13th ICCRTS
"C2 for Complex Endeavors"
"Self-synchronisation and the future maritime force"
Topic 5: Organizational issues
Paper number: 183

Jonathan Miles
Defence Science &
Technology Laboratory
D3
St Andrew's Rd
Malvern
Worcestershire
UK
WR5 2AA
+44 1684771266

Mike Davison
Defence Science &
Technology Laboratory
C41 West Court
Portsdown Hill Road
Fareham
Hampshire
UK
PO17 6AD
+44 2392217952

Abstract
Part of the potential benefit of NEC is based on an assumption that self synchronisation can be applied with advantage.

The aim of this paper is to investigate alternative forms of synchronisation to see how NEC might impact the aggregation of low-capability individual units into a highly-capable agile Maritime Force.

The alternative forms of synchronisation, from hierarchical- through to self-synchronisation are discussed. Characteristics of swarming (the extreme form of self-synchronisation) are explored and instances of swarming are included in the discussion, both from the natural world and from military history. Finally the appropriateness of self-synchronisation and swarming behaviours is discussed in the context of the maritime environment.

Introduction
This study was originally conducted as part of the Dstl "Maritime Concepts to exploit NEC - final technical report" (2007). [1] This paper was included in the report as an unclassified appendix.

Synchronisation
Synchronisation is defined as:

> "*a coordination relationship, an adjustment or agreement that causes something to occur or recur in unison*" [2].

Synchronisation can be achieved in a number of ways. Below are three military examples:

1) **Hierarchical synchronisation** involves synchronisation of unit tasks by explicit orders passed from higher command authority (although lower level units may make recommendations for the higher command to accept and promulgate as orders).

The activities of two or more peer subordinates are aligned against common time, space and/or event markers, by orders from respective superior authorities. Consequently, this method has a degree of latency inherent within the process as information flows up and synchronisation orders flows down the command chains to the subordinate peer units. The latency obviously increases with the number of levels within the command hierarchy.

2) **Mutual-synchronisation** involves units negotiating tasks directly with each other, i.e. "peer-to-peer (P2P), without contact via superior authority, although the negotiation can be done under the supervision of a superior [3].

Mutual synchronisation provides the ability to respond to rapidly changing circumstances, concomitant with sufficient communications and information capabilities.

3) **Self-synchronisation** is defined as:

> *"Independent military units automatically orchestrating their actions in accord with a Commander's intent rather than waiting for direct orders or explicit instructions. It is thus seen as a way to undertake military operations precisely and quickly*[1]*"* [4]

Self-synchronisation occurs when two or more peer subordinates independently have the authority and are able to make their own decisions to align their activities against common time, space and/or event markers, [5]. In order to do this the entities require information from some source on which to base these decisions. It can be achieved via either:

[1] It is recognised that this occurs in mutual synchronisation as well, but in self-synchronisation it is done without negotiation.

a) An indirect process where entity subordinates synchronise their activities, without supervision by higher authority, in space and/or time by:
   - reliance on information from organic sensors alone
   - and / or independently "pulling" information from a peer entity without any specific arrangement for information exchange (Figure 1a)

b) Under the supervision of a higher authority who is notified that synchronisation decisions are imminent/being taken, by monitoring details of the actual synchronisation decisions and elements of the synchronisers' Situation Pictures and Plans. The higher authority then has the opportunity to intervene if a badly desynchronising activity is performed (figure 1b), or;

c) Subordinate entities pulling information from a third party or higher authority to achieve common situation awareness and thus allowing them to independently synchronise with peer activities in space and time (figure 1c).

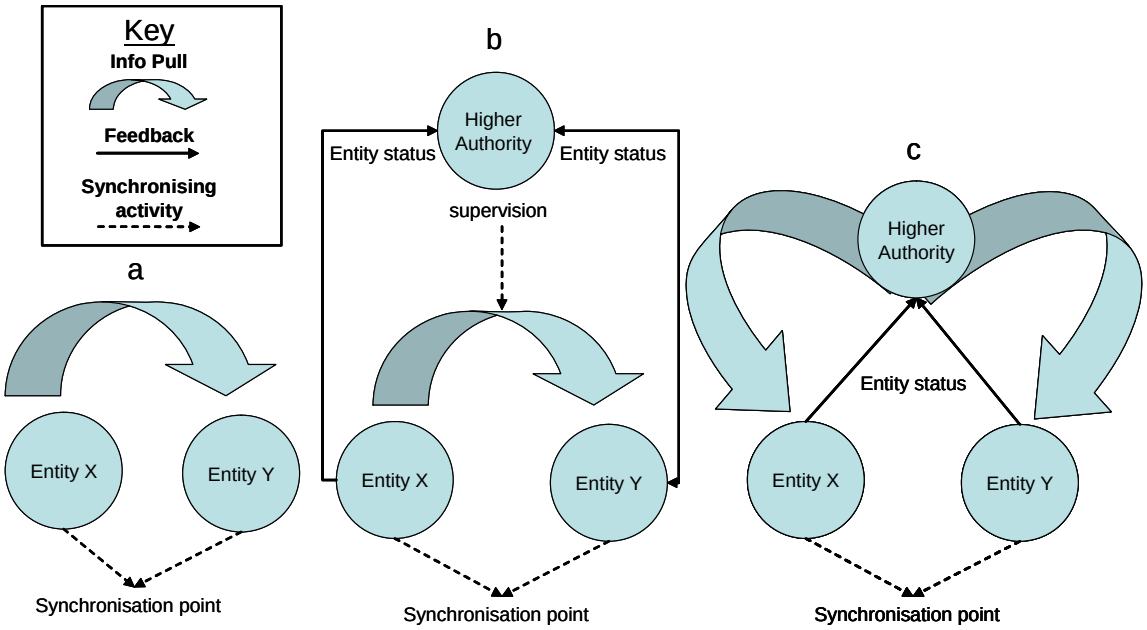

Figure 1: Alternative Self-Synchronisation processes

When two entities do not share the Higher Authority (e.g. in Joint Operations) a level of complexity and latency is introduced. When this occurs, the higher authority nodes also need to synchronise in some way. A self-synchronising example is shown in Figure 2 below, where the higher authority node (the circle) shown on the right is pulling information (denoted by the upper green broad arrow), from its peer (the square) whilst at the same time its subordinate entity Y (the triangle) is also pulling the information (denoted by a blue and green broad arrow) it needs from its higher authority node in order to synchronise with its subordinate peer entity X (the hexagon).

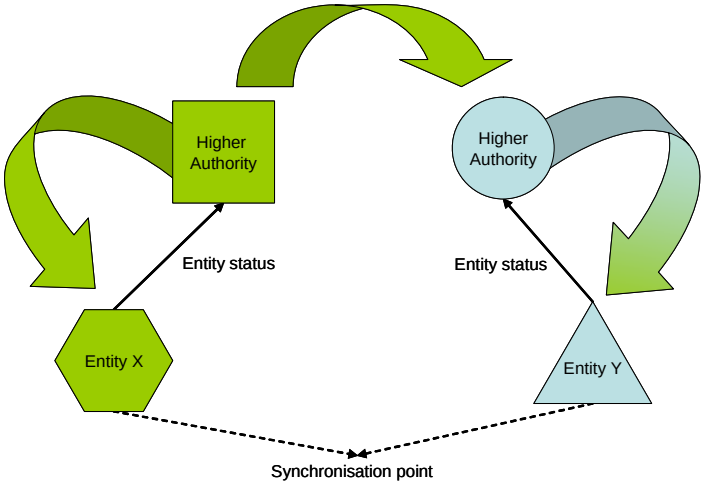

Figure 2: Two levels of command conducting self-synchronisation processes

The example shown in **Error! Reference source not found.** combines both mutual and self-synchronisation processes. The higher authority entities (square and circle) are mutually synchronising, whilst their respective subordinates (hexagon and triangle) are individually pulling information from their respective superior command levels in order to self-synchronise.

