The UK's Intelligent Ship project – exploring future human-machine and machine-machine teaming

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Synopsis

Future military forces and platforms will need to operate within increasingly complex operational environments where the threats are more diverse and increasingly challenging. This will increase the volumes and speed of data and information that platforms and their commanders will need to capture, process and respond to. This inevitably leads to the consideration of greater levels of automation and the wider use of machine intelligence techniques across the Command and Control (C2) space.

Research in this area to date has focused on the integration of intelligent machine agents, and automated systems, with human operators in specific or focused capability areas. To generate true operational advantage from the growing and diversifying data and information available to military commanders, it will be critical to build on these developments by addressing the design and operation of teams of multiple intelligent machine agents (e.g. as collaborative Artificial Intelligence (AI)) and to enable and optimise the integration of humans within those teams to form effective human-machine teams.

The UK Defence Science and Technology Laboratory (Dstl - part of the UK MOD) has funded the Intelligent Ship project, which aimed to explore these future Human-Machine Machine-Machine Teaming (HM3T) architectures and relationships, and the approaches needed to enable them. The project's vision is: *Machine learning and AI will be more closely integrated and teamed with humans, leading to timely, more informed and trusted decision making and planning, within complex operating environments*. This was undertaken through the combined developments of a range of component intelligent machine agents and through the development, evaluation and demonstration of those agents, with human operators, within a systems level architectural 'sandpit' known as the Intelligent Ship AI Network (ISAIN). This work was delivered by a multidisciplinary team of Dstl and 10+ suppliers and evaluated within Dstl's Command Lab simulation environment facility.

This paper will review the project's aims, delivery approach, lessons learnt and challenges identified in its second phase, which completed in March 2022. This phase included a series of evaluation events, with each event growing in complexity and in the number of interacting agents and operators. This paper will overview the system level architectures developed and highlight the range of agents developed (providing threat evaluation through to system control) and integrated. Finally, it will review future development needs.

Keywords: AI; intelligent systems; automation; future command control; Human-Machine Teaming

1. Introduction

1.1. Context

Future military forces and platforms will operate within, and against, an increasingly complex, diverse and technology focused set of threats. This will increase the volumes and rate of delivery of the data and information

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that commanders and their supporting systems need to capture, process and respond to. Decision making speed will also need to increase as threats themselves become faster, more numerous and less predictable.

These challenges are amplified when considering the application of future, and potentially more distributed, combat systems. Systems such as high-powered sensors and Directed Energy Weapons (DEW) drive a need for better coordination across a force, or fleet, and also improved intra-platform connectivity between internal systems, for example, power system controllers and the combat system itself.

Addressing these challenges inevitably leads Defence to consider the wider use of automation and Artificial Intelligence (AI) approaches within future Command and Control (C2) systems and, critically, their decision-making. To fully exploit and optimise these approaches requires not just effective and adaptable teaming relationships between an intelligent machine agent, its matching automation system, and human operators – a Human-Machine-Team (HMT) – but also between each of the various machine agents, i.e. both human-machine and machine-machine teaming (HM3T).

Defence needs to understand HM3Ts, their supporting infrastructure and enablers, and the optimal balance between humans and the machine elements within the team across a range of operational scenarios and tasks. This requires a paradigm shift from designing systems and then their interfaces with humans, to designing systems with human and machine teaming interaction as a fundamental element of the initial concept and design.

The use of AI in military C2 presents a number of technical challenges that will need to be addressed, including:

- Developing system designs that enable adaptive human-machine and machine-machine team structures;
- Managing computing power demand;
- Developing and maintaining trust in the system (and systems of machine-machine teams);
- Accessing suitable labelled, unbiased data sets to support AI training;
- Generating flexible and intuitive AI-human interfaces;
- Managing vulnerabilities; and
- Assurance, verification and validation of agents.

This paper focuses on the second phase of the UK's Intelligent Ship project, which has started to explore these future HM3T relationships, their supporting architectures and enablers. This was achieved through the development of a range of individual machine intelligent agents across a range of naval capability areas. These, along with a range of user interfaces (UIs), were integrated into a systems level architectural 'sandpit', called the Intelligent Ship AI Network (ISAIN). The resulting system and its usability was evaluated through a series of events hosted in a Dstl simulation environment, Command Lab, using serving Royal Navy (RN) Military Advisors (MAs) as operators and a representative naval scenario to excite the system.

