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Experiences with the MANA simulation tool

M.C. Straver
E. Vincent
P. Fournier
DRDC Valcartier Operational Research Team

Defence R&D Canada – Valcartier
Technical Memorandum
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Authors

Michelle Straver, M.A.Sc. Etienne Vincent, Ph.D. Pierre Fournier, M.Sc.

Approved by

Luminita Stemate, M.Sc.

Team Leader, Operational Research

Approved for release by

Gilles Bérubé

Chief Scientist

Abstract

Recently, the Map Aware Non-uniform Automata (MANA) agent-based simulation tool has drawn interest in the military Operational Research community. After encountering difficulties with more resource-intensive higher-fidelity models, the DRDC Valcartier Operational Research (OR) Team considered MANA as a possible tool for fulfilling some of the objectives of two Technology Demonstration Projects (TDPs). However, other difficulties were encountered in the use of MANA. These are detailed in this study, which is targeted towards OR analysts considering MANA as a tool for modelling combat simulation.

Résumé

Dernièrement, MANA (Map Aware Non-uniform Automata), un outil de simulation basé sur les agents, a attiré l'attention de la communauté de recherche opérationnelle militaire. Après avoir fait face à d'importantes difficultés dans l'utilisation de modèles plus détaillés et nécessitant plus de ressources, l'équipe de recherche opérationnelle de DRDC Valcartier à décidé de mettre MANA à l'essai pour atteindre certains objectifs de deux projets de démonstrations technologiques. Cependant, d'autres difficultés furent rencontrées en utilisant MANA. La présente étude décrit ces difficultés et vise l'analyste en recherche opérationnelle envisageant l'usage de MANA pour la modélisation de combat

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Executive summary

The Map Aware Non-uniform Automata (MANA) simulation tool, designed by New Zealand's Defence Technology Agency (DTA), has recently attracted significant attention in the military Operational Research (OR) community.

When analysts from the DRDC Valcartier OR Team were asked to explore some issues related to the Advanced Linked Extended Reconnaissance and Targeting (ALERT) Technology Demonstration Project (TDP) and the Future Armoured Vehicle Systems (FAVS) TDP, MANA was seen as a promising tool. However, attempts at using MANA for these projects ultimately proved unsuccessful.

MANA is an agent-based model that allows the exploration of a wide variety of issues with minimal set-up time. Its main advantages are simplicity and ease of use. Its designers claim that many naturally occurring phenomena are too complex to be captured accurately in models, and thus, that highly detailed models of these phenomena are necessarily arbitrary. They therefore advocate using simple models, such as MANA.

On the other hand, simplicity also entails limitations. In the case of MANA, significant limitations in sensing, communication, elevation and weapon models made the tool inadequate for its intended use in combat simulation within the ALERT and FAVS simulations. Also, agents in these simulations needed to conduct careful formation fighting while following established CF doctrine. Such sophisticated behaviours proved unattainable with MANA.

This memorandum provides many specific examples of the inadequacy of MANA for its intended use in the ALERT and FAVS simulations. Ideas of additions or modifications to MANA that might solve some of the encountered limitations are briefly listed in Annex B. This study is intended to help Operational Research analysts determine if MANA is suitable for their projects.

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Sommaire

L'outil de simulation Map Aware Non-uniform Automata (MANA), conçu par le Defence Technology Agency de la Nouvelle Zélande, a récemment attiré l'attention de la communauté de recherche opérationnelle militaire.

Quand on a demandé à des analystes de l'équipe de recherche opérationnelle de DRDC Valcartier d'explorer certaines questions reliées aux projets de démonstration technologique Advanced Linked Extended Reconnaissance and Targeting (ALERT) et Future Armoured Vehicle Systems (FAVS), MANA fut retenu en tant qu'outil prometteur. Cependant, les tentatives d'utiliser MANA pour ces projets se soldèrent éventuellement par un échec.

MANA est un modèle basé sur les agents qui permet l'exploration rapide d'une grande variété de dénouements. Ses avantages principaux sont sa simplicité et sa facilité d'utilisation. Ses concepteurs prétendent que plusieurs phénomènes naturels sont trop complexes pour être représentés adéquatement par un modèle, et donc, que les modèles détaillés de tels phénomènes sont nécessairement arbitraires. Ils prônent donc l'utilisation de modèles simples, tel que MANA.

D'un autre coté, la simplicité entraîne aussi des limitations. Dans le cas de MANA, d'importantes limitations des modèles de perception, communication, élévation et d'armements rendent l'outil inadéquat pour son usage préconisé au sein des simulations de combat effectuées pour les projets ALERT et FAVS. Aussi, les agents de ces simulations auraient dû pouvoir se déplacer en formation, suivant la doctrine établie des Forces canadiennes. Cependant, des comportements d'une telle sophistication se sont avérés hors de la portée de MANA.

Ce mémorandum présente plusieurs exemples spécifiques des carences de MANA dans le contexte des simulations ALERT et FAVS. Des suggestions visant à régler certaines des considérations soulevées dans ce travail sont énumérées à l'Annexe B. Cet ouvrage vise à aider les analystes en recherche opérationnelle à déterminer si MANA pourrait être l'outil approprié pour leurs projets.

Straver, M.C., Vincent, E., Fournier, P. Experiences with the MANA simulation tool. DRDC Valcartier TM 2006-404. Juillet 2006, RDDC Valcartier.

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Acknowledgements

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1. Introduction

The Advanced Linked Extended Reconnaissance and Targeting (ALERT) project and the Future Armoured Vehicle Systems (FAVS) project are two Technology Demonstration Projects (TDPs) that sought support from the Defence Research and Development Canada – Valcartier Operational Research Team (DRDC Valcartier OR Team). Initial attempts to simulate some aspects of these projects were conducted with the OneSAF Testbed Baseline (OTB), version 1. This high-fidelity simulation environment proved inadequate for the reasons detailed in [1]. An alternative approach was proposed using MANA, an agent-based simulation environment developed by New Zealand's Defence Technology Agency (DTA). MANA has been used, among others, by the United States Marine Corps Warfighting Laboratory [2], by Australia's Theatre Operations Branch, Aeronautical and Maritime Research Laboratory [3], and by the DRDC Centre for Operational Research and Analysis (CORA) [4]. The DRDC Valcartier OR Team evaluated MANA by attempting to use it to support simulation studies for ALERT and FAVS TDPs, and presents the result of this evaluation in this study.

This document describes the work that was done using MANA[1] in the context of the ALERT and FAVS TDPs. The attempts at simulating operations related to these projects using MANA were ultimately unsuccessful. This document primarily intends to present lessons learned from the use of MANA to CORA analysts. It also suggests possible modifications and additions to the environment that would increase its realm of applications.

The present document assumes that the reader is somewhat familiar with MANA. If that is not the case, the reader may wish to refer to the MANA user manual [5] to understand the terminology used in this report.

Some statements made in this document may be based solely on the authors' experiences.

1.1 Introduction to MANA

The MANA simulation environment was designed by New Zealand's DTA to address needs that were not met by previously existing tools. This pertains especially to behaviour-related issues. DTA has suggested that the behaviours of entities in other models can be illogical [5]. It claims that many naturally occurring phenomena are non-linear, or too complex to be captured accurately in models, and thus, that there is no need for highly detailed models of these phenomena, as they are necessarily arbitrary.

[1] In this work, "MANA" refers specifically to MANA Beta Version 3.0.37, the most recent version of the MANA simulation environment available at the time the described studies were conducted. As noted in Annex A, Version 4 of MANA is scheduled to be released soon after the publication of this memorandum.

MANA is an agent-based model that allows for the exploration of a wide variety of issues with minimal set-up time [5]. Indeed, from a user's perspective, one major advantage of MANA lies in its simplicity and ease of use. Although certain aspects may require some time to fully explore and understand, an uninitiated user can set up simple simulations within hours.

As might be expected from a simpler model, MANA comes with many limitations. The user must remember that MANA is meant to provide general insights into a problem, and that it may be unwise to rely upon any quantitative results extracted from simulation runs. The MANA user manual [5] states, "Despite being able to generate a wide range of behaviour, the current version of MANA has many limitations, and is certainly not intended to describe every aspect of a military operation."

MANA might, however, be appropriate for some applications; many groups, as cited above, have claimed to achieve significant success in its use. Nevertheless, it is not immediately clear which specific scenarios are appropriate for simulation using MANA. This work will explain why MANA was inadequate for some aspects of specific applications related to the ALERT and FAVS TDPs, and thus provide insight into that question.

1.2 Introduction to the ALERT TDP

The aim of the ALERT TDP is to significantly improve the battlefield Situational Awareness (SA) of the Coyote operator by integrating sensor and tactical data, automated processes, and beyond line-of-sight (BLOS) sensing. This is done towards the enhancement of SA throughout the levels of command within a formation [6].