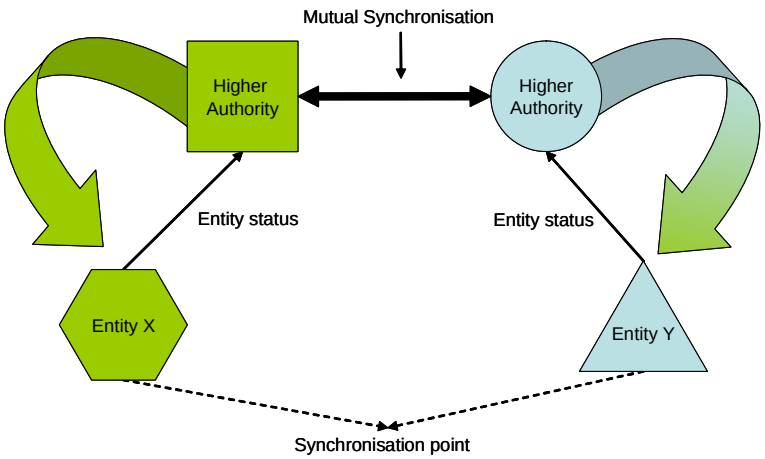

Figure 3: Combination of mutual synchronisation at higher-level and self-synchronisation processes at lower-level

Swarming behaviour is considered to be an extreme form of self-synchronisation, and is discussed in detail later in this paper.

In figures 2 and 3 the degree of agility of the self-synchronising entity is affected by the latency within the synchronisation processes of the third parties.

The choice of synchronisation method is determined, in part, by the degree of command freedom awarded to the subordinate commander based upon the availability and quality of information, the enabling equipment, and the operational and environmental conditions that exist at the time.**Error! Reference source not found.** illustrates the variation in the degree of control across the different synchronisation methods. As the synchronisation method moves from left to right along the X axis, there is less opportunity for a superior to exert control, while the degree of command freedom at the subordinate level increases.

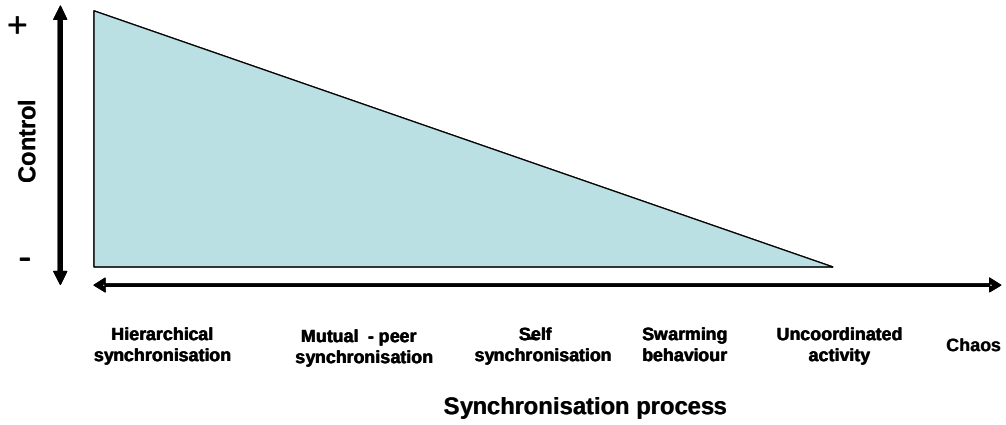

Figure 4: Degree of control that can be exercised by superior authority over synchronised activities

Figure 5 shows that hierarchical and mutual synchronisation provide for greater levels of direct coordination[2]. This is appropriate to more stable environments where there is more time available for consultation between the hierarchies and peers. Self-synchronisation and swarming provide for only indirect coordination[3], and are appropriate to more dynamic environments where less time is afforded for consultation.

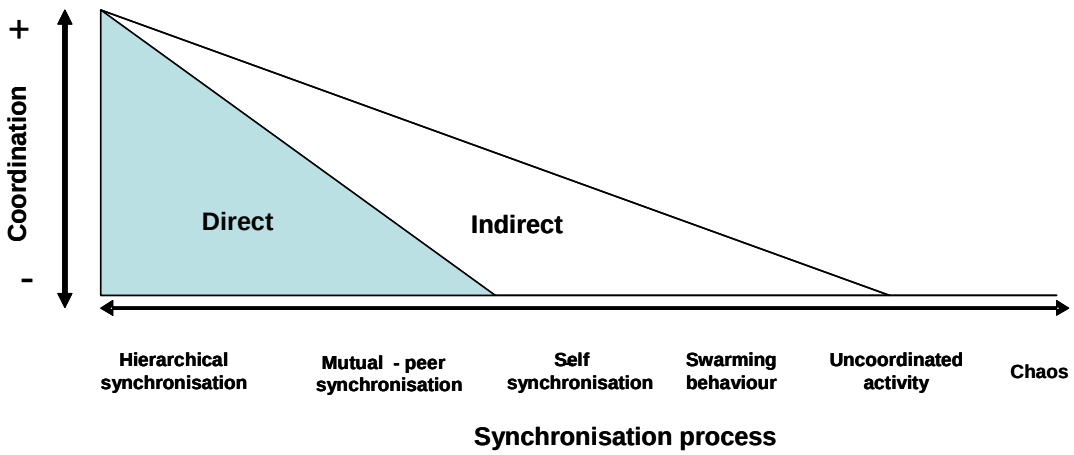

Figure 5: Degree and type of coordination within the differing synchronisation processes

Self-synchronisation and mutual synchronisation may be of use to a military force in circumstances where communication with higher authority was impossible, difficult, or too slow. Examples might include defence against a pop-up threat, or where long-range (e.g. satellite) communications are not available e.g. due to equipment failure or hostile action.

However self-synchronisation can bring some disadvantages (e.g. requires increased level of training and personnel qualification to ensure adequate level of command competence and decision-making capability). Larger units have more capable weapons with longer ranges, and so may be more widely dispersed; if these units are sufficiently dispersed then they may not be able to exercise self-synchronisation. Explicit C2 (hierarchical or peer-peer) would be needed to synchronise their effects (simultaneous weapon time-on-target is applied to swamp the defences of a capable enemy unit), because:

- one or more units may not hold the target on their organic sensors (e.g. visual range 10 miles, radar range up to 150 miles for a high-flying aircraft but down to 10 miles again for a sea-skimmer) and there could be difficulty in agreeing a common target identity without communication;

[2] Direct coordination is either where coordinating entities activities are affected by higher authority command, or by the mutual agreement of the participating peer level entities.
[3] Indirect coordination is where one entity coordinates their activities with others by remotely sensing what the others are doing and aligning their own activities with them.

- when operating in a coalition there may be differing national legal requirements and definitions for target classification [6].

All mechanisms of synchronisation share the same dependencies and requirements, but the dependencies increase and become more critical as one moves away from hierarchical toward self-synchronisation and swarming. The dependencies are as follows:

- clear and consistent understanding of command intent throughout all command levels;
- access to quality information to achieve situation awareness:
  - accurate and timely Intelligence and organic sensor pictures;
  - appropriate rules of engagement (ROE);
  - appropriate and authoritative resource allocation.
- trust of:
  - the superior, subordinates and between all peers;
  - the provenance and accuracy of the information and situation awareness and, related to this, the quality (e.g. latency, security, reliability) of the ISR collection, processing, communication and display systems;
- a high degree of command competence and decision-making capability at all levels[4].

Mission Command: Mission command[5] has been traditionally a part of British defence doctrine and was typified in the maritime domain by Nelson's 'band of brothers' approach to command[6]. Some degree of self synchronisation is already embedded in the British Command ethos as part of Mission Command, since it allows a subordinate commander/unit to act upon the superior commander's intent with a degree of autonomy (defined by the extant ROE) with regard to how the mission is conducted to meet the specific circumstances that exist at any time. The subordinate commander carries out the mission with little detailed direction from higher levels of command.

> "*Self-synchronisation relies not on one single decision but on a series of decisions", the assumption is that a 'Shared Situation Awareness' control feedback loop can be put into place through the use of a common picture to provide effective overall force coordination*[7]*… indeed self-synchronisation is not new; it is the natural default setting for those imbued with the spirit of mission command and already happens at the lower tactical levels. As the level of shared situational awareness increases, units at all levels (that share a common ethos of mission command) will instinctively attempt to synchronise their actions. Although it seems unlikely that total self-synchronisation as envisaged within Jt HLOC will be achieved, it is likely that incidences of self-synchronisation will increase and lead to a reduction in the level of control required and hence the burden of control on the staff. For these force elements the requirement will be to monitor the situation and apply the occasional light touch on the tiller as required*." [7]

[4] If self synchronising forces were not competent to make decisions, the resulting action could be badly de-synchronised activity.