The project focused on the C2 needs of a naval platform, the combination of operating spaces (i.e. Bridge, Operations Room, and Engineering control spaces), a large crew of operators and a complex and diverse set of interconnected systems represents a complex, but constrained (i.e. on a single platform) C2 challenge, making it an ideal candidate for HM3T research. The research, while focused on Naval C2, has clear and transferable applicability and relevance to any defence system, network or platform where humans and AI agents need to work together in an effective team.

1.2. Project aims

The Intelligent Ship project was initiated with an aim of starting to understand, develop and evaluate concepts that address the challenge of enabling, integrating and managing complex HM3Ts in generation after next platforms. In Phase 2 this focused on the needs and challenges of collaborative AI.

The project was challenged to consider a clean sheet approach to avoid the constraints of current Naval C2 processes and system architectures. It attempted to understand and qualify the follow project vision:

> *Machine learning and AI will be more closely integrated and teamed with humans, leading to timely, more informed and trusted decision making and planning, within complex operating environments*.

The project purposely did not focus on, or aim to demonstrate, the potential to reduce crewing, rather to understand how a system could make best use of the strength of machine and human intelligence working together. Inevitably, with greater technical maturity and trust in an Intelligent Ship concept, crewing reductions, alternative roles or cross-platform/location distribution may also be possible.

The specific aim of Intelligent Ship Phase 2 was to:

> *Demonstrate the methods and benefits of bringing multiple AI applications together to make collective decisions, both with and without human operator judgement.*

1.3. Project structure and approach

The Intelligent Ship project was funded by the UK MOD's Chief Scientific Advisors (CSA) Science & Technology research budget and was delivered via Dstl's Autonomy programme.

Phase 1, which completed in November 2020, focused on developing project 'enablers'; specifically the baseline ISAIN capability (which acts as the key infrastructure for the machine agents to team) and a range of intelligent machine agents. This included, for example, an agent focused on naval specific Tactical Navigation challenges.

Phase 2 (UK Gov, 2020), which completed in March 2022, focused on the 'integration and evaluation' of an Intelligent Ship HM3T system. It was delivered through a themed UK Defence and Security Accelerator (DASA) competition, split into two challenges:

- Challenge 1 covered the overall concept enablers (including ISAIN), integration and evaluations; and
- Challenge 2 covered the further development of Phase 1 intelligent agents and the creation of several new agent concepts, all of which represented a broad mix of naval capability areas, delivered by a mix of both small, large, defence and non-defence focused organisations.

The successful challenge 1 supplier (CGI, supported by DIEM, Decision Lab and Thales) conducted the following activities:

- Matured and further developed ISAIN;
- Integrated the successful ADeM applications developed under challenge 2 into ISAIN;
- Integrated ISAIN (with the ADeM applications) into the Dstl's Command Lab simulation facility;
- Conducted four evaluation events in the Command Lab, testing the system, agents and human interactions using a representative naval scenario and Royal Navy MAs as operators;
- Gathered self-assessment ratings and feedback from the MAs relating to workload, situational awareness (SA) and trust in automation (TiA); and
- Analysed the data captured to:
    - Gain an initial view of the potentially significant effects of networking ADeM applications to enable them to team directly, and in collaboration with, and parallel to, human teams; and
    - Inform the further development of ISAIN and the ADeM applications through a comparison of the components of workload, SA and TiA that they appear to affect.

The term ADeM (Agent for Decision Making) was used by the project, to define any group or combination of intelligent agents, or agents and operators, required to make a collective decision in any given capability area. This reflects, for example, the importance of a UI within the design of any HM3T system making a critical decision, as it forms a fundamental part of the ADeM for that decision. Individual intelligent/ AI based agents developed under challenge 2 are hereafter described as ADeM applications as they support 1 or several agents.

2. ISAIN

The Intelligent Ship Artificial Intelligence Network (ISAIN) was developed to provide the project with a framework to support experimentation with AI collaboration and HMTs. It provides a 'playground' or 'sandpit' for AIs' to support connections and relationships between applications and human users. It is owned by the UK MOD and utilises an open systems approach and standard interfaces.

As shown in Figure 1, ISAIN uses a combination of widely used free and open source software packages, such as Apache NiFi™ MongoDB™, Docker™ and Elastic Stack™. Communications between the ISAIN components are via a combination of open standards such as REST and LDAP, and MongoDB's™ wire protocol, all of which are provided 'out of the box' within NiFi, as well as being widely available within numerous open source libraries. Transferring of log files to Elastic Stack™ is through Elastic's Filebeat plugin.

