Agent-Based Simulation for Counter-IED: A Simulation Science Survey

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Abstract. Western countries face an ongoing threat from Improvised Explosive Devices (IEDs). One aspect of the response to this threat is the use of agent-based simulation to model the human networks which place IEDs. While it may not be possible to model these networks with sufficient fidelity to exactly predict IED placement, there is substantial training value in lower-fidelity simulation models which are nevertheless realistic enough to teach useful survival strategies. In this paper, we survey some relevant areas of simulation science. There are two main human aspects to IED placement. The first is *motivation* to place the devices, which influences the number of IEDs placed per day. Modelling motivation requires simulations incorporating attitudes and emotions within society. The second main human aspect to IED placement is *cognition*, which influences the choice of location for IEDs. Simulation of cognition requires modelling planning by Red forces, which takes into account an internal model of Blue processes. Modelling cognition also requires models of learning and adaptability, as Red forces create and respond to their mental representations of Blue responses.

1. INTRODUCTION

Improvised Explosive Devices (IEDs) have had a significant impact on recent military operations by Australia and NATO countries. For example, Figure 1 shows Coalition deaths in Iraq from IEDs during the six years from July 2003, while Figure 2 illustrates the impact of an IED photographically.* As well as causing deaths, IEDs are also responsible for many injuries. They remain an issue in several ongoing conflicts.

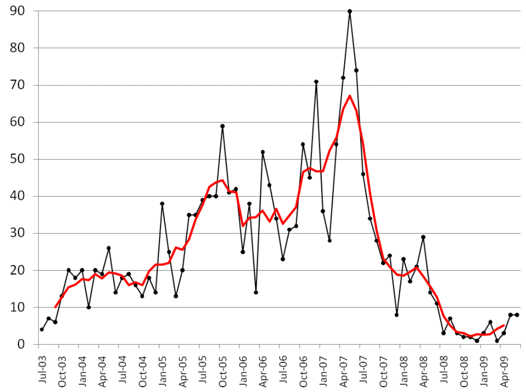

Figure 1: Coalition deaths from IEDs in Iraq each month from July 2003 to June 2009, with moving average in red (data from icasualties.org)

The process of employing an IED involves four steps (Zorpette, 2008a, 2008b):

i. **Construction** of the IED by insurgent forces;

ii. **Placement** of the IED – either well beforehand, or close to the time of the explosion (in the case of mobile IEDs, such as suicide bombers);

Figure 2: IED aftermath: a Stryker vehicle overturned by a buried IED blast (photo from www.army.mil)

iii. **Triggering** of the IED, either directly by hostile forces (using a radio or command wire), or by the victims themselves (by means of a pressure plate or infrared sensor);

iv. **Exploding** of the IED, with consequent effect on the victims, depending on the nature of the charge and the quality of their protective equipment.

Considerable ingenuity has been devoted to detecting IEDs, jamming/defeating their triggering mechanisms, or constructing vehicles (such as the US MRAP vehicles) which are resistant to their blast (JIEDDO, 2008; Zorpette, 2008a). Nevertheless, the improvised nature of IEDs, and the adaptability of IED-placing insurgents, has often resulted in countermeasures being met by insurgent counter-countermeasures.

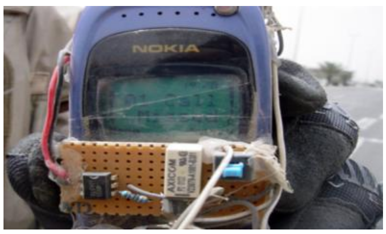

Figure 3: Improvisation in action: a mobile-phone IED trigger (photo from www.army.mil)

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* All data in this paper is taken from open sources, such as books, journals and the Internet.

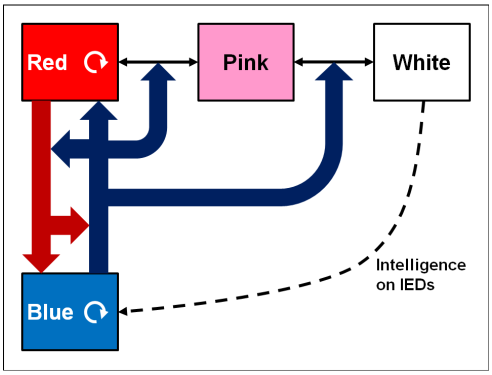

Figure 4: Systems view of counterinsurgency operations, including insurgents (red) and counterinsurgency forces (blue), showing learning loops

The wider problem of IEDs cannot, in fact, be understood without considering the broader socio-technical system of which they are a part. As improvised weapons, IEDs are used largely by insurgents, and therefore fall within the wider context of counterinsurgency (COIN) operations (US Army, 2006). Figure 4 illustrates some key aspects of such operations.