[5] "The UK, and most western armed forces, espouse a doctrine of mission command in which the principles of unity of effort, freedom of action, trust, mutual understanding and timely and effective decision making apply, and in which the ability to articulate and disseminate command intent is key". [7]

[6] "Vice-Admiral Horatio, Lord Nelson, used the phrase 'Band of Brothers', on a number of occasions to describe the remarkably close and friendly relationship that existed between him and the captains who served under his command at the Battle of the Nile, 1 August 1798. It is a quotation from the famous Agincourt speech in Nelson's favourite Shakespeare play, King Henry V. By extension it has come to encompass all those officers who were particularly close to Nelson, or who had served with him in his battles, and thus has become a metaphor for his distinctively 'collegiate' style of leadership – a style that set him apart from most other admirals of his time". National Maritime Museum , A-Z of Nelson: http://www.nmm.ac.uk/server/show/ConWebDoc.21155/viewPage/3

[7] Initial reactions to an event may be different; however this feedback loop should allow force elements to self-correct for any unexpected reactions. It is stated that self-synchronisation becomes feasible if the responsiveness of the feedback loop and the responsiveness of the force elements are higher than the stimuli (usually the adversary's actions).

Therefore self-synchronisation may be effectively applied in small communities that are experienced in working together, e.g. SF, TCT kill chain, ASW destroyer squadron. In the same reference Admiral Snelson stated

> *"the UK are pretty good at Mission Command but that the US had a different command philosophy. This difference in approach between UK and US was an issue on TELIC at the Land/Maritime boundary where the US approach was to continually refer problems upwards for resolution whereas the UK approach was to make it work at formation level and ensure that the higher command was informed. This upwards referral was further hampered by the difference in the length of the Maritime and Land chains of command leading to a time lag while the Land chain caught up with the shorter Maritime chain."*

C2 architectures: the aforementioned synchronisation types are implicit within Dekker's taxonomy [8] of possible NCW architectures (see Figure 6), based on the concepts of value symmetry (in the sense that the loss of any node is as serious as the loss of any other, some nodes being more mission-critical than others) and the heterogeneity/homogeneity of the force element mix. The different types of architecture within the taxonomy are summarised in **Error! Reference source not found.**. Any of these architecture options could be candidates for a future maritime force implementation.

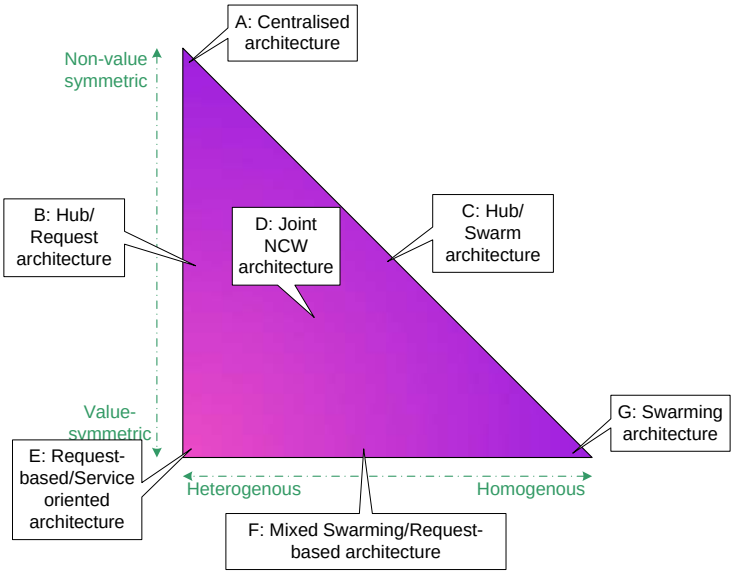

Figure 6: Dekker's taxonomy of NCW architectures

Type	Name	Description
A	Centralised	The least value-symmetric architecture, with a single high-value mission-essential hub (e.g. an aircraft carrier) surrounded by a cluster of nodes of lower value. The hub acts as a force multiplier, significantly increasing the effectiveness of other nodes (e.g. an AWACS increases effectiveness of the controlled aircraft). The hub forms a "centre of gravity"; a point of high vulnerability and a significant fraction of the force capability will be assigned to its protection, when the hub can advantageously be made the centre for communications and C^2. The presence of multiple high-value nodes moves this to a type B or type D architecture, which allows the force to continue to operate if the hub is damaged.
B	Hub/Request	Request-based architecture plus addition of central high-value hub(s) responding to service requests (easily integrated but service priorities must be balanced and the hub protected e.g. by high-priority requests to combat nodes when required).

C	Hub/Swarm	Swarming architecture plus addition of central high-value hub(s) which act as force multiplier while retaining swarming behaviour (e.g. frigate flotilla with an Air Defence destroyer, fighter aircraft directed by an AWACS, loitering area dominance munitions with centralised ISR asset). Hub must be protected & utilised effectively without introducing centralised control.
D	Joint	Mixture of other 6 types, likely to arise in a Joint Force where high-value units will tend to behave as hubs, but Action Groups can be assigned specific tasks and may work in different ways.
E	Request-based (aka Service-Oriented Architecture)	Nodes of similar value but with different specialised capabilities. Nodes must broadcast requests for services needed to fulfil their operational tasks, and the network identifies potential service providers (e.g. a SF unit may request video of the terrain ahead, which would be passed to a UAV; a subsequent call for fire support may pass through a fire-support-coordination C^2 node which will balance priorities and allocate an effector node).
F	Mixed	Value-symmetric but only partly homogenous mixture of Request-based & Swarming architectures
G	Swarming	A swarm is a force comprised of value-symmetric and homogenous elements, and may therefore be appropriate only for a single-service force (e.g. a flight of aircraft or a naval flotilla). No element has any specialist capability; each has sensor, C^2 and effector capability. If a swarm is supplemented by a hub (e.g. an ISR asset) then type C (Hub/Swarm) architecture is produced.

Table 1: Overview of Dekker's NCW architecture taxonomy definitions

Swarming

Swarming (the extreme form of self-synchronisation) has been posited as a potentially useful form of behaviour for net-centric operations, and hence must be investigated. A literature review was performed to identify instances of swarming, and produced potential examples both from nature, e.g. social insects (such as ants, bees, wasps and termites), flocks of birds, and the pack hunting behaviour of wolves and sharks [9], and from military history. The review of natural systems has allowed swarming characteristics to be listed, while the historical examples have grounded the concept of swarm tactics for military operations.

There are examples in natural swarming of cooperative behaviour of a large number of self-synchronising individual units to achieve a common purpose. One definition of military swarming is:

> *"The systematic pulsing of force and / or fire by dispersed networked units, so as to strike the adversary from all directions simultaneously*." [10]

The difference between self-synchronisation and swarming appears to be only the number of units involved. In a swarm there are large numbers with many interactions between the low-level components. Each interaction is executed on the basis of purely local information and general rules of behaviour, without reference to the overall swarm pattern or "emergent" global structure; there is little or no external ordering influence.

Social insect swarming behaviour is characterised as follows:

- There are a number (possibly many) of low-level components that have a high degree of autonomy and distributed functions. Each function requires a degree (sometimes high degree) of specialism.

- The low-level components of the swarm coexist in a number of stable states[8] (multistability). This arises as a result of clustering of the distributed functions. This multistability is the determining factor in the degree of flexibility and agility of the swarm, and it's response to random events and evolving situations. Linked to this is the existence of bifurcation processes whereby certain clusters of components will alter their behaviour (i.e. change their functional state) to assist other clusters of components to meet a crisis or event based upon primary need.
- Coordination appears to be achieved through indirect interaction (i.e. no direct communication, reacting through negative and positive feedback to events in the environment[9], such as the existence or absence of various pheromones).
- In the natural world, swarming occurs in species in which the individual appears to be less important than the collective; action is taken for the good of the swarm and in a conflict many of the individual swarm units may die.

Emergent behaviour: In a complex system unexpected behaviours emerge[10] which stem from the complexity of the interactions between the components of the system and the environment [11].High-level patterns and structure emerge from simple low-level rules. In other words, the system is more than the sum of its component parts. Emergent behaviour is not orchestrated or explicitly defined (which makes the engineering design of such complex systems very difficult). Emergent properties can be beneficial, for example if units adapt tactics successfully to support tasks for which they were not intended; emergent behaviour can also be harmful, e.g. if it undermines important safety or effectiveness measures.

