AGENT BASED MODELLING TO DEMONSTRATE SELF-SYNCHRONISATION AT THE BATTLE OF TRAFALGAR: A DEMONSTRATION OF COMPUTATIONAL METHODS FOR TEACHING COMMAND AND CONTROL

Dr Matt Offord
Adam Smith Business School
matt.offord@glasgow.ac.uk

Abstract

Command and Control (C2) research demonstrates the value of decentralised decision making and agility. However, the complex situational factors that lead to self-organisation could be a barrier to understanding *power to the edge.* This paper explores the use of Agent Based Modelling (ABM), as an educational technique to visually demonstrate the effect of decentralised decision making at the Battle of Trafalgar. Using Net Logo simulation software, the movement of two fleets of warships can replicated. By using a few simple rules, agents simulating the Royal Navy Grand Fleet clearly demonstrate self-organisation, collaboration and situational awareness. This shows the effect of emergence from complexity theory, where simple rules at one level result in self-organised and complex behaviour at another. Whilst the agents in the model cannot share information, their behaviour closely simulates self-synchronisation. The simulation allows levels of autonomy and situational awareness to be adjusted with the results demonstrating the efficacy of decentralised decision making in specific situations. The result of demonstrating the agility of independent agents makes a striking and straightforward affirmation of C2 theory, through the historically well-known example of a famous battle. The paper will demonstrate how the simulation was created and the features which show self-organisation, agility, collaborative action, and situational awareness. As well as describing the basic operation of the programme, the paper will link this with C2 and complexity theory, showing how to use the model for educational purposes.

1 BACKGROUND

In their influential book, *Power to the Edge,* Alberts and Hayes[1] describe decentralized decision making in C2 as the 'road less travelled'. When the book was published, the world was experiencing a transformation towards a more information intensive environment. This book could not have been written at a more salient time, and yet it drew on examples of warfare from over two hundred years ago at the Battle of Trafalgar.

The authors argued that the crushing defeat of French and Spanish warships, in the Bay of Traflagar in 1805, was at least partly due to the informational superiority enjoyed by the Royal Navy (RN) Grand Fleet[2]. Admiral Lord Nelson, in charge of the RN Grand Fleet, made sure his plans were widely known and discussed. His Sea Captains were thus able to pursue the plan despite being out of touch with the Flagship and each other. This is given as an example of self-synchronisation, the features of which are:

- Clear and consistent understanding of command intent
- High quality information and shared situational awareness
- Competence at all levels of the force
- Trust in the information, subordinates, superiors, peers and the equipment[3]

Informational approaches characterise network perspectives to C2 such as Network Centric Warfare (NCW) or Edge C2. Many of these approaches draw from Alberts and Hayes' seminal work in this area. However, understanding the complex factors driving Information Age C2 is a challenge in its own right[10]. In this paper, Agent Based Modelling (ABM) is offered as an educational tool to make the link between practice and theory explicit. To do this, the paper returns to the Battle of Trafalgar to explore the drivers for agility.

2 COMPLEXITY, INFORMATION AND SELF ORGANISATION

Industrial age military commanders determined optimal solutions to battlefield problems by breaking down information into manageable chunks. However, as complexity has scaled, these decompositional techniques are no longer enough to capture all the information required for agile decision making[4]. Simply understanding that something is complex is insufficient in coping when the unexpected emerges "as if from a cloud"[5]. An important difficulty in understanding complexity is the problem of "thinking in levels"[6]. Barriers exist in understanding how small differences between individuals in a system add up to aggregate behaviours (integrative understanding) or, conversely, how we can determine individual actions when we already know the aggregate pattern of behaviour (differential understanding)[6]. This is known as slipping between levels where the properties of one level are applied to another. An example given by Wilensky and Rand in their useful guide to agent based modelling, is to attribute leadership properties to the leading bird in a flock of geese, flying in a V formation. It is now know known that the goose in front is positioned because of the sum of a few simple decisions made by individual birds, rather than any conscious decision making by 'leader' birds[5]. The leader-bird behaviour is, in fact, emergent, being dependent on a pattern of variation at the lower (individual bird) level while the flock as a whole is self-organising[6].

