

Anti-Air Warfare Co-ordination - An Algorithmic Approach

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Abstract

The concept of a co-ordinated Anti-Air Warfare (AAW) weapon response utilising both active and passive systems is not new. However, without the appropriate technology, practical and effective implementation at both the ship and force level is limited. Current responses may perform satisfactorily when required to defend a single platform against a single threat, but future scenarios involving multiple threats and platforms will be very demanding and it is in this area that a machine may support the command. This paper proposes a generic co-ordination algorithm based on the exchange of system capabilities. Generating capability based information in each platform is fundamental for effective co-ordination because it enables each unit to assess response options locally but in a global context. The algorithm effectively distributes an identical decision support function across multiple units thus enabling the command to make fast, high quality weapon allocation decisions.

1. Introduction

Maritime operations are complex and diverse. A ship's Commanding Officer needs to harness his team and his equipment to maximum efficiency while running the gamut from routine, low key operations to high intensity, multi-threat situations. He must be ready for all eventualities, bearing in mind that, to him, the safety of his ship and its company is of prime importance.

At the height of the Cold War, operational crews were trained to a level sufficient to enable any Command Team to operate within a force command structure, recognise a threat, know how to react to that threat and, should the need arise, employ measures to defeat that threat.

As systems and threats became more sophisticated so did measures and countermeasures. The Falklands War of 1982 showed that Anti-Air Warfare (AAW), even in a relatively clean environment, was becoming too complex for the command team. Subsequently, team re-

structuring, allowed more effective load sharing which, in the short term, eased the difficulties for the operators but not necessarily the Command who was still faced with an increasing amount of information, yet required to make the same complex time critical decisions.

Improvements in the effectiveness of maritime Air Defence will not only be dependent on the performance of individual systems but also on the ability to harness their collective capability in an integrated and co-ordinated manner. As weapons and sensor systems become more capable there is a both a need and opportunity to automate elements of the command and control functions including co-ordination. However, automation is a significant step forward because fundamental practices will also need to evolve if advanced technology is to be fully exploited.

Figure 1 illustrates how different scenarios (S1-S5), shown by variations in threat complexity and speed of response, could influence the level of decision making undertaken by the human and that undertaken by the machine. Different scenarios will have different demands reflecting the need for a dynamic man/machine boundary. This boundary is critical, as it will enable the command to control the level of automation that is to be applied in a given situation. Algorithmic development needs to take this important characteristic into account.

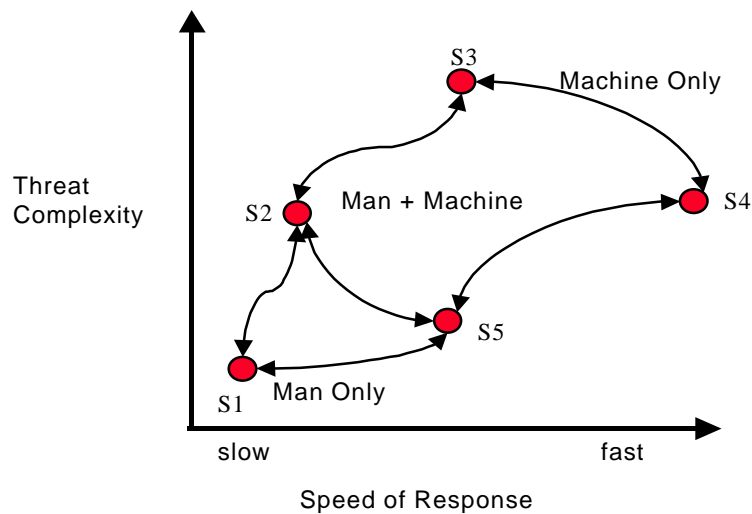


Figure 1. Flexible Machine Support for the Command

This paper outlines some of the important principles and doctrine associated with AAW co-ordination and then discusses potential C² limitations in the context of future threats, weapons and sensors. A generic co-ordination algorithm based on the exchange of capability data is developed in a qualitative manner.

2. The AAW Co-ordination Domain

2.1 Current Co-ordination Methods

The success of any mission depends upon the Anti-Air Warfare Commander's (AAWC) appreciation of the situation, his decision on a course of action and his development and promulgation of a plan and operational structure. It is important that the commander ensures that his subordinates are aware of his appreciation of the situation, his intent, the plan and its intended execution. The subordinate may then implement the commander's wishes with the minimum of direction and hence fulfils the requirement for quick reaction (one of the principles of AAW). The subordinate keeps the commander informed of what he is doing and the latter may then exercise command by veto should it be required. It is the AAWC who must ensure that all weapons contribute to AAW such that;

- (a) No target penetrates without being engaged.
- (b) Each target is economically engaged by the most suitable weapon system.
- (c) Friendly aircraft are not engaged.
- (d) Negative interactions between systems are minimised.