An insurgency involves a component of a country's population which is actively hostile to existing authority. This component may be termed "Red," and may utilise IEDs as part of its strategy. Conversely, other elements of the population, which may be termed "White," will support existing authority, and may therefore be motivated to provide intelligence on the location of IEDs and on the groups of people planting them. A potentially large intermediate group, which we will call "Pink," will be uncommitted:

> "*In almost every case, counterinsurgents face a populace containing an active minority supporting the government and an equally small militant faction opposing it. Success requires the government to be accepted as legitimate by most of that uncommitted middle, which also includes passive supporters of both sides.*" (US Army, 2006: 1-108)

The "Red," "Pink," and "White" groups will in general not be static, but people will transition back and forth between them, as indicated by the horizontal arrows in Figure 4. Understanding these transitions is important.

Counterinsurgency forces, which we will call "Blue," are shown in the lower left of Figure 4. A first-order view of Blue operations is that they are directed against Red, as shown by the large vertical blue arrow, but in fact Blue operations also have a significant effect on the transitions in the population between Red, Pink, and White (and therefore on the extent of the IED problem). Successful counterinsurgency operations acknowledge this effect: As Major General Peter Chiarelli puts it:

> "*If there is nothing else done other than kill bad guys and train others to kill bad guys, the only thing accomplished is moving more people from the fence to the insurgent category—there remains no opportunity to grow the supporter base.*" (Chiarelli and Michaelis 2005, p 6)

In order to shrink the insurgent (Red) base and grow the supporter (White) base, negative impacts on the population, such as civilian casualties, must be minimised:

> "*People who have been maltreated or have had close friends or relatives killed by the government, particularly by its security forces, may strike back at their attackers. Security force abuses and the social upheaval caused by collateral damage from combat can be major escalating factors for insurgencies.*" (US Army, 2006: 1-45)

Conversely, where Blue forces are able to provide positive help to the population, there may be a substantial shift of people towards the "White" category. For example, during the Philippine communist insurgency of the 1950s, Defence Secretary (and later President) Ramon Magsaysay shrank support for the communist guerrillas by instructing Blue forces to provide aid, medical assistance, and legal advice to villagers (Joes, 2008).

Figure 4 also illustrates the **co-evolutionary** aspect of counterinsurgency operations. Blue actions have the side-effect of altering how Red forces conduct operations, and similarly Red actions alter the behaviour of Blue. Consequently, as the US Army/Marine Corps counterinsurgency field manual notes:

> "*If a tactic works this week, it might not work next week; if it works in this province, it might not work in the next. Competent insurgents are adaptive. They are often part of a widespread network that communicates constantly and instantly. Insurgents quickly adjust to successful COIN practices and rapidly disseminate information throughout the insurgency.*" (US Army, 2006: 1-155)

With regard to IEDs, this adaptation means that technical countermeasures may become obsolete as counter-countermeasures are developed by insurgents. Even very sophisticated countermeasures may be negated by inexpensive or improvised counter-countermeasures (Zorpette, 2008a). Insurgents also adapt the design and placement of IEDs in response to Blue tactics, and are known to place dummy IEDs in order to film coalition strategies for responding to them (Zorpette 2008b). Such filming is part of an explicit "learning loop" within the insurgent organisation. Successful counterinsurgency operations require that Blue forces develop their own adaptive learning loops (Spaans *et al.* 2009) and adapt more rapidly and more effectively than the insurgents:

> "*Effective leaders at all levels avoid complacency and are at least as adaptive as their enemies. There is no 'silver bullet' set of COIN procedures. Constantly developing new practices is essential.*" (US Army, 2006: 1-155)

An important part of developing such adaptive learning loops is **simulation** – both as a concept exploration tool, and as a training aid.

To some extent, simulations have already been used for this purpose (Ayvaz *et al*., 2007; Bohemia Interactive, 2009), but such simulations have generally been non-adaptive, assuming a fixed IED placement strategy, and exploring the best countermeasure to that specific threat.

