Securing interoperable and integrated command and control of unmanned systems – validating the UK MAPLE architecture

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SYNOPSIS

Unmanned and autonomous systems have a key role to play in delivering future maritime capability, where this requires an appropriate command and control (C2) architecture to operate a heterogeneous mix of unmanned systems. The UK has made significant progress over the last 5 years in developing such an information architecture known as MAPLE (Maritime Autonomous PLatform Exploitation), as a result the integration of new unmanned systems into MAPLE has become relatively straightforward. The programme has seen its architecture iteratively developed and tested, both in live and synthetic events, most recently in Australia in late 2018 as part of a 5 eyes Autonomy Strategic Challenge. As the fourth phase of MAPLE comes to a conclusion, this paper will underline the progress that has been made in prototyping a solution that has successfully achieved stressing goals around planning, tasking, in mission control and exploitation of multiple heterogeneous unmanned systems. The paper will explore how Phase 4 has also leveraged its open architecture approach and wider research and development into manned-unmanned teaming and automated policy management, giving end users more flexibility and control in terms of vehicle tasking, whilst building overall system trust. As part of this wider focus, Phase 4 has featured an integral focus on concept development, human factors and the non-functional aspects, notably security and safety, all key to the eventual fielding of a MAPLE like capability. The paper will set out specific achievements in these areas and highlights from the final MAPLE 4 demonstrations in May 2019, set out thinking on the next phase, towards implementation, and conclude with a look at a number of MAPLE spin-out projects.

Keywords: Maritime; Autonomy; Unmanned; Command and Control.

1 Introduction

Maritime Autonomous Platform Exploitation (MAPLE) is a multi-phase Defence Science and Technology Laboratory (Dstl) programme, now in its fourth phase and fifth year. The central premise of the MAPLE programme is that the benefits offered by unmanned vehicles (UxVs) or maritime autonomous systems[1, 2] (MAS) can only be secured if operator workload is not increased. UxVs enable navies to "buy back mass", so that a single ship can have the same impact as multiple ships which are not operating unmanned vehicles. But "buying back mass" in this manner is only achieved by operating a squad or swarm of unmanned systems. Currently the deployment and operation of such a collection of off board systems would require multiple operators per vehicle – impractical and unsustainable for anything other than short term operations. Realising the future vision of a MAS enabled Royal Navy therefore requires increased levels of integration and tiered autonomy, reducing workload. This will take the operator out of direct control of the unmanned vehicles, so that a single operator, within a current RN operations room, can plan, task and manage missions involving multiple vehicles. MAPLE is addressing this need for increased integration and autonomy. A second driver for the MAPLE programme is the recognition that the lifecycle of unmanned systems is significantly shorter than that of host platforms, with many iterations and instances of UxV requiring integration over the life of a warship; consequently, reducing the burden of integration and increasing the commonality and durability of interfaces, including those with the operator is highly desirable if agility and

[1]MAS (Ref 6) are defined as off-board vehicles or equipments that operate in the maritime and littoral environment without the physical presence of human operators, although this does not preclude operators being necessarily engaged with the remote operation of the system, and the associated C2, handling and maintenance facilities. This is distinct from the autonomy increasingly being introduced for the control of onboard systems such as propulsion machinery or for remote compartment monitoring.

[2]An autonomous system (Ref 6) is capable of understanding higher level intent and direction. From this understanding and perception of its environment, such a system is able to take appropriate action to bring about a desired state. It is capable of deciding a course of action, from a number of alternatives (sic), without depending on human oversight and control, although these may still be present. Although the overall activity of an autonomous system will be predictable, individual actions may not be.

Authors' Biographies

Philip Smith is the Above Water Systems Programme Manager in Dstl, directing research conducted by Dstl and Industry focused on de-risking technologies and processes to enable the Royal Navy to build Affordable, Available and Survivable surface ships, which are able to operate freely in International and Territorial waters in support of UK interests.

