DRDO Science Spectrum, March 2009, pp. 60-65

Agent-Based Modeling in Defence

Aparna Malhotra

Institute for Systems Studies & Analyses, Metcalfe House, Delhi-110 054

ABSTRACT

Agent-based modeling and simulation is a maturing approach to modeling defence systems comprising of autonomous, interacting entities, represented by agents. This technique can be used to model combat scenarios where multiple entities sense and stochastically respond to conditions in their local environments, mimicking complex large-scale combat system behaviour. This paper discusses battlefield combat as a complex, non-linear adaptive system with emergent behaviour, and why it should be modeled as an agent-based system. Defence applications pertaining to Network-centric Warfare (NCW) and Military Operations Other Than War (MOOTW) are described. A concept of Service-oriented agents is introduced so as to enable agent-based models to interact over a Service-Oriented Architecture (SOA). This concept would be helpful for designing agents for analysing NCW scenarios. The issues that simulation analysts should be aware of when embarking on agent-based model development and some agent development architectures and tools used worldwide for the stated defense applications are also mentioned.

Keywords: Agent-based modeling, multi-agent system, combat simulation, emergent behaviour.

1. INTRODUCTION

Agent-based modeling and simulation is a maturing approach to modeling combat systems comprising of autonomous, interacting battlefield entities which have individual goals as well as overall group goals, that must be balanced to achieve the global objective. These entities, represented as agents, interact with some degree of autonomy and continually make decisions to satisfy a variety of sometimes conflicting objectives. This technique can be used to model battlefield scenarios where multiple entities sense and stochastically respond to conditions in their local environments, mimicking large-scale combat system behaviour which is essentially a non-linear complex system. In such systems, normal linear modeling and simulation techniques do not satisfactorily model or explain the behaviour that the system exhibits because processes and actions are not directly proportional to, or related to input. Further, since these complex systems have many components that interact, cause and effect cannot be separated.

Each battlefield entity has some local objective which it continuously tries to fulfill, in order to satisfy the overall group objective. Suppose, we assume that each entity has as a local measure of effectiveness (MOE) which it is trying to maximize. The group also has a MOE which is an aggregate of the local agent MOEs. The ultimate objective is to maximize the global MOE. It is quite possible that as the battle unfolds, some of the local MOE's may have a reducing trend, and some might stop existing altogether (i.e. the entity gets completely damaged). However the model should ensure that the global MOE of the friendly forces are always monotonically increasing. This effect is possible due to the adaptive behaviour of the entities involved and the huge number of interactions continuously taking place.

This paper gives some justifications as to why agent-based systems are appropriate for modeling and analysis of complex combat scenarios. Defence applications pertaining to Network-centric Warfare (NCW) and Military Operations Other Than War (MOOTW) are described. A concept of Service-oriented agents is introduced so as to enable agent-based models to interact over a Service-Oriented Architecture (SOA). This concept would be helpful for designing agents for analysing NCW scenarios. We also give some agent development architectures and tools used worldwide for the stated defense applications.

1.1 Emergent Behaviour of Combat Simulations

There have been many simulation models of combat environments, but traditionally these models have sought linear solutions. For example, the "Lanchester Model" uses coupled differential equations to model attrition rates in combat. Combat may be modeled by linear simulations, and if both teams proceed in a linear fashion then such simulations do produce predictable outcomes. However, if an opposing side is capable of adapting to the combat efforts of the other, then the resulting combat is unlikely to be linear. In fact, military conflicts possess almost all the main features of complex adaptive systems. They are as follows:

- They are composed of a large number of non-linearly interacting parts
- These parts are usually organized into a command and control hierarchical structure
- Action generally proceeds with decentralized control
- There is a high degree of self-organization
- In order to survive the parts must adapt to the changing environment

So for simulating combat, it is more appropriate to use non-linear models. In particular, agent-based models provide us with a means to simulate individual combatants/ platforms in the battlefield. The non-linear local interaction between the combatants is modeled by communication between respective agents. In such simulations, emergent behaviour [1] becomes an important consequence of the model. Emergent behaviour is defined as the action of simple rules combining to produce complex results. This implies that the rules applied to the individuals can be quite simple, but the collective behaviour of the group may turn out to be quite complex and unpredictable. Emergent behaviour is essentially any behaviour of a system that is not a property of any of the components of that system, and emerges due to interactions among the components of a system.