> *"On the other hand, merely having a large number of interactions is not enough by itself to guarantee emergent behavior; many of the interactions may be negligible or irrelevant, or may cancel each other out. In some cases, a large number of interactions can in fact work against the emergence of interesting behaviour, by creating a lot of "noise" to drown out any emerging "signal"; the emergent behaviour may need to be temporarily isolated from other interactions before it reaches enough critical mass to be self-supporting. Thus it is not just the sheer number of connections between components which encourages emergence; it is also how these connections are organised. A hierarchical organisation is one example which can generate emergent behaviour (a bureaucracy may behave in a way quite different to that of the individual humans in that bureaucracy); but perhaps more interestingly, emergent behaviour can also arise from more decentralized organisational structures, such as a marketplace. In some cases, the system has to reach a combined threshold of diversity, organization, and connectivity before emergent behaviour appears. Systems with emergent properties or emergent structures may appear to defy entropic principles and the second law of thermodynamics, because they form and increase order despite the lack of command and central control. This is possible because open systems can extract information and order out of the environment."* [12]

Military swarming: We must consider whether the previous general discussion of swarming is adequate to cover this type of behaviour in military operations, and to differentiate it from the well-known conventional warfare concepts of manoeuvre[11] and convergent attack[12]. It must be remembered that dynamic behaviour is a key element of swarming; therefore a static sensor field is not a swarm.
Edwards [13] commented:

---

[8] For example, honeybees appear to follow a simple but powerful labour allocation rule- they seem to specialize in a particular activity unless they perceive an important need to perform another function.
[9] A process termed "stigmergy", where aggregation of pheromone chemicals from multiple insects in the environment provides data fusion, and evaporation of the pheromone serves both to disseminate information to other members of the swarm and also provides information management (by removing obsolete data which is not reinforced over time)
[10] For example: the flocking behaviour of groups of birds or fish; intelligence, consciousness and mind have been postulated to be emergent properties of the interaction of billions of neurons in the brain.
[11] Which includes Blitzkrieg
[12] Which includes tactics such as besieging, pinning and flanking of enemy forces

"Admittedly, the phrase 'convergent attack' could be stretched to include every case in history in which an army or unit ended up surrounded by the enemy and attacked from all sides during the course of a battle. Encircling and surrounding an enemy has always been a desirable goal: It cuts off the enemy's supply lines and destroys his morale by cutting off any possible retreat. The distinction is that swarming implies a convergent attack by many units as the primary manoeuvre from the start of the battle or campaign, not the convergent attacks that result as a matter of course when some unit becomes isolated and encircled because of some other manoeuvre…. Most historical examples of swarming are tactical cases because of their primitive command, control, and communication technologies…Swarming can be conceptually broken into four stages: locate, converge, attack, and disperse."

Operational swarming is more difficult, because of the communications difficulties in organising widely separated units to arrive at the battlefield at the same time from different directions. He further defines two approaches to military swarming; each applicable either operationally or tactically:
Massed Swarm, whereby a swarmer begins as a single massed body, then disassembles and conducts a convergent attack to swarm the enemy from many directions. Historical examples appear to favour this approach.

Dispersed Swarm[13], whereby the swarmer is initially dispersed, then converges on the battlefield and attacks without ever forming a single massed force. This is relevant to a network-based force operating over a dispersed area.
A number of authors have suggested that military swarming behaviour can also be achieved through networked situational awareness (SA) within an overall common shared intent, for example, Dekker states in [8]:

"Situationally Aware Swarming uses networking to fuse sensor information from individual nodes to produce an integrated situational awareness picture, and also to synchronise actions. There are three basic ways of doing this:

Orchestrated Swarming: *In Orchestrated Swarming, one of the nodes is chosen as a temporary "leader." In the Centralised Architecture, the C2 node was the node best equipped for command and control activities, but in Swarming Architectures, all the nodes are identical. The choice of "leader" is therefore made on the basis of suitable position, current combat situation, or other transient factors. This approach is sometimes used in Special Forces teams, where members can, if necessary, take over command from the nominal commander. Sensor data is sent to the "leader" node, where it is fused to produce an integrated situational awareness picture and an integrated plan of action. These are then broadcast to the other nodes. If the leader is unable to continue for any reason, the nodes agree on a replacement, which takes up where the previous leader left off.*

Hierarchical Swarming: *Hierarchical Swarming is closest to the traditional military C2 architectures, and this is because it represents an extremely good solution for dealing with complex problems. The nodes are organised into a hierarchy. In the event of nodes being lost, the hierarchy is maintained by promoting other nodes. Situational awareness information is fused going up the hierarchy, and at the same time, low-level tactical detail is dropped out. This means that the commanding node gets the "big picture" situation awareness that it needs.*

Distributed Swarming: *Distributed Swarming has no "leader" role, and all decisions are made through consensus. Situational awareness is handled by all nodes broadcasting their sensor information, so that every node builds up an individual situational awareness picture. This generates a large amount of network traffic, but if the network can handle the traffic, it is extremely fast".*

[13] It can be argued that the term "dispersed swarm" is not a swarm at all as the elements do not form a single mass! However, their combined ordnance could be directed from all directions and therefore it appears (tenuously) to be a swarm of sorts.

Error! Reference source not found. (based upon [13] and shows historical examples[14] [10, 14] of possible military swarming behaviour[15]. Most reported military examples of swarming relate to land force operations, this suggests that swarming is a tactic not particularly well suited to conventional maritime forces. This may be due to the relatively low numbers and limited speed of naval units; however a number of historical records do suggest instances where maritime forces may have exhibited behaviour similar to swarming.[16]

Swarming is inherently decentralised, scalable, resilient and dynamically responsive, hence does not suffer from the disadvantages of centralised control (delay in sensing, data fusion and decision making which may be unacceptable in rapidly changing circumstances, limited span of command , and organisational bottlenecks which may suffer information/task overload).

[14] Historical accounts are few since most swarmers were nomadic with few historical records.

[15] Clearly the success of such encounters cannot be related to swarm behaviour alone, since other tactics and factors (relative numbers, mobility and weapon ranges, etc) were also involved. It was common for one type of single-arm force to meet another very different single-arm force in battle.

[16] It should be noted that the historical examples of military swarming referred to in this appendix all relate to situations where communications were fairly poor.

Conflict	Swarmer description	Non-swarmer description	Notes
Athenian vs. Persian fleets Battle of Salamis, 480 B.C.	300 Greek ships, small and agile	700 to 1200 Persian ships	"The lighter Greek ships rowed out in a circular fashion and rammed the front of their ships into the Persian vessels. The narrow straight, the speed and manoeuvrability of the Greek ships and their knowledge of the waters enabled them to sink two hundred Persian ships." [15]
Scythians vs. Macedonians, Central Asian campaign, 329– 327 B.C.	Bow cavalry	Heavy infantry phalanx supported by heavy cavalry	Horse archer against Macedonian phalanx with supporting light cavalry
Parthians vs. Romans, Battle of Carrhae, 53 B.C.	Bow cavalry	Heavy infantry in legions	Horse archer against unsupported legions
Seljuk Turks vs. Byzantines, Battle of Manzikert, 1071	Bow cavalry	Bow cavalry, bow infantry, heavy cavalry armed with lance, bow, shield and sword	Horse archers against combined arms opponent
Turks vs. Crusaders, Battle of Dorylaeum, 1097	Bow cavalry	Heavy cavalry	Horse archers against heavy cavalry and supporting light infantry
Mongols vs. Eastern Europeans 1237-1241, Battle of Liegnitz, 1241	Light (60%) and heavy cavalry, standoff range of composite bow	Heavy cavalry and infantry	Both tactical and operational swarming. Decentralized Mongol command system
Spanish vs. English Spanish Armada, 1588	Drake's "sea dogs" in light fast ships using pulsed attacks with longer range cannon than the Spanish	Spanish Armada -the greatest naval fleet of its age, but mainly slow, broad & heavy merchant ships for troop transports.	The English were far more adept at artillery and naval tactics than the Spanish, who were regarded as the best land troops in Europe. Swarm threat warning by a series of hilltop signal beacons along the English and Welsh coasts. English use of fire ships to cause disarray.
Woodland Indians vs. U.S. Army, St. Clair's Defeat, 1791	Tribal warriors (light infantry)	Light infantry, some field artillery	Swarming light infantry with superior intelligence/ scouting/ concealment ability versus regular infantry
Napoleonic Corps vs. Austrians, Ulm Campaign, 1805	combined arms (musket infantry, cavalry, horse artillery); and semi-autonomous corps	Combined arms (musket infantry, cavalry, horse artillery)	"Operational" swarming combined with conventional tactics
Battle of Trafalgar 1805	Nelson's "band of brothers" approach to "Mission Command" and large number of autonomous platforms in very close combat.	Spanish & French combined fleets.	Head on approach of 2 British columns of ships (radical at that time) interdicting the enemy line of ships to prevent concentration of their force. At the same time producing devastating raking fire as the British ships passed through the Franco-Spanish line. This was followed by a "pell-mell" engagement with the British platforms exploiting the ensuing enemy

