Academic and Industrial Partnerships in the Research and Development of Hybrid Autonomous Systems: Challenges, Tools and Methods

Emma Barden[1(✉)], Michael Crosscombe[2], Kevin Galvin[1], Chris Harding[1], Angus Johnson[1], Tom Kent[2], Ben Pritchard[1], Arthur Richards[2], and Debora Zanatto[2]

[1] Thales Research, Technology & Innovation (RTI), Reading, RG2 6GF Palaiseau, France
emma.barden@uk.thalesgroup.com

[2] Faculty of Engineering, University of Bristol, Bristol BS8 1UB, UK

Abstract. Autonomous systems increasingly are integrated into larger, connected, and hybrid (Human-Machine) systems of systems, making them complex systems - which are hard to design and predicting emergent behaviour is difficult. These issues are faced increasingly across civil and military applications, both in the UK and NATO. A holistic approach is needed to fully quantify them. Working as a partnership between industry and academia has provided greater freedom to apply innovative technologies in the context of relevant use cases. This paper presents some tools and methods we have used in our research and development to support this approach and address the challenges of deploying autonomous systems in the future. We discuss the use of simulations and how they can support every step of the process, from academic experiments to digital twins; where the right level of fidelity is needed at different times to give maximum benefit. The use of a common simulation platform to align control design exploration with human factors research is discussed, enabling questions of human-machine teaming and trust. We highlight how foundational research on: architecture and modelling, network topology, decision making processes and human interactions impact on the overall development of a system. Included are our lessons identified from this partnership.

Keywords: Autonomous systems · Simulation · Human-machine team · Mission planning · Collaboration

1 Introduction

Thales, a global engineering company, has a worked closely with UK academia in research through collaborative projects, as part of a consortium, in a bi-lateral arrangement, or through sponsorship of PhD and EngD projects in emerging technologies. As the company's interest in Autonomy, Artificial Intelligence (AI) and Machine Learning (ML) has increased over the last decade, a number of initiatives between Thales

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and academia have been established. In the United Kingdom, two of these are with the universities of Bristol and Southampton, leading academic institutions in the fields of Autonomy, AI and ML. Although this paper will focus on the relationship with the University of Bristol (UoB) it will highlight where there is a crossover with some of the research with Southampton and other academic consortia that is being leveraged.

In 2017 Thales and UoB signed a Strategic Agreement and entered into a five year Engineering & Physical Sciences Research Council (EPSRC) Prosperity Partnership, a jointly funded project called the Thales – Bristol Partnership in Hybrid Autonomous Systems Engineering (T-B PHASE). We use "hybrid" in this context to include autonomous interaction with the ""open" (i.e. unlimited, uncontrolled, not lab) environment as well as with human interaction. Key objectives of this project are:

- To innovate new design principles and processes that integrate over the system life-cycle.
- To build new analysis and design tools that enable a complex system's interactions to be mapped, understood and bounded at design concept stage.
- To develop new whole-life-course monitoring approaches.
- To train/develop people with the skills required for leadership in systems engineering.
- To engage with live Thales use cases in Hybrid Low-Level Flight, Hybrid Rail Systems, and Hybrid Search & Rescue (SAR).
- To implement a programme of impact and integration activities that engage stakeholders, policy makers and the public.

In pursuit of these objectives, the programme has assembled a team of researchers from. Both UoB and Thales, and is carrying out a suite of component projects investigating both foundational topics and integrating questions including literature reviews and analysis of previous research programmes e.g. UK System Engineering and Integrated Systems for Defense and Semi-Autonomous Vehicles Defense Technology Centre (SEAS DTC). The remainder of the paper reports on the findings from foundational work as well as the tools and methods being applied to integrate them.

2 Autonomous Systems Foundational Research

Through academic links we have been able to grow several areas of foundational research. More specifically these are in the areas of architecture and modelling, network connectivity, tasking and Sense of Agency. Also we have a number of PhD candidates who are conducting research into relevant, albeit distinct, self-contained activities. This paper focuses on major postdoc-led work streams and additional projects and PhD studies are omitted for brevity, but can be found on the T-B Phase website [16]. These all involve the use of modelling and simulation and are now integrating aspects of their research into collaborative projects with the rest of the team.