Emergent behaviour is an important property of most combat scenarios, involving a large number of autonomous, goal-oriented entities. It cannot be attributed to any individual entity but the global outcome of entity coordination and adaptation. It is the overall behaviour caused by the local interactions of the entities which cannot be determined by the initial conditions/settings of the simulation system. Emergent behaviour of a combat simulation can be used to answer many questions, including what initial parameters must be present in the system to elicit such behaviour.

1.2 Why Agent-Based Models?

Before proceeding, for the sake of completeness, we define an agent as a physical or virtual entity which:

a) is capable of acting in an environment,
b) can communicate directly with other agents,
c) is driven by a set of tendencies (in the form of individual's objectives, plans and capabilities or a satisfaction/ survival function which it tries to optimise),
d) possesses resources of its own,
e) is capable of perceiving its environment to a limited extent,
f) which possesses skills and can offer services,
g) whose behaviour tends towards satisfying its objectives, taking account of the resources and skills available to it and depending on its perception, its representations and the communications it receives.

Agent-based modeling [4, 6, 8] adds a new dimension to combat system simulation by allowing us to directly represent individual battlefield entities and their interactions. In fact, it is the emphasis on the interactions between agents that allow us to study the resulting emergent behaviour, which distinguishes multi-agent based simulation systems from other conventional approaches. These systems are composed of agents coordinating to achieve certain goals. Some of the rationales for multi-agent based systems are as follows:

- A single agent could be constructed that does everything, but such heavy-weight agent represents a bottleneck in speed, reliability and maintainability. Dividing functionality among many light-weight agents provides modularity, flexibility and extensibility.
- Specialized knowledge is not often available from a single agent. Knowledge that is spread over various sources (agents) can be integrated for a more complete view when needed.
- Applications requiring distributed computing are better supported by multi-agent systems. In this context, agents can be designed as fine-grained autonomous components that act in parallel.
- To support agent-based systems, an appropriate environment needs to be established. Agent-based development environments provide an infrastructure specifying communication and interaction protocols, and are typically open and have no centralized designer or top-down control function. Such platforms are widely available commercially nowadays.

In such agent based systems, each of the individual agents may have partial information (decentralized data) and capability (simple rules) for problem solving and thus a limited view. However, once they act in collaboration, they can effectively reach the desired outcome without any centralized global control or synchronisation.

2 MILITARY APPLICATIONS OF AGENT-BASED MODELS

2.1 Analysis of Network-Centric Warfare (NCW) Concepts

A possible area of application of agent-based models is in analysis of network-centric warfare (NCW) concepts[2, 3, 9, 10, 11]. In NCW, an overwhelming amount of information about the battlefield situations needs to be analysed. Members of a command and control team in the battlefield, for instance, often receive different information due to the difference of their sensing capabilities and their location. Finally, the knowledge and expertise are distributed among such a team according to their roles. For instance, an intelligence officer is knowledgeable about assessing enemy threats, whereas a logistic officer is knowledgeable about planning and scheduling supplies.

Each element of a network centric force has some degree of autonomy and is continually making decisions to satisfy a variety of, sometimes, conflicting objectives. For example, a fighter aircraft may simultaneously desire to move towards an objective, remain unobserved by the enemy, obey his commander's orders, stay close to his allies and at the same time, react to dynamically changing inputs and overwhelming amount of information. In addition, each of the components in a force may value the various objectives differently. Consequently, there may often appear to be disorder at the local level, but long-range order at the global level.

