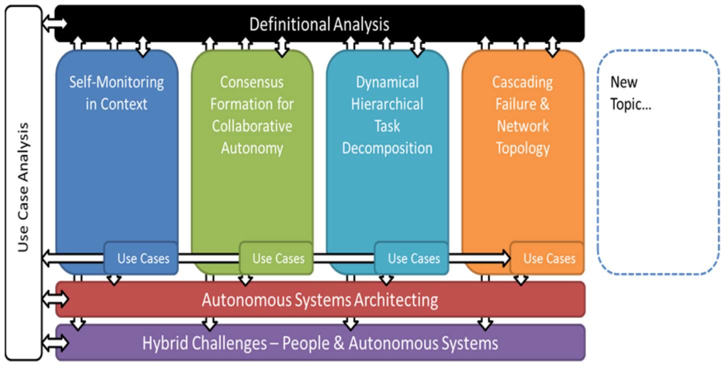
T-B PHASE: Thales-Bristol Partnership in Hybrid Autonomous Systems Engineering Year 1 highlights

Why T-B PHASE?

Hybrid autonomous systems are those where groups of **people** are in direct, ongoing interaction with groups of **autonomous robots** or **autonomous software**. Emerging technologies in **robotics**, Artificial Intelligence (**AI**) and Information and Communications Technology (**ICT**) mean that hybrid autonomous systems of this kind will become increasingly common in a wide set of situations, and **smooth, reliable, safe interaction** amongst machines and people will be key to success. As we enter this new design space, a crucial challenge for the **engineers** of hybrid autonomous systems is ensuring that the system behaviour is Robust and Resilient and that it meets Regulatory demands: **the R3 Challenge**.

The **Thales-Bristol Partnership in Hybrid Autonomous Systems Engineering (T-B PHASE)** directly addresses this R3 Challenge by bringing together expertise in robotics, AI, and systems engineering at the **University of Bristol** and **Thales**, in a five-year project that targets fundamental autonomous system design problems in the context of three **real-world Thales use cases**: Hybrid Low-Level Flight, Hybrid Rail Systems, and Hybrid Search & Rescue.

T-B PHASE priority research areas:



Ways of working

T-B PHASE brings together academic researchers from the University of Bristol with Technical Experts from Thales, who work collaboratively in shared office space at the University. Research plans have been scoped and developed collaboratively, and the relevance to Thales Use Cases is reviewed regularly. The workplans are further refined via stakeholder workshops and through ongoing engagement with Thales stakeholders throughout the year.

Objectives

- Address the Hybrid Autonomous Systems Engineering 'R3 Challenge': Robustness, Resilience, and Regulation
- Innovate new design principles and processes
- Build new tools for analysis and design for application in complex system
- Develop new life-course monitoring approaches to identify cascading failure in hybrid autonomous systems
- Train and develop future systems engineers and researchers
- Engage with real Thales use cases in Hybrid Low-Level Flight, Hybrid Rail Systems, and Hybrid Search & Rescue
- Engage stakeholders within Thales and beyond

Team

Seth Bullock (Academic Principal Investigator)
Angus Johnson (Thales Principal Investigator)
Jonathan Lawry, **Arthur Richards**, **Eddie Wilson** (Bristol Co-Investigators)
Katie Drury (T-B PHASE Project Manager)
David Harvey, **Ben Rayneau-Kirkhope** (Thales Research Technology and Innovation)
Michael Crosscombe, **Tom Kent, Lenka Pitonakova** (Postdoctoral Researchers)
Chris Bennett, **Charles Clarke**, **William Bonnell**, **Elliott Hogg** (T-B PHASE PhD students)

Expected Impact

- Design approaches and techniques for successfully deploying and monitoring hybrid systems
- Insights into the Academic approach to the R3 challenges - questioning more conventional approaches
- Wider technical peer audience for Thales: both ideas, discussion and review
- Applications to complex challenges ("Use Cases") and insights into the way that Industry can adopt research outputs
- Identification of what works with respect to Technical / Integration Maturity and rate of adoption.

Year 1 research summary

Autonomous Self-Monitoring and Context Learning (Dr Lenka Pitonakova)

Problem Statement

Systems that are expected to operate with minimal human supervision over long time scales may need to anticipate, detect and deal with situations that have not been considered at design stage. Examples include autonomous transport systems that need to identify unusual traffic density, autonomous unmanned vehicles that need to anticipate unfavourable environmental conditions, or hybrid systems that are sensitive to changes within their own structure. Self-monitoring could increase a system's resilience by minimising the impact of failures and facilitate assurance by increasing confidence of users and regulators.