ALERT will attempt to achieve this aim through the following objectives:

- improving information quality and timeliness at all levels of command;
- improving battlefield SA at all levels of command; and,
- reducing operator workload (for the Coyote operator as well as at higher levels of command) [6].

The US Army Training and Doctrine Command Analysis Center (TRAC)-Monterey has hypothesized that agent-based models are well suited for exploratory analysis early in advanced concepts exploration and requirements development. This type of model can be used to gain insights into questions that merit further exploration using higher-fidelity models [7].

Originally, it was intended that the DRDC Valcartier OR Team would use MANA for exactly this purpose – more specifically, to identify which aspects of ALERT should be studied further in higher-fidelity constructive simulation. For example, it was thought that perhaps MANA could be used to identify which combinations of BLOS sensors (such as Unattended Ground Sensors (UGS) and Unmanned Air Vehicles

(UAV)) looked the most promising. MANA was found to be an unsuitable tool for this purpose, as will be explained in this document.

1.3 Introduction to the FAVS TDP

The objectives of the FAVS TDP were to explore selected high-payoff Armoured Fighting Vehicle (AFV) technologies in virtual and real environments, and to estimate and measure the battlefield effectiveness gains from these technologies. Development of technology prototypes confirmed the feasibility of technology assumptions in virtual environments, and allowed validation of performance parameters [8].

The DRDC Valcartier Operational Research Team was tasked to provide an assessment of the battlefield effectiveness of a Light Armoured Vehicle (LAV) equipped with technologies developed for the FAVS TDP. Combat simulation was selected as the most appropriate methodology to conduct this assessment [9, 10].

Initial attempts to conduct the study using a high-fidelity simulation tool failed due to technical issues with OneSAF Testbed Baseline, version 1 [1, 9]. A model of a FAVS-equipped LAV was then created in MANA.

Because of the ease with which several scenarios could be developed and multiple runs produced in MANA, this tool looked promising for a second attempt at FAVS simulation. Crude but reasonable models of the vehicle and the following systems were implemented:

- Weapon systems;
- active camouflage;
- Defensive Aids Suite (DAS);
- High-Energy Missile (HEMi);
- Battlefield Management Systems (BMS); and
- shorter engagement times provided by sensors with Automatic Target Recognition (ATR) and by enhanced crew SA provided by immersive visualisation (360^{o} Field of View) with tactical information overlays.

This resulted in 48 different possible combinations of equipment, each of which was to be investigated in both offensive and defensive scenarios. The battlefield effectiveness of the vehicle as a function of its advanced systems and characteristics was to be assessed by running multiple iterations of these scenarios.

This work was shown to the designers of MANA at DTA before being published to seek their comments. In response, corrections were made, or comments noted throughout this work.

2. Defining agent and battlefield properties

MANA's philosophy is to keep representations of basic physical elements simple. It avoids detailed physical models to allow for easier development, faster execution, and greater transparency. Its developers claim that more complex models of basic entities often do not result in improved realism and accuracy, as the world is necessarily far more complex than any physics-based model [5]. However, increased approximation will inevitably entail certain limitations. This section describes the representation of some basic entities and functionalities in MANA, and discusses some limitations that hindered the development of simulation for the ALERT and FAVS projects.

2.1 Battlefield time and space

The MANA battlefield consists of a finite set of possible agent positions on a grid pattern. Agents may move from one grid square to another at each timestep. In order to produce a realistic model, the scale of the grid squares and the time corresponding to a timestep must be carefully chosen. In the simulations developed for the ALERT TD, each grid square was chosen to represent 20m × 20m, which was thought to represent open terrain with adequate resolution. The size of the battlefield is limited by MANA to 1000 × 1000 grid squares; thus, the maximum size of the battlefield for the ALERT simulations was 20km × 20km. This would be adequate for investigating surveillance missions involving a single pair of ALERT-Coyotes, but would not allow the exploration of higher-level issues involving more entities spread out over a larger area. Any scenario conducted in urban terrain would likely require smaller grid squares, which would limit the terrain size even further.

An important limiting factor for time and space scaling in MANA is that agent speeds should not exceed one grid square per timestep. This is to avoid agents moving through walls or other impassable terrain features [5]. Depending on the size of grid squares, timesteps may need to represent very short intervals to adhere to this recommendation. For example, if grid squares were 2m × 2m for an urban battlefield, with vehicles travelling at speeds up to 80 km/h, timesteps would have to correspond to periods shorter than 0.09 seconds to ensure that agents would not exceed a speed of one grid square per timestep. This would result in a very large number of timesteps for a simulation[2].

2.2 Sensors

The military vehicles of interest to the ALERT and FAVS projects rely on a variety of sensing equipment to detect and classify their enemies. MANA allows a single sensor per agent, described with a detection range within which the probability of detection is

[2] DTA notes, however, that the resulting amount of data could be manageable if it did not need to be recorded per timestep. They also say that MANA would still run faster than most models despite a need for more timesteps.

certain, and a classification range within which probability of classification may vary as a function of distance. (If an agent in MANA is "detected", it is registered as an unknown by the detector. If it is "classified", it is defined as either friend, enemy, or neutral.) When compared to more physics-based models, this is a low-fidelity representation of agents' sensing equipment.

There are several shortcomings of this sensor representation. Firstly, the fact that each agent can only have one sensor does not reflect reality[3]. A vehicle's sensors must therefore be represented in MANA using an estimate of the aggregate performance of all sensors together, under average conditions. Also, sensors in MANA are omni-directional, whereas many real world sensors have a limited field of view at any instant in time[4].

Another important characteristic of real world sensors is that their ability to detect and classify a target will vary with factors including the target's size, posture, and contrast with the environment. MANA's detection and classification algorithms do not consider these properties. An agent's *Personal Concealment Rate per Turn* can be used to account for the fact that one agent might be harder to detect than another agent, but does not consider the fact that different sensors have different capabilities of detecting targets. For example, consider two agents: the first one equipped with a thermal infrared sensor and an optical sensor, and a second one that has only an optical sensor. In this case, a small, warm target would be difficult to detect by the second agent, but easily detected by the first agent with its thermal sensor. Thus, a target's *Personal Concealment Rate per Turn* cannot account for differences in the opponents' abilities to detect that target[5].

Since MANA is intended to allow users to gain initial insights into problems, rather than to answer specific questions with a high level of confidence and to provide high physical realism, the previously described issues might be an acceptable trade-off to the model's simplicity. However, more important limitations of the MANA sensor model have to do with the way in which it decides whether or not a detection or classification occurs.

When a sensor is modelled in MANA, it is assigned a detection range. Any target within this range will be detected immediately, provided that visibility is not altered by the target's personal concealment parameter or by terrain features. Clearly, this is a poor representation of reality[6].

Classification in MANA is determined by a sensor's *Classification Rate per Turn.* This parameter represents the percentage of targets within detection range that the sensor can be expected to classify in a single timestep, or equivalently, the probability that a particular target will be classified in a single timestep. This is very different from the probability of classifying an agent over an unspecified amount of time.

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[3] MANA Version 4 will include up to four sensors per agent.
[4] This will be addressed in MANA Version 4 by defining sensor arcs and slew time.
[5] MANA Version 4 will allow different concealment rates relative to each sensor type.
[6] In MANA Version 4, detection will be stochastic and probabilities of detection allowed to vary as a function of range.

Consider the following example: If 100 agents are within a sensor's detection range with a *Probability of Classification* set to 0.6 over the entire range, MANA would, on average, classify $100 \times 0.6 = 60$ agents in the first timestep, then $(100-60) \times 0.6 = 24$ additional agents in the second, $(100-60-24) \times 0.6 = 9.6$ in the third, and so on. Thus, each agent would have a probability of $1-(1-0.6)^n$ of having been classified after n timesteps. In this case, each agent would have a 99.9% probability of having been classified after only 8 timesteps[7]. (Recall from Subsection 2.1 that this timestep may represent a very small period of time.)

There is no way to establish the *Classification Rate per Turn* such that it accurately represents how classifications occur in reality. The reason for this comes from the fact that the likelihood of classifying a particular target is much more time-dependent in MANA than it is in reality. For example, consider an operator looking at a sensor feed showing an image centred on a target. The image quality will be dependent on a number of factors, including range, target size, and meteorological conditions. A real operator might have a 60% chance of correctly classifying the target under these conditions. Unless conditions change, it is unlikely that the operator will be able to classify a target that could not be classified initially, regardless of how much time is given. However, in MANA, all agents that are within classification range and line of sight (LOS) of a sensor and have a *Personal Concealment* rate of less than 100% will eventually be classified by that sensor.

