications include environmental monitoring, disaster management, and homeland security.

- **Shop Visit Planning:**

  The novel Weibull mixture models developed in the project can be incorporated into Rolls-Royce’s Whole Engine Modelling programme to estimate time-to-failure of the composite system more accurately, leading to better estimates of in-service operating reliability. This will in turn lead to better estimates of service support costs and infrastructure requirements.

  The novel agent-based scheduling approach developed in the project can be directly...
incorporated into Rolls-Royce’s Operations Room toolset to provide pro-active scheduling and re-scheduling across its installed base of engine fleets. Such a tool offers considerable opportunity for constraint-based optimisation of the risk/revenue balance, and the decentralised nature of the solution means it should scale well to Rolls-Royce’s growing fleet sizes.

- **Decentralised Air Traffic Control:**

The decentralised estimation algorithms developed in the project can be applied to fuse multiple sources of uncertain data, the navigation and surveillance sensors onboard a system of aircraft, to create robust estimates of the states of each aircraft (their position, velocity, and acceleration).

The decentralised optimisation algorithms developed in the project can be applied to inform each aircraft what action it should take (how it should manoeuvre) to fly a safe and efficient route in the presence of other aircraft and potential hazards.

- **Wide Area Surveillance:**

The decentralised data fusion algorithms developed in the project, in particular the novel Bounded Covariance Inflation algorithm, can be applied to maintain and propagate consistent fused track estimates in a large-scale sensor network.

The dynamic coalition formation algorithms developed in the project can be applied to automate sensor management and thereby reduce the burden on human operators.

14. What is the total size of the market opportunity that has been created by the project?

- **BAE Systems:**

The project has created a market opportunity for a novel distributed decision-making module in support of future autonomous systems, which is a growing market in the defence and aerospace sectors. The technology developed in ARGUS II could help position BAE Systems to deliver differentiating information processing software solutions into this market.

- **Rolls-Royce:**

Rolls-Royce is not looking to market this technology directly. Instead it will apply it to the management and optimisation of the services it offers. As such, Rolls-Royce’s annual turnover in the service businesses is around £4b (and growing). The technology developed in ARGUS II has the capability to improve substantially the return on investment for the majority of Rolls-Royce’s contracts by providing ‘real time’ analysis and scheduling of engine maintenance/servicing.

- **QinetiQ:**

There is a significant global market for a next generation wide area surveillance and security system. By increasing the effectiveness of existing sensing equipment, reducing required manpower through procedure automation, and/or reducing the likelihood of a major incident occurring, it is possible for an organisation to save several millions of pounds within a decade. Moreover, if the system could thwart a potential
terrorist attack in a major international city (such as London), the economic savings alone would be (substantial) at least £50m. The surveillance market is now in a better position to capitalise/exploit the work that has been undertaken on ARGUS II. A recent Government report\(^1\) has highlighted concerns that the current surveillance capability in the UK does little to reduce offences because of the inability to analyse information streams/imagery in near real time.

\(^1\)http://news.bbc.co.uk/1/hi/uk/7384843.stm

15. What are the expected quantifiable commercial and operational impacts that the project will deliver for each partner (e.g. increased sales and profit, home and global market opportunities, IP generated, job creation and knowledge transfer)?

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<tr>
<th>BAE Systems:</th>
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<tr>
<td>The project has delivered a new technology that could offer BAE Systems a discriminating capability in the autonomous systems market. Specifically, the technology impacts autonomous systems operation by enabling multiple vehicles to coordinate their trajectories and eliminate conflicts. The technology is discriminating because it scales to large numbers of vehicles, is robust to uncertainty, and is flexible with regard to the type of mission objective and the mission control parameters. BAE Systems intends to mature this technology and seek insertion opportunities in one or more of its autonomous systems demonstration platforms.</td>
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<th>Rolls-Royce:</th>
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| • Increased process efficiency of Operations Room  
  o Reduced staff time and load  
  o Faster response to unscheduled events, delivering re-optimised schedules with minimised collateral impact  
  
| Improved service schedules  
  o Higher revenue from in-service engines  
  o Better utilisation of repair and overhaul resources  
  
| Better visibility of future projections of business decisions  
  
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<th>QinetiQ:</th>
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<tr>
<td>The ARGUS II project has developed technology that is able to improve the real-time surveillance capability of a multi-sensor system. Being able to provide an enhanced situational awareness picture and reduce operator workload provides QinetiQ with a unique selling point and thus a clear market differentiator in the multi-million pound security market in both the commercial and defence fields. QinetiQ has undertaken a road-mapping exercise to help ensure that the ARGUS II technology innovations are utilised in this context as rapidly as possible.</td>
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Potential impact and timescale

Society and the environment can benefit in many ways from a widespread deployment of data collection and communication devices. For example, the environment can benefit from a network of sensors that monitor the spread of air or water-borne pollutants and enable timely preventive actions to be taken, while society can benefit from a network of sensors and associated information processing algorithms to improve security in city streets or personal healthcare.