Research progress

- Publications including a paper submitted to the ICRA 2019 conference; two blogs posts and a research summary video (see *Publications* list). A draft abstract for a journal paper on Time Series Monitoring is planned for submission in May 2019
- Improved simulation code with multi-time-scale world dynamics, where occurrence of subsequent events can be scripted by the simulation user in order to create environments that are more realistic compared to those explored previously
- Improved GWRNN implementation code with scripted parameters and operation mode options. Location data added as an additional modality that the network can monitor
- Improved data analysis code for dealing with multi-time-scale events. Added performance meta-metrics such as Class Generalisation Index, number of encounters needed to learn an object, etc
- A working document that details the effect of various parameters and network operation modes on the ability of the network to report and learn multiple objects that appear in succession
- Preliminary literature review commenced for time series monitoring research strand

Consensus Formation for Collaborative Autonomy (Dr Michael Crosscombe)

Problem Statement

While autonomous systems are not yet capable of performing human-level decision-making, they are capable of making decisions quickly and rationally, utilising information drawn from the full array of capabilities at their disposal. Increasingly, these systems are no longer deployed in isolation, and instead exist as parts of hybrid teams composed of humans and other (possibly heterogeneous) systems with redundant or complementary capabilities which form parts of the same system. How individual systems process, combine, and disseminate information is a fundamental part of a system's overall dynamics, determining how well the system can perform in a given scenario or environment.

Research progress

- Development of multi-agent models to study different belief-revision operators which allow agents to revise their beliefs with both evidence from their environments, and with the beliefs of other agents
- Preliminary work studying the robustness properties of the operators modelled above
- Early experimentation with modified operators that allow us to control the extent to which agents become certain of their beliefs and identify how they change their minds when presented with new, conflicting information, such as when the environment changes
- Explainable Autonomous Systems – Partial literature review for Explainable AI (XAI)

Dynamical Hierarchical Task Decomposition and Planning for Heterogeneous Systems (Dr Tom Kent)

Problem Statement:

The systems architecture used to define structure, hierarchy and overall behaviour of a system is important to a wide range of areas affecting the Thales Use Cases. Many real-world decision-making problems appear large and complex but often can be broken down into smaller, more manageable, subproblems. Can a kind of systems architecture approach be utilised within decision making problems to decompose complex problems and in turn allow for defining and reasoning about things such as authority and behaviour? While the proposed research aims to be comprised of several research strands, there is an overarching aim to explore the nature of hierarchy and how it can be leveraged to solve complex decision-making problems – with a current focus towards aspects of assignment, allocation and routing problems.

Research progress:

- Research on the existing work on Hierarchical Decomposition for Optimisation (optimisation, tasking, routing and allocation) and applicability to the problems and problem sizes of interest
- Preliminary implementation of the use of Evolutionary algorithms (EA) to solve problems of allocation and routing
- Implementation of a multi-demic evolutionary algorithm for solving multi-Agent-Travelling Salesman Problem, where a deme is a smaller sub-population, is a move towards more-decentralised decision making
- Submission of preliminary work the 2019 International Conference on Autonomous Agents and Multiagent Systems. The results of this paper explore the impact of problem sizes (number of agents and number of tasks) along the effects that different levels of communication restrictions have on the decentralised decision making

Year 1 research summary

Cascading Failure and Network Topology (Ben Rayneau-Kirkhope)

Problem Statement

The modern world is built upon large-scale complex networks, including power distribution networks, the internet and large communication and transportation network; many of which are core to Thales' business. Furthermore, due to an increase in autonomy, a number of Thales' systems not typically considered in this field are becoming more interconnected and therefore more applicable to this research topic. This research focusses on two main topics: (i) Cascading failure – the way in which the failure of a single node can cause a more widespread, system level, failure and (2) Optimisation of networks – understanding the impact of certain network topologies and investigating ways of optimising behaviours to best suit a topology.

Research progress

- Augmented Graph Theory toolkit in MATLAB
- Built faster, bespoke toolkit in Python for network analysis and cascading failure
- Tool to investigate cascading failure on single and multi-layer networks
- Technical report on target attack on random and spatially dependent multi-layered networks
- Technical report on Networks and Topologies in progress
- Darwin network extraction and representation toolkit
- Working on spring-relaxation model to place Time In Point Location without associated latitude and longitude
- Implemented Hapcroft-Karp algorithm
- High level minimum fleet optimisation of over 1000 services
- Skeleton ABM model of rail network taken from previous Background IP and adapted and improved

Autonomous Systems Architecture (Validation and Verification) (David Harvey)

Problem Statement

One of the principal barriers to the successful adoption and deployment of autonomous systems is the absence of scalable, reliable and credible techniques to ensure their Verification and Validation, and subsequent certification. The T-B PHASE research on this topic to date has mostly focussed on verification with the expectation that validation will be considered in more detail later in the programme. The behaviour of an autonomous system will be specified by algorithms that will be implemented in software. The verification challenge could therefore largely be considered as a software verification problem. In this context, however, the key differentiator between an autonomous system and a conventional rule-based system is the autonomous system's capacity to 'learn', and hence update and reconfigure its behaviours. This property leads to a potentially enormous state space. Colloquially, this is commonly referred to as 'state space explosion'. The implications of this are that verifying such a system becomes difficult since any methods which are used need to be highly scalable to allow a credible portion of the state space to be considered.