The DTA addressed this issue when investigating the possibility of reproducing results from Janus-based wargames using MANA. They used an iterative process to modify the *Personal Concealment* of the enemy units and fine-tune the placements of the sensors on the terrain until the performance of each sensor reasonably reflected the classification rates in the Janus runs [11]. Although using this approach could allow a user to obtain reasonable classification rates over specific time periods, all targets would eventually be classified if the conditions remained unchanged long enough.

DTA's experience shows that statistically fitting MANA models from physical models or trials can achieve interesting results in some simulation applications. However, the MANA sensor model did not offer enough flexibility to be able to emulate, even after statistical fitting, realistic classification rates over time in scenarios of interest to ALERT and FAVS.

The lack of high-fidelity sensor modelling in MANA is especially troublesome for simulation related to the ALERT project, since ALERT focuses on sensing capabilities. It would also have a significant effect on the realism of FAVS simulations, in which the effects of active camouflage were to be studied. Other sensing issues related to terrain features are discussed in the next subsection.

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[7] MANA Version 4 will allow specification of the average time between detection and classification instead of modelling classification using a probability per timestep. It will also allow detection to be stochastically determined as a function of range as is currently the case for classification. The problem of having classification rates approaching 100% after several timesteps should thus be replaced by one of having detection rates approaching 100% after several timesteps.

2.3 Terrain features

In order to achieve a reasonable model of real-world combat, a simulation environment should permit the representation of different terrain features that would provide cover and concealment to agents.

In MANA, any region of the battleground can be established as having pre-determined *going*, *cover*, and *concealment* properties. The *going* parameter represents the impact of difficult terrain on the speeds that can be achieved by vehicles. It is implemented as a multiplier to reduce the speed of an agent on that terrain. Similarly, the *concealment* parameter is a multiplier that reduces the probabilities of detection and classification, while the *cover* parameter reduces the probability of being hit by enemy weapons. There are several pre-defined terrain types in MANA, but the user can create new terrain types having any combination of *going*, *concealment* and *cover* parameters.

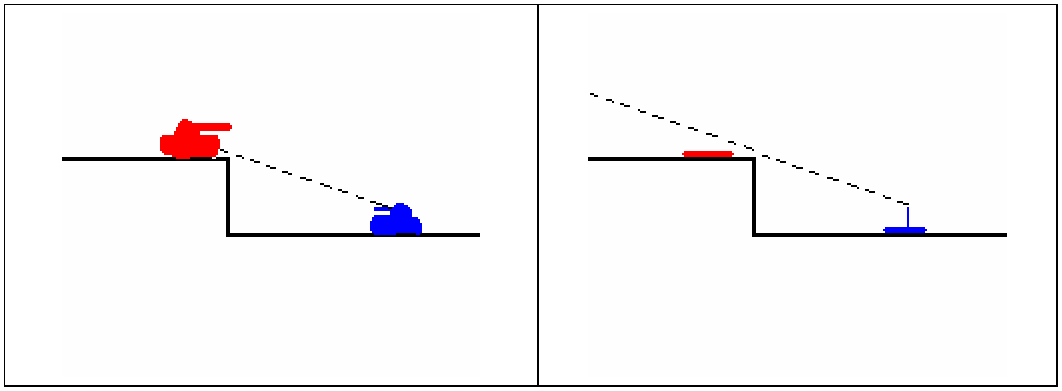
In the real world, a concealing environment can not only delay the probable time of detection and classification, but also reduce detection and classification ranges. For example, a fixed observer might be completely unable to detect a stationary LAV located in dense bush, even if it would be able to immediately detect an equally distant LAV located in an open area. However, in MANA, the previously described problem of the probabilities of detection and classification always tending toward 100% would remain, although the time to detect and classify the concealed LAV would likely be longer.

In addition to these issues with the basic characteristics of terrain features, MANA does not enable agents to employ strategies that exploit these features to their advantage. This is discussed in Subsection 3.1.

2.4 Terrain elevation

Terrain elevation is crucial to shaping tactical decisions in real combat operations. For this reason, military advisors would not be very receptive to conclusions drawn from combat simulations that do not incorporate a realistic representation of varying elevation.

MANA offers the possibility of defining elevation maps with a resolution of up to 256 levels. It also incorporates a computation of LOS that takes account of terrain and of the aboveground height of sensors, which can be placed at any height above the host agent. However, an important shortcoming of this LOS model is the lack of a height dimension for the agents themselves. Since agents are effectively flat, an agent situated higher than the sensor of another agent that is looking in its direction will invariably remain unseen. An agent must be able to see the surface on which another agent is located for a LOS to exist. As illustrated in Figure 1a, a BLUE agent should, in reality, be able to see a RED agent that is near the edge of a drop in elevation. Figure 1b shows how, in MANA, the higher agent remains invisible.



(a) **(b)**

Figure 1: *Consequence of two-dimensionality of agents.*

What is most troubling about the example shown in Figure 1 is that if the RED agent has a high enough sensor, it will be able to see the BLUE agent without ever being seen. The use of elevation maps can therefore result in higher areas that offer an unreasonable advantage. An agent in such an area can completely dominate large portions of the battlefield. On real battlefields, areas of higher elevation do offer advantages, but not to this extent.

As with terrain features, MANA agents are unable to recognize and exploit the advantages conferred by higher elevations. This is discussed in greater detail in Subsection 3.1.

2.5 Weapons

Of course, if a simulation environment is to be used to model combat operations, a capability to model weapons is essential. MANA offers the possibility of defining up to four weapons per agent. These can be area weapons or direct-fire weapons, and can have properties that vary with the behavioural state of the host agent. (In MANA, agent behaviour can change according to *trigger states*). A probability of hit (per discharge) can be defined as a function of the range between the agent and its target.

One aspect of weapon performance that cannot be accurately represented is the fact that some targets are easier to hit than others. A large stationary target, for example, would be easier to hit than a small moving one. In scenarios designed for the FAVS TD, the expected hit probabilities for the same weapon system (in this case the 120 mm APFSDS) should have been different when firing at massive T80s than at smaller BMP2s. The chosen approach was to use two different weapons to represent a single system: one with probabilities of hit for use against T80s, and another with probabilities of hit for use against BMP2s. Each weapon could be used exclusively against the specific target by assigning a different target class to the T80s and the BMP2s and restricting each FAVS weapon to fire only upon targets of the appropriate class. This ensured that FAVS would use the appropriate hit probabilities for each target.

The difficulty with this solution is related to the limited number of rounds that can be carried by one vehicle. A FAVS vehicle could carry approximately 40 rounds for its main gun. With a FAVS model implemented in MANA, these 40 rounds would have to be divided between the two weapons. The user would need to divide these rounds based on their anticipated use in the course of the simulation run, perhaps in proportion to the number of opponents of each type. However, in some simulation runs, a FAVS agent could (for example) exhaust its supply of the weapons intended for T80s. It would then be left defenceless against T80s while still having some of the weapons to be used against BMP2s, which it could have in reality used just as appropriately against T80s.

Another issue related with the use of weapons in MANA has to do with firing through areas of higher elevation. As described previously, an agent on lower ground can see one that is on higher ground if it has a high enough sensor. However, its weapon cannot hit the target located on higher ground unless the *Can't Fire Through Walls or Hills* box associated with the weapon is unchecked. If this is not the case, the agent will spot the target and shoot toward it indiscriminately, thereby wasting its ammunition on a target that it cannot possibly hit. Similarly, if BLOS engagements are to be modelled[8], then the ability to fire through walls or hills in MANA is required. However, giving agents the capability of doing so may be equally undesirable, as it makes it impossible for agents to achieve cover behind steep hills and walls.

[8] BLOS engagement refers to firing at a target with which the weapon platform has no direct LOS. This is accomplished through the use of BLOS sensors and remote target designation.

3. Agent behaviour

As stated in the user's manual [5], MANA is intended to explore a large variety of outcomes with a short set-up time. It is argued that simple behavioural rules for the agents are sufficient to achieve this. For the ALERT and FAVS projects, at least a low-fidelity model of actual combatants was required; however, many of the desired simple behaviour patterns could not be implemented in MANA.

MANA emphasizes the modelling of the interactions between many simple agents rather than the definition of sophisticated behaviours for each individual agent. The resulting simplicity in agent behaviour can be significantly limiting. The following subsections illustrate some limitations to what can be done with MANA that stem from the minimalism of its agent behaviour model.

3.1 Use of concealment and cover

It was seen in Subsection 2.3 how terrain can be defined with features offering various levels of concealment from enemy sensors and cover from enemy fire. To reasonably emulate real-world combat, agents would have to recognize and exploit these features. Agents under enemy fire should seek cover, while agents seeking to remain undetected should recognize locations that provide concealment[9].