2.2.1 Zoned Co-ordination

Traditionally, a maritime force has used zones to co-ordinate the AAW battle, mainly because the method works in scenarios of heavy jamming, poor communications and poor situation awareness. The system is based on every Medium Range Surface-to-Air Missile (MRSAM) firing platform being allocated a Missile Engagement Zone (MEZ) as shown in Figure 2. The force (including supporting aircraft) recognises that these zones are effectively danger areas and friendly aircraft penetrate them at their peril. A Crossover Zone outside each MEZ allows fighter aircraft 15 miles of airspace within which to complete their engagements but they must still break away and not penetrate the MEZ. In constricted areas the AAWC could control his MEZs to the detriment of the full range of capabilities of his missile systems. Figure 2 illustrates how the AAWC has selected a MEZ for ship B that is smaller than the weapon system envelope thus preventing an overlap with the other ship.

The zoned method of co-ordination has been in use since the introduction of SAMs at sea. The procedure incorporates safety by separation (de-confliction) and is able to function in periods of poor picture quality (including identification), marginal communications and heavy jamming (ECM). However, in the littoral battlespace of the future it would be cumbersome, overly restrictive and deny best use of potential resources.

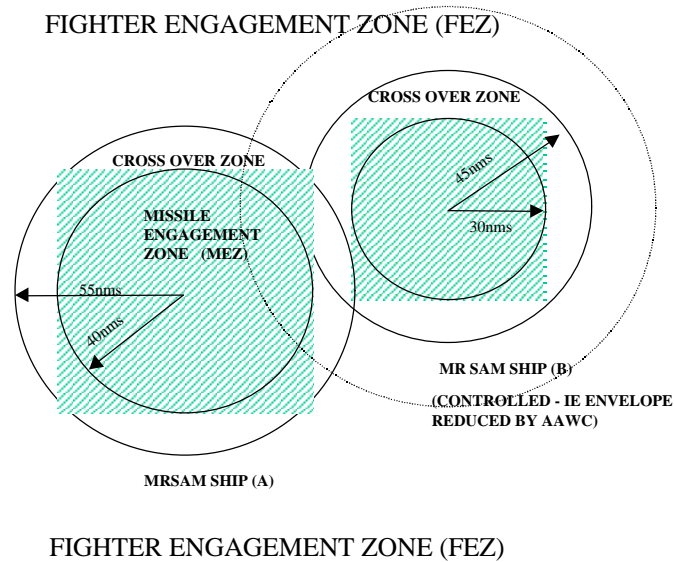


Figure 2. Zoned Co-ordination

2.2.2 Area Co-ordination

Area co-ordination has long been an option for the AAWC. In this scheme, Combat Air Patrol (CAP), MRSAMs and Electronic Counter Measures (ECM) occupy the same airspace as shown in Figure 3. The AAWC resolves any conflict that occurs and the method allows for the most effective use of the force's AAW capability. It is, however, only recommended for use when the air picture is clear and complete, communications are good and AAW co-ordination is of a high standard - a situation that has thus far eluded forces at sea. Nevertheless, it is within this environment that the Royal Navy's future combatants will need to perform.

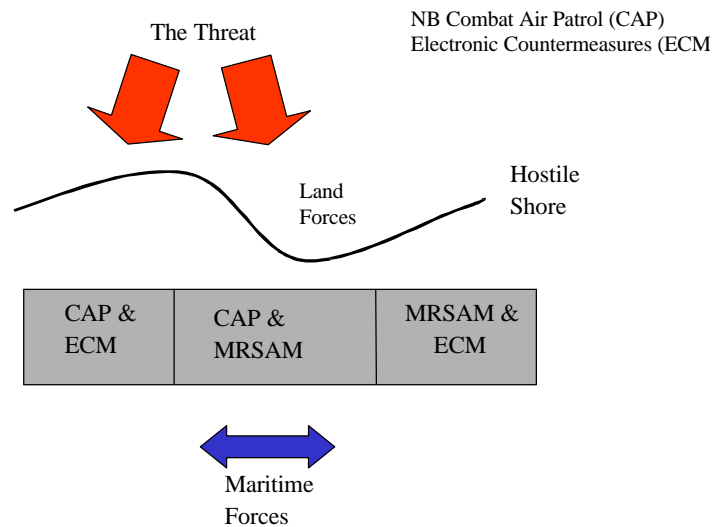


Figure 3. Area Co-ordination

3. The Need for Co-ordination

3.1 *Future Doctrine*

The task of the UK's Joint Rapid Reaction Force (JRRF), to which the Royal Navy's future combatants will be assigned is as follows:

- (a) maximise inherent mobility and flexibility;
- (b) provide an amphibious force;
- (c) deploy joint combat air power;
- (d) provide, support and defend sea-basing;
- (e) deter conflict and forestall crises;
- (f) facilitate manoeuvre of land and air forces ashore.