Research progress

- Validation and Verification technical report documenting V&V techniques and the problems that will be experienced in applying these to autonomous systems
- Analysis of Markov Chain Monte Carlo (MCMC) techniques for verification, comparing the effectiveness of a number of approaches including MCMC techniques

Hybrid Challenges

Problem Statement

This work package aims to understand, assess and quantify acceptable limits for autonomous systems to operate in close collaboration with humans by systematically identifying the appropriate limits, nature and level of autonomy. This needs to consider how humans will react to different kinds of autonomous behaviour and how effective and comfortable they will be in scenarios where critical operational decisions are being taken in real-time without the immediate opportunity to vet or override them whilst having operational protocols that ensure safe and effective interactions with humans sharing the same space.

Research progress

- Discussions are underway with Thales and the University's Faculty of Social Sciences and Law to explore both direct and collaborative approaches to this work package
- Recruitment is planned for Year 2 of T-B PHASE

Outputs and activities

Engagement activities (internal)

Thales Group, Systems Key Technology Domain
- Regular review meetings
- Management Meetings

Thales Group, Use Case Domain Experts
- Individual meetings to scope out the Use Cases with the research team

Use Case Workshops
- Two Use Case Workshops have been held, enabling the research team to share insights and co-ordinate approaches to the T-B PHASE Use Cases with Thales domain experts, internal stakeholders and customers
- Outputs: Research workplans for the core T-B PHASE programme and recommendations for future engagement activities (including researcher joint working at Thales sites in Year 2)

T-B PHASE Advisory Group
- Two meetings of the Advisory Group, comprising individuals with experience of large-scale/enterprise level solutions engineering and/or academic research activity relevant to the T-B PHASE aims, and an EPSRC representative
- Outputs: Landscape mapping across robotics, AI, systems engineering, complex systems and complexity science research. Sharing knowledge on ways in which to make the research reach industry effectively

Engagement activities (external)

- Presentation of research to the **Joint Industry & Robotics CDTs Symposium 2018** (Hogg and Bonnell) (June 2018)
- Poster presentation at **19th Towards Autonomous Robotic Systems Conference** (Pitonakova) (July 2018)
- **EPSRC Prosperity Partnership Workshop** (Drury and Johnson) (Sept 2018)
- Presentation of research to the **FARSCOPE Research Symposium** (Hogg and Bonnell) (Sept 2018)
- Poster presented at **INCOSE ASEC 2018** (Bullock and Johnson) (Oct 2018)

Awards

Keynote Speech
- Prof. Seth Bullock presented on **Autonomy and Artificial Life** at the 2018 Conference on Artificial Life in Tokyo, Japan (25/07/2018)

Acknowledgements

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Publications

Bonnell, W., Hauert.S. Richards, A. (2018). Dynamic Traffic Management for Commercial UAVs. Poster presented at Joint Industry & Robotics CDTs Symposium 2018 (JIRCS), 05/06/2018.

Bonnell, W. (2018). Traffic Control for Commercial UAVs. Presented at FARSCOPE Research Symposium, 26/09/2018.

Bonnell, W. (2018). Developing Autonomous Control and Decentralised Routing for Commercial Use UAVs. MSc Thesis.

Bullock, S. (2018). Autonomy and Artificial Life. Presented at 2018 Conference on Artificial Life, Tokyo, Japan, 22/07/2018.

Crosscombe, M. & Lawry, J. (*Submitted*). Evidence Propagation and Consensus Formation in Noisy Environments. Autonomous Agents and Multi Agent Systems (AAMAS) 2019.

Crosscombe, M. (2018). Consensus Formation for Collaborative Autonomy (Research proposal). Internal T-B PHASE report.

Harvey, D. (2018). Survey of the application of systems engineering techniques to autonomous systems. Internal T-B PHASE report.

Harvey, D. (2018). Survey of robustness and resilience engineering techniques. Internal T-B PHASE report.

Harvey, D. (2018). Verification and Validation of Autonomous Systems: An overview. Internal T-B PHASE report.