In MANA, agents can be attracted to regions having high cover or concealment factors. This is done through the setting of *Cover* or *Concealment* coefficients associated with squad *Personality*. Since agents' *Personalities* are dependent on trigger states, attraction or repulsion from cover or concealment can vary in response to many situations.

However, an important source of difficulty in using to MANA model was found to be that agents do not have a reliable way of perceiving areas offering effective cover or concealment. Agents can be attracted by objects having high cover or concealment factors, but this does not mean that they will position themselves to properly exploit these terrain features. This is mainly due to the fact that agents do not consider the relative position of threatening elements with respect to terrain features. Thus, for example, an agent seeking cover from an approaching enemy threat would move toward a nearby wall, but without attempting to place itself on the side of the wall unexposed to the enemy. This is shown in Figure 2, where a vulnerable BLUE agent fails to find appropriate cover. If this agent seeks protection through attraction to cover and repulsion from enemy agents, it will head in the direction indicated by the arrow, placing itself between a wall and the enemy threat. There are obviously areas that offer better cover, but no simple way of directing the BLUE agent toward them.

[9] Allowing agents to recognize and exploit areas providing concealment and cover would be likely to involve some black box functions, and thus run counter to the philosophy behind MANA. Thus, this subsection is not meant to advocate inclusion of such features, but rather to provide insight into agent behaviour that cannot be obtained with MANA.

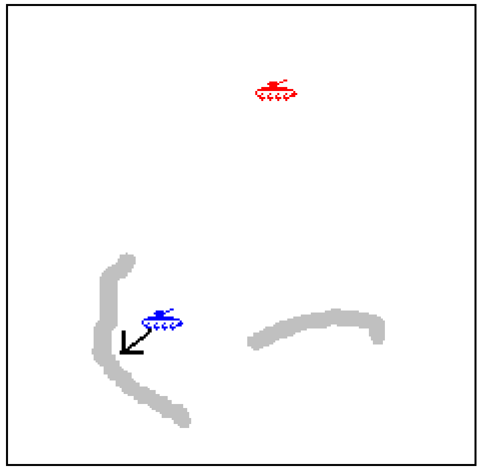


Figure 2: *An agent's attraction to cover.*

One solution to this problem is to place another object at the location where an agent should head when facing danger, and to have that agent attracted to the object. Placing an *alternate waypoint* behind the wall on the right and having the BLUE agent attracted to it, for example, might be a solution. A problem with this approach is that it removes all flexibility from the simulation. If the enemy threat were to arrive from a different direction, the threatened agent would still head for the same *alternate waypoint*, which might now offer inadequate cover. Nevertheless, trying to automatically decide which areas should be sought for cover, without being explicitly stated by the model designer, is very delicate. An area providing cover but no escape route might be less desirable than one providing only mediocre cover.

In the case of areas of cover and concealment created by terrain elevation, the situation is worse. Such regions are omnipresent with MANA terrain on which varying elevation is defined, but agents are completely unaware of the presence of these features, and unable to exploit them. Although they could, for instance, achieve an advantageous position on higher ground, they have no means of recognizing such higher ground, let alone to alter their path toward it.

3.2 Path selection

In the field, combatants such as the armoured vehicles of the FAVS project would not always head directly toward their mission objective, but rather prefer to select a path that minimizes their exposure to enemy detection and fire along the way. It would be desirable for the agents in a simulation environment to be able to similarly select appropriate paths toward their objectives.

MANA allows the behaviour of agents to be influenced by *waypoints* placed on the battlefield as well as by other agents or terrain features. Thus, the path followed by an agent will be a compromise between several influencing factors according to their respective attraction/repulsion weightings as defined in the agent's *Personality*.

However, despite these tools, agents often end up selecting unreasonable paths toward their objectives. This is partly due to the fact that, as mentioned in the previous subsection, agents have no way of recognizing and seeking positions of appropriate cover or concealment. However, another significant issue is that agents do not look ahead. They select their preferred position for the next timestep, without considering where this will take them later on in the simulation.

Figure 3 illustrates this behaviour. An agent must reach the *waypoint* (indicated by the flag) while maintaining maximum concealment using the *light bush* scattered throughout the battlefield. In most MANA runs, the agent will usually follow a path similar to the one drawn as Path A in the illustration. At each timestep, it moves to achieve an immediate compromise between approaching the *waypoint* and approaching objects with high concealment factors. Clearly, Path B would have been preferable, as it provides cover over a greater proportion of its length. However, the selection of such a path would require longer-term planning from the agent.

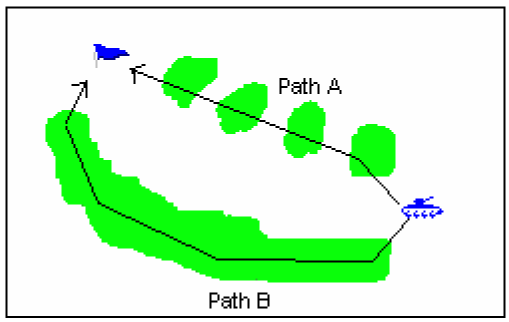


Figure 3. *Path A provides sub-optimal cover.*

An even less reasonable, but typical MANA behaviour is illustrated in Figure 4. There, the agent is strongly attracted by two *light bush* areas. As a compromise, it chooses to remain between them. Again, looking ahead to what its level of concealment would be over the full course of the displacement might allow the agent to decide that moving toward one of the two bush regions would be preferable.

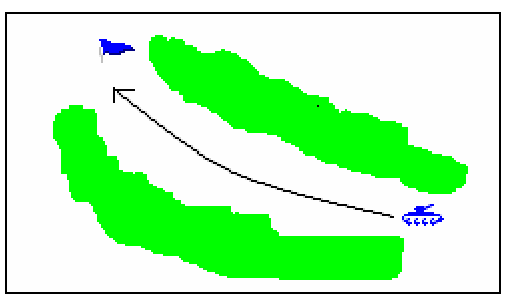


Figure 4. *Another path providing sub-optimal cover.*

One way of avoiding the undesirable behaviour illustrated above would be to direct agents more precisely, by guiding them with several *waypoints* placed along a path that would be selected by the designer as the one that should be preferred by agents.

This approach can work well for simple scenarios that have little variability, but it also results in scripted scenarios with little variability in outcome[10].

3.3 Flexibility in behaviour

In the course of several runs of a MANA scenario, the same agent can encounter a wide variety of situations, some being unforeseen by the developer. The capacity of the agents to react realistically to different and unforeseen events is important to the validity of a study's conclusion. As an example, consider an agent representing a FAVS vehicle advancing along a path indicated by successive *waypoints* laid out by the analyst who designed the scenario. This path might have been selected as one that would be expected to be relatively safe, but in some runs, the agent might find itself ambushed by an enemy. If the agent's modelled behaviour reflected reality, the agent would attempt to back up and follow an alternate path.

MANA offers some tools that permit flexibility in agent behaviour. Firstly, *trigger states* allow an agent's behaviour to change when facing different situations, such as the detection of enemies, being fired upon, being injured, or running out of ammunition. As stated previously, MANA also gives some flexibility to the use of *waypoints* by allowing an *alternate waypoint*. Thus, for example, an agent's behaviour could be defined such that it directs itself toward that chosen *alternate waypoint* when in a specific *trigger state*. MANA also offers a *Combat* constraint that inverts an agent's tendency to move toward enemies according to its perceived force advantage, and a similar *Advance* constraint that inverts the agent's tendency to move toward its next *waypoint* according to the number of agents having the same allegiance.

Despite these tools, MANA agent behaviour was found insufficiently flexible for the purposes of the ALERT and FAVS simulations. When an enemy's actions are unanticipated, there are no mechanisms that can adequately redirect an agent's actions. An agent that adopts a defensive behaviour when entering the *Enemy Contact*, *Injured*, or *Shot At trigger state* will generally revert to its initial course[11] and reencounter the same problems once it leaves the *trigger state* (which occurs after a user-defined period of time). The use of the *Advance* or *Combat* constraints also provides only limited flexibility. The *Combat* constraint, for example, can be triggered when a party advancing toward an enemy formation finds itself at a numerical disadvantage. However, the constraint provides no means for the party to fall back and attempt a different advance through another area of the battlefield. It can only reverse the agents' attraction to enemy combatants. Again, after retreating and losing sight of the enemies, the agents will pursue their initial course as though the *Combat* constraint had never been triggered.

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[10] An alternative approach, but one providing little flexibility to agents, involves finding the optimal path offline, and then having all agents follow that path. A close-to-optimal path could be found by testing for their outcome several preset paths defined by an analyst. The genetic algorithm optimization tool to be provided with MANA Version 4 will be useful for this.

[11] It is possible to use cascading *trigger states*, but these only provide limited flexibility, and can be difficult to manage. The SA map can be used to remember the location of enemy threats, at least for a limited time. However, enemy locations do not correspond exactly to the actual areas of vulnerability.