Intelligent information processing is key to realising these benefits, otherwise sensors could waste energy collecting uninformative data, communication devices could likewise be choked with uninformative data, and human operators could quickly be overcome by the sheer volume of data generated by the system. Furthermore, decentralised information processing is necessary to eliminate the computational and communication bottlenecks associated with a central processing system. A recent Government report has indicated that the current CCTV and sensor systems deployed in the UK are not that effective for deterring crime, due to an inability to have ‘real time’ image analysis and decision making.

The ARGUS II project has generated decentralised information processing technology and therefore could deliver benefits to the environment and society as indicated below. Specific examples, directly relating to the ARGUS II research and applications, include:

- In dynamic coalition formation the stability of agent coalitions can be increased over time. This can promote increased energy efficiency in any application (e.g. a large-scale sensor network) where changes to the coalitions require energy to be expended.

- The Bounded Covariance Inflation method enables multiple estimates of a target state or event to be statistically summarised by combining them before transmission over a large-scale sensor network, resulting in more bandwidth-efficient decentralised communication systems.

- Future projections of crowded skies and congested runways are argued to have an undesirable effect on the environmental and society. Agent-based negotiation methods can impact this problem by improving the throughput of aircraft between airports, consequently reducing fuel burn and passenger delays.

- For jet-engine maintenance - choosing the time at which to inspect a device for possible disruptions involves a careful balance between safety and operational efficiency. By modelling more accurately the time-to-disruption of components (e.g. in a jet engine), the Weibull mixture model technology developed in ARGUS II can substantially improve this balance.

- Better management of aero fleet engine assets through pro-active scheduling will enable higher utilisation rates and lower spare requirements (less scrap and waste), and better risk management will lead to fewer unscheduled removals,
thereby minimising inconvenience and disruption to airlines and passengers.

- Improved surveillance can help provide a more secure environment for civilian and military personnel. While this benefit is hard to quantify explicitly, any tool that helps to counter the terrorist threat faced by the UK at the current time should have a tangible social benefit. Similarly, commercial organisations wish to protect their assets. There is a clear economic benefit from improved surveillance and security when deployed to protect assets of commercial value.

17. How do you intend to further disseminate the results?

The ARGUS II project web site (www.ox.ac.uk/~argus), hosted by the University of Oxford, will remain active when the project has ended. This contains various project results, in the form of research papers and conference presentations.

The academic partners, who will maintain a strong collaboration beyond ARGUS II, are further developing the core theory and algorithms that originated in the project. These results will be disseminated through the standard academic channels: papers, conferences, and collaborations. The international research activities and outreach of each partner also ensure world-wide dissemination of ARGUS II results.

The industrial partners intend to disseminate the result of ARGUS II within their wider business and stakeholder communities to promote further potential exploitation activity.

18. What are the risks that still remain in achieving these benefits and impacts, together with mitigation measures planned?

The introduction of new technology always generates risk because of the uncertainty in overall performance, unknown maturity costs, implications of reduced manpower, and other general factors. However, all of the industrial partners have expanded their interests in the ARGUS II technology and this demonstrates a measure of their confidence in its ultimate value.

- Decentralised Air Traffic Control:

The introduction of agent technology on board an aircraft, to plan and decide routes on the basis of negotiation with other aircraft, would represent a significant departure from current practice, which is centralised and strongly based on a human decision-maker. There are therefore risks associated with such integration, implementation, validation, and certification of the technology. The mitigation measure is to phase-in the technology through a number of incremental stages. Initially, it could be installed in the air traffic control towers as a centralised decision support tool. Then a number of aircraft from the same airline could be equipped with the technology and finally, several different airlines. ARGUS II technology can be applied to a number of optimisation/scheduling problems in the air traffic domain and the least risky option would start with the landing slot assignment problem, where the penalties for wrong decisions (delays) are less severe. The intention would be to build up increased confidence with the end users/controllers on the potential benefits of the new approach to ATC that could be offered by the ARGUS II technology.
• **Shop Visit Planning:**

New IT projects within Rolls-Royce have to compete with other established programmes with regard to acceptance and implementation, budget and resource availability, and priorities - so some delay is anticipated. However, the intention is to maintain interest with the key customer area (the Operations Room), consolidate the major benefits offered by the ARGUS II technology, and develop the major project outcomes into the capabilities being delivered by Data Systems and Solutions.