The increased availability of information both drives complexity and the need to collaborate in order to master it. To depart from the Industrial Age mindset to an appreciation of the complex modern battle space, an ability to think in levels, to understand emergence and self-organisation is required. Complexity can be driven by a single variable which can reach a critical threshold or 'tipping point' known as self-organising criticality[7]. Although it may be driven by a single factor, the complex environmental context can lead to the tipping point being very difficult to predict. According to Alberts and Hayes' description of the Battle of Trafalgar, informational superiority may be such factor[1]. While the battle could hardly be said to be saturated with data in a modern sense, the RN Captains were well-versed in Nelson's tactical plans in contrast to their enemies who were reliant on strict cyclical C2 approaches[2]. Additionally, in the heat of battle, it was unlikely that vessels could communicate with each other, or the Flagship reliably.

The lack of information in the respective fleets makes the information shared, prior to battle, even more critical. From a complexity theory viewpoint, this lowers the threshold for self-organising behaviour. Complexity theory allows that complex self-organising behaviour can occur without direct leadership[3]. Self-synchronisation can be considered as a special instance of self-organisation, specific to C2 theory. Therefore, a modern understanding of complexity supports the apparently optimal, yet often undirected action of the RN vessels as self-organised units in the battle.

3 TEACHING POWER TO THE EDGE CONCEPTS

Harnessing power to the edge requires a change of mindset which relies partially on education[9]. Beyond this, Alberts and Hayes highlight the significance of experimentation as a vehicle to better understand complex Information Age battlespaces where doctrine and intuition are less effective than they once were. C2 continues to undergo a paradigm shift which is as disorienting as it is rapid. Education is one of the key pillars in adapting to the new reality[10].

As with any new subject, a number of pedagogies may be used, from traditional courses, lectures and so on to serious games and wargames. The CCRP offers a more or less traditional short course, albeit it is online and openly accessible[11]. Additionally, western military academies incorporate modern takes on C2 in their Command courses, delivered in a traditional synchronous and face to face manner. Serious games and wargames lean toward experiential learning which can increase engagement and deeper understanding[12]. In fact, military formations regularly use table top tactics to explore multiple possibilities and eventualities[12]. A significant benefit of these approaches are that they harness the imagination and out-of-the-box thinking, as well as number of 'game' elements, triggering 'what-if' questions. Such approaches are well suited to complex environments where it is prudent to expect the unexpected and where, standard operating procedures can be limited.

Simulations can also develop unexpected complexities, although this is rather more due to the interaction effects between levels discussed earlier. Simulations, therefore create memorable learning, but through a more systematic approach. The learning itself can be used to understand the systemic antecedents as well as a tool to encourage solutions. Simulations can also create high fidelity predictive tools, such as those developed by the UK MOD, and used for policy development[13]. Simulations and serious games need not be complex however. In fact simple abstractions (such as the earlier example of the geese) can be very instructive and memorable. Agent Based Modelling is an effective and simple instrument to achieve this goal.

4 AGENT BASED MODELLING (ABM)

ABM is a specific approach to simulation which focuses on the behaviour of 'agents' in an environment. It is also possible to build layered models where collections of individual or micro behaviours, can be aggregated up into system level (macro) behaviours[15]. It is an intuitive and relatively simple way to explain slippage between levels or the emergence of complex behaviour. As a kind of constructed "laboratory"[15], Agent Based Models (ABMs) can used in both experimental and educational modes. Their flexibility and well established success in modelling emergent behaviour commends them for teaching self-organisation and emergence.

ABMs create an environment in which agents exist. Agents can be used to model individuals, vehicles, organisations or anything the modeler wishes to simulate. Essentially, agents can be anything which has agency.