This research has been mainly conducted in an academic setting, enabled by the partnership and with industrial inputs where needed.

2.1 Architecture and Modelling

Architecture and modelling is a key enabler to understanding both the functional and non-functional aspects of any system. It is essential that these are identified for hybrid autonomous systems so that they are then carried through to the design and realisation of those systems and support verification and validation. An architecture itself comprises of several artefacts that cover the conceptual, service, logical and physical specifications that are articulated in the form of a set of models. Use cases are key starting points and can be derived through several methods which include the development of ontology and associated taxonomies, in T-B PHASE the use cases selected are of particular interest to Thales (e.g. SAR).

Architecture frameworks provide a formalised approach to capture and query the architecture of a system. The NATO Mission Threads Methodology provides a mechanism for developing a Mission Thread and utilises the NATO Architecture Framework Version 4 (NAFv4) [1]. This methodology has been used in conjunction with the Simulation Interoperability Standards Organization (SISO) Guide to Scenario Development (GSD) published in 2018 [2].

One of the challenges, however, remains how Non-Functional Requirements are architected. These include importantly; Security, Safety and Human Factors and well as the '–illities' such as reliability, maintainability, interoperability, etc. This became an initial focus of the architecture research on the project as well as working to develop a framework using a use case based on SAR and how autonomous systems could be exploited.

2.2 Network Topology

For any autonomous system composed of two or more interacting agents, an implicit network (communications) topology can be identified which expresses the ability for pairs of agents to interact with one another. This network may be 'logical', defining which agents are allowed to interact, or the network may be 'physical' as determined by a combination of factors of the autonomous system, e.g. by the relative distance between the pair of agents and their respective communication radii. Many autonomous systems are also designed implicitly as a result of the formation of the system as required by its task.

In Fig. 1, we illustrate different network topologies that were studied in the context of a multi-agent system applied to the problem of consensus formation. This is a distributed problem whereby the system must reach a consensus about the state of its environment, i.e., given a set of propositions which describe features of the environment, which propositions are true/false?

Through simulation experiments we have demonstrated that overly constrained network topologies, such as the star topology, exhibit bottlenecks on the communication of the agents which cannot be overcome using traditional representations of the agents' beliefs. Such topologies are likely to occur in systems that are organised according to a command hierarchy, and so special considerations are needed. More generally, the results of our studies showed that total connectivity has a negative impact on the convergence dynamics of the agents during the consensus formation process. More accurate

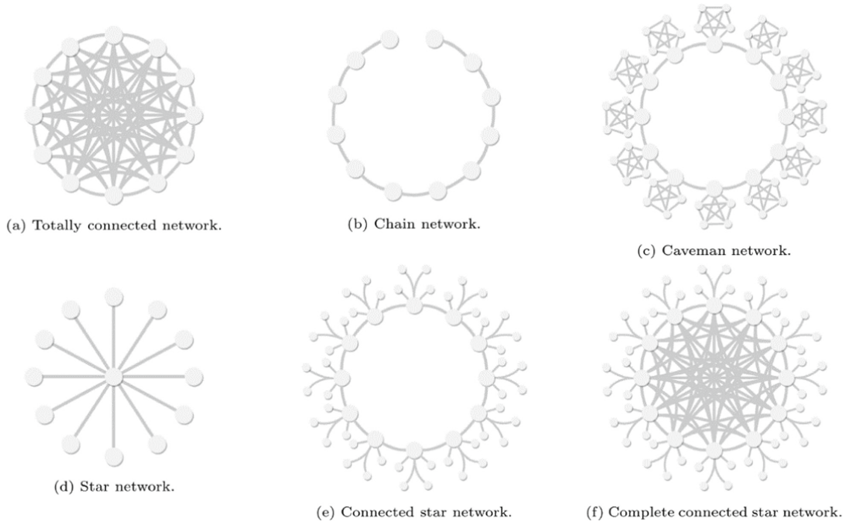


Fig. 1. Illustrations of various logical network topologies

learning of their environment is achievable with reduced levels of connectivity far below that of a totally connected network, even when the network is not especially structured but instead generated at random [3].

