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Early Assessment of Drone Fleet Defence in Depth Capabilities for Mission Success

Nikolaos Papakonstantinou, VTT Technical Research Centre of Finland

Ahmed Z. Bashir, Department of National Defence of Canada

Bryan O'Halloran, Naval Postgraduate School

Douglas L. Van Bossuyt, Naval Postgraduate School

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SUMMARY & CONCLUSIONS

Advancements in the domain of artificial intelligence, safety management, and on-board fault tolerance have led to autonomous devices to be considered as a key element for future remote defence and peaceful missions. Drones - also known as autonomous or unmanned vehicles - with different capabilities and features - can be organized in a fleet and the fleet can be organized in a way that will increase the survivability of the drones and improve mission success. This can be accomplished by balancing system effectiveness design parameters such as endurance, communications, sensor fusion, domain awareness, area coverage rates and human operator interaction against mission costs.

To manage the organization and operation of drone fleets, many high-level factors and their inter and intra-dependencies must be understood by the designer of the mission. These include but are not limited to strategic, tactical, warfighter, socio-technical, economic, security, and regulatory factors.

Defence in Depth (DiD) is an established strategy for designing cyber-physical systems with improved reliability, safety and security performance and is suitable for complex systems executing complex processes. However, DiD has not been shown to be applicable to the requirements definition and early portion of the design process before costly decisions are made. As such, the contribution of this paper is a methodology for early assessment of basic DiD characteristics of a drone fleet based on its dependency model and a other DiD-related attributes. The DiD principles that are evaluated in this paper include Redundancy, Diversity, Functional Isolation and Physical Separation. A Unified Modelling Language (UML) profile is created to define the attributes needed to support the modelling process.

The methodology presented in this paper is applied to a fleet of autonomous and manned devices on a Naval Mine Counter Measures (NMCM) mission. The interfaces as well as the dependencies are identified and modeled. The UML model of a fleet consisting of autonomous, remotely-operated, and manned underwater, surface, and air vehicles is evaluated using a prototype software tool against the DiD characteristics and a report is provided to the designer of the NMCM mission.

1 BACKGROUND

This section presents a basic background for model driven engineering, the importance of drones in defence missions and the value of DiD in the nuclear industry. This paper builds on past work on early DiD assessment of complex systems using dependency models (with a nuclear plant case study) [1]. The proposed methodology introduces key DiD concepts from the nuclear domain to drone fleet design for defence missions. The methodology also builds on past work on onboard machine learning and fault tolerance considerations for long endurance Autonomous Underwater Vehicles (AUVs) [9].

1.1 Model-driven complex system engineering

Model-driven complex systems engineering can be viewed as the use of graphical machine-readable models/diagrams to capture the topology, behavior and dependencies throughout the lifecycle of a system [2, 3]. The system can be a process (such as a power plant), a machine, a grid (e.g. electrical or heating grid), or a system of systems (a fleet). UML [4] was first developed for software modelling but UML has evolved toward different engineering domains. UML contains the mechanism of "Stereotypes" to capture new concepts. UML "Profiles" group UML stereotypes and allow modelling of a new domain. In this work we use UML's class diagram with the classes further specialized by stereotypes related to drone fleet elements. Free open source tools exist for UML modelling [5], which has helped adoption by academia and industry [6]. The UML models can be exported as standard XML files [7] for further processing by software tools.

Previous work [1] presented a methodology for the development of a UML High Level Interdisciplinary Model (HLIM) to capture complex system dependencies for early DiD assessment. The different system disciplines were process, power distribution, cabling, automation, human factors, and environment. The dependencies were between components of one system aspect (discipline), the interfaces between disciplines, and the interfaces between the system under development and its surroundings. In this paper, the HLIM

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profile was extended with stereotypes related to defence mission fleet modelling.