Bill Biggs leads QinetiQ's work on Autonomy including the QinetiQ Maritime Autonomy Centre, with its particular focus on unmanned systems in the maritime environment. Prior to joining QinetiQ, he enjoyed an interesting and varied first career in the Royal Navy as a surface Weapon Engineer. His service included several roles in acquisition and systems engineering and sea appointments in HMS INVINCIBLE and HMS MONTROSE. Most recently, he was Deputy Assistant Chief of Staff, in Maritime Capability in Navy Command.

rapid updates cycles are to be achievable and affordable. A high level schematic of MAPLE 4 functionality is shown in Figure 1.

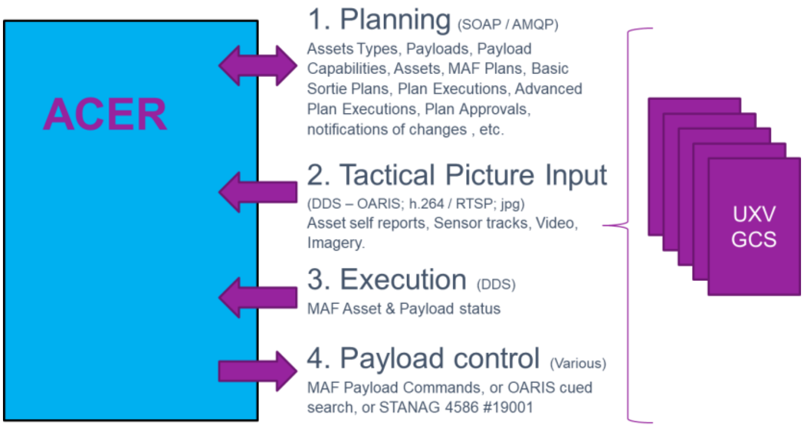

Figure 1: High level schematic of MAPLE 4 functionality

2 A Phased Approach

MAPLE has been delivered by a joint team of Dstl, QinetiQ, BAE Systems, Thales and SeeByte. Phase 1 of the programme was a feasibility study into Maritime UxV focussing on their management and governance, UxV command and control (C2) requirements and architectures, and the potential for exploitation of UxV capability into the RN (Biggs et al, 2015). The main output from Phase 2 was the development of the persistent architecture (PA) for the C2 of autonomous systems and a better understanding of the role of the human as part of delivering the autonomous capability on a warship (Smith et al, 2016). Phase 3 was designated Autonomous Control, Exploitation and Realisation (ACER) and its aim was to integrate existing capability as a showcase at Unmanned Warrior 2016 (UW16) of an early implementation of the RN approach to integrating off-board assets and their payloads into the combat system (Smith et al, 2017).


Figure 2: MAPLE in Australia as part of Autonomous Warrior 2018 (AW18)

The most recent phase of the programme Phase 4, which concluded in June 2019, has been two years in duration (Smith et al, 2018). It featured three iterations, the first of which matured the PA, established a comprehensive Synthetic Environment (SE) and enhanced the ACER system for a major synthetic event (Syn Bay) in Autumn 2017. The second stage of Phase 4 focused on the continued maturation and validation of the PA and enhancements to ACER, culminating in a 5-eyes The Technical Cooperation Programme (TTCP)[3] event in Jervis Bay Australia in November 2018, called Autonomous Warrior 18. This was an opportunity for international collaboration and benchmarking on a scale not seen since the conclusion of the Hell Bay series at UW16. Following this trial the final stage focused on more advanced tiered autonomy, folding in the non-functional and communications work and it culminated in a final live event at Cardigan Bay 19 (CB19) in May 2019.