2.3 Decision Making

The term 'decision making' encompasses a rich and complex area of academic research. Widely used in game theory [4], economics [5], operational research [6], robotics and autonomous systems [7], it essentially asks: given our current understanding of the world, what should we do? Typically, this arises as an optimisation problem: given a number of input variables (i.e. sensor data, communications values, state information) how can we decide our control variables (i.e. direction to move, set a switch on/off, number and types of stocks to buy) in order to maximise our output (i.e. money, reward function, local/global utility function)?

When these decision-making processes are deployed in an 'autonomous' setting then the decision making is crucial to ensure that these decisions are executed in a timely, appropriate and safe manner. This often acts as a catch-all for making the system (whether vehicles, controllers, algorithms) 'do the right thing'. This can become increasingly complex when these systems contain multiple, cooperating/competing, and/or a mix of human or machine actors. When designing the decision-making system, it is therefore important to simulate, test and verify the impact that different choices have on the performance of the system; this includes ideas of resilience and robustness whilst trying to mitigate any undesirable emergent properties of the system. This has been one of the motivating factors in using our own simulation software outlined in Sect. 3.3, where a scenario containing Uncrewed Aerial Vehicles (UAVs) searching for tasks in the environment is presented. When a UAV "agent" finds a task, it adds it to its list and, using the locations of those tasks, decides on a route to take to best complete the tasks (visit them). The project investigates to what extent efficiencies of collaboration can be achieved only through emergence from distributed behaviour, without explicitly commanding allocations of agents to objects. For example, agents may share tasks they have seen with others in the hope that it improves overall performance. However, without proper collaboration agents, more agents knowing about the same tasks will result in competition for those tasks, producing inefficient behaviour.

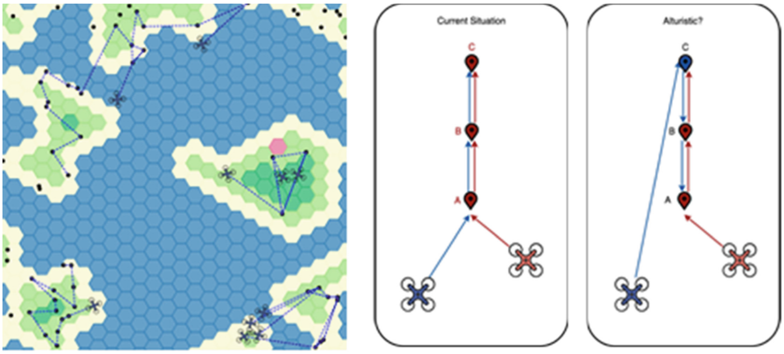


Fig. 2. TB-PHASE simulator (left) for tasking and routing for multiple agents. UAVs search an area for tasks (black dots) and optimally route (dashed lines) between them to complete all as quickly as possible. Using agent-intent modelling (right) we aim to remove potential conflicts.

If agents are able to share their locations with others, then agents can use that to predict intent and provide ways of being proactive. Figure 2(right) demonstrates this idea, where the blue agent sees that the other agent is closer to a task than it is. It predicts (but does not know) that the other agent might go for a task next, and so, instead of risking competition, it instead decides to reverse its route avoiding any potential conflict.

2.4 Human-Machine Interface and a Sense of Agency

The sense of control in psychology is referred to as the Sense of Agency. The Sense of Agency can be defined as one's prediction and perception of the effect of one's actions [8]. More specifically, it is "the subjective awareness of initiating, executing, and controlling one's actions in the world" [9].

In practical terms, the Sense of Agency (and control) arises when the human decides an action, causes a reaction and is aware of the consequence of the action. Considering Sense of Agency as one of the behaviour fundamentals, and investigating its role in the Human-Machine Interface (HMI), could in turn answer the specific issues that the HMI field is facing. Overall, investigations into the Sense of Agency and control perception have not made significant progress. No research on the role of both automation and workload on the Sense of Agency has been found; too little automation and the benefits of using the system may not be realised; too much, and the human supervisor may fail when malfunctions occur. Therefore, what constitutes a good 'level' of automation and workload that still means we feel in control? In considering the level of autonomy of the system, and the amount of workload, one would hypothesise the existence of an 'optimal situation' in which the user's sense of control is at its best. This would probably be at a middle stage of both machine autonomy and workload. Beyond that stage, and perhaps even before, control perception might decrease.