Taking full account of the adaptive human dimension of the IED threat requires modelling two different feedback loops in Figure 4. First, as people transition between the "Red," "Pink," and "White" groups in response to Blue actions, the overall **motivation** of the population to place IEDs changes – either positively or negatively. Modelling these social processes allows approximate predictions of the number of IEDs that will be placed.

The second feedback loop relates to **cognition**, which influences the choice of location for IEDs. Simulation of cognition requires modelling a sophisticated level of **planning** by Red forces, which takes into account an internal model of Blue processes. For example, Red forces may place IEDs in order to elicit a specific anticipated Blue response. Alternatively, Red forces may use their internal model of Blue processes in order to develop responses to Blue counter-measures. Modelling cognition also requires sophisticated models of **learning and adaptability**, as Red forces create and respond to their mental representations of Blue responses.

2. SOCIAL SIMULATION

In order to model the Red/Pink/White transitions in Figure 4, it is necessary to simulate the social factors driving people to join (or leave) insurgent organisations – factors which we have briefly described above. This allows simulations for training or concept exploration to explore the effect that Blue actions have on insurgents' motivation to plant IEDs.

Simulations for this purpose require models of human emotion, though not to the level of detail of, for example, Marsella & Gratch (2001), who model emotions with enough fidelity that agents can interact directly with people. Instead, it suffices to model people as simple agents having variables representing fear, anger, dissatisfaction, and the degree to which people identify with insurgent organisations. For example, Bennett (2008) models fear as a variable f on a 0...1 scale, updated on injury by $f_{t+1} = 0.9f_t + 0.1$.

Many of these emotions have been successfully incorporated into social simulations designed for other purposes. Srbljinovic *et al*. (2003), for example, used a simple agent-based model incorporating dissatisfaction and the degree of identification with ethnic groups, as a way of studying the breakup of Yugoslavia. Lustick (2002) developed a more complex model in which agents had multiple possible identities. For example, agents could have identities based on political party, religion, or ethnicity. Lustick used this model to study the rise of organisations based on religious identity following the breakup of an Iraq-like country. In order to study civil war in Africa, Bhavnani, *et al*. (2008) developed an even more complex agent-based model incorporating economic factors, government corruption, and the degree of identification with ethnic groups.

The methods developed in these and similar research activities makes it possible to model people's level of dissatisfaction and their degree of identification with insurgent groups. However, it is also necessary to model specific responses to Blue actions. Raczynski (2004), for example, described a simple agent-based model of terrorist organisations which allows modelling the growth and destruction of terrorist networks, in response to counter-terrorist actions.

Bennett (2008) provides a more realistic model of insurgency, which incorporates social changes in response to Blue actions, with a particular focus on the early stages of an insurgency. Agents have levels of fear, anger, and propensity to violence, which are influenced by Blue actions. Collateral damage caused by disproportionate or imprecise Blue responses to insurgent activities causes these factors to increase in affected individuals, thus increasing the size of the insurgency. Indeed, as Bennet points out, some insurgent attacks may be deliberately designed to provoke such Blue responses, as an insurgent recruitment campaign.

Gonzalez (2009) further explores such civilian reactions in a simulation module which has been integrated into OneSAF (2009). This module allows Red agent actions to alter the level of collaboration between groups, as well as changing behavioural parameters.

Social simulations of the motivation to place IEDs need not be integrated to this extent, however. Changes in fear, anger, and support for insurgent organisations vary over longer time scales than that of individual Red or Blue actions, and these changes can be modelled at lower spatial resolutions. For example, counter-insurgency operations by Blue may involve individual houses on an hourly basis, but civilian reactions may occur over the course of several days, and across a suburb as a whole. It is therefore feasible to have a low-resolution social simulation loosely integrated with a high-resolution simulation of Red and Blue actions, as in Figure 4. The social simulation can be regularly updated with a list of Blue actions, while the high-resolution simulation can in turn be updated from the social simulation with the probability of IED placement, somewhat similarly to the multi-layer model of Parunak *et al*. (2009).

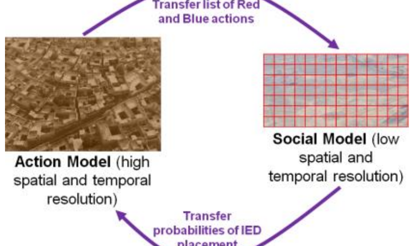

Figure 5: Integration of a low-resolution social simulation model with an action model.