1.2 Defence missions, importance of drone fleets currently and in the future

Modern Navies must acquire new or enhanced naval intelligence, surveillance, and reconnaissance systems, upgraded armament, and additional systems for current and future platforms allowing for more effective offensive and defensive naval capabilities [8]. The NMCM mission commander will need such systems to clear sea mines and several Navies around the world have either deployed systems or are in various stages of acquisition. Acquisition of these systems is necessary in order to remain cost-effective yet achieve a mine clearance rate as high as 99% in as short a time as possible. An effective operational NMCM capability must be a modular, stand-off NMCM capability. This will provide Navies with a capability to conduct the full spectrum of naval minehunting operations, seabed mapping, and contribute to underwater domain awareness. The full spectrum of minehunting operations means to detect, classify, localize, reacquire, identify and dispose of sea mines and/or maritime improvised explosive devices (IEDs) that pose a threat to domestic interests, sovereignty, or impede the conduct of maritime operations by national or allied ships. (For the purpose of this document, all references to sea mines will include conventional sea mines and maritime Improvised Explosive Devices). In order to meet the requirement for modular stand-off operations and the system effectiveness criteria, autonomous vehicles with greater complexity but reduced costs must be used in greater numbers with future NMCM systems. NMCM missions, when executed successfully, will maintain national and international political, social, and economic interests. For example, if a country has busy container ports, closure of the ports could result in an economic disaster.

Unmanned Launch and Recovery Systems, Unmanned Surface Vehicles (USVs), Unmanned Aerial Vehicles (UAVs), AUVs and Remotely Operated Vehicles (ROVs) (drones) are becoming increasingly used in defence missions because of advantages related to keeping the crew and mother ship far away from the minefield, ease of deployment and recovery, machine learning, on-board fault-tolerance, and artificial intelligence. Mission Planning and Analysis software tools are portable and easy to use. However, the major reason for this network-centric approach is open architectures and commercial standards for software and interfaces. Refer to previous work on fault tolerance of AUVs [9] for further background information.

1.3 The Defence in Depth concept

Historically DiD was a concept born in the military/defence domain. In that context it is defined as “the siting of mutually supporting defensive positions throughout the main battle area to absorb and progressively weaken the attack” [10]. Later, the basic DiD principles were applied to safety-critical domains like the process industry [11], oil & gas [12], material mining [13] and medicine [14]. DiD has also been very important in nuclear safety engineering [15-18].

The main DiD principles used in the proposed methodology are:

a) Functional isolation: the idea that a critical system function is duplicated into two redundant functions that should share no dependencies (common cause failure points).
b) Diversity: components mapped to redundant functions should use different technologies in order to avoid common faults between the redundant functions.
c) Physical separation: the components mapped to redundant functions should be located in spaces with satisfactory separation (enough distance and/or physical barriers) to avoid failures in one redundant function to affect the other.

The domain of this research -- fleets of manned and unmanned machines -- require the introduction of the “dynamic space” concept. This means that fleet components are allocated to dynamic spaces (they move during the mission) and the physical separation principle should be constantly monitored during the mission (i.e. fleet members mapped to redundant functions should not come too close to each other while the mission is being executed). The methodology presented in this paper supports the assessment of these basic principles using an early dependency model of a fleet to provide feedback to the mission commander before costly decisions are made.