• **Wide Area Surveillance:**

Given the investment already made in surveillance systems, end-users would not want to purchase large amounts of new hardware, preferring to build on what is already in place. By deploying ARGUS II technology on existing equipment, QQ can potentially enhance capability and reduce concerns about the technology, to help build confidence with the end user on what is possible, without incurring further expense.

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**Effect of DARP Programme**

**19. What did the DARP funding allow you to attempt and achieve that would not have otherwise been possible?**

The DARP enabled a strong partnership to be formed between academia and industry. The academic members of the partnership brought research expertise from two disparate subject areas, while the industrial partners brought real-world problems and domain expertise. The funding allowed the partnership to develop innovative state-of-the-art research methods and put them into practice in industry demonstrator systems.

A key technical outcome for the academic partners was the successful combination of probabilistic inference and multi-agent systems methods, to form novel approaches for decentralised decision-making under uncertainty that are theoretically and empirically better than existing methods. This was truly a joint effort that involved many meetings between the academic partners and which resulted in a number of joint publications that have been well received in the scientific community.

Furthermore, enabled by access to industrial problems, data, and personnel, the academics could test their approaches in a less abstract setting than is usual for academic research. The five year period of the project has enabled strong collaborative relationships to not only form, but also to be fully exploited and extended to other initiatives outside this project.

The direct relationship between Rolls-Royce and Oxford, leading to the novel Weibull mixture modelling approach, would not have occurred without the formation of the DARP. The ideas and concepts around the distributed scheduling approach would not have evolved without the close relationship between Rolls-Royce and the University of Southampton and the catalyst of the ARGUS II programme.

The combination of probabilistic inference and multi-agents systems, enabled through the DARP, inspired a novel approach for distributed optimisation that BAE Systems could apply to air traffic control problems. This approach is unlikely to have been
realised without the DARP, let alone developed into algorithms and be demonstrated.

DARP funding allowed QinetiQ to enhance its real-time surveillance capability and produce an internationally unique set of technological differentiators. When this technology is integrated into a surveillance product, it is believed the technology will provide an improved situational awareness picture and a system that works with an operator. Such capability would not have been possible without the unique interaction among the ARGUS II partners.

20. By how much did this project increase the R&D spend of the consortium?

Rolls-Royce R&D spend has been increased by at least £200k as a direct result of the ARGUS II project.

BAE Systems is contributing around £3m R&D spend over five years into the ALADDIN project. Partly influenced by the ARGUS II project, this is a further investigation of agent-based information fusion methods in the disaster management domain.

QinetiQ has aligned part of its business strategy around next generation WAS solutions. The ARGUS II technology forms an integral part of this strategy, and as such, has resulted in a significant alignment of resources to the WAS technology area.

21. What plans and budgets have you for further research and development related to the outcomes of this project?

It is a measure of the success of ARGUS II that the research it originated will be carried forward into other research projects by the academic partners and developed further by the industrial partners as part of their respective business programmes. Some examples of future plans and budgets are indicated below.

- The success of the technologies developed in the ARGUS project has led to funding for the ALADDIN project (£5.5m in total over five years). This aims to extend multi-agent information fusion and assessment methods to challenging real-world disaster recovery and situation assessment scenarios. For example, the work on dynamic coalition formation and auction methods, started in ARGUS II, will be developed in ALADDIN.

- The Head of Reliability at Rolls-Royce and Oxford are planning to meet to discuss further opportunities for modelling time-to-disruption of jet-engine components.

- Southampton and Rolls-Royce have an EPSRC grant (value £150k) to perform a feasibility study of decentralised scheduling and coordination within the setting of engine overhaul.

- Rolls-Royce is currently spending £30k beyond the project budget to consolidate the project outputs and identify appropriate exploitation plans. Bidding into the relevant company budget processes will begin shortly.

- QinetiQ has aligned its future (higher TRL) research programmes to accommodate the ARGUS II technology and its integration into future real-time surveillance
• QinetiQ and BAE Systems are undertaking a joint program of work that builds on
the information fusion knowledge generated by the ARGUS II project.

Appendix A: Contacts

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<th>Project web site</th>
<th><a href="http://www.argusiiproject.org">www.argusiiproject.org</a></th>
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<tr>
<td>Project Management</td>
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<td>Email: <a href="mailto:sjrob@robots.ox.ac.uk">sjrob@robots.ox.ac.uk</a></td>
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Appendix B: Publications

1. **Computational-Mechanism Design: A Call to Arms**  
   R.K. Dash, D.C. Parkes, and N.R. Jennings  

   Abstract: Game theory has developed powerful tools for analyzing decision making in systems with multiple autonomous actors. These tools, when tailored to computational settings, provide a foundation for building multiagent software systems. This tailoring gives rise to the field of computational mechanism design, which applies economic principles to computer systems design.