In other situations, it might be desirable to trigger changes in behaviour more randomly, rather than in reaction to events on the battlefield. For example, it might be useful to model equipment malfunctions occurring at random times during operation. In the case of mini-UAVs employed in the ALERT simulations, for example, accidental crashes play a significant role in the field. MANA currently does not provide any tool to directly model such occurrences[12].

3.4 Situational awareness

Agents in MANA have the capability of remembering the locations where contacts were reported, and of updating these locations on their *SA map*. However, agents cannot remember other important facts, such as locations where they found themselves to be vulnerable, or at a strategic advantage[13]. Also, this capability only addresses Level 1 SA (i.e. an agent's knowledge of the identity and locations of contacts. There is no way for agents in MANA to understand the current overall situation (Level 2 SA) or to foresee upcoming events (Level 3 SA). Clearly, a non-interactive simulation tool that runs without the participation of experienced operators cannot be expected to represent Level 2 and Level 3 SA, but accounting for these higher levels of SA can be important to the realistic unfolding of combat scenarios. The following example illustrates, in part, why MANA was not a suitable tool for the simulations required for the FAVS and ALERT projects.

Figure 5 depicts part of a scenario used in FAVS simulations. Here, the BLUE agent is part of a firebase, positioned to cover the advance of a Company of FAVS not shown in the figure. This agent is placed to effectively cover the advance of the Company, but might need to alter its position if it comes under fire. A *waypoint* and an *alternate waypoint* (shown as flags) are used to allow the agent to seek cover. By default, the agent is attracted to the exposed *waypoint*, but when under enemy fire, it temporarily enters the *Shot At* trigger state, at which point it becomes attracted to the *alternate waypoint* located behind the grey wall. Thus, the agent stays near the exposed *waypoint* until it is threatened, then hides for some time and re-emerges after the duration of the *Shot At* trigger state has expired. It has no way of knowing whether or not the threat remains.

[12] Randomly occurring equipment failure could be modelled using wandering agents whose only effect is to cause the failures when they happen to meet other agents.
[13] When the scenarios unwind in a predictable fashion, areas of vulnerability and strategic advantage can be set explicitly by the analyst, but not when the results of successive runs vary more significantly.

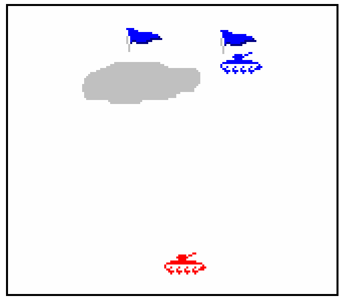

Figure 5. *A firebase.*

Ideally, instead of re-emerging at the same location, the BLUE would form a firebase at an alternative position. This is not only impossible due to the inflexibility of the way in which agent behaviour is defined, but also because the BLUE agent does not even remember that the firebase location was vulnerable. Provided that the BLUE agent's *Contact Persistance* parameter is longer than the duration of the *Shot At* trigger state, it will remember the identity and location of the enemy contact (Level 1 SA), but it will not remember that it was fired upon by that contact (Level 2 SA). Furthermore, the BLUE agent cannot attempt to predict, as would a real combatant, the actions of its enemy (LEVEL 3 SA). Fortunately for the BLUE agent, its RED opponent also suffers from the same weakness, and is likely to stray away, if the BLUE agent stays hidden long enough.

3.5 UAV control

One of the goals of the ALERT project was to generate a suitable Concept of Operations (ConOps) for a mini-UAV. However, finding a way to make the UAVs fly an appropriate trajectory proved impossible.

It first appears that flight paths could be defined using *waypoints*. The problem is that these must be placed in the set-up phase, before the run begins, and are thereafter fixed. In reality, a UAV path would be dependent on the events occurring during the scenario, so its *waypoints* cannot be predetermined.

In an attempt to define reasonable UAV behaviour, *Personality* parameters were adjusted so that the UAV was attracted to unknowns on its inorganic SA map, i.e. the unknown contacts that were sent to the UAV by other friendly agents. This was done so that the UAV would fulfill its role confirming the identity of agents on the battlefield. One weakness of this approach is that the UAV would not effectively classify the unknown, but rather create a second classified contact. Being attracted to unknowns, it would thus stay in the vicinity of the unknown contact for a longer period of time determined by its *Inorganic Contact Persistence* (the time a contact stays on the inorganic SA map). Furthermore, as the friendly agent that initially sent the unknown contact keeps seeing that contact and sending a report of it, the UAV will remain in the area. There is no way for the unknown contact to be reconciled with the UAV contact sent back to the agent. Fusion of contacts between organic and inorganic SA maps is not allowed by MANA.

In an attempt to improve this behaviour, the *Personality* parameters were adjusted so that UAVs were both attracted to unknowns on their inorganic SA map and repelled by classified enemy contacts on their organic SA map. It was hoped that these settings would cause the UAV to fly toward unknown contacts, classify them, and then move toward other unknowns. However, the results were unsatisfactory. Similarly to the situation illustrated in Figure 4, UAVs flying between two unknowns would find themselves equally attracted to both, and consequently immobilized between them. Even in the presence of a single unknown contact, UAVs were found to “bounce” repeatedly on an invisible bubble surrounding the contacts, rather than move on to other areas after classifying them. After the UAVs had classified the unknowns, they would move away, but after a short distance they would forget the just-classified enemy and be attracted to the unknowns again.

The inability of achieving sufficiently realistic and flexible UAV behaviour with MANA proved to be an important reason for eventually discarding this tool for the ALERT simulations. It was found that behaviours similar to those that could be obtained through user interaction available in some other simulation environments could not be replicated with MANA.

3.6 Firing

For a LAV, any reasonable combat behaviour would, at some point, be influenced by the state of its ammunition levels or the probability of a kill at the distance from which it is firing. For example, it would be unreasonable for a LAV to fire its last remaining missile at a low threat enemy, so distant that the hit probability is very low.

In MANA, agents fire as soon as they have an enemy within sensor range and at a distance where there is a non-zero hit probability. This means, for example, that when an agent possesses a weapon with a 1% hit probability from a distance of 4 km, it will fire indiscriminately when it classifies a target at that range. In reality however, an agent might try to get closer before firing, especially if using expensive ammunition and if not under threat from its target. A solution to this problem is to set weapon hit probabilities to zero at ranges from which they should not be fired. This could be the case only in certain trigger states, as the agent might still want to attempt a shot at maximum range in desperate situations.

What cannot be overcome, however, is the fact that agents cannot use ammunition levels in their decision processes. There are *Ammo Out* trigger states for each weapon, but no trigger states dependent on low ammunition levels.

4. Coordination among agents

Formation fighting is omnipresent in modern warfare. The actions of combatants in the field are hardly random. They are rather guided by a commander's tactical plan, established doctrine, and coordinated through interaction with other combatants. The MANA user's manual [5] clearly states that MANA is not intended for careful formation fighting, but at least some limited aspects of formation fighting are necessary to model realistic scenarios[14].

4.1 Communication between agents

Communication among combatants plays a crucial role in modern combat. Simulations of military operations often require models of the communications that take place between friendly agents. Armoured vehicles, such as the ones studied in the FAVS project, use their communication systems to coordinate their actions, to signal their circumstances, or to report the presence of uncovered enemy positions. MANA provides communication links between agents, but these can only be used to share information from agents' SA maps; that is, the location and allegiance of agents spotted on the battlefield. This subsection examines the properties of MANA communication links, while the following subsections will investigate the need for further communication tools enabling coordination among agents.

As the ALERT studies intended to analyze the flow of information through the chain of command, they required a good model of communication among agents. Conceptually, ALERT Coyotes would receive information on agent locations from their BLOS sensors, which is then transmitted up the chain of command to contribute to a commander's SA. MANA models the transmission of information on friendly and enemy agent locations, with different parameters to represent the *Latency*, *Capacity*, and *Contact Persistence* of the communication links.

The *Latency* parameter represents the number of timesteps needed for a message to reach the receiving squad. This could be used to represent the processing time for a particular piece of information. One limitation of this parameter is that it cannot be varied according to the specific contact. It can be varied for different senders, receivers, and the type of contact being sent (i.e. self, friendly, enemy, or unknown), but it cannot be varied according to different classes of enemies.

The *Capacity* parameter represents the maximum number of messages that can be sent by one agent to another in a single timestep. If it is set to less than one, the value entered represents the probability that a message will be sent in any given timestep. This parameter can be used to account for restrictions on the amount of messages that are sent. However, it cannot realistically model bandwidth, as it applies only to

[14] MANA Version 4 will include the explicit definition of formations of agents. It is already possible to have agents stay close together using their SA map and influence ranges, but the difficulty will always be to have agents cooperate effectively in a formation - covering each other, for example.

specific links between agents, and not to the total amount of information exchanged by *all* agents of a common allegiance. As with *Latency*, the *Capacity* parameter is limited in that it can be varied only with the sender, receiver, and type of contact being sent. Also, contact information is sent in the order in which it is received – it cannot be prioritized[15].