Agents are typically programmed with a few simple rules which abstract some characteristics from their real life equivalents. Similarly any simulation of the environment in which the agents are operating needs to be focus on a few pertinent contextual features. These could be physical, psychological, social constraints or feedback, for example.

The conditions within which the agents operate can be changed. An advatange of this approach is the ability to create conditions which could not be safely rehearsed in a physical environment. For example, an ABM study of decision making in RN warships allowed the researcher to simulate information flows in so-called flat hierarchies, something that could not be done on a real warship[19]. Furthermore, simulations using simple rules and a bottom-up design generate comparable results with more complex top-down approaches, such as equation based modelling (EBM)[16].

5 MODEL DESIGN

5.1 Model Platform

The Battle of Trafalgar model was designed using Net Logo[17]. Net Logo is an open platform, using a creative commons licence[3], allowing modellers to readily develop ABM. The software is designed to be accessible to a wide range of users, regardless of their experience in coding. The programming language is simple, requiring only a basic knowledge of coding. The platform is both hosted on the internet and is also available as a software download, being compatible with a wide range of operating systems and other applications such as R (for statistical computing), providing a powerful and extensible tool[3].

The associated Integrated Development Environment (IDE) consists of an interface, information area and coding environment. The interface consists of a 33 X 33 grid where agents are visualized. The interface is shown at figure 1.

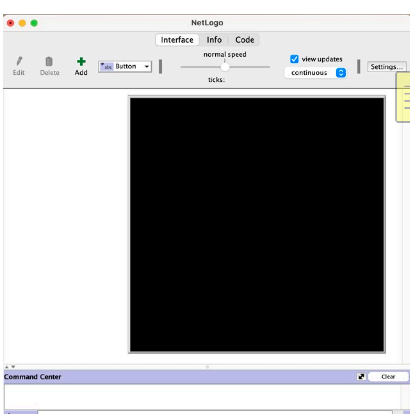

Figure 1 – Netlogo interface

The user interface has basic features and a terminal to write code directly. It is designed so that buttons, switches and plots can be added, making the user interface for the model highly customizable. The information feature allows the author to supply information on the design and function of the model as well as instructions. Finally the coding environment allows the model itself to be designed using the Net Logo language. An example of the coding environment is at Figure 2. Once the programme has been written, it is necessary to add buttons such 'go' to make the model run from the interface. Inputs can also be built into the interface to allow the simulation to run in varied conditions.

Figure 2 – An example of Netlogo code using the code environment

5.2 General Description

The following provides a brief explanation of how the model operates. The model starts with two fleets of ships, simulated by primitive agents in Net Logo, called turtles. The fleets, red and blue respectively, approach each other at right angles (as happened at the famous battle). Some of the initial variables, such as the size, speed and firing accuracy of the ships can be set using the interface, prior to running the simulation. By default the red ships (simulating the RN Grand Fleet) are slightly smaller, faster and with a higher firing accuracy than the blue fleet. The number of vessels in each fleet can also be altered. Therefore the simulation can be run to model many variations, including offering different advantages to each fleet from the battle, and with different initiation fleet dispositions. Alternatively, the simulation could be run with fleet parameters set as equal. An example of the different fleet dispositions (starting positions) is shown at figure 3 below.

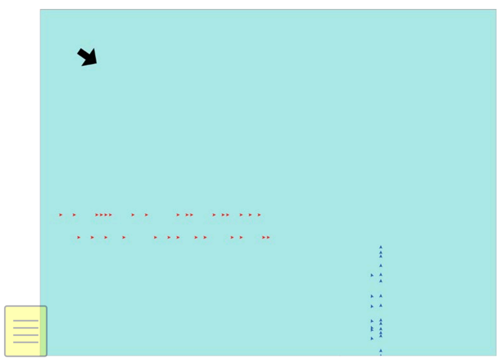

Figure 3 – Starting positions of red and blue fleets modelled in NetLogo (wind direction shown by black arrow)