Maritime doctrine for future operations is developing towards Maritime Manoeuvre and Composite Joint Protection. Maritime Manoeuvre seeks to collapse an enemy's cohesion and effectiveness through a series of rapid, violent and unexpected actions and Composite Joint Protection includes the integrated exploitation of an enemy by sea-based joint forces. These policies take maritime forces to the Joint littoral battlespace and thus reduce the priority for deep, blue water ASW of previous years.

3.2 *The Co-ordination of Future Weapons and Sensors*

By the end of the Cold War, the Former Soviet Union (FSU) had been making sophisticated weapons available to a wide range of countries and this proliferation continues today.

Defence against anti-ship missiles (ASMD) becomes increasingly difficult as the threats become faster, stealthier and more manoeuvrable. This difficulty is compounded, from a co-ordination perspective, by the introduction of more versatile and capable weapon and sensor systems. The inherent flexibility in advanced Electronic Warfare (EW) systems, Multi-Function Radars (MFRs) and SAM systems means that there is much more to understand and assess if successful co-ordination is to be realised.

3.3 *Decision Making and System Interactions*

An AAWC has a number of AAW active and passive defensive systems at his disposal. Current tactical procedures were originally developed to defend a single ship against a single threat, and are unlikely to cope adequately with more complex situations. When multiple threats are involved, the number of potential interactions increases rapidly. The management of such interactions is a fundamental goal of co-ordination.

At force level, co-ordination becomes more complicated because there are more system interactions each of which may be dependent on the force disposition.

4. Co-ordination - A Simple Analysis

4.1 *Generic AAW Process Model*

Figure 4 is a typical generic model showing the main functional components of the AAW process. The model illustrates the cyclic nature of an AAW engagement and the sequence of functions that should be present for a successful outcome. The model is used primarily as a basis for discussion and has proved very useful for simple analysis of AAW engagement incidents taken from recent conflicts. Two such conflicts are discussed later in this section.

An important aspect of the 'generic' model is that it can be used for the analysis of both single and force engagement situations.

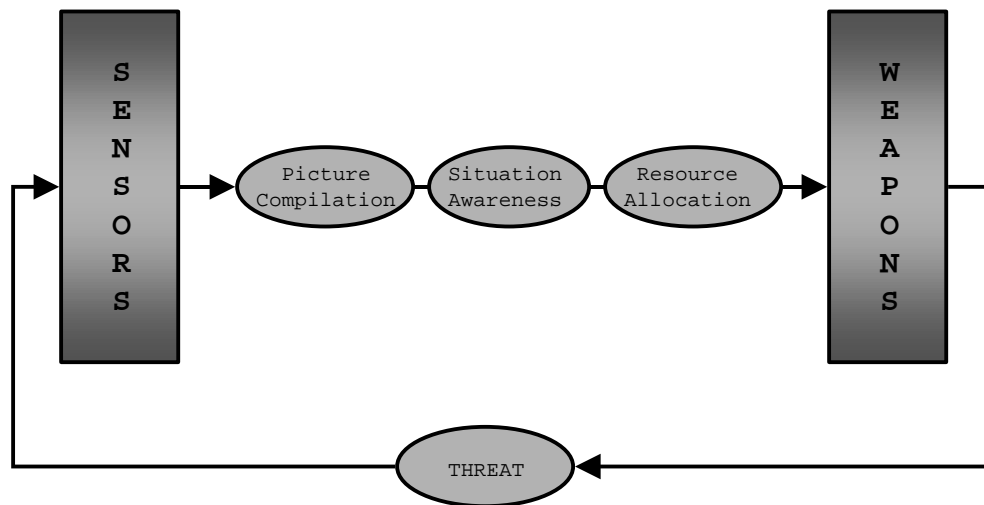


Figure 4. Generic AAW Process Model

In the following examples the five components of the model are analysed from the ship and force level perspective. 'Smiley face' and 'ambulance' icons are assigned to components depending on whether they were considered to be functioning correctly or in urgent need of assistance!

4.2 *HMS Sheffield Incident - 4th May 1982*

On the 4th May 1982, while on patrol as an Air Defence picket off the Falkland Islands, *HMS Sheffield* was hit by an AM39 Exocet missile launched from an Argentine Super Etendard aircraft. In her Operations Room the Electronic Surveillance Measures (ESM) equipment was blanked by satellite transmissions preventing detection of the sea-skimming threat until 6 seconds prior to impact. The lack of ESM detection prevented the necessary prompt for radar detection and tracking causing a failure in the picture compilation and situation awareness components. Consequently there was nothing to allocate resources to. There were, in hindsight, many clues to be derived from the UHF radio but events were confusing, the AAW process had broken down. The ship level analysis is shown in Figure 5.