2 METHODOLOGY

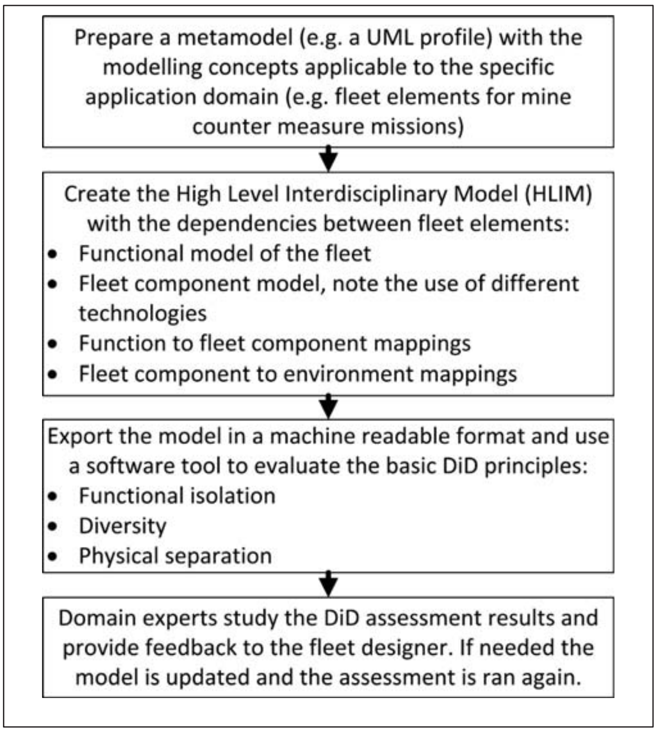
2.1 Methodology workflow

The workflow of the proposed methodology for using a dependency model to assess basic fleet DiD capabilities is presented in Fig. 1.

The first step is to develop the domain specific metamodel that will enable the modelling of the system/process of interest. In the case study, the HLIM UML profile [17], developed in previous work with a focus in the nuclear domain [1], was extended with additional stereotypes to cover the modelling concepts relevant to defence mission fleets. The focus was on the Naval Mine Counter Measure (NMCM) domain. A fleet element is defined as any modelling element relevant to the fleet which includes a function, a physical fleet member, or an environmental space. Fleet components are only the physical members of the fleet (e.g. surface vessels, unmanned vessels, etc.)

The next step is to build the dependency model of the fleet. The main diagram is the functional decomposition of the fleet with special attention paid to add the functional redundancy information. For instance, if two sub-systems perform the same function and the fleet can still perform its mission if one of them is lost. The model of the fleet components captures the interfaces between all the members of the fleet. Then these fleet components can be mapped to the fleet functions and to environment spaces.

After the dependency model is ready, it is then analyzed by a software tool, developed as part of this research, to assess the DiD capabilities of the fleet design. The tool first identifies the redundant functions and mapps the fleet components to the functions. For functional isolation, the requirement is that redundant functions share no components and that components mapped to redundant functions share no common dependencies.



Prepare a metamodel (e.g. a UML profile) with the modelling concepts applicable to the specific application domain (e.g. fleet elements for mine counter measure missions)

Create the High Level Interdisciplinary Model (HLIM) with the dependencies between fleet elements:
- Functional model of the fleet
- Fleet component model, note the use of different technologies
- Function to fleet component mappings
- Fleet component to environment mappings

Export the model in a machine readable format and use a software tool to evaluate the basic DiD principles:
- Functional isolation
- Diversity
- Physical separation

Domain experts study the DiD assessment results and provide feedback to the fleet designer. If needed the model is updated and the assessment is ran again.

Figure 1 - An overview of the proposed methodology for early DiD assessment of fleets for defence missions.

The diversity property is checked by comparing the technology used in components of redundant functions. In the example presented here, this technology is a property of the fleet component (like TechnologyA, TechnologyB, etc.)' in real-world cases, the different technologies can be different models (and suppliers) of unmanned vehicles or a very different approach such as using air drones in one redundant function and unmanned surface vessels in another. The third DiD principle is the physical separation of fleet components mapped to redundant functions. In a static system like a machine or a plant, this can be easily reasoned based on the mappings of components and the physical layout. In the case of fleets of devices, this is more interesting because the fleet components are moving. The software tool can identify the dependencies that exist between the dynamic spaces allocated to fleet components and generate a list of requirements for dynamically monitoring the fleet during the mission so that fleet components of redundant functions do not come close to each other.

The results of this early DiD assessment should be evaluated by domain experts. It is possible that some dependencies that "break" DiD principles are judged to be insignificant (the risk can be accepted) or unavoidable. Other results may lead to feedback to the fleet designer who can revise the model and run the DiD assessment again.