Additionally, the red fleet can be set in either control-free and not control-free modes. In control-free mode the red fleet will execute the 'crossing the T' manouvre and then act independently afterwards. The red fleet ships observe 3 rules:

- Link to a random blue ship (target) if no current targets
- Face and close the target
- Fire when in range

Both blue and red ships fire on each other when their enemies are abeam (at relative 90 degrees) or directly ahead. Neither ship can fire astern (behind). The blue ships will continue to steer the same course and speed, firing on red ships in range, unless the user commands the ships to turn, speed up or slow down. These user commands are applied to all blue ships, it is not possible to control a single ship or sub-group.

Another feature unique to the red ships is the sense variable. This variable affects the ability of a red ship to detect a blue ship. It can be set such that all blue ships are visible, only neighbouring enemies can be detected, or anything inbetween. The purpose of this variable is to demonstrate the impact of information volume on control-free applications. When the sense variable is low, the red ships behave in an ineffective and aimless way. The interface allows the following inivital variables to be set:

- Wind speed (global)
- Wind direction (global)
- Number of ships (red and blue)
- Health (red and blue) – a proxy for size
- Firing accuracy (red and blue)
- Speed (red and blue)
- Directional control (blue)
- Sense (red) - detection range
- Control-free (red) – on/off

Additionally, it is possible to plots, monitor and record the progress of the battle in terms of losses and damage and see this on the user interface. An image of the complete user interface is provided at Figure 4.

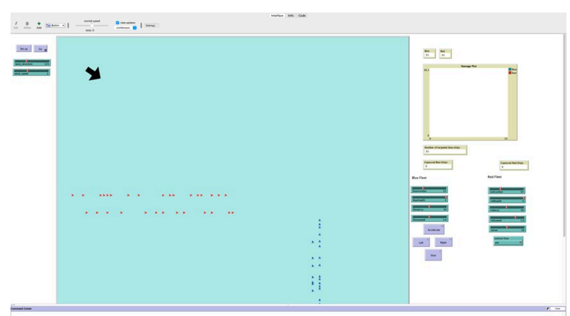

Figure 4 - The Battle of Trafalgar model interface

5.3 System Dynamics

The system dynamics can be described clearly with a UML activity diagram[18], representing the logic driving the behaviour of the agents. This also shows how similar the actions of the blue and red ships are, indicating the limited advantage that one might have over the other. Specicially, the set of rules governing control-free activity is the main difference between the two fleets. The activity diagram is shown at Figure 5.

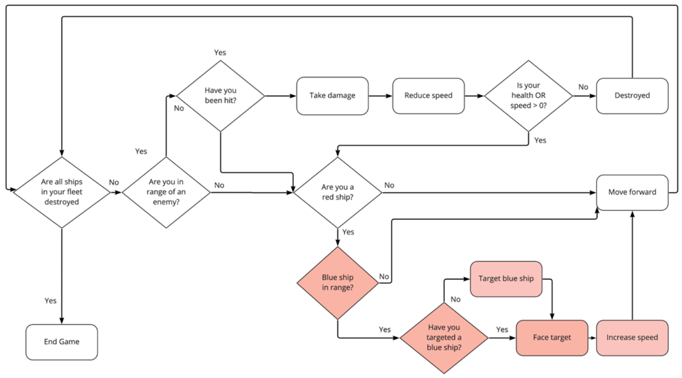

Figure 5 – Activity Diagram for Battle of Trafalgar ABM (red shapes indicate steps applicable to red ships only)

The activity diagram at Figure 5 shows that the red ships have only 5 additional steps, where they differ only in their simulation of autonomous movement. The diagram also shows the simplicity of the model. Agents only need check for damage (based on the probability of being hit, according to the set firing accuracy) and move through the modelled world. The grid used by the model is programmed in such a way that ships cannot leave the environment, but rather exit from one extremity of the grid to appear on the opposite side. There is no need for a separate firing sequence because the check for damage applies the accuracy of any enemy ships in range and applies damage if successful. The model therefore has a stochastic element which means that two simulation runs will never be alike. However, the model can be run by setting a seed for the pseudo random number generator, ensuring runs can be replicated.