2. **Selfish Sensors in Wireless Micro-Sensor Networks**  
   A.Rogers, E.David, and N.R. Jennings  

   Abstract: In this paper we develop an energy aware decentralised routing algorithm for ad-hoc networking of battery-powered wireless micro-sensors (as found, for example, in security or environmental monitoring applications). The useful life of such networks is limited by the battery life of individual sensors and thus the goal of any networking algorithm is to maximise both the lifetime and the coverage of the network, whilst dealing adaptively with sensor failures and changes in network topology. As sensors may be owned and supported by different stakeholders, we view them as selfish agents maximising their own utility. Given this, we present a mechanism that enables such agents to follow locally selfish strategies which, in turn, result in the achievement of good global performance and robustness to changes in the position and number of individual sensors. We show that our mechanism performs close to the optimal solution (as computed by a centralised optimiser) and extends the useful life of the network by a factor of three over the traditional approach.

3. **Trust-Based Mechanism Design**  
   R.K. Dash, S.D. Ramchurn, and N.R. Jennings  

   Abstract: We define trust-based mechanism design as an augmentation of traditional mechanism design in which agents take into account the degree of trust that they have in their counterparts when determining their allocations. To this end, we develop an efficient, individually rational, and incentive compatible mechanism based on trust. This mechanism is embedded in a task allocation scenario in which the trust in an agent is derived from the reported performance success of that agent by all the other agents in the system. We also empirically study the evolution of our mechanism when iterated and show that, in the long run, it always chooses the most successful and cheapest agents to fulfill an allocation and chooses better allocations than other comparable models when faced with biased reports from agents.
4. **A Mechanism for Multiple Goods and Interdependent Valuations**
   R.K. Dash, A. Rogers, and N.R. Jennings

Abstract: This paper reports on the design of an auction mechanism for allocating multiple goods when the buyers have interdependent valuations. We cast the problem as a multi-agent system consisting of selfish, rational agents and develop an auction mechanism which is efficient, incentive compatible and individually rational. We first discuss the necessary assumptions that any mechanism developed for this scenario should satisfy so as to achieve the aforementioned properties. We then present our mechanism and show how it is a generalisation of the Vickrey-Clarke-Groves mechanism.

5. **Statistical Reasoning in Decentralised and Distributed Multi-Agent Systems**
   S. Reece
   Presentation for DARP members, 16 September 2004.

6. **Dynamic sensor coalition formation to assist the distributed tracking of targets: Application to wide-area surveillance**
   M. Briers, S. R Maskell, S. Reece, S. Roberts, I. Rezek, V.D. Dang, A. Rogers, and N.R. Jennings

Abstract: The protection of infrastructure and facilities within the UK is of prime importance in the current environment where terrorist threats are present. Surveillance of large areas within such facilities is a complex, man-power intensive and demanding task. To reduce the demands on manpower, new systems will need to be developed that use a mixed sensor suite associated with access to databases containing historical data and known threats. This requires fusion of mixed type data from disparate sources. The methods used for the fusion process, and the location of the fusion process, will be dependent on the data, sensor or database. The communication requirements will also be of paramount importance within the monitoring network. As computers increase in performance and reduce in cost and power consumption, there is a growing trend for more processing to be carried out locally. This raises issues of compatibility, timeliness, global awareness of the situation and distributed versus centralised control of the system. This paper presents a generic solution to the wide-area surveillance problem through the application and combination of Covariance Inflation (a distributed fusion mathematical framework that circumvents problems with data incest) with agent-based technologies (allowing the dynamic formation of sensor coalitions) to track, and potentially risk assess, targets within the region of interest. A discussion will be provided into the distributed detection and tracking of an intruding vehicle at a commercial airport to place the seemingly abstract technology into context.

7. **Tighter Alternatives to the Cramer-Rao Lower Bound for Discrete-Time Filtering**
   S. Reece and D. Nicholson

Abstract: The Cramer-Rao Lower Bound establishes a fundamental performance baseline for gauging parameter estimation accuracy in tracking and data fusion. However, it is known to be a
weak lower bound for some problems. This paper presents a set of tighter alternatives: the Bhattacharyya, Bobrovsky-Zakai and Weiss-Weinstein lower bounds. General mathematical expressions are obtained for these bounds and their calculation is described. Then the bounds are applied to a nonlinear/non-Gaussian estimation problem. It is found that the alternative bounds are tighter than the Cramer-Rao bound, but they are still somewhat conservative.