2.2 Small generic example

The proposed methodology is presented with the small generic example of a fleet presented in Fig. 2. The fleet's main mission can be performed by two redundant functions A and B. The fleet has three components including component A and component B, which are mapped to the corresponding redundant functions, and component C which has dependencies to the first two components. All the fleet components are mapped to dynamic environment areas that are linked to the area of operations for the mission.

In this example, the assessment first recognizes the redundancy between function A and function B. Then it checks if the functions share fleet components (they do not). Next, the assessment reasons if the components A and B have any shared dependencies; component C is identified as an issue that can be a common cause failure point which would result in disabling both redundant functions A and B. The assessment continues by evaluating if components A and B are diverse (in this example they are both unmanned air vehicles, but they come from different vendors, so the check is satisfied). Then the assessment recognizes the dynamic environments (air volume spaces) mapped to the fleet components and to the area of operations. The result is that during the mission, it is required that the dynamic environments A and B should not overlap to protect the physical isolation of the redundant functions.

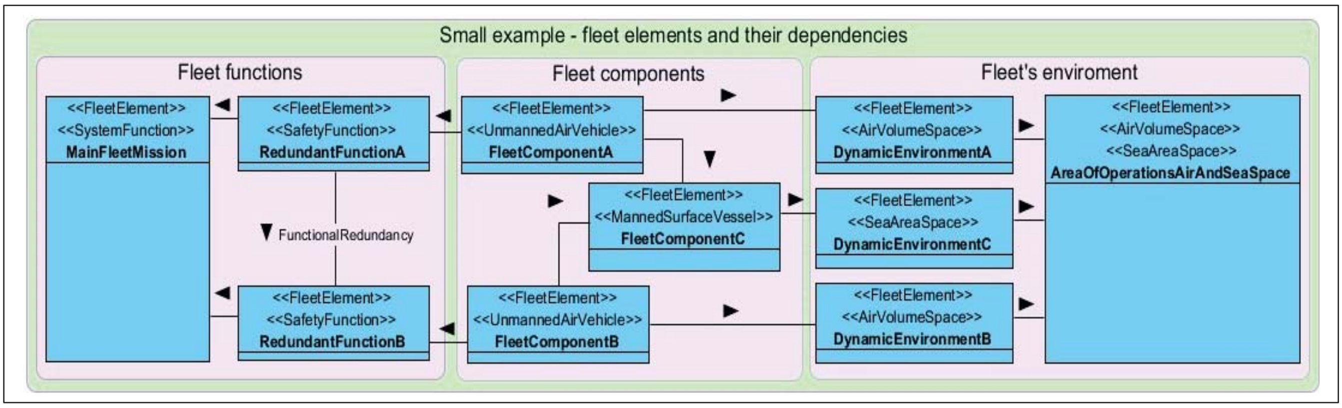

Small example - fleet elements and their dependencies
Fleet functions
Fleet components
Fleet's enviroment
<<FleetElement>> <<SystemFunction>> MainFleetMission
<<FleetElement>> <<SafetyFunction>> RedundantFunctionA
FunctionalRedundancy
<<FleetElement>> <<SafetyFunction>> RedundantFunctionB
<<FleetElement>> <<UnmannedAirVehicle>> FleetComponentA
<<FleetElement>> <<MannedSurfaceVessel>> FleetComponentC
<<FleetElement>> <<UnmannedAirVehicle>> FleetComponentB
<<FleetElement>> <<AirVolumeSpace>> DynamicEnvironmentA
<<FleetElement>> <<SeaAreaSpace>> DynamicEnvironmentC
<<FleetElement>> <<AirVolumeSpace>> DynamicEnvironmentB
<<FleetElement>> <<AirVolumeSpace>> <<SeaAreaSpace>> AreaOfOperationsAirAndSeaSpace

Figure 2 – A small example of a fleet with manned and unmanned components. It includes a simple functional model, a model of the fleet components and their allocation to the environment.