	SHIP LEVEL	FORCE LEVEL
SENSORS		
PICTURE COMPILATION		
SITUATION AWARENESS		
RESOURCE ALLOCATION		
WEAPONS		

Figure 5. HMS Sheffield on 4th May 1982

The situation in the force, however, was different. The AAWC was receiving the information - the raid had been detected by *HMS Glasgow* and reported by both voice and data link. There had, however, been several false alarms prior to this incident and this may have contributed to *Glasgow's* reports not being believed. Consequently the raid went unmolested.

4.3 *HMS Gloucester Incident - 25th January 1992*

During Operation Desert Storm, *HMS Gloucester* was in company with a number of coalition ships at the head of the Persian Gulf. Mine clearance operations were being conducted and sea-room was restricted. The Iraqis launched two Silkworm missiles at the group. One missile ditched early but the second flew on towards the *USS Missouri*. *Gloucester* detected and identified the missile and destroyed it with a Seadart missile. Although a success from the coalition perspective, in truth the Silkworm was not locked on to any of the combatants and *Gloucester's* Seadart intercepted the Silkworm as an opening target.











	SHIP LEVEL	FORCE LEVEL
SENSORS		
PICTURE COMPILATION		
SITUATION AWARENESS		
RESOURCE ALLOCATION		
WEAPONS		

Figure 6. HMS Gloucester on the 25th February 1992

The AAWC did not appear to assess the situation properly or allocate the threat to *Gloucester's* SAMs. Indeed, did he have the picture?

4.4 *Generic AAW Process Model with Explicit Co-ordination*

The above examples demonstrate how the degraded performance in one or more of the components can lead to a breakdown of the AAW process. However, the examples also show that in certain situations component failure is not necessarily due to the inherent performance of a specific system but a result of interference with other systems. The model shown in Figure 7 explicitly includes a 'co-ordination' component that is responsible for managing the dependencies within and between components.

Co-ordination is regarded as a critical function that could help to overcome the ship and force level problems described in the previous examples. AAW needs to be addressed holistically so that emerging technology is directed towards those areas of the process that will yield the greatest benefit. Another important characteristic of the generic model is that it is not incident specific and this suggests that it could be used as a useful top-down approach for AAW research.

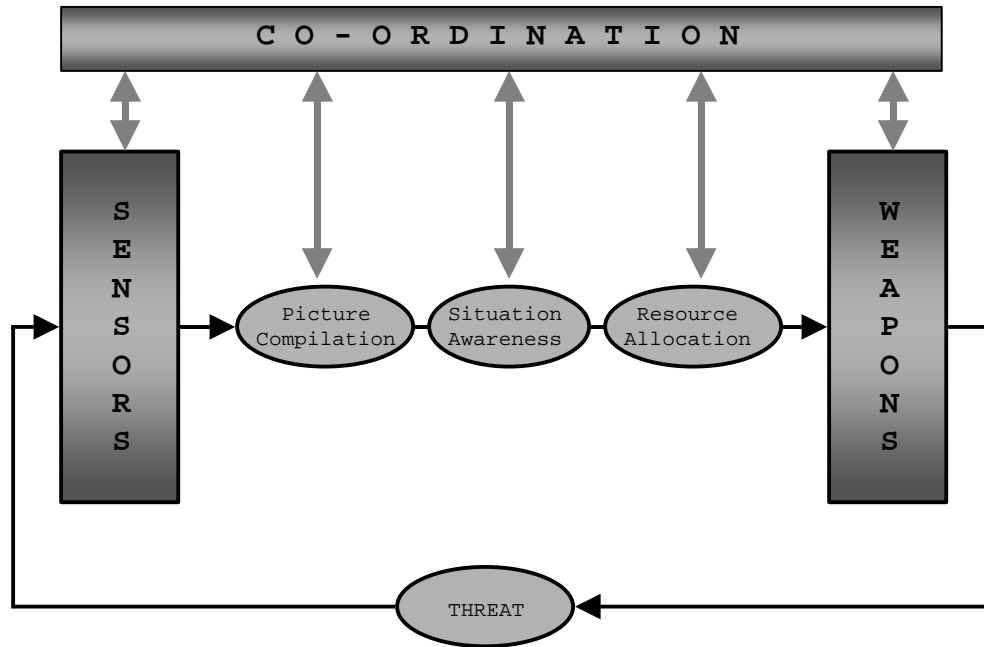


Figure 7. AAW Model with Explicit Co-ordination

5. Co-ordination - An Algorithmic Approach

5.1 Overview

The examples described in the previous section indicate how AAW could be improved using better co-ordination of intra-ship and inter-ship sensor and weapon system capabilities. This discussion focuses on countering threats at force level which is fundamentally different from ship level co-ordination as the actions of each ship must now be synergised to meet the force level objectives. This may, for example, require individual platforms to engage threats that are non-threatening to the platform but pose a significant threat to higher priority units within the force. In extreme situations platforms may be required to focus all defensive actions against such 'force' targets while at the same time offering little or no resistance to other threats. As in many walks of life, difficult decisions have to be made when resources and capabilities are limited.