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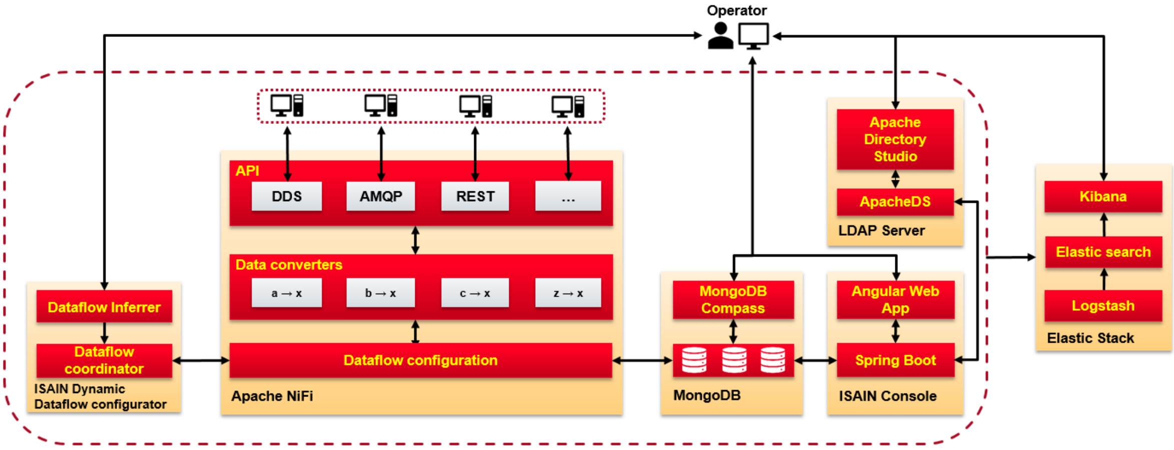

Figure 1 – ISAIN 'Sandpit' Architecture Overview

Functionality added to ISAIN during Phase 2 included:

- Simplified configuration of the ISAIN data-flows between ADeM applications and the Command Lab simulation environment through the integration of AI planning tools;
- Improved fault diagnosis and post experiment analysis, through extended integration with the Elastic Stack™ suite of applications;
- Facilitation of human in the loop (HITL) approvals for ADeM application decisions/outputs at the network level;
- Data cleansing operations to correct and populate incomplete and/or incorrect simulation data;
- Implementation of an ISAIN software development kit (SDK) to assist ADeM providers, ensuring their ADeM applications were 'ISAIN ready'; and
- Implementation of a Data Query API which allows ADeM applications to treat ISAIN as a black box for querying data, publishing data or requesting a task is performed without requiring knowledge of the destination ADeM or data repository.

ISAIN uses a highly configurable technology, namely Apache NiFi™, as the underlying framework to integrate standalone applications for the purpose of data routing and queuing, mediation and transformation. Apache NiFi™ is a domain agnostic technology that can support a range of Application Programming Interfaces (APIs) and hence allows applications developed in different languages and operating systems to interact within a common data system. Consequently, this enables ISAIN as a whole to be domain agnostic, and as such, could be potentially applied to numerous other areas, both within defence (i.e., air or land), and beyond.

Both ISAIN and each of the ADeM applications supplied to the project were delivered as Docker™ containers to aid flexibility and integration. The integration of a new ADeM application was achieved through configuration of the NiFi™ flow which included both input and output processors to connect it to the ADeM application, and any additional data converters required to connect to and from ISAIN's internal data model. These processors and converters were incorporated into the SDK to ensure that each ADeM application was 'ISAIN ready', i.e.: that the ADeM application could connect to ISAIN, send data to ISAIN and receive data from ISAIN in the expected format prior to integrating with ISAIN. In addition to the out-of-the-box NiFi™ input and output processors, Data Distribution Service (DDS) processors were developed using Vortex OpenSplice Community Edition to provide DDS publish and subscribe functionality. Custom input and output processors can easily be added for future AI or ADeM applications which utilise protocols that are not currently supported.

ISAIN, specifically the Apache NiFi™ component, facilitates HM3T by providing automatic routing of data between the different ADeM applications according to its dataflow configuration. This dataflow configuration allows an ADeM application to task or request information from another ADeM application as part of its own task, but importantly the request is made through ISAIN rather than directly to the target ADeM application. This distinction allows for both ISAIN to determine which of its connected ADeM applications to route the request, and for a target ADeM application to be substituted with an alternative that can provide the same or a similar function without requiring changes to the requesting ADeM application.

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3. ADeMs

The Intelligent Ship project quickly identified that the linkages between individual machine agents, other agents and operators were complex, multidirectional and highly dependent on the decisions to be made or influenced. This is reflected in the use of the term ADeM as already described.