[3] The UK involvement in Autonomous Warrior 18 was in response to an "Autonomy Strategic Challenge" set by the TTCP Principals. This challenge has the intent of bringing together work from across the TTCP community to drive the pace of unmanned vehicle exploitation. As well as bringing together a range of unmanned vehicles that cover the full spectrum of air, surface, underwater and ground vehicles, the event also integrated a set of Command and Control tools from Australia, USA, Canada & UK to deliver a significant level of autonomous and digital command and control. The build up to the live event included a series of international synthetic serials, referred to as Wizards, the last of which was Wizard 4 in Sydney in Summer 18.

Figure 3 shows how the final phase of the programme has been executed, including the major design artefacts and the design gates. Based on a mixture of study, design, experimentation and demonstration, adopted a 3 staged iterative and spiral development approach whereby small increments of "autonomy" have been envisaged, tested with a Stakeholder community and then assessed in terms of operational utility and feasibility of delivery. The requirements phase of each spiral has seen the concept of employment (CONEMP) and the MAPLE user and system requirements documents (URD and SRD) reviewed and updated.

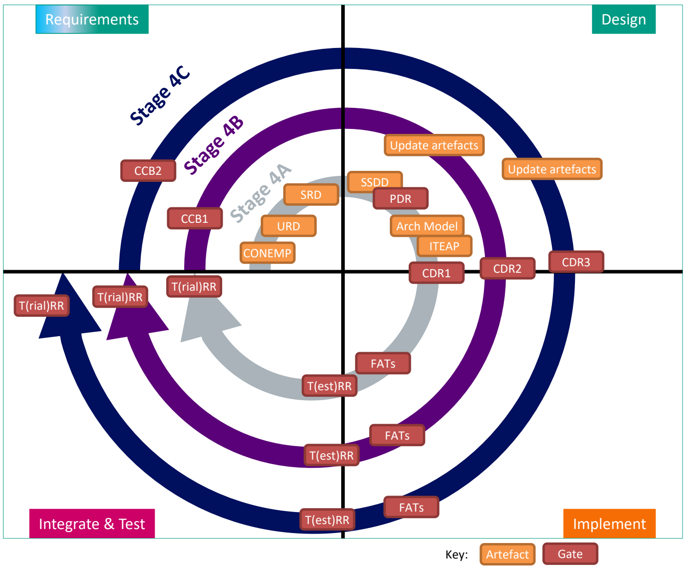

Figure 3: MAPLE 4 Spiral Development Approach

The design phase entailed sub system definition (SSDD), architectural modelling and planning for integrated test and evaluation (ITEAP), as well as preliminary and critical design reviews (PDR & CDR). This was followed in the implementation phase by factory acceptance tests (FATs) and a test readiness review. Once integration and test were completed the increment then underwent a trials readiness review.

In order to develop and test the architecture a set of scenarios has been developed; these scenarios were developed with end users to ensure operational credibility and to expose the key information flows and operational processes. The features of each scenario were examined against the required scenario characteristics above to ensure that the combination of these scenarios would allow validation of the PA and demonstrate capabilities of the MAPLE system. The three scenario types that were of particular interest to the customer were: extended range situational awareness (ERSA); mine-countermeasures (MCM) in support of littoral manoeuvre; and, harbour protection. These scenarios were extensively utilised in synthetic demonstrations, with a subset of use cases being used for the live trials. The latter including a particular focus on surveillance and arms smuggling; counter piracy operations; and infrastructure attack from surface craft.