As the armed forces move towards incorporating Network Centric Warfare (NCW) doctrine and concepts, one of the key challenges in evaluating their benefits is the need to quantify the operational value of the available information. It is becoming mandatory to study the impact that different degrees of networking and different command and control (C2) structures may have on the operational effectiveness of a networked force. Hence, in order to properly model and analyse the operational value of information and assess the benefits of NCW, we need to model the dynamic interactions (information exchange, decision making, issuing of commands etc) of all the entities involved in the networked operation. These networking and C2 structures are expected to vary with time during an operation as requirements and situations change. Due to the huge number of entities involved and the highly complex nature of such interactions multi-agent based simulation is an appropriate approach to model such systems. The reasons why such an approach is well-suited for modeling complex, adaptive systems have already been discussed in the previous section.

Agent-based simulations used for analysing NCW concepts will consist of a network of interrelated agents representing the key activities of NCW: sensing, influencing, deciding, and targeting. These activities define the key functions of all combat entities involved and will be represented as simple agent functionality. The activities may be form the capability set of individual agents or a group of agents, each representing a different platform. The links between the various nodes of NCW may be captured by the interactions between individual agents. These interactions may be defined probabilistically. The probability of sensing (the likelihood that a sensor really detects a target) is influenced by many factors, such as the effective range of the sensor, the line of sight between the target and sensor, if the sensor is actively sensing, if the target doing something detectable (such as moving, shooting, communicating), types of sensor and target, etc.

The dynamically changing networking and C2 structures can also modeled as dynamic interactions between agents. The ideas of roles, responsibilities and delegation are well established in teams of agents[5, 7]. These concepts can be used to dynamically reassign C2 responsibility and delegation, often termed as “self-synchronisation” in a networked force.

Since NCW is about how members of a team or an organization may better work together with the help of network technology, each member of the team must be aware of the existence of the others in order to be able to model their collaboration and coordination of action. Such team-oriented decision-making skills are an inherent capability of agent-based systems and numerous toolkits are readily available to model this.

Another advantage of this approach is that NCW systems inherently have emergent behaviour, i.e., where the behaviour of the organization may be more than the sum of the behaviours of its individual components, and also model compositional behaviour, i.e., where the behaviour of the organization is merely derived from the behaviours of the individual agents that constitute the organisation. As discussed all these are properties of agent-based systems as well.

Hence, in order to support the analysis of NCW concepts, conventional discrete event simulation is not sufficient. Models must be driven by elementary capabilities connected with properties describing simulated entities as well as processes. Simple, light-weight, distributed rule-based processes as defined by agent-based systems are more appropriate. Agent-based simulation provides the metaphors needed to build the necessary models. Computational challenges exist, but they seem to be easier to overcome than conceptual weaknesses of alternatives.

2.2 Analysis of Military Operations Other Than War (MOOTW)

Agent-based models may provide an approach to developing models to examine various aspects of Military Operations Other Than War (MOOTW). Modeling MOOTWs [13] has become a challenge of increasing importance with recent national events. However, much of the science that is necessary to model the complex social interactions for many MOOTWs has yet to be developed. The traditional military modeling techniques such as Lanchester-based attrition equations are of limited utility for modeling such scenarios because they are based on attrition rates and assume a priori that casualties will be non-zero. The goal of any tactic in MOOTW should be, while meeting the constraint of accomplishing the mission, to minimize casualties of all involved (combatants and civilians). In fact, capturing the opponents alive is also often an objective. In such scenarios, success is measured by non-occurrences of events such collateral damage and civilian deaths. Further the outcome is very much dependent on the actions of individuals.

In agent-based models, these individuals can be modeled as agents. The model should reflect the effect of individual actions, capture the process by which casualties occur and allow the implementation of different tactics, techniques, and procedures (TTP). The goal of the simulation would be to gather a better understanding of the process of MOOTW encounters. While simulating different tactical concepts and studying the functioning of the model, the analyst may gain insight as to why a tactic may work in a certain setting. This insight would enable the generation of better TTP’s in such scenarios.