The scope of the Intelligent Ship 'decision space' for HM3T is shown in Figure 2. On the vertical dimension are the different types of decisions that could be made, from learning to outcomes. On the horizontal dimension are the different stages of the decision cycle, from observation to action. On the final axis are the different mission concepts that the Intelligent Ship needs to have the capability to deliver, based on the changing environment and resulting demands in relation to the command aim.

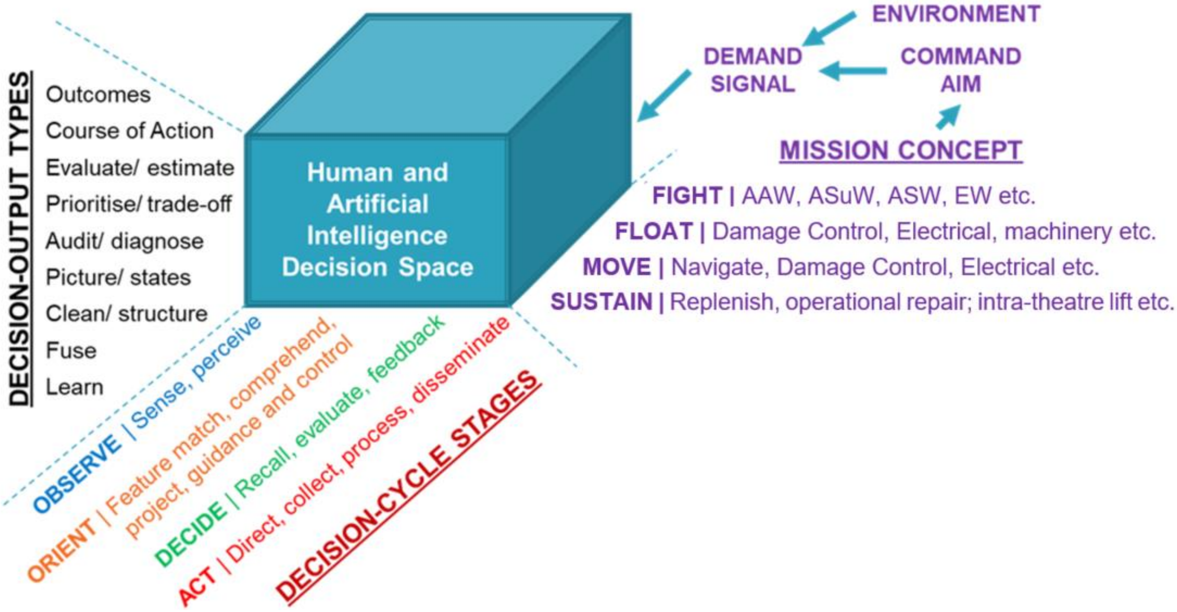

Figure 2 – Intelligent Ship scope of 'decision space' for HM3T

Figure 3 illustrates how the current human teaming interactions between, for example, the Commanding Officer (CO), Air-Warfare Officer (AWO) or Principal Warfare Officer (PWO), Weapon Engineering Officer (WEO), Marine Engineering Officer (MEO) and Logistics Officer (Logs), can be translated into the idea of ADeMs supporting the execution of the command aim, the capability to meet the aim, and the setting of the aims, needs and priorities. Note, this is one of many examples and does not cover all potential human interactions.