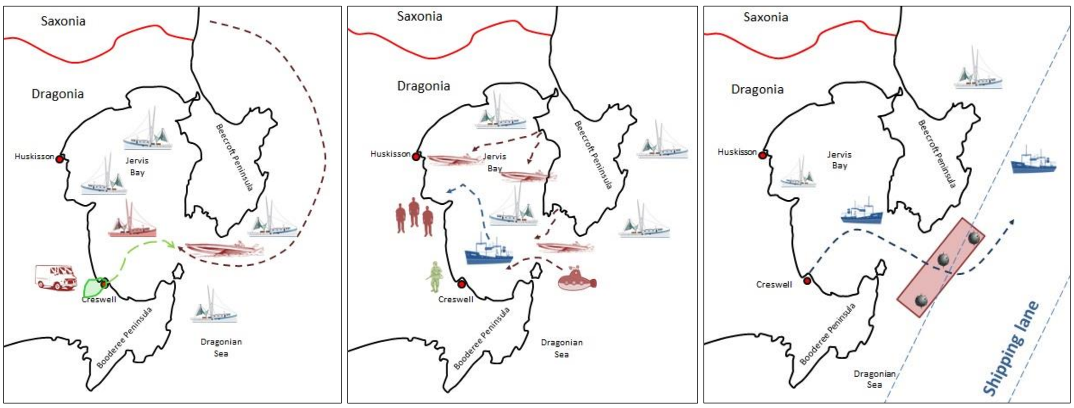

Figure 4: Core scenarios used at AW18: Arms Smuggling, Base Protection & Mine countermeasures
(Clip art curtesy of Publicdomainvectors.org)

3 Validating the MAPLE Architecture

The PA has been modelled in detail in Enterprise Architect a high level view is shown in Figure 5, the red dotted line indicates the area of principle focus and the scope of the validation activity.

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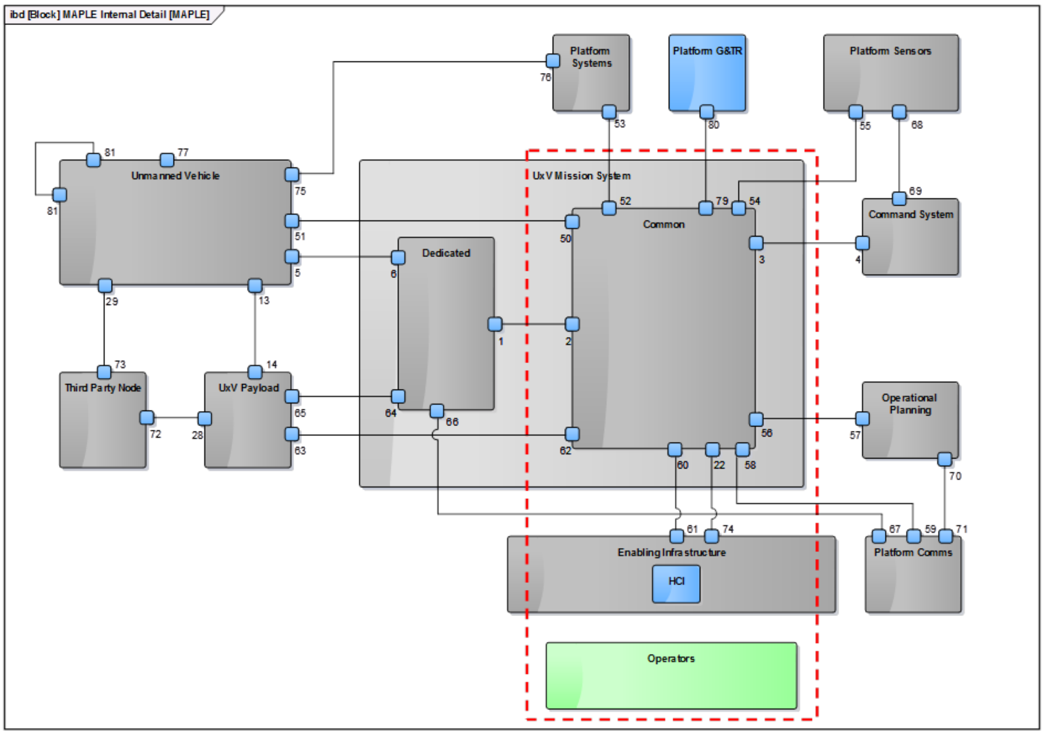

Figure 5: MAPLE 4 Persistent Architecture – High Level View

A simplified view of the common (as opposed to vehicle specific) C2 components of the PA is shown in Figure 6.