In large-scale scenarios, the actions of individuals can be aggregated, as is done in most conventional warfare simulations. In MOOTW, however, individual actions have much greater potential for far-reaching impact. Agent-based models show the greatest potential for modeling the complex scenarios of MOOTW where the actions of individuals are important. The benefits of this kind of simulation are not so much in the answers they yield, but in the questions that their study generates. The true intent of the simulation would be to increase insight into various types of MOOTW scenario. By modeling at the entity level, the analyst is forced to study the scenario from the bottom up. Agent-based modeling provides an important tool for combat modeling and experimentation in the MOOTW combat.

3. SERVICE-ORIENTED AGENTS

Service-Oriented Architecture (SOA) is appropriate for simulating NCW Scenarios, while software agents are appropriate for enabling such services to realize their complex interaction and coordination behaviors. We therefore propose a unified entity, i.e., service-oriented agent to bring the best in both. These self-autonomous, goal-oriented entities act as providers and consumers of services in a loosely coupled environment. A service-oriented agent and its interactions with other agents via HTTP are represented in Fig. 1. Since an agent is an individual collection of primitive components that provide a focused and cohesive set of capabilities, each of its components can be associated with a particular functionality supporting a specific agent's mental state as related to its goals. The objective is for agents to model the behaviour of the entities (in form of capabilities) so as to provide requested services to other agents. The basic components of service-oriented agents would include problem-solving, interaction, and communication components. The agents will have to be provided with knowledge interchange and communication languages. Each agent will have a localized knowledge-base of the rules and some partial information (facts) about its environment. Some form of problem-solving logic will also need to incorporate in each of these agents so that they can work toward the assigned goals. The service operations will be realized through agent's interaction behaviours. Standard SOAP/XML protocols will be used for communication over HTTP as it happens in any SAO-based web service.

A particular arrangement (or interconnection) of the agent's components is required to constitute an agent. This arrangement reflects the pattern of the agent's mental state as related to its reasoning about achieving a goal. In the context of an NCW scenario, the agents play different roles (or provide services) and are able to coordinate, cooperate and possibly compete with the other agents. Software agents have been provided with sophisticated description and interaction technologies. There have been several attempts to provide software agents with sophisticated description and interaction technologies, for example, DAML[14], and KIF[15].

4. PITFALLS IN AGENT-BASED MODELS

There are pitfalls in the use of agent-based simulation models. There is a temptation to continuously increase the fidelity of the simulation, increasing the complexity of the agents, and the richness and diversity of the rules. This can lead to two different kinds of problem areas: transparency and extrapolation. Transparency in agent-based simulation relates to the simplicity of the individuals, their rules, and the physics of their simulated world. While the aggregate behaviour of these kinds of models may be complex, transparency of the individuals and their relationships contributes to understanding the roots of the complex behaviour. As the modeler makes the individual agents more complex, the understanding of the cause and effect relationships in the model decreases. Perhaps the most difficult part of developing an agent-based simulation model is finding the simple set of rules that make a useful first-order approximation of battlefield entity behaviour. It will always seem easier to add more rules, more features, and more functionality to the model in order to try and generate more realistic behaviour. This will lead to more complexity but not necessarily more realism. A careful balance must be struck between the complexity necessary to capture a behaviour and the simplicity necessary to understand what is happening in the model. Transparency has the additional benefit of aiding the analyst in conveying results to other parties. Ease of analysis for the analyst translates into ease of understanding for the end user.