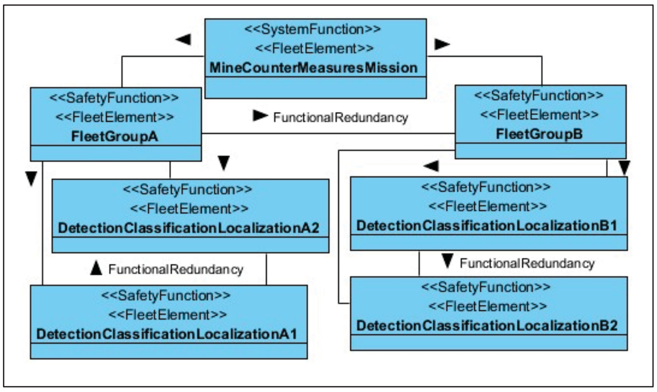


Figure 3 – The functional model of the case study. Notice the functional redundancy between the two fleet groups and within these groups the functional redundancy between the mine detection function.

3 CASE STUDY

In this section, the methodology is applied to a generic NMCS scenario inspired by the Remote Minehunting and Disposal System (RDMS) project [19] and the Minewarfare Association's 2017 Essay Contest first (Scott Savitz) and second (Daniel Stefanus) prize winners [20]. The background is that there is a need for a quick response to the event of mining of a major Eurasian trade route. This mining operation actually occurred. "In the early hours of July 6, 1984, a small merchant vessel glided out of her Libyan homeport bound for the crux of Eurasian trade: the Suez Canal. Her crew was gone, replaced by sailors hand-selected by Libyan dictator Muammar Gaddafi. A few days later the sailors quietly lowered their cargo into the Red Sea: deadly Soviet mines. In the coming weeks panic rippled throughout the region as 19 vessels reported striking mines near the Suez Canal. Global trade shuddered, its agents more self-conscious than ever of the system's fragility. The world's powers raced to sweep the region free of mines and terror, but the United States, the West's naval hegemon, was forced to take a backseat due to a lack of ready, deployable mine countermeasure forces. A few dozen Soviet mines laid by a third-rate power in an act of state-sponsored terrorism had rendered the world's greatest naval power impotent" [21]. In the case of the 1984 Libya incident, it was not destruction of merchant vessels that Libya cared about; it was the fear and international turmoil that laying inexpensive mines causes which Libya was interested in creating. This is the asymmetric threat – a few state actors that can paralyze allied nations and a Eurasian trade route – on which this case study is based.

The AUV mission planning component of the Transportable Command Centre Sub-System provided a solution for the planning for clearing the mined channel. Three medium weight AUVs and three man-portable AUVs were launched into the water at the same time, leaving one of each onboard the two Maritime Coastal Defense Vessels (MCDVs). The two mine disposal subsystems complete with their ammunition and explosives pre-loaded were launched from Rigid Hull Inflatable Boats (RHIBs) carried on the MCDVs with their operators. After successful reacquisition of the mines, the operators destroyed the mines and verified this using the training/inspection vehicles. Furthermore, the successful destruction of the MDS vehicles themselves was verified.

As the channel to be cleared was very deep, the 200m depth capability of the medium weight AUV was invaluable in surveying the bottom for any bottom mines that may have been deployed.

The functional model for this fleet contains two redundant functions (fleet group A and B), both capable of performing the NMCM mission. The mine detection in each fleet group is performed by two redundant functions, see Fig. 3.