6 MODEL FEATURES

6.1 REALISTIC FEATURES

The model is not an attempt at a realistic re-enactment of the battle. However, it is possible to incorporate some well known factors such as the larger size and number of French and Spanish fleets plus the higher speed and firing accuracy of the RN fleet. These features allow the model to be compared with known historic outcomes. Running the model with these features over 1000 runs always leads to a red victory, although red casualties are always experienced. These consistent outcomes imply that control-free conditions are conferring a clear advantage to one side. The default 'Trafalgar' settings are outlined in Table 1.

Table 1: Trafalgar default settings

Settings	Red	Blue
Health	4	5
Number	27	33
Accuracy	75	50
Speed	1.5	1

6.2 CONTROL-FREE CONDITION

As noted earlier, the red fleet can be set in a control-free mode of operation. This action allows the red ships to behave in accordance with the red shaded activities in Figure 5. These parts of the activity diagram simulate autonomous behaviour and self-organisation. If the model is run in control-free mode, the red ships will act as if fully controlled until the 'crossing the T' manouvre is complete. That is the red columns will interact with the blue columns attacking at right angles. This allows the model to preserve an element of the actual battle and visually demonstrate the change in behaviour when the ships become completely independent. The sudden change in direction and swarm-like behaviour of the red ships at this point makes a very graphic illustration. Alternatively the model can be run with control-free mode switched off. The outcome of the battle then becomes very variable and there are no clear winners. Switching to control-free mode again creates a sudden and striking difference in behavious which normally allows red to win, even from an apparently losing position.

6.3 DETECTION RANGE

The sense input allows red ships to detect blue ships at differing ranges. This highlights a feature of the model which demonstrates self-organising criticality (SOC). Because this threshold itself varies with different contexts, a simple tipping point parameter can become very complex. In the case of Edge C2, information availability may be an SOC. This can be seen by reducing the detection range. At a certain point the red ships become disorganized and ineffective.

6.4 OTHER FEATURES

All of the variables discussed can be manually adjusted before or during the simulation. This would enable potential instructors or students using the model to experiment to see which variables have a significant impact on the outcome. For example, in control-free mode, the number of blue ships can be increased to 100 but will still loose the battle. Thus, we may summise that decentralized C2 has more relative impact than sheer numbers.

7 TEACHING WITH THE MODEL

7.1 THINKING IN LEVELS

ABM is especially useful in encouraging thought about levels of activity. To monopolise on the bottom-up design, it is necessary to highlight the rules driving agent behaviour. Lessons should incorporate the simulation but explain the differences between red and blue rules first. Once students are aware of the differences, the simulation can be run to demonstrate the emergence of self-organisation from individual behaviours. Students can be encouraged to run the simulation themselves in control-free mode, or with this option disabled. Discussion about the results should be encouraged.

7.2 THRESHOLDS

The sense variable, which is adjustable in the interface, will allow red ships to behave in a more or less coordinated fashion . This variable is akin to having an adjustable range at which red ships can detect blue ones. Demonstrations of the simulation with different settings will highlight the level at which self-organisation spontaneously emerges (self organizing criticality). Again students should be encouraged to experiment with this setting and discuss their activities.

7.3 MISSION COMMAND

The concepts of centralized intent and decentralized execution describe the action of the red ships in control-free mode. Dependent on prior learning and experience, lessons on mission command should ideally be provided first. As the mission command term is widely used and can, therefore, be subject to misinterpretation, it is worth clarifying this at the outset. It will be important to point out the differences between autonomy and mission command. The red ships have a goal (intent) and also control measures as they have only a small number of rules which govern and constrain behaviour. After demonstrating and using the model independently, students should reflect on how the model demonstrates mission command or any limitations of the model.

