Force Flexibility Modelling in BactoWars

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EXTENDED ABSTRACT

Force flexibility is often referred to when considering the effectiveness of a force. Flexibility is all too often loosely defined and ill-communicated due to the number of factors involved and the nature of the English language. During the Army Experimental Framework Experiment Headline 2006 a key variable in determining a forces ability to continue its mission was the flexibility of the force and its sub-elements. In an attempt to harden our collective definition of flexibility and provide a starting point to improve the flexibility of forces through modelling and simulation, the Flexibility model was developed in the BactoWars Agent Based Simulation. In the past we have captured qualitatively the definition of flexibility, and whilst we will try to do so again, this quantitative method attempts to provide a more rigorous support to our analytical findings and provide us the communication medium to improve our definition of what makes a force flexible.

One can think of many different factors that affect the make-up of a force. These factors collectively form the notion of having a broad range of skills available, to which we refer to as 'completeness'. An object is known to be complete when "having all the necessary or appropriate parts; entire" (Oxford Dictionary, 2007). Having a complete force allows for adaptability in an uncertain environment, an important factor in modern warfare. Further to the idea of completeness is the knowledge that in a hostile environment one has the 'redundancy' to maintain their adaptability whilst sustaining loses to the force. These notions of completeness and redundancy form the basis of the Flexibility model. A stronger bias is given to the completeness as it is a prerequisite of redundancy.

In order to further refine the idea of completeness, characteristics must be chosen which represent important factors in an environment. In the Flexibility model we have chosen three factors; mobility, engagement and protection, from the Army as a System (AAAS) as defined in Curtis N, Dortmans, P (2004, 2003). However, the model has been developed with the scope to increase the number of characteristics as needed.

The Force is initially divided up into groups of elements based on the number of groups required, and the force elements' proximity to each other. Using the values of the characteristics for each force element the model moves redundant elements at regular periods. The movements intend to increase the completeness of each group maintaining a high level of flexibility. The redundant elements can be part of another group within the Flexible force, or from an external group that is providing support to the Flexible force.

In the scenario developed to test these ideas the force groups swarm around an invincible target. The most flexible force group moves in and attacks the target, sustaining loses. As the group sustains loses its flexibility reduces until it is reinforced by another group or becomes weaker than another force group and backs away. Once again the most flexible group moves in and the process continues. We use this basic model to investigate the impact of reorganisation time between the groups.

The ultimate aim of this work is to use force flexibility as a tool to assist in the evaluation of future concepts and force structures. In particular we have started to look at force flexibility in terms of its application to Army's future concept of Adaptive Campaigning and in particular the issue of swarming. This work is showing the benefits of the model and the use of BactoWars as a tool to implement the model.

1. INTRODUCTION

The Australian Army has recently developed two key documents defining how Army will operate in the future. The first of these is the Future Land Operating Concept that outlines how Defence sees land environment of the future (Australian Army 2006a). The second is the Australian Army's response to this future environment, Adaptive Campaigning (Australian Army 2006b). One of the key tenants of Adaptive Campaigning is the ability of the future Land Force to be adaptive within the future Land Battlespace. Although this document provides some general direction it does not provide the detail of how this might be achieved. Although work has been done in this area, such as that by Grisogono and Ryan (2007), it has focused around the decision process of adaptation rather than the intent of developing flexible forces that will able to adapt within this future environment.

An adaptive decision process has limited value on the battlefield if the force does not have the ability to adapt. Force flexibility is about providing the systems, equipment and procedures to the soldier so they can make informed decisions and adapt to changing circumstances. The aim of this work is to look at what we consider to be the hard problem of building an adaptive force. That is, a force flexible enough to adapt to the decisions made.

This paper discusses an approach to developing a formal definition of flexibility and using that definition, as expressed as an Agent Based Model to explore the concept of swarming as discussed in Adaptive Campaigning.

Army Experimental Framework

The Australian Army in conjunction with DSTO has developed a modernisation program using techniques from operational research, analysis and experimentation. A key part of this program, the Army Experimental Framework (AEF) has been established to enable the development of new concepts of war fighting and test new capabilities that are grounded in well established scientific practices (Bowden et. al. 2006). Once these concepts have been developed through the framework, they can then be used to inform the development paths for capability.