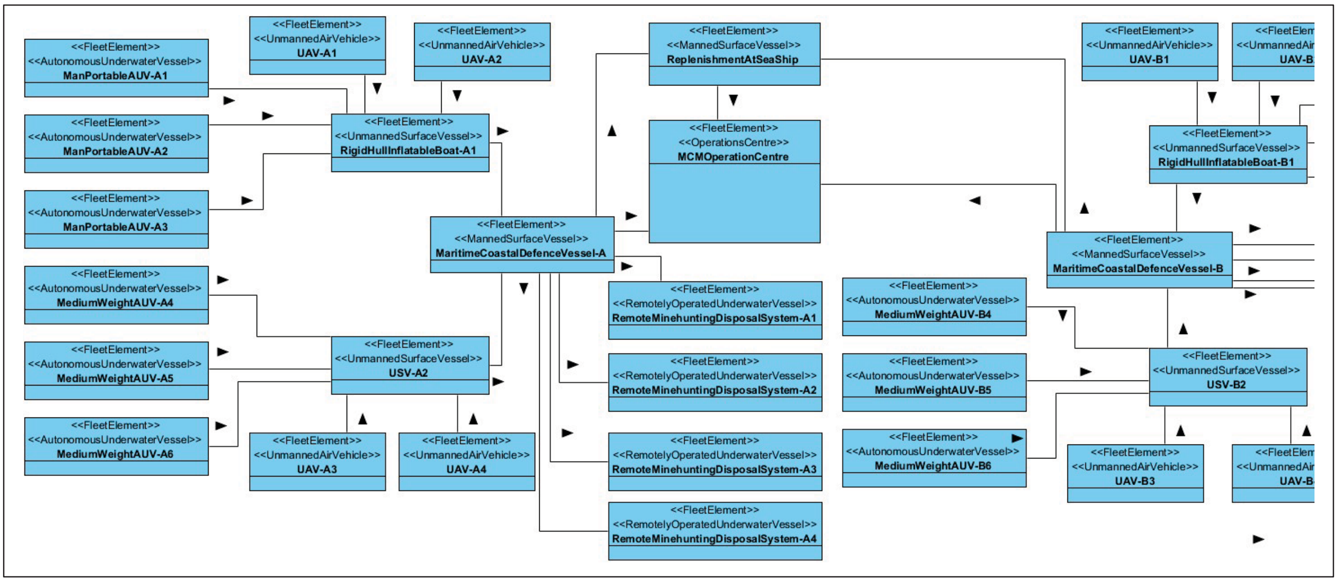
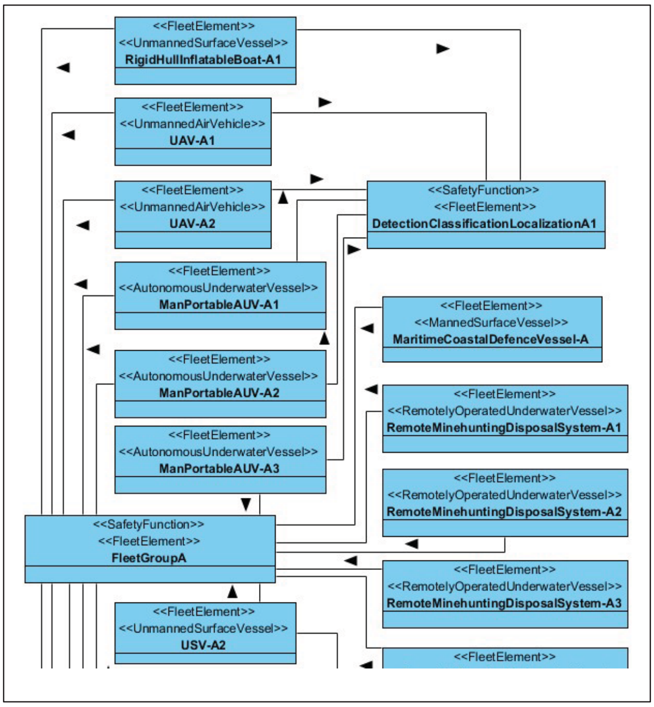


Figure 4 – The dependencies between the fleet components of the case study (partial).