It is not possible for MANA to accurately represent the communications that would occur in a typical scenario for the ALERT studies. In reality, it is possible that the ALERT-Coyote would find contacts using both its organic sensors and its BLOS sensors, and add these contacts to its local database. An update including all of its contacts would periodically be sent up the chain of command, the timing being dependent on the pace of the battle. In MANA, however, agents cannot "hold" their contacts for some time before sending them all at once in a later timestep. Instead, an agent will send its contacts as soon as possible after they are obtained, subject to the limits imposed by the *Capacity* and *Latency* parameters.

An additional complication concerns the processing of information at different points in the chain of command. One possible ALERT-Coyote configuration would be for the Coyotes to send their contacts to a troop commander, who would fuse them to the extent possible before sending a consolidated update of all of the troop's contacts to the All-Source Cell (ASC). (The ASC acts as a data fusion and analysis centre for the data coming from all BLUE entities on the battlefield.) With MANA, it proved impossible to model the fusion of contact information taking place at the level of the troop commander. This was undesirable as it resulted in the same contact information being transmitted more often than necessary, thereby using capacity that could have been available for more important communications such as updates on contacts of particular interest or new contacts.

A similar problem occurred when the *Force Addition of New Classified Contacts to Map* option was selected. This has the consequence of updating the position of a contact every time it is classified, provided that the new position is within the *Contact Aggregation Radius* of the old position. Although updates are desirable, it would be more useful if the position was updated either after a set amount of time, or after a certain amount of change in the contact's position.

4.2 Intra-squad offensive coordination

When LAVs are operating in hostile territory, they will not normally advance without appropriate cover from a friendly element. It was decided that in the FAVS simulations, LAVs would be paired up, and that each LAV should work in close cooperation with their partner. Ideally, a LAV would only move under the cover of its partner. Then, an advance toward a significant objective would be done through a succession of bounds where LAVs would alternately advance under cover and then cover their advancing partner.

[15] A partial solution is to create different communication links for each category of contact data to be prioritized. Then, the bandwidth attributed to each link provides a form of prioritization.

Unfortunately, MANA does not provide agents with the tools needed to communicate the state of their advance to other members of their squad[16] – communication links can only relay the location and classification of contacts spotted on the battlefield. Nor does MANA provide means by which agents can observe their fellow squad members and notice whether they have reached a position from which they would be able to provide cover. Consequently, agents have no way of considering their fellow squad members' positions in deciding when to proceed with an offensive. Coordination among agents within a squad therefore cannot be implemented effectively.

In MANA, when a squad advances toward a selected objective, its agents proceed in an uncoordinated manner, in a somewhat random formation. Although not appropriate for the FAVS simulations, one solution for representing a pair of closely cooperating LAVs might be to model the pair as a single agent. The loss of one of the LAVs could then be modelled using the *Injured* trigger state, where the behaviour and capabilities of the agent would be modified to represent those of a single vehicle.

In the field, one of the important reasons for LAVs to work in teams is that it allows them to subdivide their surroundings so that each can concentrate its attention on a different sector. This is made necessary by the limited FOV of many of their sensors – most real systems are not able to cover all directions at once. With MANA's simple sensing model, however, agents are able to detect, classify and fire at enemies in any direction simultaneously, without consideration for the direction of their gaze or the direction in which their weapons are initially pointing. Given these model limitations, intra-squad coordination's intended benefits become somewhat irrelevant. This coordination was sought so that it could provide an improvement that would make the agent's behaviour more realistic, but the pairing up of squads and their cooperation in the battlefield would probably only have limited effects on the final results of a simulation run. There might be no point to simulating complex agent interaction when the sensors making this interaction necessary are not, themselves, modelled with the same degree of realism.

4.3 Inter-squad offensive coordination

In the previous subsection, it was seen how in some combat situations, a high level of coordination should exist between agents within a squad. Coordination should also extend to agents belonging to other squads of the same allegiance. For instance, a role for a squad might be to establish a firebase that will cover the advance of agents from another squad. The advancing squad will only proceed when it is certain that the squad forming its firebase is adequately positioned to provide effective cover.

To model interactions between squads, a mechanism for cueing is needed. As with intra-squad coordination, it could come from agents being able to observe the progress of friendly entities, or from direct communication between squads. Again, MANA does not provide the capabilities that would be required for inter-squad coordination, because the only information that agents are capable of exchanging is the contact

[16] In some simple cases, a solution may be attained using the *Reach Waypoint trigger state*, but even then, no natural way of signalling another squad is available.

information (i.e. classification and location) of agents on their SA map. There is no direct way of sending signals or reports of progress toward an objective.

What could be done to give an *appearance* of coordination between different squads in simple scenarios is to fix the timing of the squads' movements. For example, a squad could time its advance so that it only begins moving after the expected time for its firebase to be established has elapsed. For very simple scenarios, this could give results similar to those that would emanate from proper coordination among squads. Of course, only rough estimates of the proper timings could be used, and all variability in the way in which an operation is conducted would be lost.

4.4 Flexibility in squad behaviour

Ideally, the movements of friendly squads should not only be coordinated, but also responsive to events as the simulation unfolds. In the field, a mission does not necessarily fail disastrously when it meets unanticipated events, as troops can reasonably adapt to many events. In Subsection 3.2, it was mentioned that it would be desirable for squads to modify their trajectory in response to dangerous situations. It would also be desirable for their allies to be made aware of these modifications so that they too can modify their behaviour in response to the event.

As an example, consider the firebase and advancing squads of the previous subsection. After a change in the path taken by the advancing party, the squad providing the firebase might want to reposition itself to provide more adequate cover. Similarly, if the firebase were to be compromised, the advancing party should have a way of knowing that it will not receive adequate cover and change its course of action accordingly.

Again, to obtain flexibility in squad coordination, some form of cueing is needed. Although not currently available in MANA, one desirable capability that would help solve this problem would be through enhanced communications. It would also be desirable to enable squads to be cued by their own observations. This would require more extensive SA capabilities that would keep track not only of other agents, but also of their locations relative to goals and intended paths.

4.5 Coordination of retreat

In real-world warfare, combatants often attempt to retreat, when at an overwhelming disadvantage to their opponents. A squad might abort its advance, or abandon a defensive position after suffering heavy losses or when its ammunition levels have been significantly depleted. In other circumstances, the reaction to debilitating losses within a squad might be to join another squad, when the friendly force as a whole remains strong enough. MANA includes *Move Constraints* that are intended to prevent squads from advancing under unfavourable conditions, but more comprehensive retreat behaviour was sought for the FAVS simulations.

Another solution was found to force squads to retreat effectively after experiencing heavy casualties. It involves using the agents' fuel and the *Squad Death* trigger state. For this solution, agents are given an initial amount of fuel that does not deplete except when it enters the *Squad Death* state, which happens each time a fellow squad member is killed. When the fuel has run out, the squad agents enter the *Fuel Out* trigger state, in which their behaviour is to move to a waypoint located behind a wall that provides 100% concealment and cover.

A difficulty is however that an agent does not always enter the *Squad Death* state at the timestep during which one of its squad members is killed. This is because the simulation processes the agents in a randomly selected order, which changes at each timestep. Therefore, if one agent dies in a given timestep, a second agent will only be aware of the first's death if it is processed after the first is processed. Otherwise, it will only learn of the death in the following timestep and will not enter the *Squad Death* state until then.

The problem is overcome by leaving agents in the *Squad Death* state for more than a single timestep. For example, if a retreat should be initiated after n deaths, each agent should be given n^2 units of fuel and the *Squad Death* state given a duration of $n+1$ timesteps. Then, each time an agent dies, the others will consume either n or $n+1$ units of fuel, depending on whether the death was noticed before or after their fuel consumption was calculated in the timestep during which the death occurred. Then, after $n-1$ deaths, each agent has consumed a maximum of $(n+1)(n-1) = n^2-1$ units of fuel, while after n deaths, they have consumed a minimum of n^2 units, thus triggering a retreat. This works, as long as no additional squad deaths occur during the short period where agents are in the *Squad Death* state.

Retreat behaviour can be modelled as repulsion from enemy agents, coupled with attraction to an alternate waypoint located in a safe area. However, this sometimes results in inadequate escape paths, as it provides little flexibility and does not guarantee a well-covered escape when threats could come from any direction. The alternative of having agents join other friendly squads after heavy squad losses is simply not realizable in MANA because agents cannot change squad. Thus, although retreats can be effectively triggered, it is difficult to choose a proper response.