7.4 FREE PLAY

Finally, one other option would be to offer free play, providing an opportunity for students to experiment and learn about C2 independently. A number of factors can be modelled such as fleet numbers, speed and size of vessels. Students could experiment with the model independently to discover how self-synchronised units fare when out-numbered, or other situations where military force is diminished. Free play can support more engaged learning and discovery, strengthening the understanding of C2 and military forces operating in complex endeavours.

8 CONCLUSION

ABM is a simple, accessible and engaging way to think about complex ideas. The Battle of Trafalgar provides a memorable anchor for learning about self-synchronisation, while the model itself draws from the seminal analysis of *power to the edge*[1]. Beyond the lessons for Edge C2, the model opens a window on complex dynamics from the perspective of individual combatants, which is an effective and intuitive method to teach military decision makers.

REFERENCES

[1] Alberts, D. S., & Hayes, R. E. *Power to the Edge. Information Age Transformation Series, 2003*. www.dodccrp.org. 4.

[2] Alberts, D. S., & Hayes, R. E. *Power to the Edge. Information Age Transformation Series, 2003*. www.dodccrp.org. 30.

[3] Alberts, D. S., & Hayes, R. E. *Power to the Edge. Information Age Transformation Series, 2003*. www.dodccrp.org. 27.

[4] Alberts, D. S., & Hayes, R. E. *Power to the Edge. Information Age Transformation Series, 2003*. www.dodccrp.org. 56.

[5] Alberts, David S. The Agility Advantage : A Survival Guide for Complex Enterprises and Endeavors. 2011. 50.

[6] Wilensky, Uri, and William Rand. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press, 2015. http://www.jstor.org/stable/j.ctt17kk851. 12

[7] Frigg, R. Self-organised criticality - What it is and what it isn't. *Studies in History and Philosophy of Science Part C :Studies in History and Philosophy of Biological and Biomedical Sciences*, *34*(3), 613–632, 2003: https://doi.org/10.1016/S0039-3681(03)00046-3

[8] Wilensky, Uri, and William Rand. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press, 2015. http://www.jstor.org/stable/j.ctt17kk851. 102.

[9] Alberts, D. S., & Hayes, R. E. *Power to the Edge. Information Age Transformation Series, 2003*. www.dodccrp.org. 90.

[10] Alberts, David S., and Richard E. Hayes. *Understanding command and control*. Assistant secretary of defense (C3I/Command Control Research Program) Washington DC, 2006.

[11] http://www.dodccrp.org/education_nec2.html

[12] Bosio, Nick. "Moulding war's thinking: Using wargaming to broaden military minds." *Australian Army Journal* 16, no. 2 (2020): 25-48.

[13] Moffat, James. *Adapting modeling & simulation for Network enabled operations*. OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE FOR NETWORKS AND INFORMATION INTEGRATION WASHINGTON DC, 2011.

[14] Eisenberg, D. A., Alderson, D. L., Kitsak, M., Ganin, A., & Linkov, I. Network Foundation for Command and Control (C2) Systems: Literature Review. *IEEE Access*, *6*, 68782–68794, 2018. https://doi.org/10.1109/ACCESS.2018.2873328

[15] Gu, X., and K. L. Blackmore. "A systematic review of agent-based modelling and simulation applications in the higher education domain." *Higher Education Research & Development* 34, no. 5 (2015): 883-898.
[16] Wilensky, Uri, and William Rand. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press, 2015. http://www.jstor.org/stable/j.ctt17kk851. 32.
[17] Wilensky, U. NetLogo. (1999) https://ccl.northwestern.edu/netlogo/index.shtml
[18] Gilbert, G. Nigel, and Klaus G. Troitzsch. 1999. *Simulation for the social scientist*. Buckingham: Open University Press. 208
[19] Offord, Matt, Roger Gill, and Jeremy Kendal. "The effects of prestige on collective performance and information flow in a strictly hierarchical institution." *Palgrave Communications* 5, no. 1 (2019): 1-11.