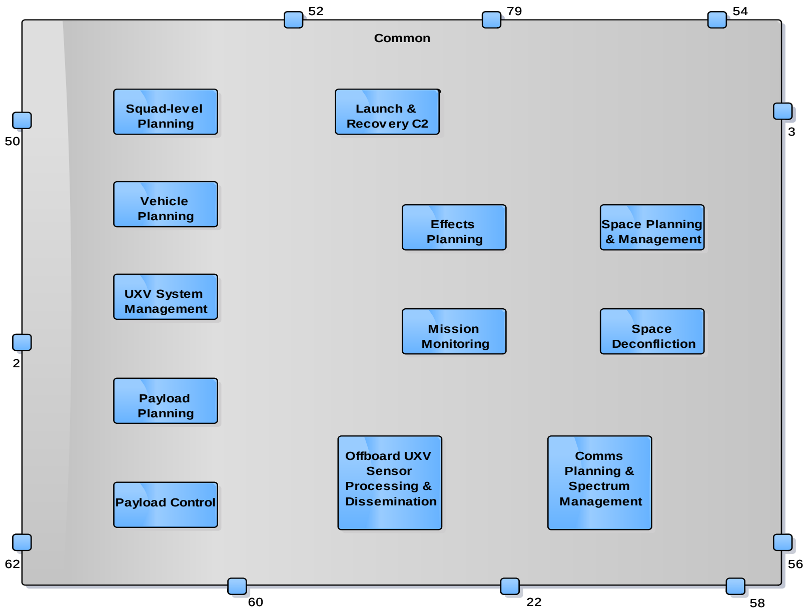

Figure 6: MAPLE 4 Persistent Architecture – Common C2

The ACER demonstrator has been progressively adapted and updated to deliver a sufficient implementation of the PA (ACER 2.1.3 was fielded in AW18 and version 2.2 at CB19). ACER itself provides a flexible capability that allows modular components to be inserted into an existing open combat system, which is a realisation of the Combat System Architecture Model (CSAM) maintained by the Maritime Combat System organisation within Defence Equipment and Support (DE&S). The ACER system utilises the Open Architecture Combat System (OACS) Infrastructure, which is based on operational system components (including a Shared Infrastructure) similar to the combat system architecture that is being deployed in-service in the RN. In addition to core services provided by OACS, the heart of ACER is a shared data core and a set of interfaces based around open standards for data exchanges: OARIS for track data, ALMAS for alerts, NNSI for navigational data and OGC for chart and geospatial data. During MAPLE 4 this was greatly extended to include support to STANAG 4586 and Dstl MAF open interfaces. It is this data core and these interfaces which underpin ACER and in turn MAPLE as an information architecture.

A high level view of the ACER2.1.3 demonstrator, showing the superset of applications, including those established at UW16 is shown in Figure 7. Shown clearly are the components which have been drawn from other

Dstl research programmes, Collaborative Autonomy (CA) and MAF.