The solution presented above can be successful, but it does not address the problem of the coordination of a retreat among different squads of the same allegiance. A more complex attempt at the implementation of inter-squad coordination of a retreat is presented in Annex C.

5. MANA exploitation

5.1 Data output

In general, the same MANA scenario can produce widely different results from one run to the next. Averages taken over several runs should be used to increase confidence in results. MANA's multiple runs capability achieves this by iteratively executing chosen scenarios while varying the seed value of its pseudorandom number generator. It offers users a number of output options that will generate files containing data pertaining to detections, kills, communications, etc. [5]. More data can then be obtained through the extraction and processing of various fields from the output files.

Data of interest, such as the times at which specific agents were detected and classified, the ranges at which detections and classifications occurred, the times at which contact information was transmitted, and the locations of detected agents at the time their contact information was transmitted were successfully extracted from the ALERT simulations by processing MANA output files. Nevertheless, not all of the desired data elements could be extracted because some data cannot be saved in the output files. This is the case for the location of friends and foes, as perceived by an agent during the simulation. SA maps showing these locations can be viewed during execution, but cannot be saved for further analysis. This is an example of data that exist in the simulation environment but cannot be made accessible to analysts using MANA.

5.2 Adapting agent behaviour to different scenarios

In the context of the FAVS project, simulation was used to compare the effectiveness of different combinations of defensive and offensive systems for LAVs. When making such comparisons, it is important to note that the optimal behaviour of an agent could vary with the equipment at its disposal. For instance, a LAV equipped with stronger armour might be more willing to expose itself to enemy fire, while a LAV with more ammunition decide to fire more liberally. Thus, differently equipped systems can only be fairly compared when their respective behaviours are adapted to their respective equipment.

MANA offers some flexibility in defining agent behaviour through squad *Personality* parameters. However, there is no easy way of selecting the most adequate values for these parameters. They must generally be adjusted manually, through trial and error[17]. The following paragraphs describe an experiment that demonstrates the importance of adapting agent *Personality* parameters to their equipment.

[17] MANA Version 4 will be distributed with a genetic algorithm optimization tool that will allow *Personality* parameters to be adapted automatically.

Consider two enemy squads facing each other. The goal of the exercise was to determine the effect of a change in a BLUE weapon's range on the battle outcome. This scenario was kept as simple as possible, and in no way attempted to model a likely situation. In the first variation, BLUE agents had a weapon with a slightly shorter range than the one used by RED agents. When the BLUE agents were given a *Personality* that attracted them to their RED enemies, an average of 1.1 BLUE deaths occurred for each RED death over 200 simulation runs. However, when the same BLUE agents were given a *Personality* that was repelled by their RED enemies, 2.3 BLUE deaths now occurred for each RED death. With both personalities, BLUE agents were at a disadvantage, but their *Personality* settings greatly influenced the magnitude of this disadvantage. In this simplistic scenario, agents with the shorter-range weapons were better off charging toward their enemy to put them within range, and thus leaving the zone in which they were vulnerable to their enemy's fire while unable to return fire.

To demonstrate the need for adapting agent *Personality* settings to their weapons, a second variation was developed where the same BLUE agents were now given a weapon with a range longer than that of the RED agents. The RED force was unchanged in number, weapons and behaviour. In this scenario, the preferable behaviour was shown to be diametrically opposite to the one described in the previous variation. BLUE agents with a *Personality* that was attracted to RED agents were killed at a rate of 1.1 per RED agent dead, while they were killed at a rate of only 0.9 per RED agent dead when their *Personality* was repelled by RED agents.

The experiment that was just described clearly demonstrates the importance of adapting an agent's behaviour to its equipment. In fact, if the ratio of BLUE to RED agents on the field was changed, it could be shown that BLUE agents with shorter-range weapons could often win a battle when they were attracted to RED agents, while losing if they were repelled. This is the opposite of what was happening in the case of the second variation where they had longer-range weapons and were fewer in number. Failing to adapt agent behaviour to their different capabilities could result in false conclusions for a study of those systems.

6. Conclusion

The analyst selecting a simulation environment to be used for a given project faces a trade-off between, on one hand, the simplicity and ease with which scenarios can be developed, and on the other, the level of realism in the resulting scenarios. In this respect, MANA has chosen to favour simplicity. Its developers claim that there is no advantage to highly detailed models as these will never accurately capture every aspect of nature and will obscure the simulation's workings [5]. They have sought to produce a tool that allows the exploration of a great range of outcomes with minimal set-up time.

On the other hand, simplicity also entails limitations. Although simplicity is generally desirable, specific problems may require models having higher-fidelity in specific areas. As described in previous sections, some limitations of sensing, communication, elevation and weapon models in MANA were found to make this simulation tool inadequate for the needs of the ALERT and FAVS projects.

The MANA user manual [5] presents the simulation environment as a useful tool to explore a wide range of situations using scenarios subject to significant variability. Such variability entails that many runs then exhibit surprising and illogical behaviour. After several runs, the range of possible outcomes can be explored to extract the highest pay-off tactics, and the kinds of actions that lead to disaster. Only these extreme cases might then be of interest to the analyst performing the simulation.

In the DRDC Valcartier OR team's attempts to use MANA, however, it was required that agents follow established CF doctrine throughout the simulation runs. The simulation outcomes would then be studied to extract optimal equipment combinations in the case of FAVS, or optimal concepts of UAV employment in the case of ALERT. The idea of using MANA to conduct such experiments was thus fundamentally flawed, as careful formation fighting and complex non-scripted interaction among agents are not attainable with MANA.

This work was written with the intention of exposing the difficulties encountered by the DRDC Valcartier OR Team in its attempts to use MANA in two specific projects. It is hoped that it will help other analysts to determine if MANA is suitable for their projects. Two main conclusions can be drawn. Firstly, users of MANA should be warned of important limitations that might prevent it from being used for projects requiring greater realism in some areas. Ideas of additions or modifications to MANA that might solve some of the issues raised in this work are briefly listed in ANNEX B. Secondly, the attempts to use MANA for formation fighting in simulations where agents needed to behave reasonably in every run were misguided. MANA is not an appropriate tool to conduct research using such an approach to combat modelling.

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12. Correspondence between DRDC Valcartier Operational Research Team (Pierre Fournier and Michelle Straver) and DTA (Mark Anderson) from June to September 2004.

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Annex A – Response from DTA

Before the publication of this memorandum, feedback was sought from the designers of MANA to ensure the fairness and validity of the points that it raises. This annex presents, on the following pages, a response from DTA.

DTA provided the authors with many comments that resulted in several additions and corrections to the memorandum's main body.

DTA
DEFENCE TECHNOLOGY AGENCY

13/12/2005

Dear Michelle,

Thank-you for the opportunity to comment on your team's MANA report. We have had a read through it and have contributed a range of comments directly into the report script, which I have attached to this email.

To begin with, we feel that the particular models you were attempting to build with MANA required a greater level of detail than most ABDM are capable of. I believe that we indicated this at the outset of your study. That said: it was interested to read how you persevered and the specific limitations you discovered for future reference.

You have made some good points in the report which have been noted for future development. You will note from the comments attached therein that we have actually already addressed a number of these issues in the soon to be released version (v4) of MANA. You could perhaps mention that a significant number of the issues raised are resolved in that future version.

We would dispute the significance of a number of the points made in the report. For example:

- The grid resolution issue you raise is true for most ABDM and also for other models across a wide range of the scientific spectrum. We have not found it to be a significant limitation in most studies, but we are looking long-term to move to a continuous battle space that will solve problems like the one your team experienced.

- You raise the question of agent's intelligence with regard to finding and using cover. It seems unlikely that other models would do any better. The level of detail you are interested in would most likely require "black box" algorithms embedded within the model.

- As commented in the script, a number of the problems your team encountered can be dealt with by some lateral thinking. ABDM typically require a different mindset to constructive models and the scenario to be framed in an appropriate way.

We would be interested to know what model/technique you eventually used to solve your modeling problem? Discussion of this vs MANA would form a useful part of the report.

Please feel free to contact us with any further queries.

Best Wishes,

David Galligan, PhD
Operations Analysis Section
Defence Technology Agency.

Annex B – Suggestions for improvement

The following is a list of potential modifications or additions to the MANA simulation environment that might address some of the issues brought forward in the previous section. It is not the intention of the authors to imply that it would be easy (or worthwhile) for the creators of MANA to implement these suggestions. Neither is it thought that the implementation of these suggestions would rectify all problems described in this work. This list is simply an attempt to summarize some of the more simple issues that came to the attention of the authors. Resolving these issues might increase the scope of MANA's applicability, and could warrant further investigation.