<<FleetElement>>
<<UnmannedSurfaceVessel>>
RigidHullInflatableBoat-A1
<<FleetElement>>
<<UnmannedAirVehicle>>
UAV-A1
<<FleetElement>>
<<UnmannedAirVehicle>>
UAV-A2
<<SafetyFunction>>
<<FleetElement>>
DetectionClassificationLocalizationA1
<<FleetElement>>
<<AutonomousUnderwaterVessel>>
ManPortableAUV-A1
<<FleetElement>>
<<MannedSurfaceVessel>>
MaritimeCoastalDefenceVessel-A
<<FleetElement>>
<<AutonomousUnderwaterVessel>>
ManPortableAUV-A2
<<FleetElement>>
<<RemotelyOperatedUnderwaterVessel>>
RemoteMinehuntingDisposalSystem-A1
<<FleetElement>>
<<AutonomousUnderwaterVessel>>
ManPortableAUV-A3
<<FleetElement>>
<<RemotelyOperatedUnderwaterVessel>>
RemoteMinehuntingDisposalSystem-A2
<<SafetyFunction>>
<<FleetElement>>
FleetGroupA
<<FleetElement>>
<<RemotelyOperatedUnderwaterVessel>>
RemoteMinehuntingDisposalSystem-A3
<<FleetElement>>
<<UnmannedSurfaceVessel>>
USV-A2
<<FleetElement>>

Figure 5 – The mappings between the "FleetGroupA" function and the fleet components (partial).

The fleet components and their dependencies are shown in Fig. 4. The main Mine Counter Measures (MCM) operations centre communicates with a replenishment at sea Manned Surface Vessel (MSV) alongside the two MCDVs MSVs. Each MCDV is linked to two Unmanned Surface Vessels (USVs) and four Remote Minehunting and Disposal Systems (RMDSs) which are Remotely Operated underwater Vehicles (ROVs) able to destroy or neutralize mines. Each USV is using two Unmanned Air Vehicles (UAVs) and three AUVs to perform mine detection and classification tasks. The RHIB USVs can carry man-portable AUVs while the generic USVs can carry medium weight AUVs.

Fig. 5 presents the mappings from the fleet group A and detection classification and localization functions A1 & A2 to the relevant fleet components. The mappings between fleet components of the fleet group A and the environment are shown in Fig. 6. The dynamic air/sea volumes and sea area spaces are part of the same area of operations for the NMCM mission.

A prototype software tool developed as part of this research analyzed the system model and produced an assessment on the DiD capabilities of the fleet. The "MCMOperationsCentre" and the "ReplenishmentAtSeaShip" were identified as potential components that link the two redundant fleet groups. Diversity of mine detection was good within the fleet groups (the AUVs used two different models -- the man portable and the medium weight) but it was not acceptable when considering both fleet groups. In that case, four different AUV technologies are required. In this model many other redundant components used the same technology, which was identified as an issue. The dependencies between the dynamic environments linked to components of redundant functions produced a list of checks that need to be evaluated throughout the mission. For example the Dynamic Sea Volume A1, connected to AUVs of the first mine detection redundant function of fleet group A, should not overlap with the Dynamic Sea Volume A2 (connected to AUVs of the second mine detection redundant function of fleet group A).