Harvey, D. (2018). Modifications of systems engineering practices for autonomous systems. Internal T-B PHASE report.

Harvey, D., Johnson, A., Bullock, S. (2018). Definitional Analysis Report. Internal T-B PHASE report.

Hogg, E., Hauert, S., Richards, A. (2018). Investigation of Human Swarm Interaction Under Limited Situational Awareness. Poster presented at Joint Industry & Robotics CDTs Symposium 2018 (JIRCS), 05/06/2018.

Hogg, E., Richards, A., Hauert, S. (2018). Evolving Swarm Control Strategies Under Limited Swarm State Information. Presented at FARSCOPE Research Symposium, 26/09/2018.

Hogg, E., Richards, A., Hauert, S., Jones, S. (2018). Evolving Swarm Control Strategies Under Limited Swarm State Information. MSc Thesis.

Hogg, E. (*Submitted*). Evolution of Behaviour Trees for Supervisory Control of Robot Swarms. Autonomous Agents and Multi Agent Systems (AAMAS) 2019.

Johnson, A. and Bullock, S. (2018). Thales-Bristol Prosperity Partnership jointly funded with the EPSRC. Poster presented at Annual Systems Engineering Conference (ASEC 2018), Cranfield Univ. 20/11/2018.

Johnson, A. & Drury, K. (2018). T-B PHASE Prosperity Partnership. Presented at EPSRC Prosperity Partnership Launch, 25/09/2018.

Kent, T. (*Submitted).* Decentralised Multi-Demic Evolutionary Approach to the Dynamic Multi-Agent Travelling Salesman Problem. Autonomous Agents and Multi Agent Systems (AAMAS) 2019.

Kent, T. (2018). Dynamic Hierarchical Task Decomposition and Planning for Heterogeneous Systems (Research proposal). Internal T-B PHASE report.

Pitonakova, L., Crowder, R., Seth Bullock, S. (2018). Information Exchange Design Patterns for Robot Swarm Foraging and Their Application in Robot Control Algorithms. Frontiers in Robotics and AI, 5(47).

Pitonakova, L., Giuliani, M., Pipe, A., Winfield, A. (2018). Feature and performance comparison of the V-REP, Gazebo and ARGoS robot simulators. Poster presented at 19th Towards Autonomous Robotic Systems Conference (TAROS 2018), 25/07/2018.

Pitonakova, L. & Bullock, S. (*Submitted*). Robustness and Structural Plasticity of Grow-When-Required Neural Networks. 2019 International Conference on Robotics and Automation (ICRA 2019).

Pitonakova, L., Winfield, A., Crowther, R. (2018). Recruitment near worksites facilitates the robustness of foraging e-puck swarms to global positioning noise. Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2018), IEEE.

Pitonakova, L., Crowder, R., Seth Bullock, S. (2018). The Importance of Information Flow Regulation in Preferentially Foraging Robot Swarms. Proceedings of the 11th International Conference on Swarm Intelligence (ANTS 2018), Springer, 277-289.

Pitonakova L (2018). Fast Data Analysis Using C++ and Python. [Blog post] http://lenkaspace.net/code/dataScience/fastDataAnalysisCppPython

Pitonakova L (2018). Novelty Detection with Robots Using the Grow-When-Required Neural Network. [Blog post] http://lenkaspace.net/code/simulationModels/growWhenRequiredNeuralNetwork

Pitonakova, L. (2018). Self-Monitoring in Context (Research proposal). Internal T-B PHASE report.

Potts, M., Sartor, P., Johnson, A., Bullock, S. (*Submitted*). A Network Perspective On Assessing System Architectures: Foundations and Challenges, Wiley Systems Engineering Journal.

Potts, M., Sartor, P., Johnson, A., Bullock, S. (*Submitted*). A Network Perspective On Assessing System Architectures: Robustness and Resilience, IEEE Systems Journal.

Potts, M., Sartor, P., Johnson, A., Bullock, S. (2019). Through a Glass, Darkly? Taking a Network Perspective on System-of-Systems Architectures. In: Bonjour E., Krob D., Palladino L., Stephan F. (eds) Complex Systems Design & Management. CSD&M 2018. Springer, Cham,

Rayneau-Kirkhope, B. (2018). Cascading Failure and Network Topology (Research proposal). Internal T-B PHASE report.

Wisetjindawat, W., Wilson, RE., Bullock, S., Espinosa Mireles De Villafranca, A. (*Accepted*). Modelling the Impact of Spatial Interdependencies in Transport Infrastructure Risk on Travel Times during Adverse Weather Conditions. 98th Transportation Research Board Annual Meeting.