			confusion and applying local supremacy of force.
Boers vs. British, Battle of Majuba Hill, 1881	Dismounted cavalry	Infantry	Guerrilla warfare with swarming-like tactics
World War 2, Battle of the Atlantic, 1939–1945	“Wolf packs” of five or more U-boats deployed in widely dispersed fashion	Convoys of merchant ships and naval escorts	Naval example. U-boat Command guided U-boats to convoy targets reported by electronic espionage, air reconnaissance, or other U-boats. Early instances seem to have been coordinated personally by Admiral Doenitz.
World War 2, Coastal Defence Force flotilla ops	Motor Torpedo/ Gun Boats	Enemy Naval / Merchant ships	Coordination by on-scene flotilla commander
World War 2, Battle of the Pacific	Kamikaze air attacks	Allied naval forces in the Pacific	Coordination by Fleet commander and on-scene Pilots
Korean War 1950	North Korea & Chinese	NATO forces	North Korean and Chinese forces that Infiltrate well beyond any recognized front, and then attack from all directions.
Yom Kippur war	Israeli FPB	Egyptian OSA missile boats	Naval example
Somalis vs. U.S. Peacemakers, Mogadishu, October 3–4, 1993	Tribal militia (light infantry)	Light infantry, light vehicles, helicopter gunships	Peacemaking operation. Swarm coordination by megaphone, cell phone
Chechens vs. Russians Grozny 1995	Chechen anti-armour hunter-killer teams	Russian T-72 tanks	3- or 4-man cells. Machine gunner & sniper would pin down supporting infantry while antitank gunner would engage the armoured target. Five or six teams simultaneously attacked a single armoured vehicle. [16]
Sri Lanka vs. Tamil Tigers, May 2006	Sea Tigers’ small boats	Sri Lankan Navy patrols	[17, 18]
Iranian Navy, present day	Small boats, highly agile missile/torpedo attack craft	U.S. Naval forces, tanker convoys	Iran has practiced both mass and dispersed swarming tactics [19]

Table 2: Some historical examples of military swarming behaviour

Maritime examples of swarming

Most examples of military swarming behaviour appear to relate to land warfare, however a few have been found that appear to relate to the maritime environment, and these are discussed below.

Battle of Trafalgar (21 Oct 1805): The battle of Trafalgar can be cited as a naval example of swarming tactics used by the Royal Navy as they attacked the Franco-Spanish force using a large number of autonomous platforms in such a way as to cause confusion and create disorder amongst the enemy line in a "pell-mell" type engagement. Control of the force was through the distribution of command intent. It is recorded that the night before the battle that Admiral Lord Nelson outlined his strategy and tactics and told his subordinate commanders that:

> *"no Captain can do much wrong should he place his ship adjacent to that of the enemy".*

Force Coordination was achieved through low-level, simple interactions between the platforms – through the use of flag signals[17] immediately up to the point of engagement and then through the individual platform commanders reacting to localised events. Force agility was achieved by dynamically clustering force elements at the appropriate point and time.

Battle of the Atlantic (1939–1945): The German use of U-boat "Wolf pack" tactics was an example of naval swarming. Packs of five or more U-boats would converge on a convoy of transport ships and their naval escorts. Each U-boat commander attacked as best he could without attempting to coordinate his movements with those of any other boats. It has been stated [20] that the packs were coordinated centrally by Admiral Doenitz who required his commanders to report in daily and to await his final decision before launching their attacks and that this centralised control contributed to the initial containment and final defeat of the U boat offensive [18] [21].

Approximately 140 wolf packs were created between 1941 and 1943 specifically to operate mass attacks against allied convoys. The Atlantic was divided into prearranged grids and was patrolled to scout for convoys. Once a convoy was detected, a single boat would shadow it and report its position to U-boat HQ. The main body of the pack would then be called in and vectored onto the convoy.

A section of a convoy would be earmarked for target and the pack would attack in unison, usually under cover of darkness. *"Since U-boats could not be detected by ASDIC when they were on the surface and they could outrun all escorts except destroyers, they usually surfaced just before closing with the convoy. After reaching a firing position, most U-boats increased to full speed, fired a salvo of four torpedoes, turned away, fired stern torpedoes if fitted, then retired as rapidly as possible on the surface. After disengaging, U-boats would reload, regain a firing position, and attack again".*

WWII UK RN Coastal Defence Force (1939-45): The UK RN operated CDF flotillas of 8 to12 MTB/MGBs. Several boat types were used, averaging 60-70ft hulls capable of cruising quietly at 8 Kn, but at 30 to 40 Kn on main engines. [22].

These boats were usually tasked to patrol an assigned section of coastline or were vectored toward targets picked up by shore-based radar. MTBs and MGBs had much success working together in a coordinated organisation. The boats would attack targets in repeated waves

---

[17] Flag signals from the scouting frigates were repeated, along a line of communicating ships, to the main body of the fleet cruising 50 miles offshore as Nelson was hoping to draw the Combined Fleet out of port at Cadiz.

[18] "When the effect of Ultra on the course of the campaign is considered"

based upon capability, e.g. first MTBs next MGBs. These tactics were more successful than that carried out by any single capability and suggests that heterogeneity of function and weaponry are of benefit. However, it was also found that flotillas formed from more than one type of platform (e.g. different manufacturer's engines and hulls) created problems in coordinating speed and movement as the platforms performed differently, making it harder to coordinate an attack as the boats would not arrive in unison, thereby degrading the unity of force.

Battle of the Pacific, Japanese kamikaze air attacks (1939-45): It has been stated [23] that by the end of WWII:

> *"7,465 Kamikazes flew to their deaths, 120 US ships were sunk, with many more damaged, 3,048 allied sailors were killed and another 6,025 wounded. Although there may be some question about the exact numbers, the damage done by Kamikazes is almost unbelievable"*

Evidence shows that the kamikaze force coordinated its attacks with timed waves of aircraft causing a target to turn away from the first wave, only to find that it was turning into the paths of subsequent attacking waves. The commanders and individual pilots knew that the swarming force would be destroyed, but hoped that because it was both agile and had large numbers, enough units would get through to destroy the targets.

FIAC swarms (present day): More recent examples of naval swarming behaviour focus on both the Iranian navy and the Sea Tigers (the naval arm of the Liberation Tigers of Tamil Elam) who have reportedly [24, 25, 26] developed swarming and asymmetric tactics for ASuW attack by small, fast patrol boats.

Other applications: Swarming techniques have recently been applied to various aspects of commercial systems (e.g. automotive paint booth scheduling, a large retail distribution centre, phone call routing within a telecoms network, airline cargo routing [27]), while "social swarming" appears to be increasing among anarchists and activists that oppose the globalisation of trade [28], and recent terrorism also appears to employ swarming as the major doctrine.

Synchronisation metrics

A serious problem in analysis of C2 systems and synchronisation is that there are no agreed metrics to measure self-organisation, emergence, etc. One possible metric is the "entropy" or "order" within an organisation or system, a concept which originated in classical thermodynamics but which Shannon extended into Information Theory. The way units form into a coherent organisation or swarm is a complex problem and a significant area of study in organisational research.

"The natural tendency of a group of autonomous processes is to disorder, not to organization. Adding information to a collection of agents can lead to increased organization but only if it is added in the right way" [29]

Command and control of a maritime swarm force

A commander's aim is to concentrate force onto enemy weak points or centres of gravity. Force concentration may be achieved through application of any of the previously-discussed NCW architecture options; however NEC particularly emphasises the potential value of self-synchronisation with Dekker's "Situationally Aware Distributed Swarming" and Edward's "Dispersed Swarm" concepts. The question that must be explored is whether swarming or self-synchronisation can be more effective than explicit hierarchical coordination of

behaviour. Swarming does not fit easily into current RN maritime force strategy and there are practical factors while this is so.