Results have shown that automation and mental workload are interconnected in playing a key role in influencing the Sense of Agency [10]. Both automation and mental workload have a degrading effect on the user's Sense of Agency. More importantly, results showed the presence of a residual Sense of Agency for the hybrid condition (namely the system warning). A combination of warning from the computer and low workload can keep the user in control and improve Sense of Agency. This has important implications for the design of future systems, for which mental workload should be cautiously balanced.

The present research demonstrates the possibility of integrating individual and machine actions while maintaining the individual's Sense of Agency.

3 Tools and Methods: Use of Simulation

The research strands discussed on Sect. 2 are united by their dependence on numerical simulation, not just for their scientific studies but for their connection to the motivating use cases. Meeting the needs of these diverse investigations demands an innovative approach to simulation. Moreover, in the light of the digital transformation, a simulation is not just a research tool but an engineering asset to accompany a system through its lifetime. For these reasons, simulation and visualization are cross-cutting activities of pivotal importance to T-B PHASE.

These kinds of tools can be used very differently between industrial and academic settings. The approach and availability will vary with factors such as the size of the project, stage of development, cost of software and equipment and the experience of users. This can make sharing information and recreating work between partners difficult.

3.1 Fidelity

As computing power and data storage improve dramatically there is a natural desire to take advantage of all the methods available, leading to simulation capabilities with more realism than ever before.

High fidelity simulations offer a great new opportunity to reduce the reliance on physical testing. However, this has associated risks; a great deal of investment of time and effort is needed to represent the systems within the simulation and this leads to large dependencies on accurate models of sensors, platforms, and the environment at a stage when that may not be well defined. There is also the need for specialist computing equipment that is not as easy to use (for example high performance Graphics Processing Units (GPUs), high resolution screens, headsets, and custom dashboards).

Conversely, low fidelity simulations can offer quick insights into the use of the system and any emergent behaviour but will be less realistic. Investing in such simulations early in the project can provide insight to basic questions of team composition or sensor selections before significant investment is made.

Careful consideration is therefore needed to pick the level of fidelity appropriate for the stage of the system's lifecycle and the needs of the system itself. The next sections discuss three different approaches to simulation projects which are at different levels of fidelity.

3.2 T-B PHASE Simulator

Initial investigations used bespoke simulations, but to promote collaboration and use-case engagement the project has decided to develop a common Agent-Based Modelling (ABM) simulator framework.

The framework provides a set of means and associated functions which allow an instance of a simulator to be built in a shared environment. The aims of this were to allow sharing of algorithms and methods across the research team as well as having a consistent environment for the development of scenarios.

There are many established platforms for ABM, in most languages. For ease of accessibility and familiarity, Python and the Mesa [11] modular Python framework for modelling and analysis have been selected. Visualisation modules that can be displayed via a server with a JavaScript interface simplify information dissemination.

We adapted this framework to facilitate the scenarios and behaviours we were investigating. This meant the adding of certain agent types, such as uninhabited air and water based vehicles, and environment functionality such as linear zone divisions and areas defined by polygons. All of these features are intended to be modular and adding to a growing code base that can be used by the whole team. By approaching the simulator in this way, it has allowed us to continually incorporate current, as well as combine previous, work in new ways.

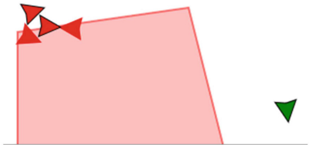
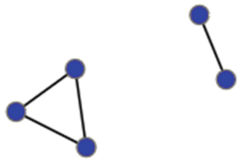
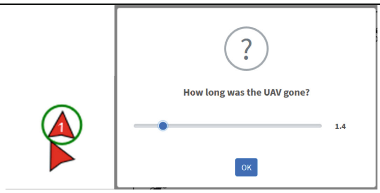
As mentioned, the simulator framework developed is modular, consisting of server, model and agent files shown in Table 1. This allows developers to select functionality that has already been implemented and provides the rest of the team access to new developments.