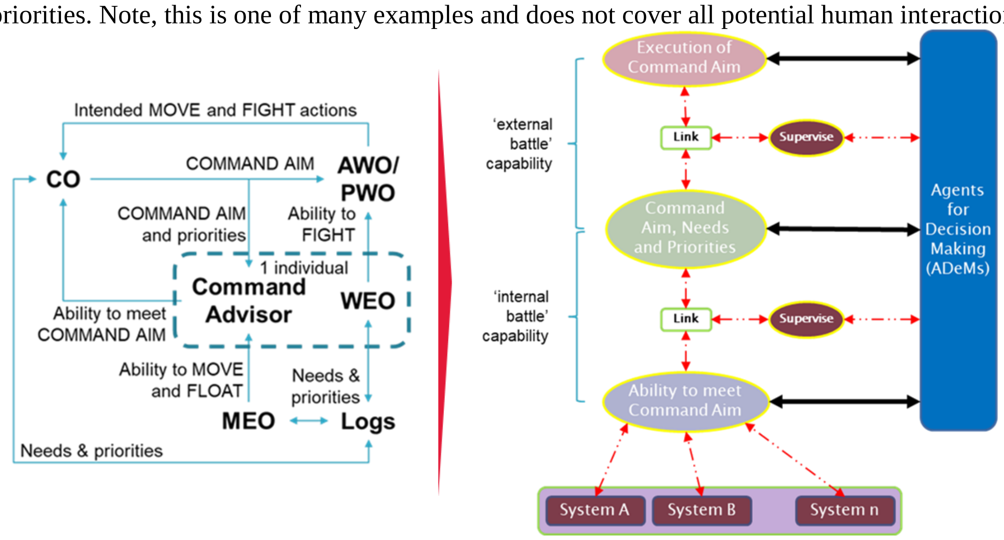

Figure 3 – Illustration of human teaming translated into higher level capabilities and ADeMs

Under challenge 2, ten ADeM applications were developed by a range of both large and small companies, representing a broad mix of naval capability areas. Some were further developments of agents created in Phase 1, but a range of new capabilities were also developed. SYCOIEA, a decision support research tool developed by

Dstl's Above Water Systems programme, was also included in the overall system to provide a Threat Evaluation and Effect Coordination (TE2C) capability.

A summary of the ADeM applications included in Phase 2 is shown in Figure 4.

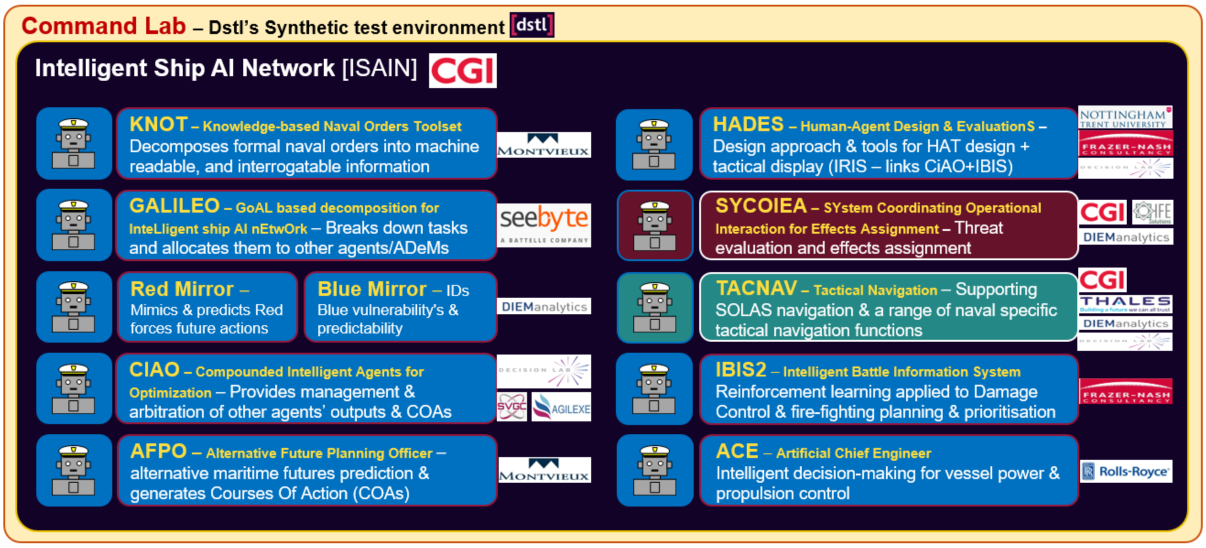

Figure 4 – Phase 2 of the Intelligent Ship project – ADeM Applications & suppliers

The individual challenge 2 projects included the evaluation of the agents as a standalone application used by an operator i.e. the traditional human-machine team. Challenge 1 then integrated these, via ISAIN, into overlapping ADeMs charged with making different types of decisions; at the highest level this included:

- KNOT, Galileo, AFPO, ACE and TacNav interacting amongst themselves and with the CO to plan the route and waypoints of the Intelligent Ship, given the mission and constraints;
- TacNav, AFPO, ACE, IRIS and SYOCIEA interacting amongst themselves and the Officer of the Watch (OOW) to monitor and update the route and waypoints in response to the situation;
- SYCOIEA, TacNav and Red Mirror interacting amongst themselves and the AWO and PWO to predict and assess threats and decide on courses of action for the 'external battle' (against threats); and
- SYCOIEA, TacNav, ACE and IBIS interacting together and with the PWO and MEO to predict and assess the condition and capability of the Intelligent Ship and decide on courses of action related to the 'internal battle' (against fire and flood etc. following damage).