Commanders (and their staffs) exercise C2 by following a serial process of estimating a situation, developing alternative courses of action, deciding upon and applying what is considered to be the most appropriate course of action.

However, Figure 5 above shows that swarming behaviour is a non-linear process which operates very near to uncoordinated activity and a state of chaos. Only very short term predictions may be made about future behaviour in such a near-chaotic system. Therefore a conventional command estimation approach is not compatible with a swarming force as there is no time to perform COA analysis and planning, or to relay orders through a command hierarchy.

Within a swarm force, individuals will have the opportunity to perform high tempo decision-making cycles as they will not be reliant upon a vertical chain of command. A swarm force, therefore, would be agile in response to rapidly changing events. A swarm force would need to be monitored and its activities supervised but its behaviour could only be influenced through prior communication of Command Intent and ROE.

The potential size of a swarming force: It is very difficult to be precise about the size of a force that is capable of swarming tactics. The range in the numbers of platforms that performed such tactics cited in the historical maritime examples varies greatly:

- The record of the British line of battle at Trafalgar states that it was comprised of 26 platforms in 2 columns, the first numbering 11 and the second numbering 15, although it is likely that there were many other small boats that were not in the line of battle, and likely to be involved in the ensuing “pell mell” battle (swarm);
- The British WW2 CDF flotillas numbered 8 to12 MTB/MGBs;
- U boats would converge on a convoy in packs of five or more;
- In1945, 10 massed assaults containing up to 400 kamikaze aircraft (in each assault) carried out against U.S. ships. On 11th April 1945, in a kikusui[19] attack on USS Enterprise alone comprised 185 aircraft[20]; these kamikaze attacks sank 28 ships and damaged 176.

It is therefore difficult to estimate the numbers necessary for a self-synchronising force to make the transition to a swarming force; it would depend very much on the circumstances of the task. In a massed swarm, a convergent attack upon an enemy from many directions would require large numbers of platforms. A very naïve example of such a massed attack would be a force made up of small homogenous FIAC platforms with low-cost weaponry (machine guns and RPGs) attacking a single target in a single pulse from (say) 8 cardinal points of the compass. The numbers of platforms could be as few as 8, but if one adds in the requirement for multiple pulse attacks, and reserves, the numbers of platforms would increase dramatically. If there were to be one group attacking, one group withdrawing, one group preparing to attack, and one group in reserve, this would require a total of 32 platforms.

[19] A massed kamikaze attack- 'kikusui' literally translated means 'floating chrysanthemum' after the emblem of 14th-century samurai hero Masashige Kusonoki.
[20] www.angelfire.com/fm/odyssey/ops.htm

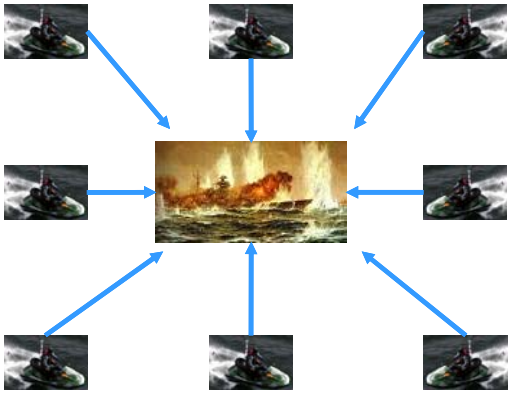

Figure 7: Naïve massed swarm example

A less naïve, but still simple, example based upon an attack spread around an azimuth might deploy FIACs at 50 metre intervals (for collision avoidance) around the circumference of a circle surrounding the target. A single pulse attack at 300 metres range (as a "whites of eyes" range with machine gun & RPG) implies the order of 36 FIACs (assuming 2 metres beam width). If additional pulses and reserves were to be employed, the number of FIAC platforms needed would increase rapidly to approximately 150. The number of pulses required would presumably depend on the hit probability and damage capability of the FIAC weapons against the intended target's defensive capability.

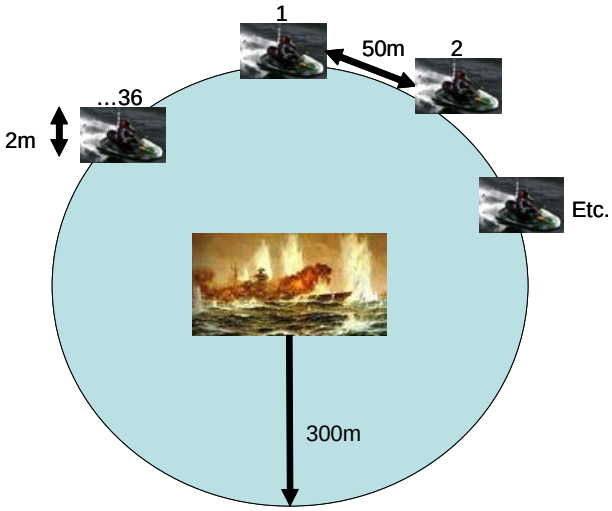

Figure 8: numbers of swarming platforms based upon the azimuth system

Obviously in the real world the numbers and direction of attack of the swarming platforms would be based upon more complex factors, including the number and type of targets, the degree and type of force protection offered to each target, and the type, positioning and arc of each of the weapons. From the above discussion it should be apparent that the number of swarming force platforms would be significant and mission specific. A relevant USN concept is based upon "a swarm comprising of many (50+) Corvette-or-smaller sized craft, fast, stealthy, lightly crewed, identical vessels, intensively digitised and completely interlinked with each other with one or two key weapon systems and without extensive magazines" [30].

Military swarm tactics: Before swarm tactics can be safely adopted by a future maritime force, the possible emergent characteristics must be understood. It will be necessary to model[21] a swarming/self-organising force to fully explore possible emergent characteristics:

- The first emergent characteristic of swarming tactics relates to the likely casualty figures. Historical evidence (e.g. Japanese Kamikaze attack) suggests that a swarming force is prepared to take many individual

[21] however there are insufficient historical examples of maritime swarming found to date to provide validation of any modelling

casualties to achieve force effectiveness, and relies upon agility and robustness for unit survival long enough to achieve the objective.

- Another emergent characteristic is the relationship between cohesion and survival. If the swarming force loses cohesion during the engagement then it is likely that the opposing force will exploit this to inflict heavier damage on the disorganised components resulting in more rapid losses. However, if cohesion is subsequently regained as the swarming force regains order the casualty rate should slow down.
- A further emergent characteristic is that a swarming force will gain localised advantage over its opponents. Swarming is inherently decentralised, scalable, resilient and dynamically responsive, hence does not suffer from the disadvantages of centralised control[22]. The force will be able to dynamically exploit disarray and confusion amongst opponents and be able to cooperate in groups to manoeuvre quickly to a position where it can inflict damage from many directions or to exploit a gap in opposition capability. However, this dynamic behaviour could also be turned against the swarm force by an enemy deception manoeuvre.
- Another possible emergent characteristic might also assist in alleviating bandwidth limitations for a distributed force. As swarm units only communicate with near neighbours, intra-force communications might be achieved by a series of short-range hops allowing OTH bandwidth reuse.

Three factors appear to play a role in the success or failure of military swarming:

- elusiveness, either through mobility or concealment;
- a longer range of firepower (standoff capability, especially by lightly armed swarmer units to wear down the adversary through pulsed attacks);
- superior situational awareness.

Defensive swarming must necessarily be “porous” to a degree [14], allowing the enemy to penetrate defended territory to an extent so that local units can then defeat the attacker by swarming them. Hostile swarms may in turn be countered by:

- pinning manoeuvre, or preventing concealment, or limiting their standoff advantage (e.g. through the use of minefields, terrain features, linked fortifications/defensive networks and other obstructions);
- constraining their SA (deception, jamming) or logistics base.

A maritime force could apply swarming tactics if sufficient units were available (e.g. coastal defence force MTB/MGB). A swarm of small boats with low-cost weaponry (e.g. 0.5 cal machine guns, RPG) could self-synchronise as long as they can see the target and can fire independently. Synchronisation of effects is not critical in this instance, since their weapons are fairly capable against a frigate-type target [23] and the summed effectiveness of their low-capability weapons (e.g. 0.5” calibre machine guns, RPG) might, for example, be equivalent to two Harpoon missiles fired from larger units. But their small size then limits their seagoing capability & hence deployability. There would be a fundamental problem for a maritime force made up of small platforms in that they are generally not ocean-going, and therefore not themselves able to sustain a power projection role without assistance from larger platforms.