The second problem is extrapolating the model results beyond its assumptions. Simulations of combat can yield such seemingly realistic results, particularly if supplemented with 3-D animation, that users may be lulled into the belief that model is a faithful replica of reality. It must be kept

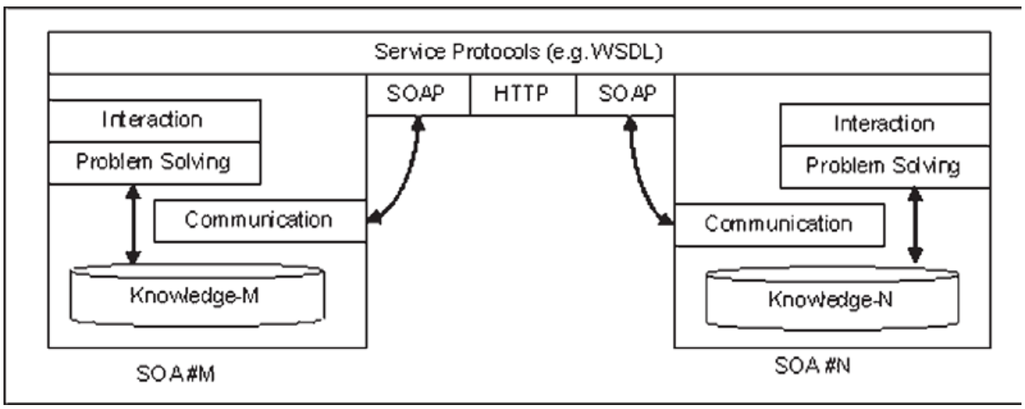

Figure 1. Service-oriented agents.

in mind that merely because an agent-based model mimics a battlefield entity behaviour in a certain setting does not mean that in different settings the response will be valid. Use of these models for predictions must be done with great caution. The role of agent-based simulations is not to predict the behaviour of the system being modeled but to aid in its understanding.

Perhaps the greatest use for agent-based simulation will be in its synergistic application with other modeling methods. Combining one or more analytical models of a combat scenario with an agent-based simulation could yield far more insight into the process than either method alone.

5. RELEVANT AGENT FRAMEWORKS AND TOOLS

5.1 Collaborative Agents for Simulating Teamwork (CAST)

CAST is a multi-agent architecture, developed at the Research Center for Team-based Agents. It enables a team of agents to establish a computational shared mental model. Using such a shared-mental model, agents can 1) anticipate others' information needs, 2) perform dynamic task allocations with minimum inter-agent negotiation, 3) choose whether to proactively inform teammates about the information relevant to their needs, and 4) rationally fuse information to meet teammates' different levels of information needs. CAST is a teamwork model that enables agents to anticipate potential information needs among teammates, and exchange information proactively. It has been designed to study teamwork-related issues emerging from teams with well-defined structure and process, distributed expertise, and limited communication in time-stress domains.

The design of CAST architecture is guided by three objectives: scalability, efficiency, and adaptability. Scalability is achieved using a high level language (MALLET) for describing team task knowledge. Efficiency is realized by algorithms that utilize the team task knowledge effectively. Adaptability is accomplished by dynamic responsibility assignment built into the architecture.

5.2 The Dynamic Agent Representation of Networks of Systems (DARNOS)

DARNOS is a modelling and simulation tool, which was originated by the Defence Science and Technology Organisation (DSTO) and jointly developed with KESEM International. DARNOS utilises a new Organisation-Oriented Agents technology to model the dynamic interactions (information exchange, decision-making, and action) among the entities of a networked force. DARNOS allows the analysts to carry out comparative analyses of operations in the NCW context with a special emphasis on the dynamic management of the information environment and C2. DARNOS achieves this by taking an organisation-oriented approach to modelling the dynamic interactions between players in a networked organisation, where the impact of different C2 and information network structures on the operation of the organisation can be most significant. Therefore, DARNOS is well suited for studying trade-off problems such as whether we should invest more in network technology versus weapons with greater fire power.