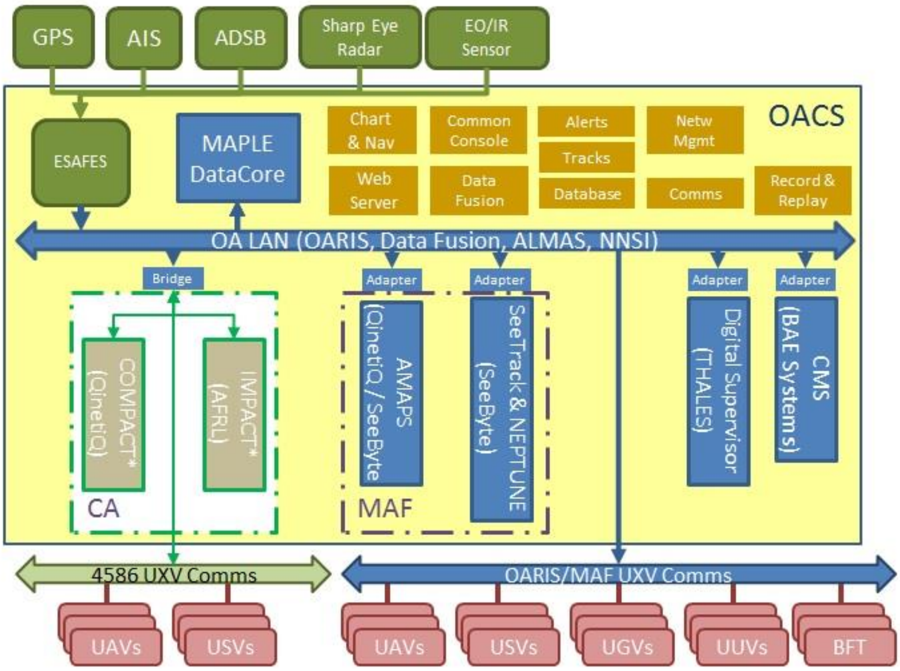

Figure 7: ACER2.1.3

The ACER2.1.3 implementation provides a representative RN combat management system, 2 levels of mission planning (Tier 1 and Tier 2) as well as the vehicle specific C2 components for a number of vehicles. It also has applications which support policy management and data analysis, reducing operator loading; and tools which allow a single operator to re-task vehicles in mission. However ACER is not intended to be a complete implementation of the PA, only allowing sufficient coverage for validation and research purposes. Further, beyond limitations in scope, ACER has not been designed for operational use, and therefore it does not currently meet the necessary requirement for availability and resilience. Whilst many of the components utilised within the solution are already operational, the Technology Readiness Level (TRL) for the set of integrated components deployed on the ACER system is TRL 5/6 with all of the components are to be operated by the component provider. Finally, to confirm its current role as a demonstrator, ACER operates at no higher than OS classification in accordance with the specific Authority or Customer requirements.

The Validation Plan produced for MAPLE 4 identified 9 generic and 14 specific validation criteria. The generic criteria have been successfully validated through architectural review, whereas the specific criteria have been progressively assessed as part of the experimentation programme. The generic criteria featured: completeness/ consistency of the information and service architecture; adaptability, conceptual integrity; layering to separate out enabling Infrastructure; modularity (low functional coupling and high functional cohesion; openness; satisfaction of need; separation of concerns; and, subsetability. The specific criteria related to the core functionality of the architecture; these included:

- The architecture’s support to the MAPLE 4 use cases and scenarios.
- The architecture’s agnosticism to payloads and vehicle types; its independence of domain and its ability to support multiplicity of vehicles.
- The extent to which the multi-domain control system (MDCS) concept (forthcoming STANAG relates, STANAG 4817) is enacted and can be assessed.
- The degree to which the anticipated levels of autonomy (under Phase 2) have been generated
- The operability of the system with current complementing (a core MAPLE premise), utilising the mission system interfaces.
- Resilience and performance of the architecture to likely failures and the noting the constraints enforced by meeting the requirements of the safety, security and communications architectures.

In addition to this validation work, the latter phases of the programme have seen extensive work to explore the human factors (HF) aspects of ACER2.1.3, and by extension MAPLE. This has included: extension of the HF elements of the PA, followed by modelling and analysis using a tailored approach; Early Human Factors Analysis; and, experimentation design to allow exploration of the impact on operators of the level of autonomy within the system, the number of assets and the adaptability or adaptive –ness of the system[4]. This work fed into the design of the live and synthetic experiments. Two levels of autonomy were explored, high and realistic (as considered by relevant subject matter experts). Six areas were identified for specific investigation in the HF work:

- Vehicle & Squad level planning: Launch & recovery
- Space planning & management: Understand battlespace limits & identify need for more battlespace
- Space de-confliction: Battlespace conflicts
- Mission monitoring: Monitor UxV mission
- Offboard sensor exploitation & planning: Assess sensor information
- UxV C2 Track based tasking