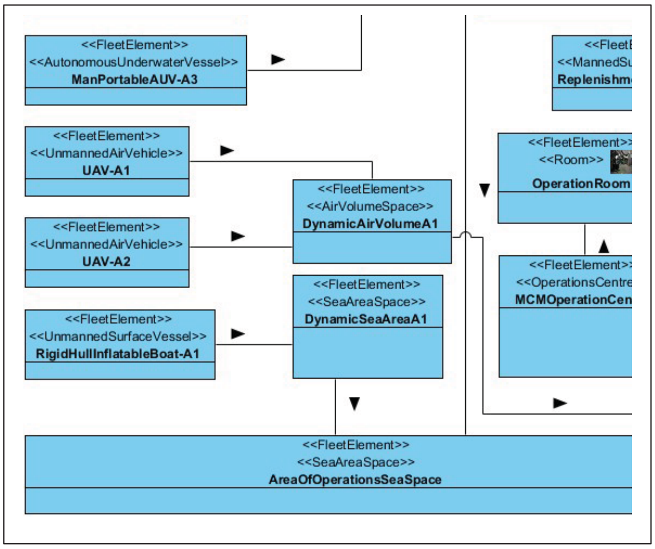


Figure 6 – The dependencies between the fleet components of the case study and the environment (partial). Notice the environment elements with the "Dynamic" prefix connected to the areas of operation.

The feedback from the proposed methodology can then be provided to the mission planner to modify the fleet architecture before commencement of operations. The output of the method in this case may be straight-forward because the fleet model is simple, but in more complex cases the method outputs may be more interesting and unexpected. Future work may focus on the development of a real-time monitoring and reconfiguration system based on AI for fleet-level fault prediction and situational awareness.

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BIOGRAPHIES

Nikolaos Papakonstantinou, D.Sc. (Tech.)
VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland

e-mail: nikolaos.papakonstantinou@vtt.fi

Dr. Nikolaos Papakonstantinou has a diploma in Electrical & Computer Engineering from the University of Patras (Greece) and a doctorate degree in Information Technology in Automation from Aalto University (Finland). Currently he is a senior scientist in the area of system modeling and simulations. He focuses on data and model driven approaches to system design, operation and safety. His current interests also include security of complex systems and safety critical industrial applications of data mining / machine learning.

Ahmed Z. Bashir, B. Eng., P. Eng., PM2
Department of National Defence
Attention: DNCS 4-6
101 Colonel By Drive, Ottawa, Ontario, K1A 0K2, Canada

e-mail: ahmed.bashir@forces.gc.ca

Ahmed Z. Bashir is the Vice-President of the Society of Reliability Engineers in Ottawa, Canada. He has been working on Naval Combat Systems for over 25 years and currently serves as a certified project manager and supervising engineer in the Canadian Dept. of National Defence on Naval Mine Warfare. The work involves high risk, high dollar value delivery of major projects requiring skills in ammunition management, readiness and sustainment, Availability, Reliability, Maintainability and System/Software Safety. Recent domains include submarine fire control, submarine electronic warfare and unmanned underwater systems. His current interests lie in artificial intelligence control and safety. He is a licensed Professional Engineer in Ontario Canada.

Bryan O’Halloran, PhD
Naval Postgraduate School
833 Dyer Road, Bullard Hall 218, Monterey, CA 93943, USA

e-mail: bmohallo@nps.edu

Dr. Bryan O'Halloran is currently an Assistant Professor in the Systems Engineering department at the Naval Postgraduate School (NPS). Previously he was a Senior Reliability and Systems Safety Engineer at Raytheon Missile Systems (RMS) and the Lead Reliability and Safety Engineer for hypersonic missile programs. He holds a Bachelor of Science degree in Engineering Physics and a Master of Science and Doctorate of Philosophy in Mechanical Engineering from Oregon State University. His current research interests include risk, reliability, safety, and failure modeling in the early design of complex systems.

Douglas L. Van Bossuyt, PhD
Naval Postgraduate School
833 Dyer Road, Bullard Hall 218, Monterey, CA 93943, USA

e-mail: douglas.vanbossuyt@nps.edu

Dr. Douglas L. Van Bossuyt holds an Honors Bachelor of Science in Mechanical Engineering, an Honors Bachelor of Arts in International Studies, a Master of Science in Mechanical Engineering, and a Doctorate of Philosophy in Mechanical Engineering from Oregon State University (USA). He is currently an assistant professor at the Naval Postgraduate School in the Systems Engineering Department. His area of research focuses on risk and failure-informed conceptual design and trade-off study philosophies for complex systems.