It is also possible to use systems-dynamics models of social changes (rather than agent-based models), as in Leweling & Sieber (2007), although such models do not address the spatial and network aspects of insurgent organisations. This is a serious limitation: Swanson (2007) points out the importance of the IED social network, while Brandoff *et al.* (2008) demonstrate that social models of terrorist activity without a spatial component lead to radically different results from spatial agent-based models.

Whichever type of social model is used, it should incorporate factors such as fear, anger, and propensity to violence, as in Bennett (2008), as well as economic dissatisfaction and the degree of identification with the insurgency, as in Bhavnani, *et al.* (2008). The number of IEDs placed will reflect the number of people identifying with the insurgency who also have a propensity to violence. Calculating these numbers realistically will require calibrating the social model with empirical data, such as that in Figure 1 (Wells & Horowitz, 2005; Weidmann *et al.*, 2006), and the US JIEDDO has been collecting data of this kind (JIEDDO, 2008). Failure to perform such calibration may result in a model which teaches the wrong lessons.

3. PLANNING

Modelling the process of IED placement within a simulation requires the integration of planning technology (Rich & Knight, 1991) into agents (an alternative is to give the agents representing insurgents a repertoire of placement methods chosen by subject matter experts, but this alternative requires a greater degree of agent adaptivity, as discussed in Section 4).

Planning requires agents to have four components, related to the three of Rao & Georgeff (1991):

Beliefs – a representation of the world (which may be incomplete or partially incorrect). Importantly, this representation should include a model of Blue's reactions – that is, a "theory of Blue's mind" (Marsella & Pynadath, 2005). For example, insurgents may use their beliefs about Blue responses to plant a dummy IED intended to halt a Blue convoy, which is then targeted by a genuine IED. At the strategic level, insurgents may also act in order to elicit specific Blue responses, such as excessive retaliation (which boosts insurgent recruitment) or eventual Blue withdrawal. Beliefs may be represented either explicitly, as a set of statements in logic (Reich, 2004); or implicitly, using data structures such as maps and tables, with the beliefs being the statements inferable from the map or table, as in MANA (Ayvaz *et a*l., 2007).

Desires or **Goals** – a representation of how an agent wishes the world to change. This may be done explicitly, using statements about the world expressed in logic; or implicitly, with a "reward function" that measures how good each possible world states is from the agent's point of view (Marsella & Pynadath, 2005).

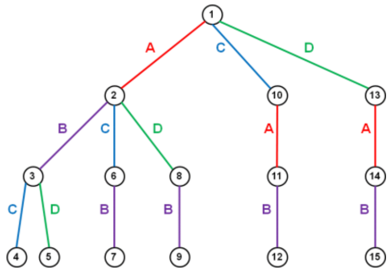

Figure 6: A planning tree. Here actions A, B, C, and D are possible (though A must precede B, and C cannot be combined with D). The planning agent therefore has 15 possible future worlds from which to choose the best.

Intentions or **Plans** – actions, or connected sequences of actions, which the agent intends to carry out in order to achieve its desires/goals

Reasoning – a tool which takes the agent's beliefs and desires/goals and produces intentions/plans. This tool may take the form of a distinct module within the simulation.

If beliefs and desires/goals are expressed explicitly using logic, reasoning will involve some kind of theorem-prover, possibly one allowing reasoning about other agents' beliefs (Dekker, 2000). If beliefs and desires/goals are expressed implicitly, planning involves exploring a range of possible plans, applying them to representations of the world, and selecting the action with the best outcome (Dekker & de Silva, 2006). If plans consist of more than one action, planning requires exploring a tree of possible action sequences, as in Figure 6.

Such planning is time-consuming, and this may be an argument for giving agents a repertoire of "canned responses" selected by subject matter experts. However, the advantage of such sophisticated planning is that it can generate genuine surprise when agents representing insurgents find and exploit Blue vulnerabilities. This can produce more realistic training scenarios.

4. ADAPTIVITY

We described above the importance of adaptivity on both sides of the IED conflict. There are several aspects to such adaptivity. The first is that some strategies – both for Blue and Red – are inherently more robust and flexible, and are therefore more effective when the opponent's actions are uncertain. Figure 7 illustrates this.