HADES and Blue Mirror were potential evaluation ADeMs, with the former being used to inform the design of the UIs (specifically CIAO and IRIS in Phase 2) and the latter to indicate the level of predictability of the Intelligent Ship using AIs (specifically TacNav in Phase 2).

4. Evaluations

A total of four evaluation events were conducted during Phase 2. Each event aimed to excite and test the developed system and the human interactions with it, through the running of a series of vignettes from a representative naval scenario. Each event was made up of an integration phase (bringing all suppliers together into command lab); a system testing phase; a training phase and finally an evaluation phase which brought in Royal Navy MAs to act as operators during each vignette run. An incremental approach was taken to the scope and focus of each event, in order to iteratively de-risk and generate insight for the planning and running of the follow-on and final evaluations.

Following consideration of the maturity of the ADeM applications and their UIs supplied under challenge 2, and consideration of the challenges of evaluating a wholly new system with limited operator pre-evaluation training against existing RN approaches, the aims of the evaluations were agreed as follows:

- Demonstrate and evaluate a number of different AI agents, working together with humans in a collaborative environment to deliver military effects; and
- Evaluate the usability of the ADeM applications in different HM3T configurations to inform the design of the system (ISAIN and the ADeM applications) in future phases of the Intelligent Ship project.

Feedback from Dstl MAs and discussions with Dstl Human factors analysts highlighted that basing the evaluation around current operators comparing the usability of ADeM applications to the current systems (the 'baseline') would not be useful, for a range of reasons including that:

- Current team structures, roles and training are based on the need to operate the current systems and so may not be representative of the structures and roles needed to operate a future Intelligent Ship;
- Current operators are so well trained and practiced in the use of current systems to fulfil the current process, that they may focus purely on the ability of the ADeMs to deliver the current process rather than future potential alternatives;
- The ADeM applications, their respective UIs, their integration within ISAIN, and the Dstl Command Lab, are less mature (some with less than 2 years of development) than the current baseline which will exacerbate the previous issue, particularly with limited time to train operators, or to allow them to gain experience and identify unexpected emergent behaviour; and
- A future Intelligent Ship concept could drive the recruitment and training of very different types of individuals e.g. those with the skills and interest in overseeing AI applications.

Instead it was agreed that the ADeM applications should be considered as fulfilling the role currently played by the layers of 'supervisors/ controllers' and 'compilers/ operators', and that the evaluation should be structured around two 'configurations' (as shown in Figure 5):

- Having the ADeM applications as stand-alone decision-aides for individual human decision makers (i.e. 'non-networked AI' subservient to human operators, who control the passage of information between AIs); and
- Allowing the ADeM applications to directly interact with other ADeM applications and provide inputs to human operators as an equal 'team of AIs' (i.e. 'networked AI').

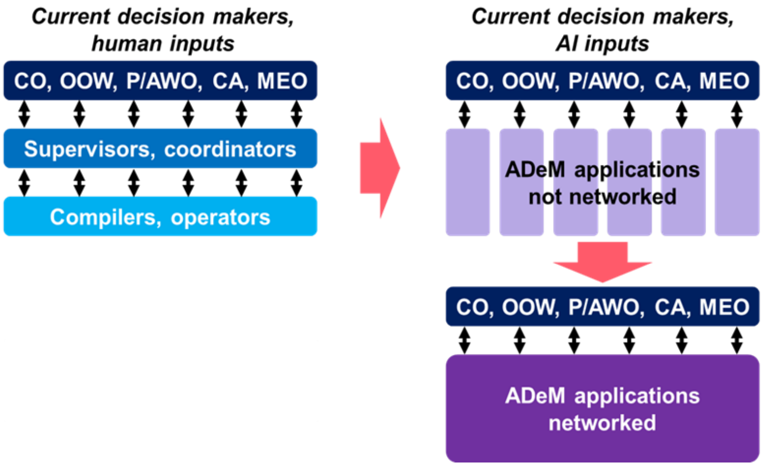

Figure 5 - Current system (left, in blue) and the evaluations (top and bottom-right, in purple)

TiA and usability assessments were made using operator feedback and based on industry standard approaches (Körber, 2018).

The evaluations were based on an agreed set of vignettes from a larger naval scenario. These vignettes were designed to cover a wide range of typical naval tasks, but also to exercise both individual agents and groups of agents and operators working to creating alternative courses of action. The scenario was divided into five mission events:

- Mission area entry planning;
- Transit (to the Area of Operation (AO)) including a submarine event;
- Intelligence gathering (the Intelligent Ship tasking) including dealing with probes;
- Air-defence; and
- Damage control.