A major research question is how can software based machines support the command decision making process during AAW? In fact, can a machine automatically generate a force solution that encompasses the optimum use of defensive assets within a multiple threat scenario? There are many questions regarding the application of C² decision support in this area because of the inherent uncertainty and lack of information that makes algorithmic design difficult. A primary objective of the applied research effort is to develop and demonstrate advanced technology and evaluate its effectiveness in both simulated and real environments.

Co-ordination performance is dependent on the type of information exchanged between co-ordinating units and how each unit processes the information. It is therefore important to consider the relationship between exchange of information and force co-ordination. This algorithm focuses

on the capabilities of different systems rather than on the underlying techniques employed to achieve those capabilities. It is a generic approach based on the intuitive assumption that 'capability' information can be effectively exploited in a machine to achieve co-ordination of multiple systems. In general, a weapon system would continuously generate capability statements describing the 'potential effectiveness' against a range of threatening targets. A simple example of a capability statement could be "*change trajectory of track X to T at time t with probability P*" or "*destroy track X with probability P*". A key driver behind this approach is that co-operating units within a force do not need to be aware of 'specific' characteristics that, in a multi-national operation, could cause concerns over security.

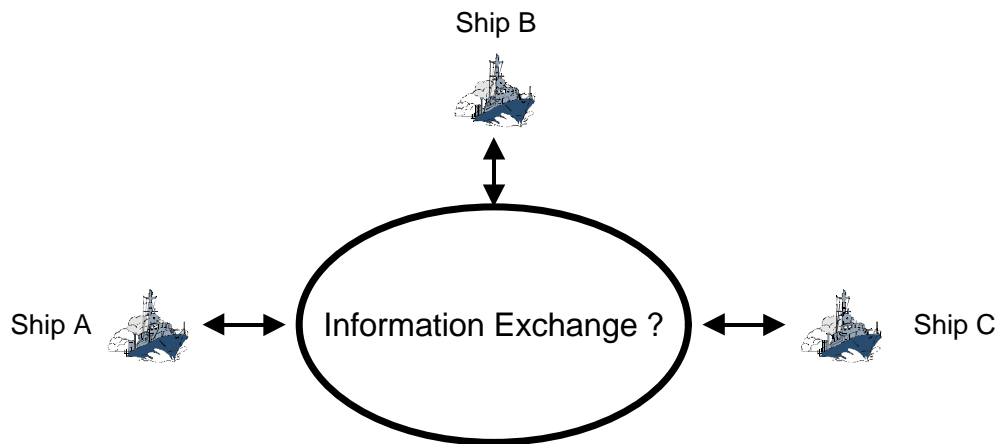


Figure 8. Ship Network and Information Exchange

5.2 *Perspective Switching*

Figure 8 shows a 3-ship network where each ship can send and receive capability-based data. In this discussion weapon system performance is used as a simple measure of a unit's capability. If units have the ability to reliably broadcast their predicted performance values against threats, it may be possible to generate a co-ordinated force level response. In this algorithm each unit executes an identical processing algorithm using the shared capability data to determine its contribution to the force response. In this way the processing is done individually at unit level thus precluding the need for the collection of data at a central point for assessment and decision making.

A generic force algorithm based on capability data is shown in Figure 9. A key feature of the algorithm is the ability to switch between ship and force level perspectives. Initially the algorithm builds a local perspective of ownship responses which is then combined with information from other units to develop a more global perspective. This wider perspective enables each unit to evaluate the force response situation. In the final stage of the algorithm, the perspective switches back to the ship level so that an ownship response can be generated.

The communication of data provides a framework in which units can make independent decisions in a force context. The capability data enables each unit to discriminate between multiple options

in an objective manner. In this analysis weapon performance has been selected as the discriminant. Multiple discriminants could be used if necessary.