Table 1. T-B PHASE simulator structure

Simulator		
Server File	Model File	Agent File(s)
• Visualisations • Model parameters • Maps and canvases • GUI elements	• Communications Network • "World" rules • Agent interactions • Schedules for agents	• Movement rules • Communication rules • Individual beliefs

The basic features that have been implemented to complement those already within the framework have enabled us to support our foundational research as well as include them in our industrial use cases. Some of these features are outlined in Table 2:

Table 2. T-B-Phase simulator examples of useful features

	Environment elements such as barriers or areas
	Network based communications and visualisations
	Human control of elements and feedback (forms and logs) for human trials

It is the culture of academic research to conduct studies in a minimalist way, constructing the simplest possible experiment and then delivering a paper study of the results. Industrial impact often demands a different approach, involving more interactive demonstration and more reliant on the relevance of the application context. By embedding an agreed set of use cases into simulations, made as simple as possible, we have developed a tool that can enable scientific study and quick conversion to impact and uptake. This has provided new avenues for exploration, such as the combining of disparate concepts in one environment as well as overcoming data sharing constraints. It has also fostered more effective collaboration between the industry and academic team which will continue into the next phase of the project. For this we will use the simulator to explore the problem space and subtleties of design realisation that would typically be defined much later in the design cycle, namely in a User Requirements Document and Systems Requirement document.

3.3 TANDEM

TANDEM (Thales AutoNomy Domain Extensible Map) is a Thales tool developed to aid our work with academia. TANDEM is a standalone, lightweight web server, which has a SocketIO API, and the ability to extend core functionality, either via the API, through a client, or by writing a plugin to extend functionality on the server. Most aspects of the interface can be configured via a text file, to allow multiple use cases.

TANDEM was created as a lightweight, free-of-licensing tool, which allowed Thales to rapidly create visual demonstrators with our partners. In addition, the simulators which were then in use within Thales, required GPUs and restrictive (sometimes expensive) terms of use. TANDEM enables close working with Third Parties without complex licencing and other overheads.

To maximise the number of use cases TANDEM could be deployed against, adaptation was a key requirement in its design. The resulting program can be run on hardware as simple as a Raspberry Pi with, or without, a network connection and is distributed as a standalone binary file which can be simply operated on Windows, Linux or MacOS. The core functionality is provided by TANDEM, with clients providing the specific business logic for a given use case.

These features provide some useful advantages when working with academia as it can be distributed and operated on existing hardware, without needing to build any libraries, and ensures the same setup on all machines for all parties involved. Additionally the interface allows multiple languages to communicate with TANDEM, and without tying developers to a particular language.

Fig. 3. TANDEM preview and simulating plan interface

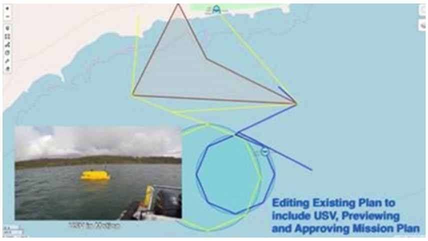


Fig. 4. TANDEM editing of existing plan

The Thales – University of Southampton Intelligent Mission Management System (IMMS) utilised TANDEM, as the mission interface, with clients connecting to a MAVLINK based UAV, and a Robot Operating System (ROS) based Uncrewed Surface Vehicle (USV) and an Uncrewed Underwater Vehicle (UUV) which communicated via Iridium in a successful live sea trial. High level tasks were set on the TANDEM Interface, and a planner client was triggered. This used the available data to construct asset level plans which could then be previewed on TANDEM (an example in Fig. 3). The operator could then verify the plan, and see deviations from allowed behaviour. Once the plan was approved, it was sent out to the assets to be acted on, and live asset monitoring was provided by TANDEM (example shown in Fig. 4). After the trial the data could also be replayed through TANDEM as an after action review tool.

Development on this tool is continuing with integration with the T-B PHASE simulator to provide for mission planning components, and incorporation with other Thales tools, for further experimentation opportunities.

3.4 Digital Twins for Maritime Test Environment

In other academic partnerships Thales has used a Digital Twin (DT) to support a number of applications ranging from rapid prototyping, training, and equivalence for virtual integration, verification, validation, qualification, acceptance and certification, monitoring and predictive optimisation of process, maintenance and control. A DT is a digital representation, often at physics level, of a system and its environment in all relevant aspects.