Further to the development of new concepts, the AEF also provides a stimulus for the development of new technologies to support the analytical and war gaming efforts required to support the experimentation of new concepts. To date a number of simulation and war gaming technologies have been developed in an effort to enable the required analytical outputs from experimentation to be realised. Some of these include the Joint Seminar War game Adjudication Tool (jSWAT) (Millikan *et. al.* 2005), BactoWars, an Agent Based Simulation (White 2007) and other analytical support tools.

Each year the AEF holds a number of limited objective experiments followed by a culminating major experiment Headline. In 2006 the Headline experiment's main simulation effort used the Janus war game. The analytical team developed requirements and some analytical gaps were identified and resolved using BactoWars (White 2007). Due to the success of using BactoWars to fill this analytic gap at Headline it was chosen as the platform in which to create a model to measure force flexibility. The remainder of this paper details the manner by which the Agent Based Model, BactoWars was developed to support the operational requirements of the large Headline experiment for an initial effort towards a quantitative method of information capture to analyse force flexibility.

2. FLEXIBILITY ALGORITHM

The flexibility algorithm developed was founded in factors developed prior to the Headline Experiment. Whilst not all the factors were included in the initial version, their scope was included in the model. This paper describes the factors in terms of the initial model design.

Flexibility is defined as "able to change or be changed to respond to different circumstances" (Oxford Dictionary, 2007). Further, it is noted that flexibility of a system becomes valuable when there is inherent uncertainty in the system. In a warfare context, uncertainty is a major component.

Roshanak (2005), has developed a six element framework that enables people to capture the benefits of flexibility at different physical and temporal scales for space systems. These six elements are system boundaries, time window, system aspects, uncertainty, response to change and degree of access.

Of the six elements described, the framework utilises the first five elements as design time characteristics, such that we gain a holistic view of the system, whilst the sixth element is one of a baseline implementation based on accessibility.

System Boundaries

As the application of this model was to refine the general concept of swarming as described in Adaptive Campaigning, our system boundaries were defined as being that of tactical. Whilst there have been developments in other countries with operational level swarming, it was of interest to explicitly target the low-level tactical system. Further, the AC document described five lines of operation. For the purposes of constructing a baseline case, we have focused on a general combat model and have not addressed the other lines of operation that also include non lethal effects.

Time Window

The time window for this study is the Army After Next (AAN) which has a time-frame date set outwards of the year 2025.

System Aspects

The system aspects of interest are defined as those "to what aspect the flexibility is measured." From our previous experimentation, we decided to capture aspects such as movement, engagement and protection as a measure of completeness and redundancy of the force.

Identifying Uncertainty

McManus (2004) categorised uncertainty as the lack of knowledge, lack of definition, statistically categorised phenomena, known unknown and unknown unknowns.

Uncertainty for the swarming concept could include a vast number of characteristics. Such characteristics range from the lack of knowledge in the environment such as situation awareness (known unknown and also unknown unknowns), to mechanical failure in equipment.

The process of understanding the major uncertainties in the system supported our modelling to include redundancy as a major influence in system design.

Response to Change

The response to change in value delivery is described as being the most important element in the study of flexibility. For example, a change in value delivery could be seen as the loss of a fighting element in a group, and the response to this change could be that the fighting element is dynamically replaced by one of equal capability. Our model addresses response to change by reallocating force elements amongst the groups. This is done on the basis of the completeness of each group. Where a complete group is defined as one that is more capable to respond to unknown future events. As will become clear later, our algorithm measure had a bias towards this aspect of our flexibility measure.

Degree of Access

The Oxford Dictionary (2007) defines access as the "right or opportunity to use something or see someone". This element refers directly to the degree by which one has access to the system, in our case the force in order to apply the option or flexibility. As flexibility has been seen to be a measure of completeness in terms of movement, engagement and protection, this element can directly relate to the ability to sustain and resupply the force. Our model included such characteristics by explicitly modelling both intra-element sustainment and inter-force support. That is, by having combat elements sustain each other in a swarming or dynamically recombining manner, whilst having resupply support by an external body.