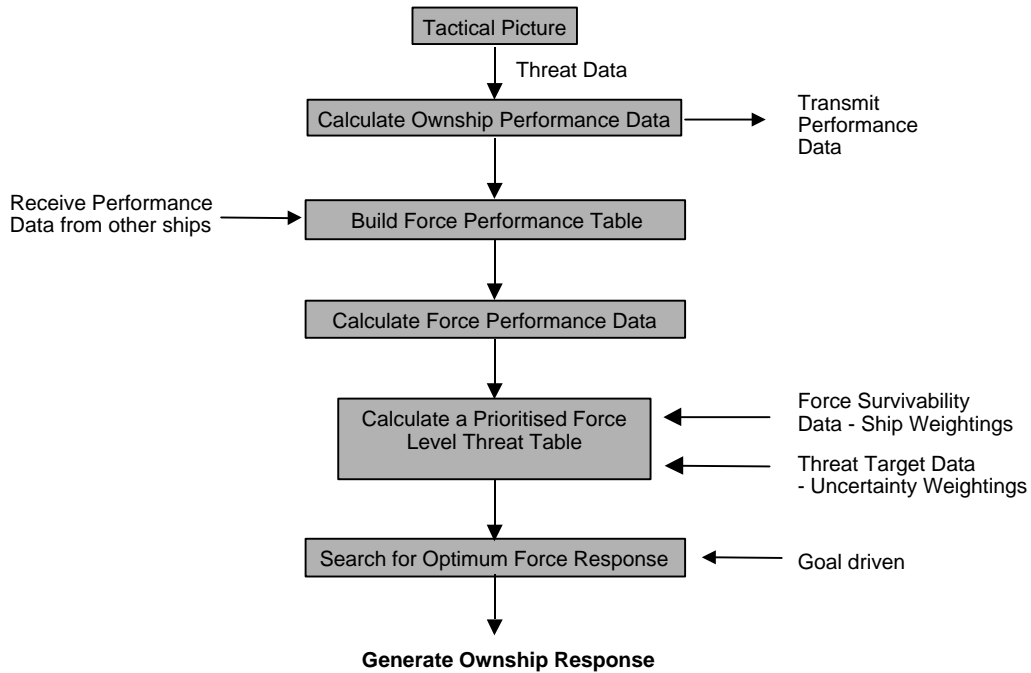


Figure 9. Generic Force Level Co-ordination Algorithm

5.3 Data Generation

Figure 10 shows a multiple ship multiple threat situation. Ships A and B are the air defensive units and are tasked with the protection of Ship C, which has a no defensive capability. Ships A and B will also operate in both a self-defensive and mutually defensive mode where appropriate. To illustrate some of the important factors that need to be considered during this operation, two missiles are simultaneously targeted at Ships A and C. To simplify the analysis each ASM has a straight-line trajectory.

Figure 10 shows that each ship has an engagement opportunity against each threat. The objective of this situation is to demonstrate the need to fully evaluate each of these opportunities so that an effective and co-ordinated response may be generated. For this situation there are 16 different response outcomes ranging from the case where neither ship fires at either threat to the case where both ships fire at both threats. A pre-requisite for evaluating each of the 16 possible responses is to communicate the appropriate data to the evaluating functions.

Each ship generates a performance table that holds ownship capability data against each scenario threat. To simplify the analysis, each ship only has a single weapon system. The performance of the weapon is given by a probability value where 0.0 would represent 'no' capability against a particular threat. A value of 1.0 would represent complete certainty of being effective against the threat.