[22] Data fusion and decision delay which may be unacceptable in rapidly changing circumstances, limited span of command , and organisational bottlenecks which may suffer information/task overload

[23] Frigate / destroyers are not armoured, and also carry lots of critical hardware topside.

The small platforms would therefore need to be transported to the zone of operations and sustained by a "mothership" e.g. the Victorian former-cruiser HMS VULCAN [24] in a similar way that aircraft are sustained by aircraft carriers, however VULCAN carried only 6 MTBs. Assuming that the force can be transported to the zone of operations, the distributed nature of the swarming force creates further problems:

- Small boats can safely position closely (say 45 to 50 metres apart) to form a swarm, but this cannot be achieved with larger platforms which are less manoeuvrable and so need to be spaced further apart (approximately half a mile / 800 metres).
- A self-synchronising /swarm force might be susceptible to enemy deception manoeuvre & there would be no mechanism to prevent this or recall them
- If the small platforms are manned, there must be sufficient crew numbers for the force to operate 24/7. It is more efficient to brief and billet the crews in a group. The distributed nature of a swarm force would generate problems for these processes.
- Maintenance of platforms is more efficient if the consumables and spares are also grouped. This means that the platforms would need to keep returning to a centralised node reducing their range of operation.

These sustainment problems associated with a swarming force as part of an expeditionary operation mean that it will be difficult to achieve sufficient numbers of maritime swarm components in the zone of operations and the concept of a swarming force of manned platforms is unlikely to be realistically achievable, although the larger number of platforms in a coalition force might increase the feasibility of a maritime swarm. However swarming possibilities may exist for smaller platforms e.g. unmanned vehicles, helicopters, or platforms of a size similar to the WWII Motor Torpedo Boat in a coastal defence role.

UXV swarm: the following potential examples of future UXV swarming are adapted from [31, 32, 33]

- **Maritime ISTAR:** Reconnaissance by swarming would be the result of sensors fitted to swarms of unmanned vehicles, cooperating in groups and capable of acting in an autonomous way with emergent behaviour to provide sophisticated intelligence, surveillance and reconnaissance (ISR) to extend and complement existing capabilities, extending the reach into areas that are currently denied, and in water too shallow for conventional platforms. High-resolution sensing is needed in a littoral environment to determine intent and allow rapid reaction; sensor swarms should be able to contribute this robust close-range monitoring. The initial implementation might be an "ISR periscope" type of mission, leading to target designation, launch and coordination of platforms for battle

[24] HMS Vulcan was a Torpedo Boat Depot Ship, built at Portsmouth Dockyard and launched 13th June 1889. Her main purpose was to launch smaller torpedo boats against enemy shipping. "She was a cruiser, fighting ship, repairing shop, torpedo depot, and floating dockyard. As a cruiser and fighting ship, she mounted 20 quick-firing guns and torpedo tubes; as a repairing shop she was fitted with lathes, drilling, planing, slotting and punching machines, circular saws, workshops and smithy, forges and furnaces; as a torpedo depot, she carried on board large supplies of torpedoes, torpedo stores, mines and mining apparatus; as a floating dockyard, she contained a small flotilla of torpedo boats with cranes for lifting them, as well as all sorts of special appliances. Her raison d'etre was torpedo nurse and general repairing establishment afloat for general service with a Fleet. She measured 350 ft between perpendiculars, breadth of 58 ft, mean draught of 25 ft and a displacement of 6,630 tons". In 1915 she was used as a submarine depot ship and in 1931 became a training hulk and was renamed HMS Defiance III, finally being scrapped in 1955. http://www.battleships-cruisers.co.uk/vulcan.htm

damage assessment and intelligence collection purposes, and ultimately to engagement via missiles.

- **Underwater search and survey:** Swarming unmanned vehicles might also perform: clandestine battle space preparation; rapid mine reconnaissance and clearance; and hydrographic and oceanographic environmental mapping. This range of UUV capabilities will support operational needs from deep-ocean to littoral environments.
- **ASW search:** Autonomous unmanned UUVs might provide a submarine search, detection, tracking, trailing and "handoff" capability, for Intel gathering ASW engagement.
- **Communication/Navigation Aids:** Autonomous vehicle swarms could become nodes of a net-centric sensor grid (above or below water), providing connectivity across multiple platforms, both manned and unmanned, as well as the ability to provide navigation assistance upon demand.

A UAV swarm might be formed from the organic UAV carried by frigate/destroyer platforms (if sufficient numbers accompanied the force), or the UXV numbers might be increased by flying them either from the CVF or from a specialist UAV carrier (possibly a converted commercial ship).

Self-synchronisation and the future maritime force

It must be stressed that a maritime force can apply tactics based on self-synchronisation, even with insufficient numbers of units for swarm tactics to be effective. A key part of the NEC concept is that benefit may be accrued from:

- Low capability units with good communications may call in firepower as required from other force units with long-range weapons, hence such units effectively become tremendously powerful.
- Improved ability of military forces to self-synchronise in order to speed the decision cycle. This already happens where circumstances and allocated authority permit, but NEC advocates that this should be the foundation of future tactics. It has been suggested that the Joint military organisation should change to a flatter structure, to promote such self-synchronisation. However this has potential disadvantages as well as advantages; for example, a hierarchical organisation is a good method for C2 of a situation which is too complex for any one individual to comprehend in its totality, the various organisational levels provide abstraction and fusion of key information for higher level commanders to understand and action.
- The facilitation of Joint/Coalition distributed training, which can be a cost-effective means to increase level of readiness and system shakedown prior to deployment (c.f. USN Community Development Employment Program (CDEP)).

Historically, naval commanders have had considerable autonomy at both tactical and operational levels, due to difficulty with long-range communications between maritime forces afloat and headquarters ashore. This resulted in the RN's early application of a Mission Command ethos, which includes aspects of self-synchronisation, and a relatively flat C2 organisation.

Centralised decision making may require time-consuming process of information queuing, verification and collation, overhead imagery analysis, as well several communications transfers which may be bandwidth-limited and involve high latency.

The choice is further complicated when additional real-world factors are included (E.g. some agents may be better-equipped in terms of decision-making ability / experience / support CIS, available information, etc). Dekker [34] poses six questions which must be addressed when selecting between a centralised or decentralised approach to decision-making:

- where are the facilities for decision-making located?
- is a global optimum solution necessary?
- is a global optimum possible?
- where is the necessary information available for decision making?
- within what timeframe must decisions be made?
- what communications infrastructure is available?

For example maritime Anti-Air warfare Force Threat Evaluation and Weapon Assignment (AAW FTEWA) is currently a centralised process aiming to achieve an optimum allocation of threats to defensive channels of fire to avoid serious loss of capability, however this is a time-constrained problem where a distributed approach might be worthy of consideration. However achievement of an optimal solution involves an exponential growth in time to process all possible combinations of potential solution. Dekker points out that if a single potential target allocation permutation takes only one nanosecond to analyse, then 10 targets will require a total of 4 milliseconds, 20 will require 11 minutes and 50 will require 14 months. Clearly an optimal decision cannot always be feasible in complex situations, especially where real-world factors (e.g. clutter and false targets) complicate the situation. Decentralised decision making requires an organisation and a network (e.g. the Maritime Tactical Wide Area Network (MTWAN)) that supports rapid peer-to-peer communications. This network would also support centralised decision making, if long-range (satellite) comms are available; the deciding factor should be on the need for optimality, speed and robustness though political sensitivities may also intrude in some circumstances (i.e. "president to foxhole"). Decentralised decision making may be the only option in situations where communications are hindered or inadvisable (e.g. Special Ops, long-range comms failure, under Emissions control (EMCON)). Potential maritime applications where distributed decision-making may hold merit include:

- Force Threat Evaluation and Weapon Assignment (FTEWA);
- Air Tasking order (ATO) planning;
- Maritime Interdiction Operations (MIOPS);
- Anti-Submarine Warfare (ASW).