The DT can be used to simulate the process of observation/supervision of the physical entity, to predict future states of the physical entity based on data collected from the physical entity and possibly historical measurements and/or modelled behaviour. They can also be used to optimise the performance of the physical entity again based on data collected from the physical entity and possibly historical measurements and/or modelled behaviour by sending optimised data into the physical system.

To increase the use of synthetic environments in test and evaluation activities, the use of real world data to improve and tune the fidelity and accuracy of mathematical and physics models is essential. Using captured real world data and comparing with the tuned synthetic environment provides equivalence arguments that prove the safe use of the environments.

A DT was used to great effect in the MIMRee project (Maritime Inspection Maintenance and Repair in Extreme Environments) [12], discussed in Sect. 5.1, which required a safe and secure approach to the design, development, test and integration of cutting-edge maritime autonomy technologies. Many of the challenges presented by the MIMRee project can be resolved by the development and utilisation of two interoperable DTs: For the MIMRee project, Thales developed an environment DT of Plymouth Sound, the autonomous systems and key infrastructure. The DT utilises multiple data feeds to create an up-to-date virtual representation of the maritime area and is used in the first instance for supervising autonomous vessels to aid with mission planning, execution and debrief (strategy and planning). The DT accelerated the development, test, evaluation, and certification (assurance) of future autonomous systems operating in the maritime environment and any supporting infrastructure as part of an integrated system of systems, expediting the introduction of technologies for Net-Zero ambitions. The DT, in a Bayesian approach, will continually calibrate and optimise the system performance (performance optimisation) with collected sensor data to increase fidelity and situational awareness, opening up opportunities that require higher fidelity and safe and secure environments for training and testing.

In T-B Phase the level of fidelity that a DT provides was not appropriate but the lessons identified in developing such projects as MIMRee with academic partners has been applied.

4 Human Factors

Human factors are important in the development of autonomous systems, but perhaps not as prevalent in research as the algorithms, and is a growing area of research. The focus of Human-Machine Teaming (HMT) has traditionally focussed on:

- Optimising human performance – reducing the user's workload, costs, and errors while increasing precision and improving continual feedback [13]
- Improving acceptance, trust, and cooperation [14]
- Improving transparency and shared awareness [15].

From a psychological point of view, these challenges address predicting human behaviour when interacting with a system. However, the approaches used so far in the literature to investigate them is lacking a precise direction. The main focus has been, in fact, in analysing the variables that could affect the human behaviour in HMI from a design-specific point of view.

On the T-B PHASE project there is a mix of specialities, including psychology and human factors, enabling the inclusion of these considerations. Industry has often suffered from having the human elements considered too late in a product's development, or even disregarded completely. Our focus has been on the Sense of Agency (discussed in Sect. 2.4) and how this can help us understand a user's feeling of control.

4.1 Who is in Control?

Human-machine teaming strongly depends on cooperation and trust. These two components have been studied in different scenarios, although no specific framing around how they work in HMI design has been found to date. One of the key aspects that has not been fully considered is the human perception of control during the interaction with the system. Cooperation addresses the issue of reaching a common decision/goal with the system, whilst trust incorporates the feeling of commitment to reach that goal. This, in turn, implies that the human needs to be intentionally aware of their decision and the potential consequences of that decision. Hence, the human perception of control needs to be investigated in the context of HMT.

The question of human control perception arose several decades ago. To quote Baron [13] "Perhaps the major human factors' concern of pilots about the introduction of automation is that, in some circumstances, operations with such aids may leave the critical question, who is in control now, the human or the machine? At the extreme, some pilots argue that automation reduces the status of the human to a 'button pusher'."

Although the cockpit is just one example, this suits an enormous number of scenarios that involve cooperation with AI and machines. Overall, when the system fails, the users' supervision capabilities seem dramatically helpless in assessing the situation and determining the appropriate solution. This is mostly due to the absence of the system state awareness by the human.