6. CONCLUSION

One need not look too hard to see similarities between many features of warfare and key aspects of agent-based models. Simple agent-based models have already proven useful in generating insights and focusing high-resolution simulation experiments world-wide. Agent-based simulation enables insights with regards to the emergent behaviour of the individual combatants, groups of combatants, or the system as a whole.

Using agent-based models, complex behaviours can be generated from simple, reactive entities. These simulations could be used to test ideas of how entities function in complex systems and evolve useful models describing their behaviour. The simplicity of these individual models and the rules that govern their interactions grant transparency to the model. Transparency is an important attribute in agent-based simulation as it facilitates both the analysis of the model and the communication of its results. Agent-based models are best used as approaches to improve intuition rather than as means to generate predictions.

ISSA has done some work on agent-based modeling and simulation. A number of prototypes have been developed to demonstrate the viability of the concept[5, 7, 12]. With the competence readily available, further work can be easily initiated in this direction. Agent-based toolkits can be commercially acquired or custom-built in-house to model and analyse the relevant combat scenarios. Agent-based simulation deserves continued study and exploration as a valuable method for the modeling of military combat.

REFERENCES

1. Zhengping Li, Cheng Hwee Sim, Malcolm Yoke Hean Low. A Survey of Emergent Behaviour and Its Impacts in Agent-based Systems, 2006 IEEE International Conference on Industrial Informatics.
2. Michael Ling and Mario Selvestrel. An Organisation-Oriented Agents Approach to Modelling Network-Centric Warfare,
3. Ang Yang, Hussein A. Abbass, Ruhul Sarker. Evolving Agents for Network Centric Warfare, Proceedings of Genetic and Evolutionary Computation Conference, GECCO'05, June 25–29, 2005, Washington, DC, USA.
4. Susan M. Sanchez, Thomas W. Lucas. Exploring the World of Agent-Based Simulations: Simple Models, Complex Analyses, Proceedings of the 2002 Winter Simulation Conference.
5. Sanjay Bisht, Aparna Malhotra, S.B. Taneja. Modelling and Simulation of Tactical Team-behaviour, published in Defence Science Journal, Nov, 2007.
6. G. Balakayeva, and A. Aktymbayeva. Multiagent Systems Simulation, Proceedings of World Academy of Science, Engineering and Technology, Vol 22, July 2007, ISSN 1307-6884.

7. Aparna Malhotra, S.B. Taneja, Sanjay Bisht. Simplifying the Tactical Modelling of Armour scenarios using Teams of Agents, 3rd International Conference on Quality, Reliability and Infocom Technology (ICRQIT'06), 2 - 4 Dec, 2006, New Delhi.
8. Jeffrey R. Cares. The Use of Agent-Based Models in Military Concept Development, Proceedings of the 2002 Winter Simulation Conference.
9. Henrik Friman, Gary E. Horne. Using Agent Models and Data Farming to explore Network Centric Operations, Proceedings of the 2005 Winter Simulation Conference.
10. Andreas Tolk, Robert J. Bowen, Patrick T. Hester. Using Agent Technology to Move from Intention-Based To Effect-Based Models, Proceedings of the 2008 Winter Simulation Conference.
11. Timothy Hanratty and John Dumer, John Yen and Xiaocong Fan.Using Agents with Shared Mental Model to Support Network-Centric Warfare, Proceedings of the 7th World Multi-conference on Systemics, Cybernetics and Informatics (SCI 2003), Orlando, USA, July 27-30, 2003,.
12. Aparna Malhotra, Sanjay Bisht, S.B. Taneja. Using Intelligent Agents to Simulate Battle Tank Tactics, International Conference on Cognitive Sciences (ICCS), 2004, Organized by NIIT at IIT, Delhi.
13. Fazal Ahmad, Kevin Wagstaff, Co-operative Agents for Modelling Operations Other Than War, Fall 1997, Simulation Interoperability Workshop.
14. http://www.daml.org
15. http://www-ksl.stanford.edu/knowledge-sharing/papers/kif.ps