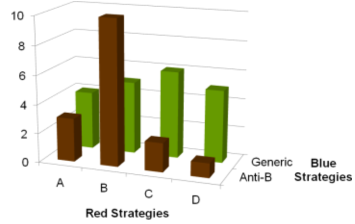

Figure 7: Adaptive *vs* non-adaptive strategies. Blue's "Anti-B" strategy is optimised against Red's "B," but the "Generic" strategy is best when Red's strategy is unknown.

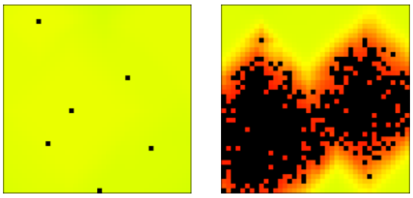

Figure 8: A simple social simulation , based on Bennet (2008). On the left, isolated insurgent incidents (black squares) have had no wider effect, but on the right, social impacts have led to spreading of the insurgency.

Failure to incorporate adaptivity into simulations for counter-IED training and concept exploration may be dangerous, in that the wrong lessons may be learned.

The simulation models we are discussing must allow the simulated Red forces to apply such adaptive strategies. In practice, these strategies may simply involve a choice between a set of options (as part of the planning process), or they may be more sophisticated in nature.

A second aspect of adaptivity involves changing in response to events. If simulated Red forces use the kind of sophisticated planning which we described in Section 3, it is sufficient that they **learn**, by updating their beliefs – particularly their beliefs about Blue responses (Ito *et al.*, 2007). Future planning by these Red agents may then result in different actions being taken.

When sophisticated planning is not used, more complex adaptivity is required to adequately model insurgents placing IEDs. Where agents simulating Red forces have a repertoire of "canned responses," human intervention in the simulation may be necessary in order to add new Red responses. Alternatively, agents may begin with a very large repertoire of actions, most of which are inactive, and some of these may be activated in response to Blue actions. This activation may involve a learning process of **updating weights** associated with each action. These weights give the agent's preference for each action, and can be updated as a result of experience, by methods such as Q-learning (Sun & Naveh, 2004) or neural-network learning (Dekker & Piggott, 1995). Even greater realism is obtained if Red agents are able to employ a **reasoning** process which activates the action which is most effective against the most recent Blue strategies. Alternatively, the approach of Bosse et al. (2006) may be used to integrate logical and learning-based approaches.

5. TECHNOLOGY AND INTEGRATION

As we have seen, simulations for counter-IED training or concept exploration potentially involve quite complex social modelling. Furthermore, such simulations may involve several distinct modules, such as the model of motivation described in Section 2, a reasoning module as described in Section 3, or a module for visualising the state of the simulation.

Developing counter-IED simulations therefore requires tools which support complex programming and integration of multiple modules, as well as assisting with simulation development. The ideal technology is therefore a simulation toolkit with an underlying programming language that supports modularisation, such as the Java[TM] language (Gosling *et al.*, 2005).

Of the many technologies used for agent-based simulation (Nikolai & Madey, 2009), several use the Java language. One frequently used toolkit is Repast, the "Recursive Porous Agent Simulation Toolkit" (Repast, 2009). Repast offers several aids to the simulation developer (including sophisticated visualisation facilities) and was the technology used in the work of Bennett (2008), though other technologies have also been used with success in the construction of social simulations. The simple simulation in Figure 8 was coded directly in Java, without a simulation toolkit.

6. DISCUSSION

In this paper, we have briefly surveyed the problem of Improvised Explosive Devices (IEDs). Concept exploration and training are both important aspects of combating this threat, and simulation is one of many tools which can be applied to these two tasks. Although no researchers have yet produced a complete tool for conducting such simulations, we have identified the major components of such a simulation tool. The literature shows successful examples of the use of each of these components. Assembling them should be feasible, requiring some applied (but no pure) research.

A tool for simulating IED placement would need to be constructed in a modern programming language with modularisation capabilities, using a high quality simulation toolkit. Essential parts of such a simulation include adaptivity by insurgent (Red) forces in response to Blue actions; and modelling of social changes resulting from Blue actions, since these affect the number of people who are motivated to place IEDs (Bennett, 2008; Gonzalez, 2009).

Ideally, the simulation would also model the process by which Red forces plan where to place their IEDs. If this process is not modelled at a sophisticated enough level, the modelling of adaptivity must be made more complex in order to compensate. Failure to do this makes the task of responding to IEDs too easy, and can result in a simulation which teaches the wrong lessons. However, well-constructed simulations may provide valuable assistance to training and concept exploration activities.

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