4.2 Human Factors and Simulation

Future work will be focused on integrating the present findings in a simulated environment to investigate the Sense of Agency in a more applied context. The aim is to replicate and extend previous fundamental research in a scenario that can suit an HMI setting. Collision avoidance, loss of communication and different failure modes could be implemented to test their effect on the operator's Sense of Agency. This would also include different degrees of automation intervention. The hypothesis behind these studies would be that a higher Sense of Agency should be associated with greater performance, although it might be possible to find a hybrid condition where the intervention of the system does not undermine completely the user's Sense of Agency. These studies would deliver new information about the operator's mental and cognitive state under different type of tasks, such that new system design guidelines could be delivered.

Overall, the aim of this research is to embed Human Factors' features on the T-B PHASE simulator (Sect. 3.2), such that a dynamic environment for HMI can be created. This would take the shape of an interface that can address several HMI issues. From a psychology perspective, the benefit of using a common interface for different tasks would reduce the encounter of confounding effects and deliver more reliable results. From the engineering perspective, this research could offer the possibility of gathering useful information about the operator suitable for improving both the knowledge about HMI and the simulator platform itself.

5 Use Cases

Outside T-B PHASE Thales has been involved with many other projects with academia and other innovation organisations. The use cases that support two of these projects have proved useful in informing the approach to academic partnerships. In this section, we explore two use cases that highlight some of these key learnings applied in practice that were used to support T-B PHASE and vice versa where our outputs were used to inform other projects.

5.1 MIMRee

Thales collaborated in the Innovate UK project MIMRee, from the Robotics and AI in Extreme Environments call in 2018. Here we proved the concept, through a series of demonstrations, of how to utilise maritime autonomous systems to complete inspections and repair of offshore wind turbines without humans needing to be present in this dangerous environment (shown in Fig. 5).

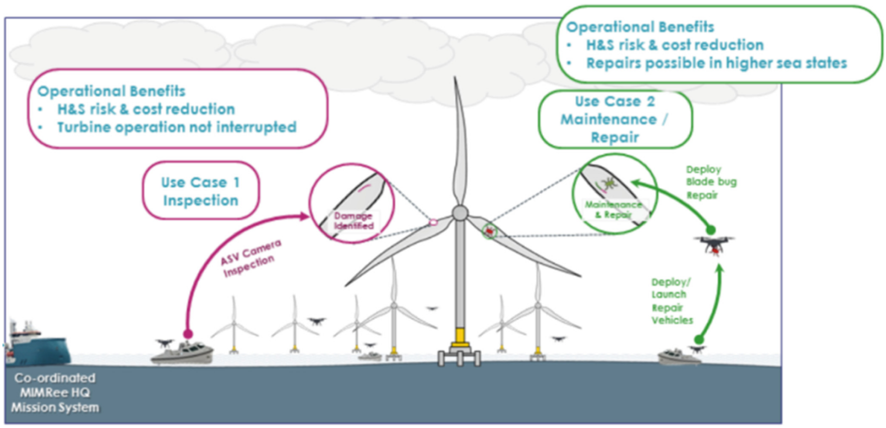


Fig. 5. MIMRee use case

The large and diverse consortium of Wootzano, Thales, Perceptual Robotics, Plant Integrity, Bladebug, The Welding Institute, Offshore Renewable Energy Catapult

(OREC), University of Bristol, The Victoria University of Manchester, Royal Holloway University, and Royal College of Art assembled their unique capabilities to address this challenge.

No single participant could have covered the full breadth of the problem space alone. Through close end-user engagement, facilitated by OREC, the project was able to define a new concept of operation and prove the concept of a new, coherent capability that could solve these challenges.

The lessons identified in MIMRee including the use of TANDEM and the concept Digital Twins have been instrumental the work in T-B PHASE, particularly the need for an easily deployable shared environment for all organisations involved.

5.2 Autonomous Last Mile Resupply

Although not directly linked to T-B PHASE, Thales led the development of the new Concept of Operations (ConOps) for Project Workhorse for the UK Defence and Security Accelerator (DASA) Autonomous Last Mile Resupply (ALMRS) challenge. In this project, the current, manned and unmanned, operations were identified and expanded with near and long-term development of operational practice. Working closely with the customer and our partners on that project meant we were able to apply the approaches defined from T-B PHASE, particularly the Engineering for Trust processes and the guidance for fostering trust in Human-Machine Teams.