Full and final analysis of this work is still concluding, but overall performance was not statistically different between realistic and high levels of autonomy, in part driven by operators being intuitively more comfortably and familiar with the lower level systems. The experiments also pointed up issues with the current human computer interface. That said, once the team was established, a small team of 4 were able to operate with in excess of 20 assets. The experiments covered operationally realistic ranges, therefore some of these vehicles were in states demanding limited operator oversight, such as transit out to operational areas, but this was considered an operational reality. Of note, the experiments did see significant changes in workload and performance[5] as: autonomy performance varied due to factors such as environment; or mission complexity increased. Adaptable and adaptive solutions were seen to support operators in managing these variations, but trust was unsurprisingly a key factor and all practicable systems are likely to have limitations in their ability to manage complexity and poor quality inputs. This rather unsurprising insight is a reminder that in the fog of war, sometimes all a Commanding Officer can do is 'fight what they can see', not unduly worrying on what they do not know. Regarding trust, it was clear that operators needed to fully understand 'what's going on underneath the hood' and there was a preference for modes that retained operator control, an example being a reference for operator controlled adaptable autonomy, vice a fully adaptable system which adapted autonomy levels without reference to the operator.

Figure 8: The Ops Team in one of the MAPLE Synthetic Experiments

4 Wider use of the MAPLE Architecture: beyond MAPLE 4

Building on the success of MAPLE, a number of related projects have extended or developed on the MAPLE baseline. QinetiQ, working with support from the RN and Dstl, are now working on a European Union project, Ocean 2020, a research action which addresses the opportunities presented by UxVs for surveillance and situational awareness in the maritime domain. With demonstrations planned in the Mediterranean (2019) and Baltic (2020), the project has 42 partners

[4] Adaptable autonomy presumes a human determination as to the appropriate level whereas adaptive autonomy is based on a machine based determination of the level of autonomy and human involvement (within defined constraints).

[5] As measured by Situation Awareness (SA) probes, Task Load Index (TLX) and Instantaneous Assessment of Workload (ISA)

including a number of EU navies and research institutes.

In the sphere of asset protection, Dstl are running a parallel autonomy demonstration programme, AMAPS (Autonomous Management Asset Protection System) with a MAPLE core using UxVs above and below the water to protect a high value asset; AMAPS is a UK/US programme with a demonstration planned for Summer 2020.

Pointing to end user interest in Autonomy and the drive for rapid fielding of autonomous systems, the RN have recently launched an accelerator programme and associated programmed team under the title of NavyX. A key strand of NavyX is operational experimentation and MAPLE, and the deployable ACER demonstrator (both in ISO and peli-case form) is already positioned to support this work. A first iteration of this operational experimentation, Advanced Autonomous Force, was conducted in March 2019 and more serials are planned in September and November of 2019. This work will increasingly have an international dimension under the NATO maritime unmanned systems (MUS) grouping. The expectation is that this work will seek to accelerate the incorporation of a subset MAPLE functionality into RN platforms (and not just commercial trials platforms), most likely with an interface into the RN's Artificial Intelligence programme, Project NELSON, which is on its own deployment pathway. Non-functional considerations will be key in the early stages of this progressive migration of MAPLE into deployment.

Looking forwards therefore is an emerging requirement for MAPLE to meet 3 core needs: to answer the remaining research objectives; to support and act as a core for a growing body of unmanned systems experimentation (as the information architecture and data core), mainstreaming user interaction as part of NavyX; and to be part of forcing function which takes MAPLE like functionality to sea on an RN warship. Whilst these 3 needs overlap and have mutual dependencies they are likely to be tasked separately and may, subject to agreement, see separate teams undertaking delivery.