Each of these events drive a corresponding definition of: the key decisions to be made; the interactions between operators; interactions between operators and ADeM applications, and; ADeM applications and other ADeM applications. Figure 6 shows the scenario events, and the key high level interactions.

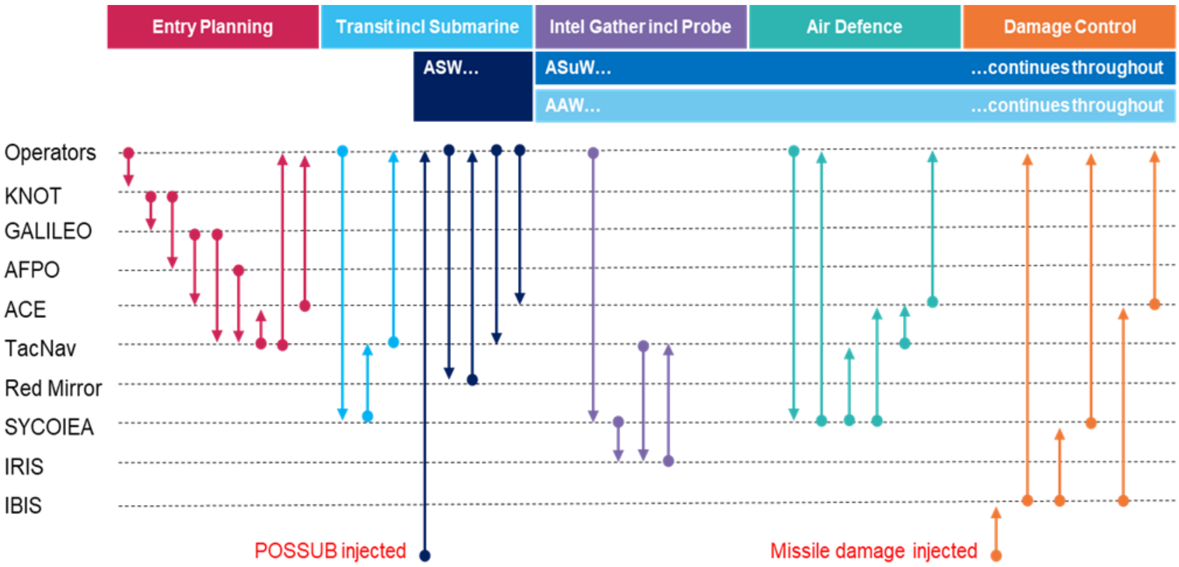

Figure 6 - Scenario tasks, events and key high level interactions

5. Conclusions

The project's primary aim was to develop and assess an initial system concept to provide military advantage through the use of collaborative AI. The evaluations successfully affirmed the potential to design a system that could host and integrate multiple intelligent machine agents, that would allow them to communicate and collaborate, and that supported both machine-to-machine and machine-to-human interactions. It also showed the benefits of openness with the ability to integrate intelligent machine agents designed in very different capability areas, developed in different languages and contexts, and with different levels of autonomy (and hence operator interaction) and levels of technical maturity.

The project provided the MOD and its suppliers insights into the design and architecture of HM3T systems and into the design of evaluations of these systems and their components. It showed clear benefits of wider agent-to-agent interactions in often stove-piped capability areas. This included, for example, closer collaboration between combat focused and platform focused systems to support improved planning and to understand current and even future constraints on available Courses of Action (CoA).

It also developed an initial understanding of some of the enablers and system design elements needed to support HM3T. This included CoA arbitration and task allocation agents, but also indicated the need for new data sets and data-layers that can support multiple agents and tools.

Other lessons learnt include gaining an understanding of:

- The potential benefit in being able to use common tools, simulation environments and simulators between government and industry teams, which would allow earlier testing of new components and de-risk evaluation events;
- Experimental design needs to address the tools and techniques needed to capture what is happening both within a system (communication logs) and the impacts on operators through a range of human factors approaches and metrics; and
- The need for common but flexible and reconfigurable user interfaces that allow integration of different agents and enable different approaches to operator roles, different degrees of automation that can vary the levels of information provided based on tempo and tasking.

Lessons with respect to undertaking evaluations of collaborative AI and HM3T, include:

- The use of multiple self-assessment metrics, in particular the NASA TLX for workload, 3DSART for SA and TiA for trust, proved practical and successful;
- Combining the metrics with debriefs and recordings of both the human and machine interactions, provided useful support information particularly for the ADeM application developers; and
- A range of lessons around the management and organisation of evaluation events. This includes ensuring adequate separation of key activities (integration, debugging, testing, training etc.), and enforcing a strict experimental protocol to ensure the needs of one set of stakeholders do not interfere with the running and analysis of the evaluation.