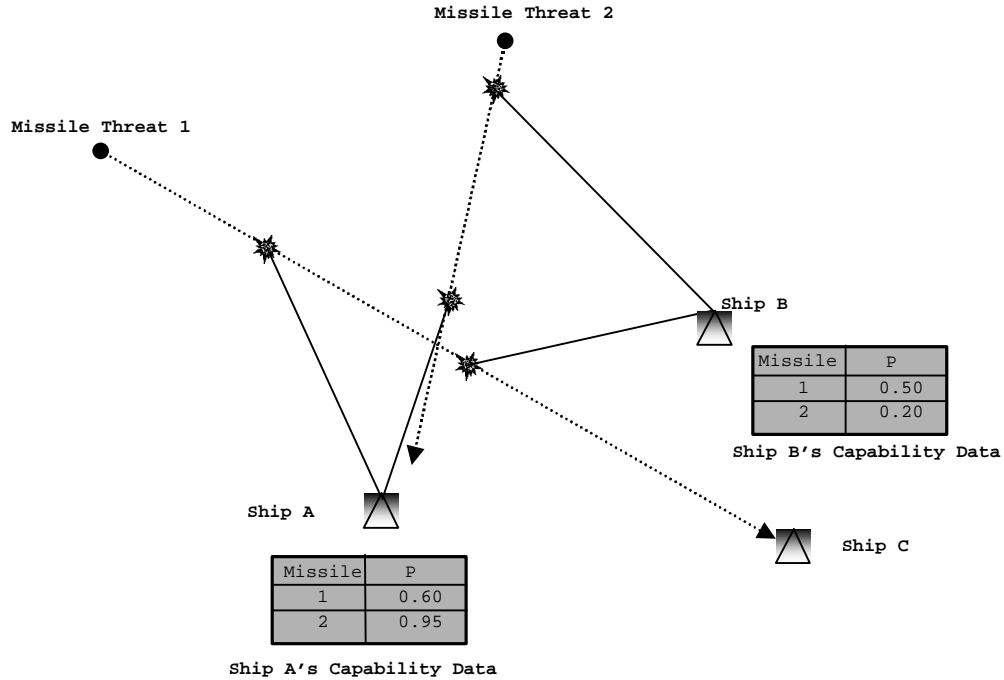


Figure 10. Capability Data Generation

5.4 Force Weapon Integration

Figure 11 shows how the ship level threat performance tables are extended to force level through exchange of the weapon performance data over the network. Initially, each ship only has performance data associated with its own weapon system against each threat. As each ship continuously assesses these performance figures, the data is also broadcast to other ships on the network.

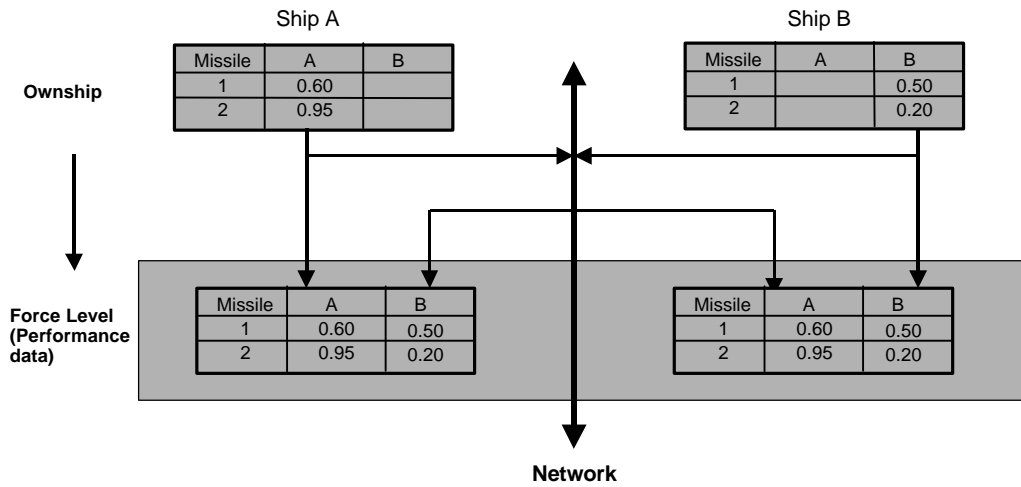


Figure 11. Exchanging Capability Data

5.5 Force Level Measurements

Figure 12 shows the identical processing that would take place on each ship in the force network. The first stage is to calculate the force performance data from the ship level data that has either been generated locally or received over the network. In Figure 12, P is the ship level performance data and predicts the engagement performance of each ship/threat pair. P_f is the force performance table that is calculated by combining the individual ship performance probabilities. P_f is a measure of the force capability against each threat. It is important to recognise that the method of combining these performance figures will depend on the type of system. In this example, the systems are considered to act independently which enables the combined probability to be calculated using the simple formula $1-(1-P_1)(1-P_2)$ where P_1 and P_2 are the individual weapon system probabilities.