8. **Robust, Low-Bandwidth, Multi-Vehicle Mapping**  
S. Reece and S.J. Roberts  

Abstract: This paper addresses the problem of decentralised simultaneous localisation and map building for a team of agents where the communication bandwidth is limited. We present an extension to current approaches that enables multiple vehicles to acquire a joint map, but which can cope with communication bandwidth limitations. Nettleton’s approach uses a hybrid information filter/Covariance Intersection algorithm on each communication link to manage the inter-vehicle communication and ensure that information vehicles share does not get ‘double counted’. The Covariance Intersection algorithm is a highly conservative method for managing double counting and its use can produce highly uncertain maps. We introduce a novel and more efficient tool, called Bounded Covariance Inflation, for managing the double counting (or rumour propagation) problem. We show that the parameters required by the new approach can be determined locally by each vehicle and therefore the decentralised nature of the network is not compromised. We provide experimental results that illustrate the effectiveness of our approach in comparison with the original approach of Nettleton et al.

9. **Unifying Learning in Games and Graphical Models**  

Abstract: The ever increasing use of intelligent multi-agent systems poses increasing demands upon them. One of these is the ability to reason consistently under uncertainty. This, in turn, is the dominant characteristic of probabilistic learning in graphical models which, however, lack a natural decentralised formulation. The ideal would, therefore, be a unifying framework which is able to combine the strengths of both multi-agent and probabilistic inference.

In this paper we present a unified interpretation of the inference mechanisms in games and graphical models. In particular, we view fictitious play as a method of optimising the Kullback-Leibler distance between current mixed strategies and optimal mixed strategies at Nash equilibrium. In reverse, probabilistic inference in the variational mean-field framework can be viewed as fictitious game play to learn the best strategies which explain a probabilistic graphical model.

10. **Optimal Design Of English Auctions With Discrete Bid Levels**  
E. David, A. Rogers, J. Schiff, S. Kraus, and N.R. Jennings  
Abstract: In this paper we consider a common form of the English auction that is widely used in online Internet auctions. This discrete bid auction requires that the bidders may only submit bids which meet some predetermined discrete bid levels and, thus, there exists a minimal increment with which a bidder may raise the current price. In contrast, the academic literature of optimal auction design deals almost solely with continuous bid auctions, and, as a result, there is little practical guidance as to how an auctioneer, who is seeking to maximise his revenue, should determine the number and value of these discrete bid levels. Consequently, in current online auctions, a fixed bid increment is commonly implemented, despite this having been shown to be optimal in only limited cases.

Given this background, in this paper, our aim is to provide the optimal auction design for an English auction with discrete bid levels. To this end, we derive an expression that relates the expected revenue of the auction, to the actual discrete bid levels implemented, the number of bidders participating, and the distribution from which the bidders draw their private independent valuations. We use this expression to derive numerical and analytical solutions for the optimal bid levels in the general case. To compare these results with previous work, we apply these solutions to an example, where bidders’ valuations are drawn from a uniform distribution. In this case, we prove that when there are more than two bidders, a decreasing bid increment is optimal and we show that the optimal reserve price of the auction increases as the number of bidders increases. Finally, we compare the properties of an auction in which optimal bid levels are used, to the standard auction approach which implements a fixed bid increment. In so doing, we show that the optimal bid levels result in improvements in the revenue, duration and allocative efficiency of the auction.

11. *Constrained Bandwidth Allocation in Multi-Sensor Information Fusion: A Mechanism Design Approach*

Abstract: Sensor networks are increasingly seen as a solution for a large number of environmental, security and military monitoring tasks. Typically, in these networks, noisy data from a number of local sensors is fused to reduce the uncertainty in the global picture. A central issue in this information fusion is the decision of what data should be shared between sensors, in order to maximise the global gain in information, when the bandwidth of the communication network is limited. In this paper, we study the problem from a selfish agent perspective. We show how the uncertainty in the measurement of an event can be cast as a utility function derived from the Kalman filter. We then use the tools of mechanism design to engineer an incentive-compatible mechanism that allows rational selfish agents to individually maximise their own utility, whilst ensuring that the overall utility of the system is also maximised. We apply the mechanism to multi-sensor target detection and consider the complexity of finding an efficient solution with broadcast communication protocols.