Evaluation Methodology

By developing an Agent Based Model, our refinement of the systems required becomes more tangible than that of high level concepts. In particular the component based design of BactoWars enables us to easily develop new behaviours for evaluation and to compare against the baseline force design.

In summary, our model has been characterised by two key factors, these are redundancy and completeness or diversity. Redundancy allows us to have the confidence that the required response can be achieved given a limited degree of access, whilst the completeness actually gives us the capability to perform the required response.

Support Elements

It was determined that a force is able to be more flexible when its force elements have elements that are able to support it where required. Further, the knowledge that supporting elements are available, enable the military planner to have a broader range of options at their disposal. In terms of the model, this was represented as a function of the flexibility and the physical distance between each of the Hub Nodes. A better measure for distance is still being investigated. Such a measure should take into account the range of the effect each characteristic can bring to the battlespace.

3. FLEXIBILITY MEASURE

Shewchuck (1999) described a flexibility measure as a "formula, algorithm, methodology or the like, for generating a value for a given flexibility type under given conditions".

The flexibility function (1) was developed to calculate a measure which provided a relative ranking of forces based on completeness and redundancy. This function calculated the force flexibility based the flexibility of groups of entities on the battlefield, referred to here as Node Groups (B_i) and the average distance (D) between those groups. That is,

$$F = \frac{\sum_i B_i}{D}, \quad (1)$$

In the current model the average distance has been used to represent the ability of the force to reallocate elements between groups. Work continues to develop a better measure for this aspect of flexibility. The flexibility of each node group i was determined by the completeness and redundancy of a node group. That is,

$$B[R(i) \mid X_i(n)] = \frac{[X_i(k) + 4R(i)]}{5[2 - X_i(k)]}, \quad (2)$$

where X_i is the completeness and R(i) is the redundancy of the node group. This formulation, along with those for completeness and redundancy are developed based on the related measures given in Perry and Bowden 2003.

3.1. Completeness and Redundancy

In the context of determining a quantitative measure of force flexibility we talk about completeness of capability characteristics within a given group.

The completeness is defined by

$$X_i(k) = \left(\frac{k}{C}\right)^{\xi}, \quad (3)$$

where k is the number of characteristics in node group i, C is the total number of characteristics overall and ξ is a shaping constant. For the work presented here C is 3. For the initial model a shaping constant of 5 has been used but more work needs to be done to ensure that the resulting shape is correct.

The value of k is calculated by

$$k = \sum_{j=1}^{3} \underset{\forall n \in i}{Max}(c_{nj}), \quad (4)$$

where c_{nj} is the characteristic value of characteristic j for battlefield entity n, referred as node n.

Another way of viewing completeness is as a representation of the diversity of characteristics available within a node group, where this value takes into account the maximum level at which the character is met within the node group.

The redundancy (5) is defined by

$$R(i) = \frac{1}{3}\sum_{j=1}^{3} r_i(p_j), \quad (5)$$

where p_j is given by

$$p_j = \sum_{n \in i} c_{nj}, \quad (6)$$

again c_{nj} is the characteristic value of characteristic j for node n.

3.2. Characteristics

The initial model uses three of the seven descriptors of the Army as a System (AAAS) as defined in Curtis and Dortmans (2004, 2003) to determine the abilities of each node. However the ability to investigate the other descriptors has been developed into the model architecture. The three characteristics used in the initial model were movement, engagement and protection. These three characteristics were selected as they could be readily determined from the Janus data. Each characteristic is defined as a value between zero and one.

Each node is given a value for each characteristic representing its ability to perform that characteristic within the context. In this, zero means the node does not have any ability to perform this characteristic, for example a zero in movement would mean the node is unable to manoeuvre in the given environment. A value of one means the node has the maximum capability in terms of this characteristic, for example a value of one for protection would mean a given node has the greatest survivability within the given environment.

4. BACTOWARS

BactoWars was developed by Land Operations Division in response to problems faced whilst trying to utilise conventional modelling techniques to answer problems in the littoral domain Wheeler and White (2004). BactoWars utilises data farming concepts Horne (1997) to search the parameter space in order to gain a better understanding of the wider problem. Written in Java, the BactoWars model implements many concepts found in Agent paradigms, Artificial Life and Complex Adaptive Systems. The software has been developed for use as a customisable tool aiding in the analysis and investigation of complex problems and is intended to be used by people with an Operations Research background, White (2004).