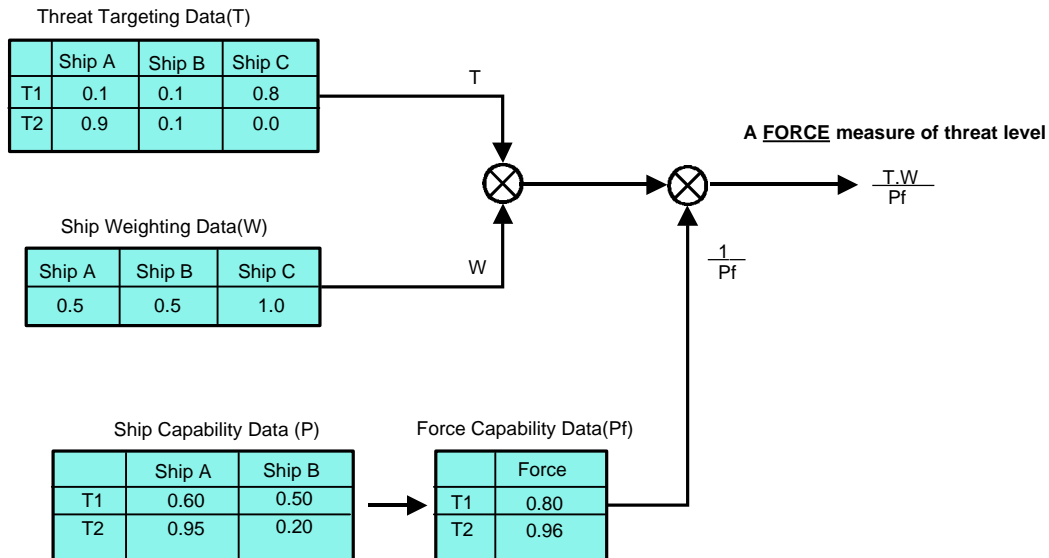


Figure 12. Force Level Measurement of Threat Priorities

The threat targeting table (T) predicts which ships are targeted by which threats. It is important that the data is able to capture the inherent uncertainty relating to where individual threats are heading. One method of achieving this is to assign a probability to each of the possible threat trajectories. The accuracy of this information is likely to have a significant impact on the performance of any subsequent decision making processes. The ship weighting table (W) specifies the relative worth of each ship. As expected, ship C (the defended unit) has the largest value and this data will be used to bias the decision making algorithm.

T , W and $1/P_f$ are then combined (multiplied) to generate force level threat priority data. In this algorithm each threat has been considered in a force context such that threats targeted at lower value units will not be afforded the same level of defensive capability should higher value units demand them. In the same calculation, the level of force defence against each threat is also taken into account.

5.6 Force Response

In Figure 13 the force level response, R , is generated using the ship performance table (P) and the prioritised threat data. The response generator searches through each of force response options in threat priority order. A solution is found when the response satisfies the force goal. If the force goal is set to 1 then, by definition, every available ship weapon resource will be selected as part of the solution and it may be difficult to satisfy the requirements of lower priority threats. It is not the intention of this analysis to determine what the value of this goal should be although it is obviously another key parameter within the algorithm. It should also be noted that prioritising is only necessary if resources are limited. The output of the force response generator is shown in Figure 13 in the form of a force allocation table (R). In this analysis the force response defines force allocation at the ship level as shown by a 1 or 0 in the response table. This is because each ship has been restricted to a single weapon system. In reality, ships have multiple active and passive weapon systems.

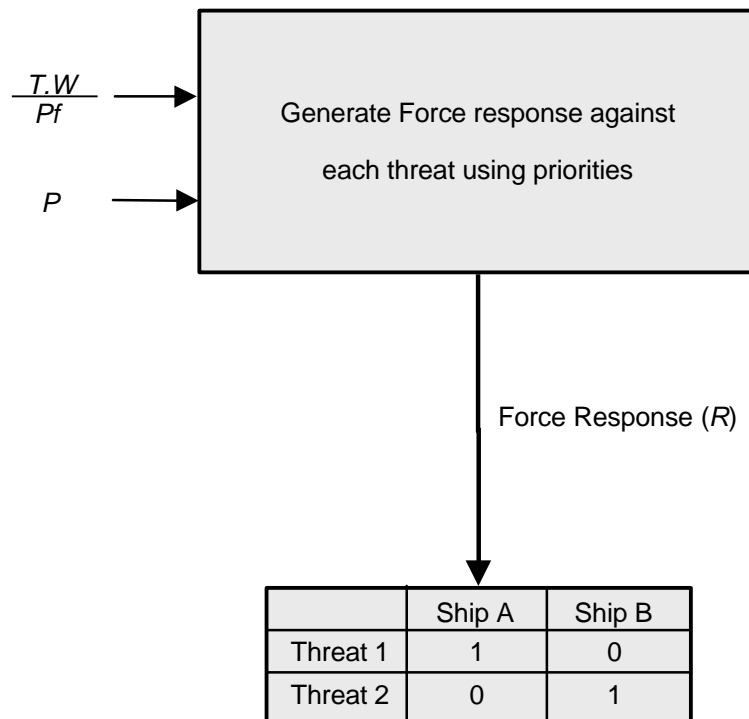


Figure 13. Force Response Generation

6. Conclusions

This paper has raised some important issues associated with how AAW co-ordination is currently managed and some of the difficulties that are anticipated in the future as new sensors, weapons and C2 systems are introduced into operational service. A primary concern is ensuring that this new technology is capable of defeating both current and future threats. The historical incidents have shown how important it is for the different components of the AAW process to be treated in

a holistic manner and how co-ordination could provide a significant improvement in AAW effectiveness by ensuring that interference between different systems is properly managed.

The key steps and characteristics of a generic co-ordination algorithm have been described. The algorithm is based on the exchange of capability information between co-ordinating elements of the force. Further research is necessary to explore the information exchange requirements and effective distributed processing techniques that will support the command's decision making. Another key research area is extending the algorithm to allow analysis of multiple systems at both platform and force level. Practical demonstration of these techniques in a real-time laboratory based prototype will take place during the next 2 years. The eventual aim is to evaluate the real military benefit of co-ordination technology by taking the demonstration system to sea.

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