12. *Self-Organized Routing For Wireless Micro-Sensor Networks*
   A. Rogers, E. David, and N.R. Jennings
Abstract: In this paper we develop an energy-aware self-organized routing algorithm for the networking of simple battery-powered wireless micro-sensors (as found, for example, in security or environmental monitoring applications). In these networks, the battery life of individual sensors is typically limited by the power required to transmit their data to a receiver or sink. Thus effective network routing algorithms allow us to reduce this power and extend both the lifetime and the coverage of the sensor network as a whole. However, implementing such routing algorithms with a centralized controller is undesirable due to the physical distribution of the sensors, their limited localization ability and the dynamic nature of such networks (given that sensors may fail, move or be added at any time and the communication links between sensors are subject to noise and interference). Against this background, we present a distributed mechanism that enables individual sensors to follow locally selfish strategies, which, in turn, result in the self-organization of a routing network with desirable global properties. We show that our mechanism performs close to the optimal solution (as computed by a centralized optimizer), it deals adaptively with changing sensor numbers and topology, and it extends the useful life of the network by a factor of three over the traditional approach.

13. A Unified Framework for Game Theoretic and Probabilistic Learning - Playing Bayesian Games
   I. Rezek
   ARGUS-II Workshop, 5 January 2005.

14. Learning Environmental Parameters For The Design Of Optimal English Auctions With Discrete Bid Levels
   A. Rogers, E. David, J. Schiff, S. Kraus, and N.R. Jennings

Abstract: In this paper we consider the optimal design of English auctions with discrete bid levels. Such auctions are widely used in online internet settings and our aim is to automate their configuration in order that they generate the maximum revenue for the auctioneer. Specifically, we address the problem of estimating the values of the parameters necessary to perform this optimal auction design by observing the bidding in previous auctions. To this end, we derive a general expression that relates the expected revenue of the auction when discrete bid levels are implemented, but the number of participating bidders is unknown. We then use this result to show that the characteristics of these optimal bid levels are highly dependent on the expected number of bidders and on their valuation distribution. Finally, we derive and demonstrate an online algorithm based on Bayesian machine learning that allows these unknown parameters to be estimated through observations of the closing price of previous auctions. We show experimentally that this algorithm converges rapidly toward the true parameter values and, in comparison with an auction using the more commonly implemented fixed bid increment, results in an increase in auction revenue.

15. Game Theory, Graphical Models and Probabilistic Inference
   I. Rezek, A. Rogers, and D.H. Wolpert
16. **Overlapping Coalition Formation for Efficient Data Fusion in Multi-Sensor Networks**  
V.D. Dang, R.K. Dash, A. Rogers, and N.R. Jennings  

Abstract: This paper develops new algorithms for coalition formation within multi-sensor networks tasked with performing wide-area surveillance. Specifically, we cast this application as an instance of coalition formation, with overlapping coalitions. We show that within this application area sub-additive coalition valuations are typical, and we thus use this structural property of the problem to derive two novel algorithms (an approximate greedy one that operates in polynomial time and has a calculated bound to the optimum, and an optimal branch-and-bound one) to find the optimal coalition structure in this instance. We empirically evaluate the performance of these algorithms within a generic model of a multi-sensor network performing wide area surveillance. These results show that the polynomial algorithm typically generated solutions much closer to the optimal than the theoretical bound, and prove the effectiveness of our pruning procedure.

17. **Coalition Structure Generation in Task-Based Settings**  
V.D. Dang and N.R. Jennings  

Abstract: The coalition formation process, in which a number of independent, autonomous agents come together to act as a collective, is an important form of interaction in multi-agent systems. However, one of the main problems that hinders the wide spread adoption of coalition formation technologies is the computational complexity of coalition structure generation. That is, once a group of agents has been identified, how can it be partitioned in order to maximise the social payoff? To date, most work on this problem has concentrated on simple characteristic function games. However, this lacks the notion of tasks which makes it more difficult to apply it in many applications. Against this background, this paper studies coalition structure generation in a general task-based setting. Specifically, we show that this problem is NP-hard and that the minimum number of coalition structures that need to be searched through in order to establish a solution within a bound from the optimal is exponential to the number of agents. We then go onto develop an anytime algorithm that can establish a solution within a bound from the optimal with a minimal search and can reduce the bound further if time permits.

18. **Computational Mechanism Design for Information Fusion within Sensor Networks**  

Abstract: Conventional centralised information fusion and control architectures will be challenged by developments in sensor networks that allow sophisticated autonomous sensors, owned by different stakeholders with individual goals, to interact and share information. Given this, we advocate the use of tools and techniques from computational mechanism design (CMD), a field at the intersection of computer science, game theory and economics, to address the challenges posed by these networks. In particular, CMD allows us to engineer networks with
desirable system-wide properties, in which sensors act as rational selfish agents, each attempting to fulfill their own individuals goals through the exchange of observations and information. In this paper, we present our work developing such networks. Specifically, we discuss our development of a generic and principled information valuation metric for sensor networks and we report our experiences applying it within a real world information fusion sensor network scenario.