The project pioneered new ways of working with autonomous systems for UK military and these new concepts are still being validated and experimented with today, such as recent trials with the Royal Marines and further work in project THESEUS (Framework Agreement for experimentation tasking in the field of Autonomous Logistics).

6 Lessons Identified, Further Work, Recommendations and Conclusion

The approach taken by T-B PHASE is unusual from an academic point of view, allowing researchers to combine their work and apply them to the applications that would not be available without the industrial input. We hope that the next phase will accelerate this as these new work packages are collaborative and introduce these real world requirements.

6.1 Lessons Identified from Initial Partnership Engagement

Although there was excellent research produced from individual activities, they were often conducted without being grounded in a use case that reflected the business of Thales. We have found having clear common themes, particularly in the form of use cases and scenarios help to overcome this.

Another lesson identified is that for a partnership to work, co-location and shared infrastructure is critical. We have found this to be the best way of ensuring that all participants work to a common vision while also facilitating knowledge exchange. Because Covid-19 meant that we could not be physically co-located for an extended period of time we were still able to work virtually because of the shared infrastructure.

A key lesson has been the use of the simulator framework (described in Sect. 3.2) which is being used to combine strategies and algorithms in a shared environment. This, in particular, has enabled creative sharing of ideas and knowledge while also allowing for industrial best practices to be explored. Alternative tools such as TANDEM (Sect. 3.3) have been used alongside other Thales tools, and to demonstrate to stakeholders and customers. Being able to use these open tools for collaboration between other industrial and academic partners has already proved to be of great benefit and is proving to be a corner stone in our T-B PHASE work streams.

6.2 Further Work

The first three years of the project were foundational research activities which although individually furthering our knowledge of autonomous systems it was clear that we needed to integrate the capabilities that have been developed in that research. As the T-B PHASE project moves forward, this research will be used to continue activities targeted towards realistic business use cases, combining research themes towards a cohesive simulator toolkit that can aid the Systems Engineer in informed early stage lifecycle decision making. Of particular interest is to ensure the Hybrid (Human and Machine) nature of autonomous teams is addressed with the inclusions of human factors exploration in technical demonstrations and experiments that will additionally lead to design guidelines. As part of this work, three sub projects have currently been identified to integrate the research strands that have been analysed in the project. These are focusing on the concept of empowered agency in autonomous systems, human swarm control training strategies and including failure modes and business specific use cases.

6.3 Recommendations

Co-location is critical to the success of a partnership and needs to be established from the onset including shared infrastructure. We have found that having a shared physical space with regular interactions between all parties helpful, but this can also be achieved virtually.

We have found relevant use cases need to be established to support the overall vision and goals of the research.

Working processes (for example filing and naming conventions, reporting timetables and templates) need to be agreed and implemented to the satisfaction of all partners.

Simulation plays a major role in all autonomous research but it needs to be cost effective and address the questions being asked. The level of fidelity needs to reflect the aims of the research. What we have found is that the simulation tools that are most useful in a partnership with academia are of a much lower fidelity that are usually used within the business to validate products. To support this the simulation environment again needs to be supported by a shared infrastructure that is accessible by all parties.

6.4 Conclusion

Industrial partnership has allowed for us to bring in experts and specialists, in specific domains or technologies (such as the maritime environment and use of communications and sensors) to share knowledge within the team and add credibility to the use cases. Reciprocally academic partners have been able to offer us creative thinking and perspectives on the cutting edge of their respective fields that are not always easily accessible in industry which can be more product focused and may be limited by processes.

So far we have found significant benefits from working in this way as it gives industrial partners greater access to the fundamental academic research, and therefore more able to quickly identify opportunities to imbed new ideas into future design and development of its products. There have also been improvements in collaboration and the breadth of research that has been able to be included, especially from new areas such as the psychological aspects for HMT or research into areas that we may not have considered applicable previously. Industrial partners have been able to share knowledge of working practices and use cases to enable researchers to produce more relevant outputs. Overall we have found this a very beneficial approach especially through a reliance on tools and simulations that are accessible to everyone.

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We would also like to honour the memory of Angus Johnson who we sadly lost during the preparation of this paper, he was the driving force for the T-B Phase project and is greatly missed.

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