BactoWars was used during the Headline 2006 experiment as a parallel simulation that could handle numbers of up to four hundred thousand entities at different resolutions and complexities from multiple sides. This software was indirectly connected to the Janus war game via the RTDB and the necessary analytical requirements for capturing an insight into the effect on the civilian population could be captured.

Representing Adaptive Systems in BactoWars

In order to represent a complex adaptive system, one must understand what the key characteristics are of that domain. An accepted list of these characteristics is given by White (2004); include two main groups, namely properties and procedures of CAS. Of these groups, seven key descriptors exist, including;

Aggregation – Complex behaviours emerge from the interaction of less complex system components.
Non-Linearity – The behaviour of the system may be more complicated than expected by the sum of the parts.
Flows – A flow of resources and information through the system.
Diversity – The components of the system exhibit diversity amongst themselves.
Tagging – The attributes of system elements that enable the identification between elements. An example of this would be the Army, Navy and Air Force, who are differentiated by the uniform they wear.
Internal models – Components of the system have an internal view of the environment, which affects the manner by which they interact with that environment.
Building blocks – Discreet components that may recombine to produce a great many patterns.

As previously discussed, BactoWars is well suited to the application of the development of adaptive procedures as the component based nature of behaviour design allows. The following sections describe an application of this philosophical concept to suit the purposes for exploring flexible military structures.

5. MODEL ARCHITECTURE

Organisation and C2 in the model was deliberately flat i.e. every entity could communicate with each other. Based upon concepts from Australian Army (2006a, 2006b) was not intended to be an aspect under consideration for flexibility. However, given broad guidance, two controlling measures were developed based upon subject matter advisors. Firstly was the notion of an Area of Influence of a hub node and the second was a model of Area of Operations of a hub node. The basic model architecture is given in Figure 1 and described in more detail below.

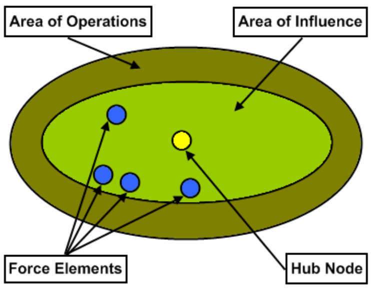

Figure 1. Area of Operations and Area of Influence concept

An Area of Influence for a hub node was the area by which the hub node had control over those other nodes within it. The current model uses a simplistic radius of influence. In the future we intend to extend this simplistic model to be based upon force capability characteristics which may not be purely physical but have used this simple approach in our initial model. Whenever an entity was within a hub nodes area of influence, it associated its control with that hub node. For example, if a node group is determined to have sufficient flexibility some entities within that node group will move out of its area of influence into the area of influence of a weaker group.

As is currently the case, an Area of Operations (AO) is the region in which a military force is operating. This area may not actually cover the entire area of the military operations, but it should be sufficient to cover the area to accomplish a forces mission In the case of the swarming concept, the AO is a very much a localised region that distances groups from each other. The AO was modelled as an extension to the Area of influence and its purpose was to ensure that no other hub node, as described later, would operate over the same space as another hub node.

5.1. Model Actors

There are three model actors in the BactoWars model; nodes, hub nodes and node groups.

Nodes in the model are represented as entities. They have the characteristics of movement, protection and engagement. These characteristics were associated such that entities with a higher protection value would take more hits before becoming ineffective at their main capability.

Hub Nodes are a special kind of node. Initial hub nodes are selected when the model is initiated. This is done based on the desired number of groups and the distribution of nodes across the area of operations. They represent those nodes in the model that are most centrally located and form the centres of any groups. At appropriate intervals a recalculation is performed to update the current list of nodes in a group and the Hub Nodes. In the model, every force element has the same potential to become a Hub Node it is their placement relative to all other elements that determines if they become Hub Nodes.