Phase 2's evaluations focused on understanding the potential impacts of networking intelligent agents within a HM3T and the overall usability of the system and its components. These evaluations must be considered in the context of the relative maturity of the system, its component and user interfaces. The evaluations were the first time that this combination of ADeM applications and system configuration had been implemented; as such the project made no specific efforts to optimise the system or its components to improve Situational Awareness, support TiA or to optimise user interfaces. In effect the project created a baseline for future activities to develop against. The assessments are discussed in more detail in the following sub-sections:

5.1. Effect of networking AIs directly to work together

The analysis indicated that networking AI applications directly has a potentially significant effect in reducing the temporal demand component of workload, i.e. how hurried or rushed operators viewed the pace of the task. Networking applications may also have a potentially significant effect on reducing the mental demand component of workload. These two effects were particularly the case in the air defence and damage control mission events.

In the mission area entry planning, transit and probe events, the analysis indicated that networking the AI applications has a potentially significant impact on the operators' SA, reducing their SA rather than increasing it. It is unknown at this stage whether this was due to the loss of SA that comes from delegating the process of working-up a plan (i.e. delegating to the ADeM applications), the learning effect from running the networked cases first followed by the non-networked cases, or the specific details of the entry planning, transit and probe events.

Similarly, the analysis indicated that there is potentially a statistically significant negative effect of networking the applications on operator's trust in the system.

Finally, the Blue Mirror AI application was used to predict the changes of course output by the Intelligent Ship ADeM applications using only information that an opponent's forces could potentially observe. Depending on the precision of the prediction required, e.g. 40 degree sectors down to 10 degrees sectors, it was able to achieve a 50% to 90% prediction accuracy, which is higher than standard prediction benchmarks, e.g. assuming it will do what it has done most frequently previously etc.

5.2. Usability of the ADeM applications

It was found that the individual ADeM applications themselves had a potentially significant effect on the workload components of physical demand, performance and frustration, and all of the components of the TiA.

For all the operators, each using one to three ADeM applications relevant to their role, the physical demand component of workload was reported as being relatively small. The performance component of workload stretched from low to high, whilst the frustration component stretched from low to very high, with some applications showing a wide range of values. Some operators reported low performance-related workload combined with a high frustration-related workload, whilst others showed high performance-related combined with low frustration-related workload.

For the TiA components, there was a general trend for the ADeM applications for understanding, familiarity, propensity and overall TiA, i.e. some gained consistently high scores and some gained consistently low or wide-ranging scores. This may be explained by a combination of the development path each ADeM application took, its maturity and design language.

5.3. Recommendations

The project has shown that designing HM3T systems requires humans (and their matching UIs) to be considered early and throughout the system's design. It has also shown the necessity of CoA arbitration between machine agents. Based on these issues, it is recommended that future work should focus upon:

- Confirming and understanding the significance of the effects of networking Agents/ ADeM applications on mental and temporal demand related workload, SA and system trust;
- Investigating system robustness and resilience against poor quality data and system component failures;
- Developing further understanding of decision arbitration needs of a collaborative AI and the corresponding required interactions and interventions of operators and decision makers; and
- Creating best-practice design guidance for HM3T.

The Phase 2 Intelligent Ship system was an amalgamation of a range of intelligent agents offered and selected in a competitive call. As such, it was not designed against a specific capability need and this restricted the ability to optimise the design of the interactions with human operators, or to influence the number and roles of those operators. It is recommended therefore that follow-on work should also consider:

- Building on the initial focus on collaborative AI, to understand and optimise the design of the human element of a HM3T system; and

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- Focusing on a more constrained sub-set of capabilities to allow a more optimised approach to system (and hence human interaction) design to be investigated and to enable more robustness testing.

Additional consideration of the following areas would also be beneficial in any activity exploring HM3T:

- Understanding any hardware, software or enabler agent constraints that may negatively influence additional experimentation. These includes a focus on improving standardisation in areas such as data types, messaging and user interfaces;
- Gaining an understanding of how to port the capability to other experimentation systems and platforms and the need to improve, test and implement approaches to internal system messaging and experimentation assessment tools; and
- Focusing on experimental design, e.g. developing schedules that provide separation between training, integration and de-bugging activities and actual experimentation. It is important to consider and allocate sufficient time pre-evaluation to provide sufficient operator training and familiarisation to avoid an evaluation measuring operator inexperience rather than system performance.

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