In terms of remaining research goals, there is work to do to refresh the user interface and to progress and deepen our understanding of the human factors aspects of MAPLE. Force aspects of MAPLE deployment, including multiple MAPLE instances and delegation of command and or control of UxVs, alongside more work into adaption are all potential areas of work. Alongside this some targeted application development and some support to standards development will likely be required. Recognising the need for a hand off into main-stream acquisition part of the work will need to address making MAPLE procurement ready, identifying the procurable entities and specifications and documentation such as URDs & CONEMPs.

5 Reflecting on the achievements to date

Over the last 5 years, MAPLE has been on a significant journey enabled by a stable and highly productive collaboration between Dstl and 4 industry partners. Literature suggests others have developed some similar components, but nowhere else internationally has there been the same consistent focus on multi-vehicle C2 within an open architecture, and on the practical components required to unlock the potential benefits of solutions employing large numbers of unmanned systems in the maritime. Whilst there is still research and development still to be done, the four phases to date have:

- Developed and validated a persistent architecture that sufficiently describes a solution which can integrate multiple heterogeneous unmanned systems together operating warfare disciplines and domains without either driving up operator numbers[6] or, within limits, overloading existing operations room teams.

- Developed and promulgated a common set of open standards and interfaces that have underpinned a significant body of international research and which will support the agile and flexible delivery of interoperable solutions for the Royal Navy.

- Undertaken a concerted programme of both architectural development and trials and evaluation, using live events and synthetic experiments, building in complexity and scope to prove the feasibility and benefits of the persistent architecture and to provide a baseline for future work.

- Established a deployable research and development demonstrator capability, based around existing components and targeted new developments that has allowed meaningful user engagement at sea and in shore based experiments to test and hone candidate concepts and uses cases and to shape the solution using military judgement and an understanding of human factors. This demonstrator is at the core of the Royal Navy's operational experimentation programme for autonomous systems as part of the new NavyX accelerator. Underpinned by open standards, relative ease of integration of new systems will be central to the future use of this demonstrator.

- Pushed boundaries with the fielding of multi-vehicle heterogeneous squads, employing surface, underwater, ground and air vehicles, broadening employment from mine countermeasures and single vehicle ISR missions into a broad set of missions. In diversity of UxV alone, the achievement is significant and believed to be unmatched: 48 different vehicles integrated from 23 organisations representing 8 countries in 5

[6] But noting the need for some rebalancing and reallocation of existing roles to achieve this.

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environments[7].

- Introduced novel components into the persistent architecture and demonstrator that allow team based planning, tasking, management and exploitation of multiple unmanned systems. These include a hierarchy of planners, a data core, data analysis and exploitation using AI, functionality to allow dynamic replanning and in-mission tasking of systems from within the core C2, and the introduction of a policy manager to underpin trust and provide user assurance. This work has exploited S&T research sponsored by MOD programmes in other areas, notably Maritime Autonomy Framework (MAF) and Collaborative Autonomy.

- Used tools that permit a less centralised and more delegated form of C2 and which pave the way for force level capability and the passing of control and tasking between platforms and users.

- Generated a much greater understanding of the options for delivering safe, secure and accreditable solutions.

6 Conclusions

MAPLE has had a very successful 5 year history and is now poised to be a cornerstone for the RN's plans for autonomy into the future. There is still important research to be done, but the project is increasingly being broadened out, with potential work to support new use-cases, to act as a core for multinational operational experimentation and to support fast track plans for fielding of a prototype capability at sea.

Future success will require continued collaboration, not just between the partners to date, but also including new players as part of both future research and any work under NavyX. In this endeavour, MAPLE has shown what is technically feasible, but end user desire for this to be delivered at pace and with agility will require a new level of industry partnership and a willingness to work together to address significant issues, not least around safety.

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[7] UW16: 25 vehicles, 12 organisations, 7 countries; AW18: 14 vehicles, 10 organisations, 5 countries, 5 environments (including human); CB19: 11 vehicles, 5 organisations.