A number of constraints were put on the allocation of Hub Nodes. These constraints included a minimum redundancy level and a minimum average completeness in the potential force structure.

A Node Group in the model contains all those elements who share the same Hub Node. As defined earlier each Node Group has a flexibility value based on its completeness and redundancy. The Node Group flexibility value influences its behaviour within the model.

5.2. Scenario Description

For the purposes of developing a baseline model, a simple scenario was developed to explore the configuration of the characteristics of the flexibility measure. The scenario consisted of a randomly placed force dispersed over a region of the terrain, a support force and an invincible enemy in a location in the centre of the screen.

5.3. Key Agent Behaviours

FlexibleMovementBehaviour: Nodes can take one of four states defined as hub nodes, grouped nodes, ungrouped nodes and supporting nodes. Depending on the nodes state the FlexibleMovementBehaviour will determine the node movement. For example, unassigned nodes will try and move to a group that lacks the characteristics the node can provide.

BalanceForceBehaviour: Attempts to take the strongest redundant entity for a particular characteristic, from the other hub group and send it to the weakest hub group.

HubAllocationBehaviour: Makes a best effort to allocate a certain percentage of nodes as hub nodes dynamically as required.

6. INITIAL RESULTS

To look at the dynamics of the flexibility measure we have run an initial test to look at the impact of distance between node groups on flexibility over time. In this scenario the node group with the highest flexibility value was moved towards an invincible enemy. As it got within range of the enemy it would begin to lose nodes, reducing its flexibility value. This had a number of potential impacts. If the node group was no longer complete, redundant nodes from other groups would be assigned to that group, moving towards it. Also if node group no longer had the highest flexibility value it would move away from the enemy.

We ran two scenarios, each with identical initial states except for the minimum allowed distance between the node groups. Some of the results of this initial study are shown in Figure 2. These results show the clear advantage in being able to rapidly reconfigure the structure of the groups.

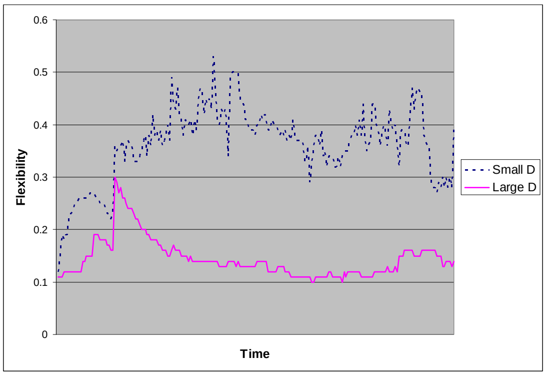

Figure 2. Impact of distance on flexibility

In Figure 2 there is an initial peak in flexibility for both scenarios. This was when the groups initially organised themselves. After this peak, the small D scenario behaved somewhat erratically but maintained a higher level of flexibility than the larger D. This erratic behaviour demonstrates the ability of the groups to organise themselves quickly to maintain a "complete" group. The large D scenario was never able to maintain a high flexibility due to the fact the reorganisation of node groups were never faster than the speed at which those groups were destroyed.

7. CONCLUSIONS AND RECOMMENDATIONS

By exploring the swarming concept by means of developing an autonomous tactical model, we have begun to appreciate many of the subtleties which should be considered when exploring future concepts. As shown in our results, a factor in determining the flexibility of our force will be determined by how quickly its components can reorganise themselves. In scenarios where the distance between groups are greater, it becomes more difficult for the elements to successfully sustain each other. Importantly, this work has covered the following areas:

Appropriateness: Of the 6E Flexibility Framework to developing force flexibility.
Force Balancing and Re-supply: We have developed an algorithm for autonomous control of agents within a simulation that automatically rebalances and resupplies the force elements.
Thresholds: We have identified important factors to consider when implementing concepts such as swarming. Those include minimum redundancy and minimum diversity, also how often hub nodes should be calculated.

Throughout this paper we have described a number of areas of future work. In general our natural progression of this work will be to support our efforts in refining the Adaptive Campaigning concept. To help us gain a greater understanding of the overall best characteristics that give the most flexible force we also plan to look at developing learning algorithms that will allow us to automatically search a larger part of the state space.

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