After transmitting this list to the designers of MANA at DTA, the authors found that many of their suggestions would already be incorporated in MANA Version 4, which was to be available soon. These future additions to MANA are noted in footnotes below.

1. Allow larger battlefields with more grid squares[18].

2. Introduce a "height of agent" property, and consider it in the computation of LOS.

3. Prevent agents from wasting ammo by firing towards targets located behind walls or hills when the *Can't Fire Through Walls or Hills* property is checked[19].

4. Allow the specification of different tables of *Hit Rate per Discharge* versus range for different targets, as opposed to the single table currently associated with all targets.

5. Allow *Classification Rate per Turn* tables that would contain different classification ranges for different target-sensor pairs, instead of the same classification ranges for every target.

6. Introduce *Detection Rate per Turn* tables to allow a probability of detection that varies with range, as does the *Classification Rate per Turn*, rather than using a 100% probability of detection up to the maximum range[20].

7. Separate the *Can't Fire Through Walls or Hills* constraint into *Can't Fire Through Walls*, and *Can't Fire Through Hills*.

8. Add parameters to define the Field of View and the scan rate of sensors that could prevent, when desired, simultaneous detections in different direction by the same sensors[21].

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[18] Increasing the number of grid squares reduces speed, but the ability to choose larger battlefields over run time would still be desirable.
[19] This will be implemented in MANA Version 4.
[20] This will be implemented in MANA Version 4.

9. Currently, agents are able to use their level of *fuel* by entering the *Fuel Out* trigger state when they run out. Agents could similarly make use of other quantities, such as the number of enemies seen, the number of allies remaining, the number of kills made, the number of squad deaths, the number of messages of a certain type received, the number of times a trigger state was entered, the state of ammunition levels, and the amount of time spent in their current trigger state.

10. Allow user-defined trigger states that are entered according to simple conditional expression involving agent variables such as those proposed in Suggestion 9.

11. Allow the explicit fusion of contacts found on agent's inorganic and organic SA maps.

12. Allow trigger state-dependent *waypoints*, rather than having a single set of *waypoints* used throughout a simulation run.

13. Allow more than one *alternate waypoint*, and a *Personality* parameter for attraction to the closest alternate waypoint.

14. Allow the definition of hierarchies of *alternate waypoints* to define alternate paths toward mission objectives.

15. Provide a randomly initiated trigger state that that could account for the occurrence of unexpected events such as equipment failures.

16. Allow agents to remember the locations where they have been, and where they came under fire. Then add *Personality* parameter that would allow agents to be attracted or repelled by these locations. These locations could be added to the agents' SA maps and forgotten after given lapses of time.

17. Associate additional conditions with weapons that would have to be satisfied before firing. This would be trigger state-dependant and could include required ammunition levels, whether the agent is injured, and *Threat* level of the target.

18. Allow the *Capacity* and *Latency* of communication links to vary with the type of message being sent.

19. Enable messages to be prioritized in the *Message Queue,* according to contact type and *Threat* level.

20. Allow agents to send new types of messages when they enter specified trigger states. For example, when an agent reaches a waypoint, a message could be sent to let others know. The recipients might then enter selected trigger states associated with the messages.

21. Add a *Personality* parameter consisting of an attraction to the squad *Home* that could be used by retreating agents.

---

[21] MANA Version 4 will define sensor arcs and slew time.

22. Generalize the *Squad Death* and *Squad Injured* trigger states so that they are triggered only after the occurrence of a chosen number of squad deaths or squad injuries.

23. Generalize the *Fuel Out*, *Ammo Out*, and *Reach Waypoint* trigger states so that they may be triggered only after given fuel or ammunition levels have been attained, or after given numbers of successive waypoints have been reached.

24. Provide capabilities for more extensive output files that could be configured to contain only the data selected by the user[22]. It would be useful to have access to the following data for each agent at each timestep:

    a. ID
    b. squad
    c. squad name
    d. location
    e. status (active, injured, or dead)
    f. fuel level
    g. ammunition level
    h. IDs of other agents on a given agent's local SA map (unknown and classified)
    i. IDs of other agents on a given agent's inorganic SA map (unknown and classified)
    j. IDs of agents to whom messages were sent
    k. IDs of agents from whom messages were received
    l. IDs of agents fired upon; weapon used; hit or miss
    m. trigger state

25. Include areas of cover and concealment created by terrain elevation in the regions toward which an agent will head when having the appropriate *Personality* setting.

26. Allow additional user-defined variables that are incremented when agents enter user-selected trigger states, or when a given conditional expression is satisfied.

[22] MANA Version 4 will include expanded data output capabilities through a plug-in tool.

Annex C – Alternative approach to inter-squad coordination of retreat

The purported advantages of MANA include its short set-up time and simplicity. However, as illustrated in the main body of this work, simplicity in aspects of a model that are critical to certain applications can also be an important limitation. An analyst will often feel the need to overcome MANA's simplicity to model specific systems or behaviours. It was however the experience of the DRDC Valcartier OR Team members that many attempts at working around limitations of MANA gave rise to equally important limitations in other aspects of their models. It was the team's inability to effectively overcome certain limitations in the MANA model that lead to its decision of eventually using other tools for the ALERT and FAVS studies. This annex describes an attempt at modelling a simple retreat behaviour that led to ever-increasing complexity and obscurity.

A solution to coordinating intra-squad retreat was presented in Subsection 4.5. It worked fairly well in many circumstances, although subject to some limitations. It was however limited to the coordination of the retreat of agents within a single squad, as there does not exist a trigger state entered in the event of any friendly death, there is only one for same-quad deaths. A more complex solution to the problem of coordinating a retreat among agents of various squads will now be presented. It is based on the idea of emulating a form of communication using secondary weapons with no power of penetration.

First, two agents are placed within a small enclosure built from a material that prevents them from leaving but allows them to see outside. For simplicity, these agents will be referred to as the commander and the communicator. To ensure that they have minimal effect on the simulation, they are both invisible and of no threat to the other agents. The commander is positioned as to have good visibility over the battlefield, and the *Combat* constraint is used to determine when to call a retreat. By default, the commander is repelled by the communicator. When the ratio of forces on the battlefield falls below a certain threshold, the *Combat* constraint applied to the commander reverses this repulsion. When the commander then gets close to the communicator, it shoots at and injures it with a short-range weapon. Then, the communicator enters the *Injured* trigger state where it changes allegiance and uses a long-range secondary weapon, having no penetration power, to shoot at friendly agents. This weapon is then the mean of communication that causes friendly agents to permanently enter the *Shot At (Secondary)* trigger state in which their behaviour is to withdraw.

This implementation of a coordinated retreat often can work well, but fails in some circumstances. Firstly, if, by chance, a regular agent gets too close to its commander, it might repel that commander enough to push it toward the communicator, thus initiating a premature retreat. Another problem is that the commander will only initiate the retreat at the right time when it sees each friendly and enemy agent. Thus, any battlefield features that block the commander’s LOS can cause this coordinated retreat to be called too early or too late. Nevertheless, this implementation is obviously more complicated than it should have to be. Simple additional tools for the design of simulations, such as the ability for agents to send signals and react to them would greatly simplify the implementation, and could make it more robust.

The above example illustrates the consequences of the lack of capabilities to model a command structure with MANA. Although it is not the objective of MANA to reproduce command structures, command is a force multiplier that has a great impact on the battlefield. In the opinion of many experienced war gamers, the absence of a command structure considerably reduces the credibility of simulation studies conducted with MANA [13].

List of acronyms

AE	Army Experiment
ALERT	Advanced Linked Extended Reconnaissance and Targeting
ASC	All-Source Cell
BLOS	Beyond Line-Of-Sight
BMS	Battlefield Management System
CA	Cellular Automaton
ConOps	Concept of Operations
CORA	Centre for Operational Research and Analysis
DAS	Defensive Aids Suite
DRDC	Defence Research and Development Canada
DTA	Defence Technology Agency
FAVS	Future Armoured Vehicle System
HEMi	High Energy Missile
LAV	Light Armoured Vehicle
LOS	Line Of Sight
MANA	Map Aware Non-uniform Automata
OR	Operational Research
SA	Situational Awareness
TDP	Technology Demonstration Project
TRAC	TRaining doctrine command Analysis Center
UAV	Unmanned Air Vehicle
UGS	Unattended Ground Sensor

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Recently, the Map Aware Non-uniform Automata (MANA) agent-based simulation tool has drawn interest in the military Operational Research community. After encountering difficulties with more resource-intensive higher-fidelity models, the DRDC Valcartier Operational Research (OR) Team considered MANA as a possible tool for fulfilling some of the objectives of two Technology Demonstration Projects (TDPs). However, other difficulties were encountered in the use of MANA. These are detailed in this study, which is targeted towards OR analysts considering MANA as a tool for modeling combat simulation.

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