19. Learning Environmental Parameters For The Design Of Optimal English Auctions With Discrete Bid Levels
A. Rogers, E. David, J. Schiff, S. Kraus, and N.R. Jennings

Abstract: In this paper we consider the optimal design of English auctions with discrete bid levels. Such auctions are widely used in online internet settings and our aim is to automate their configuration in order that they generate the maximum revenue for the auctioneer. Specifically, we address the problem of estimating the values of the parameters necessary to perform this optimal auction design by observing the bidding in previous auctions. To this end, we derive a general expression that relates the expected revenue of the auction when discrete bid levels are implemented, but the number of participating bidders is unknown. We then use this result to show that the characteristics of these optimal bid levels are highly dependent on the expected number of bidders and on their valuation distribution. Finally, we derive and demonstrate an online algorithm based on Bayesian machine learning, that allows these unknown parameters to be estimated through observations of the closing price of previous auctions. We show experimentally that this algorithm converges rapidly toward the true parameter values and, in comparison with an auction using the more commonly implemented fixed bid increment, results in an increase in auction revenue.

20. Computational Mechanism Design for Multi-Sensor Information Fusion

Abstract: See #17.

R.K. Dash, P. Vytelingum, A. Rogers, E. David, and N.R. Jennings

Abstract: This paper reports on the design of economically inspired mechanisms for task allocation in complex, multi-party environments. In particular, we consider environments in which sellers have finite production capacities and a cost structure composed of a fixed overhead cost and a constant marginal cost. These conditions are common in many applications including job-shop scheduling, grid computing applications, sensor networks and electricity markets. Specifically, we cast the problem as a multi-agent system consisting of selfish, rational agents and view the interactions as being organised through a computational economy. Against this background, we first develop a centralised mechanism that finds the set of producers that have the
lowest total cost in providing a certain demand. We achieve this by extending the standard Vickrey-Clarke-Groves mechanism to allow for multi-attribute bids (to fully characterise the cost structure) and by introducing a novel penalty scheme. Our extended mechanism ensures that producers do not misreport their capacities and/or their costs (i.e. it is strategy-proof), produces the cheapest allocation (i.e. it is efficient), and ensures that individual agents find that it is in their best interest to participate in the mechanism (i.e. it is individually rational). Furthermore our mechanism is able to handle sellers’ uncertainty about their production capacity and is computationally efficient (the allocation of production can be computed in pseudo-polynomial time using a dynamic programming algorithm). However, a potential drawback of our mechanism is that it is centralised. Thus for cases where robustness (i.e. the system still performs even when certain nodes fail) and scalability are more important than efficiency, we develop a complementary decentralised mechanism based around the continuous double auction. Again because of the characteristics of our domain, we need to extend the standard form of this protocol. Specifically, we present a novel format based around an order book (a publicly observable billboard on which offers to buy and sell are queued). With this modified protocol, we achieve high efficiency despite the fact that an efficient equilibrium price is not guaranteed to exist (because of the seller’s cost structure). This result is shown through empirical evaluation of our modified protocol using basic buying and selling strategies. In particular, we observe that despite this simplicity, the traders can still derive a profit from the market which makes our mechanism attractive since these results can be viewed as a likely lower bound on their expected returns.

22. The Effects of Proxy Bidding and Minimum Bid Increments within eBay Auctions
A. Rogers, E. David, J. Schiff and N. R. Jennings
ACM Transactions on the Web 1 (2) article number 9 (28 pages).

Abstract: We present a mathematical model of the eBay auction protocol and perform a detailed analysis of the effects that the eBay proxy bidding system and the minimum bid increment have on the auction properties. We first consider the revenue of the auction, and we show analytically that when two bidders with independent private valuations use the eBay proxy bidding system there exists an optimal value for the minimum bid increment at which the auctioneer’s revenue is maximized. We then consider the sequential way in which bids are placed within the auction, and we show analytically that independent of assumptions regarding the bidders’ valuation distribution or bidding strategy the number of visible bids placed is related to the logarithm of the number of potential bidders. Thus, in many cases, it is only a minority of the potential bidders that are able to submit bids and are visible in the auction bid history (despite the fact that the other hidden bidders are still effectively competing for the item). Furthermore, we show through simulation that the minimum bid increment also introduces an inefficiency to the auction, whereby a bidder who enters the auction late may find that its valuation is insufficient to allow them to advance the current bid by the minimum bid increment despite them actually having the highest valuation for the item. Finally, we use these results to consider appropriate strategies for bidders within real world eBay auctions. We show that while last-minute bidding (sniping) is an effective strategy against bidders engaging in incremental bidding (and against those with common values), in general, delaying bidding is disadvantageous even if delayed bids are sure to be received before the auction closes. Thus, when several bidders submit last-minute bids, we show that rather than seeking to bid as late as possible, a bidder should try to be the first sniper to bid (i.e., it should “snipe before the snipers”).
23. **Optimal Design Of English Auctions With Discrete Bid Levels**  
   E. David, A. Rogers, J. Schiff, S. Kraus, M.H. Rothkopf, and N.R. Jennings  
   ACM Transactions of Internet Technology 7 (2), article 12 (34 pages).