There are various possible techniques, (some from "e-business" origins) that might be applied to achieve bottom-up, distributed synchronisation [35], among these are:

- **Mission swapping**, where the best available target is successively assigned to each agent in turn, and then pairs of agents are found which can benefit from swapping their targets.
- **Voting**, where subordinates "vote" on possible courses of action.
- **Bidding/auctioning**, where subordinates "bid" for missions or resources based on some estimate of "cost" or performance.
- **Service/request**, where some battlefield agents offer a "service" and other agents place "requests" for those services. This technique has historically been used for artillery support, and can easily be extended to other services; such a Service Oriented Architecture is being developed by the USN within their

FORCEnet initiative to realise NCW and is clearly of significance to future RN operations.

- **Distributed search**, where multiple agents cooperatively search an area (in physical-, sensor- or information-space), sharing information of search paths and results.

The choice of which technique to use is complex. In general distributed techniques may be less efficient than a centralised technique (which may achieve an optimum solution) but may offer higher robustness and speed, which are clearly of military benefit in rapidly changing tactical situations.

Conclusions

The threats that the armed forces facing are changing; there is likely to be a greater variety and a greater level of asymmetry. The UK's manoeuvre approach emphasises greater force agility to cope with such uncertainty. Increased agility is an aspiration behind NEC and it has been suggested that self-synchronisation and swarming might provide an appropriate tactic.

Force-wide synchronisation of sensor, command, and effects is necessary in order to facilitate a network-enabled operation. Various mechanisms are feasible to achieve synchronisation. In a hierarchical organisation a top-down centralised process is applied whereby low level units report their capability status, the high level commander produces and promulgates a plan that allocates low-level capability units to the desired task, the low-level units then action the plan. However the aim of this paper was to investigate more novel approaches to synchronisation which could allow individual units to coalesce their capabilities into an integrated agile maritime force. Since traditional maritime forces are based on hierarchical command then this has driven this study to investigate self-synchronisation, and its extreme form of swarming. It should be noted that implicit within the notion of self-synchronisation, as commonly used in NCW parlance, is that a Mission Command approach has been adopted, i.e. Mission Command would inherently allow distributed decision and execution encompassing both self-synchronisation and mutual-synchronisation with peers, as long as this occurs within the framework of the Commander's intent.

Swarming can only realistically happen in a situation where there large numbers of swarming units and they each have simple decisions to make. From the restricted platform numbers in the current (or foreseeable) RN fleet it is difficult to see how a future UK maritime force could apply swarming behaviour, although if maritime aircraft and UXVs were to be included then the potential for swarming increases. Swarming might be a suitable technique for maritime forces involving cheaper/less capable units that might be constructed in larger numbers, such as MTB/MGB.

However non-swarming tactics involving self- or mutual-synchronisation can be applied by a maritime force with fewer units.

The C2 of self-synchronising and swarming forces will rely on conveying the commander's intent, providing the required information and resources to accomplish the mission. Consequently plans employing self-synchronising or swarming forces will be less detailed. Commanders of a force using self-synchronising or swarming tactics must be willing to accept less direct control to facilitate self-synchronisation.

Not all components involved in a swarming force will share the same information picture. The individual swarming components will have their own very localised information, the scope of which is what they can immediately see and pull from their nearest neighbours. Decisions and reactions will be based upon this information feedback from the immediate environment. Individual components can not therefore have the same information view. This

differs from the NEC concept where situation awareness seems to be posited on a high-quality common picture across the whole force.

Since a threat may appear from any environment several single-purpose ships would need to continually act together in consort in order to provide mutual defence.
Furthermore maritime communications can be unreliable due to environmental constraints, equipment failures or enemy jamming, and units might be dispersed too widely; hence the level of networked support could at times be very low, so the argument for a fleet comprised of low-cost single-purpose ships is complex. A more viable approach might be to procure ships which provide a reasonable level of Anti-surface warfare (ASuW), Anti-Air warfare (AAW), Anti-Submarine Warfare (ASW) self-defence and which provide capability for mission payload optimisation by a “plug & play” mechanism, akin to the USN’s Littoral Combat Ship concept.

End of paper

References

1. Davison M, et al, (2007) "Maritime Concepts to exploit NEC - final technical report", Dstl/TR25826 V1.0, appendix D, 5 September, 2007
2. dictionary.com http://dictionary.reference.com/search?q=synchronisation&r=66
3. Ibid.
4. http://www.dsto.defence.gov.au/research/4051/page/4312
5. Miles J, Saunders M, Marsay D, How can Network-Enabled Capability contribute to better Command and Control? Proceedings of 9th ICCRTS, Copenhagen, Denmark 2005
6. Davison M, Coalition Force Dynamic ROE study, Dstl/TR06143, April 2003
7. Lt Col Couzens DMA & Harland S, Future Conflict (insights from interviews with senior commanders), CBM J6, Jan 2006, http://www.nec.dii.r.mil.uk/Default.htm.
8. Dekker A, A Taxonomy of Network Centric Warfare Architectures, Defence Science & Technology Organisation Australia
9. Bonabeau et al, Swarm Intelligence – From Natural to Artificial Systems, Santa Fe Institute, Studies in the Science of Complexity. Oxford University Press 1999
10. Arquilla, Ronfeldt, Swarming and the future of conflict, RAND Corporation 2000
11. McDermott, R., (2004), "Modelling Hoplite Battle In Swarm", BSc Thesis Faculty Of Information Sciences and Technology, Department of Computer Science, Massey University
12. Lenahan J & Charls P, Assessing Self Organization and Emergence in C2 Processes, CCRTS 2006
13. Edwards SJA, Swarming on the Battlefield Past, Present, and Future, MR1100 RAND corporation
14. Edwards SJA, Swarming and the Future of Warfare, RAND corporation dissertation, Sept 2004
15. http://joseph_berrigan.tripod.com/id29.html
16. http://www.fas.org/man/dod-101/sys/land/row/rusav.htm
17. Maritime threat: tactics and technology of the Sea Tigers, Jane's Intelligence Review, 01 June 2006
18. http://www.iiss.org/whats-new/iiss-in-the-press/press-coverage-2006/may-2006/tigers-sink-peace-hopes-with-suicide-raid
19. Haghshenass F, Iran's Doctrine of Asymmetric Naval Warfare, 21 December 2006http://www.washingtoninstitute.org/templateC05.php?CID=2548
20. Parker, J, Task Force untold stories of the heroes of the Royal Navy, ISBN 0 7553 1203 1
21. Burn A, The fighting captain, Pen and Sword Military Classics, ISBN 1 84415 439 4
22. Reynolds, LC, Home Waters-MTBs & MGBs at War, Sutton Publishing in association with the Imperial War Museum ,2000
23. Thomas, G W, Suicide Tactics: The Kamikaze during WWII, http://www.airgroup4.com/kamikaze.htm
24. CNN.com, Deadly attack on Sri Lanka navy, Friday, January 6, 2006; Posted: 10:26 p.m. EST (03:26 GMT)
25. BBC News on-line report, Craft 'rammed' Yemen oil tanker, Sunday, 6 October, 2002, 21:56
26. The Estimate, Volume XII, Number 22, 3rd November 2000
27. Bonabeau E & Meyer C, Swarm Intelligence a whole new way to think about business, Harvard Business Review, May 2001
28. Vail J, Swarming, Open-Source Warfare and the Black Block, Wednesday, January 05, 2005, http://www.jeffvail.net/2005/01/swarming-open-source-warfare-and-black.html
29. Van Dyke Parunak H & Brueckner S, Entropy and Self-Organization in Multi-Agent Systems, Proceedings of the International Conference on Autonomous Agents, 124-130
30. Scholer, A (2002) , The return of friction and the transformation of US naval forces in the 21st century" Proceedings of the annual meeting of the American Political Science Association, Boston Marriott Copley Place, Sheraton Boston & Hynes Convention Centre, Boston, Massachusetts, Aug 28, 2002

31. Fletcher, B., (2000) “UUV Master Plan: A Vision for Navy UUV Development”, SPAWAR, San Diego, www.spawar.navy.mil/robots/pubs/oceans2000b.pdf
32. Futrell DJ, Technological fundamentalism? the use of unmanned aerial vehicles in the conduct of war, Masters thesis, Virginia Polytechnic Institute and State University, 7 December 2004
33. NATO, Future use of Unmanned Air Vehicles in the Maritime Environment, AGARDAR-307 V0l.1
34. Dekker AH, Centralisation and decentralisation in network centric warfare, Journal of Battlefield Technology Vol 6, # 2 July 2003
35. Dekker AH, Centralisation vs. Self-Synchronisation: An Agent-Based Investigation , 11TH ICCRTS