Abstract: This article considers a canonical auction protocol that forms the basis of nearly all current online auctions. Such discrete bid auctions require that the bidders submit bids at predetermined discrete bid levels, and thus, there exists a minimal increment by which the bid price may be raised. In contrast, the academic literature of optimal auction design deals almost solely with continuous bid auctions. As a result, there is little practical guidance as to how an auctioneer, seeking to maximize its revenue, should determine the number and value of these discrete bid levels, and it is this omission that is addressed here. To this end, a model of an ascending price English auction with discrete bid levels is considered. An expression for the expected revenue of this auction is derived and used to determine numerical and analytical solutions for the optimal bid levels in the case of uniform and exponential bidder’s valuation distributions. Finally, in order to develop an intuitive understanding of how these optimal bid levels are distributed, the limiting case where the number of discrete bid levels is large is considered, and an analytical expression for their distribution is derived.

24. **A Multi-Agent Simulation System for Prediction and Scheduling of Aero Engine Overhaul**  
   A. Stranjak, P. S. Dutta, M. Ebden, A. Rogers, and P. Vytelingum  

Abstract: The Aero Repair and Overhaul industry is facing an increasing challenge of prediction and scheduling of engine over- hauls to remain competitive in a complex business arena. An appropriate technology solution is required to achieve efficient schedules while satisfying multiple opposing constraints in a highly dynamic environment. In this paper, we describe *Overhaul Prediction and Scheduling*, an agent- based simulator developed to tackle this challenge. Using negotiation strategies, it deals with the multi-dimensional scheduling optimisation problem by trading off repair costs, capacity and capability of overhaul bases, among others, in light of in-service unforeseen events. It supports effective strategic decision-making via business scenario modelling.

25. **Decentralised Coordination of Low-Power Embedded Devices Using the Max-Sum Algorithm**  
   A. Farinelli, A. Rogers, A. Petcu, and N. Jennings  

Abstract: This paper considers the problem of performing decentralised coordination of low-power embedded devices (as is required within many environmental sensing and surveillance applications). Specifically, we address the generic problem of maximising social welfare within a group of interacting agents. We propose a novel representation of the problem, as a cyclic bipartite factor graph, composed of variable and function nodes (representing the agents’ states and utilities respectively). We show that such representation allows us to use an extension of the max-sum algorithm to generate approximate solutions to this global optimisation problem.
through local decentralised message passing. We empirically evaluate this approach on a canonical coordination problem (graph colouring), and benchmark it against state of the art approximate and complete algorithms (DSA and DPOP). We show that our approach is robust to lossy communication, that it generates solutions closer to those of DPOP than DSA is able to, and that it does so with a communication cost (in terms of total messages size) that scales very well with the number of agents in the system (compared to the exponential increase of DPOP). Finally, we describe a hardware implementation of our algorithm operating on low-power Chipcon CC2431 System-on-Chip sensor nodes.


27. Dynamic Coalition Formation in Sensor Allocation
    M. Ebden, M. Briers, and S. Roberts

Abstract: We present a method of dynamic coalition formation (DCF) in sensor networks to achieve well-informed sensor-target allocations. Forecasts of target movements are incorporated when choosing sensor states, as is a memory of target observation. The algorithm can be run in a centralized or decentralized configuration; the latter relies on local message passing in the form of the max-sum algorithm. We show how the DCF algorithm has been applied to synthetic and real data.

28. A Mixed Weibull Distribution with Confidence Intervals from Variously Censored Data
    M. Ebden, A. Stranjak, and S. Roberts
    Submitted to: Annals of Statistics.

Abstract: We construct a mixed Weibull distribution from a large data set subject to censoring at various times, rather than simultaneously. Confidence intervals are derived and are mapped visually onto the functions of use in reliability theory, such as the hazard function and survival function. We demonstrate the use of the method on a real database of disruption times for jet-engine components. Although it is of immediate interest in failure analysis, the method is easily extensible to other mixture-model settings.