Multi-Layer Simulation for Analyzing IED Threats

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Abstract—*IEDs, made infamous in Iraq and Afghanistan, are a potential terrorist weapon anywhere in the world. Most counter-IED technologies are targeted at the point of the blast. DEFUSE can interdict and disrupt OPFOR activities left of the blast, well before planting and detonating the IED. The system integrates three layers of simulation: social, process, and environmental.*

I. Introduction

The **D**etecting **E**nemy **F**orces **U**nited to **S**trike with **IE**Ds (DEFUSE) system helps security forces understand and anticipate activities up to and including the blast. It can forecast IED activities including resource gathering, bomb making, reconnaissance, placement, and events, simulate faction leadership activities and explore the impacts of these activities (e.g., changes in targets, level of effort, and goals) on the IED activity in a region, and anticipate the spread of tactics, targets, and goals throughout a faction network. DEFUSE supports proactive counter-IED activities including *intelligence operations* by providing estimates of hidden IED activities, *strategic operations* by providing impact estimates given changes to the leadership and resource infrastructure, and *tactical operations* by providing intelligence estimates that can be "pushed down" to lower echelons.

DEFUSE is a multi-layered simulation (Figure 1) that integrates three perspectives.

A *leadership simulation* explores network models of leaders, where each leader is modeled as an intelligent agent able to reason and act to achieve its goals. The leadership simulation within DEFUSE explores faction leadership and strategic thinking, enabling forecasts of events driven by changes in faction goals and strategies.

A *process model* describes the relationship of activities such as bomb making, resource gathering, and reconnaissance.

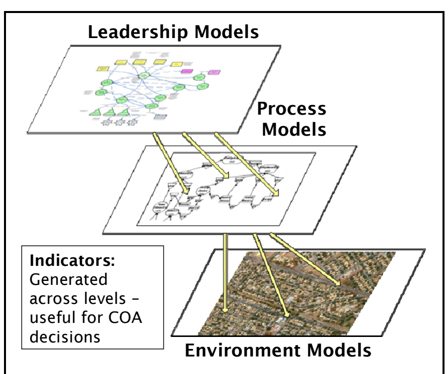

Figure 1 - Three modeling levels.

An *environmental model* provides simulation and forecasting of spatio-temporal events (such as OPFOR movements and IED detonations). Within DEFUSE, the environmental simulation provides models of the interaction of entities with each other and physical constraints (such as roads/buildings) and forecasts of future IED activity.

Table 1 summarizes the innovations and expected operational impact of DEFUSE. Section 2 of this paper provides more detailed background on the IED problem and DEFUSE's technologies. Section 3 outlines the CONOPS for the system, while section 4 describes its technical architecture. Section 5 walks through a demonstration of the system. Section 6 concludes.

II. Background

Core Problem: Too Much Reaction, Focus on Blast

More than 40% of hostile deaths in Iraq during the war are due to IED attacks (http://icasualties.org/). The US has spent significant resources to counteract this threat, mostly directed "at the point of blast" [2], when the IED is armed and a direct threat to nearby US forces. These countermeasures have reduced fatalities, but do little to curb the number and sophistication [3] of IED attacks. We need tools and procedures aimed at understanding and disrupting IED processes earlier in their lifecycle. These tools and procedures must be *predictive* [4], enabling friendly forces to anticipate and preempt attacks and the processes leading to them. These tools and must incorporate a larger subset of the IED lifecycle [2] and the "social context in which [IEDs] are invented, built and used." [5].

The tribes and factions in the insurgency are a major part of this social context. There are dozens of factions, each with its own goals, tactics, and resources. These factions sometimes compete but sometimes cooperate, sharing knowledge and resources. To our knowledge, no current IED prediction/analysis tool incorporates factional influences such as the resources, skills, and unique relationships, or the battlefield impact of potential cooperation between factions. Predictive technologies that incorporate these influences will identify the factors that lead to an explosion and target disruptive courses of action earlier in the IED activity cycle.

Recently Developed Technology

DEFUSE rests on three recently developed technologies.

DARPA's RAID program developed an Adversarial Reasoning Module (ARM) to predict IED locations, frequency, and tactics. The underlying technology [7, 10] has been tested in multiple phases of the program and is an effective tool for predicting more general (non-IED) intents in urban terrain [9]. This technology incorporates historical data and knowledge bases on IED attacks, models of insurgent behavior, and models of blue courses of action and patrol behavior. Though predictive, it does not yet incorporate factional, social, and lifecycle influences that could lead to predictions of attacks and tactical evolution well in advance of real-world threats.

In DARPA's COMPOEX program, we developed the Power Struggle Toolkit (PSTK) [14]. Analysts use the PSTK to develop network models of country and faction leadership and simulate the flow of power between entities and groups within that graph, given individual and group goals and relationships. The PSTK has been used by domain experts to rapidly build models for large scale experiments that anticipate the effects of policy and strategic COA decisions. These experiments show that COMPOEX is able to anticipate more than 20x more potential outcomes than a trained human staff during the same time period.

Under ONR's CIED program, we are developing technology to allow rapid simulation of complex IED processes (such as bomb making and deployment) using a hierarchical task network. Thousands of swarming agents move through this graph, producing probability distributions for various process trajectories, which are translated to forecasted activity sequences within the process network.

Table 1 - DEFUSE innovations and benefits

Innovation	Warfighter Benefits
Hybrid leadership and cell modeling	A richer, more complete model of IED activity, including strategic, social, and physical interactions, leading to more comprehensive forecasts that can anticipate strategic and tactical shifts in behavior as well as gradual emerging effects.
Covers full range of processes and interactions	Can examine and plan for counter activities at multiple stages of IED activity, including processes well left of the blast such has bomb making and site reconnaissance.
Forecasting (future estimation)	Can explore a much wider range of possible futures than can be generated by hand or in one's head. Able to anticipate future events in a wide variety of circumstances and explore possible preventative COAs.
Estimation of Discontinuities	Can systematically explore and analyze possible discontinuities (e.g. radical changes in approach or changes of effect) with their causal factors, leading to early warning indicators for possible discontinuities and proactive prevention.
Based on tested DARPA and ONR technology	Core algorithms have been well researched and rigorously evaluated. High quality, actionable results. Issues can be resolved generally through adjustments to theory and design rather than less robust ad hoc solutions.

III. CONCEPT OF OPERATIONS (CONOPS)

DEFUSE will be deployed within a task force analyzing how the IED threat is likely to change over time and react to specific blue courses of action (COAs).

Building/Configuring the Models

An analyst begins with a set of questions that drive the contents of the models used in DEFUSE. Table 2 summarizes some of the central questions that analysts are asking about insurgent activities in Iraq, derived in cooperation with experts.

Next the analyst assembles three types of models to explore these questions: a leadership model defined by a set of leadership actors, their goals and beliefs, and connections between these actors; an environmental model defined by environmental influences and constraints such as roads, buildings, and activity overlays; and a process model defined as a hierarchical task network. These models are built up over time and can be reused, and modified.

Table 2 - Example Analyst Questions

Analyst Question	DEFUSE Mechanism for Answering the Question
What is the enemy level of effort – how many people are involved, how much product or production?	• Environment model shows level of effort • Leadership model shows strategic decision making impact on LOE
How effective are insurgent efforts? How is that effectiveness likely to change?	• Environmental model shows estimated outcomes
What is the enemy targeting?	• Leadership model shows strategic targeting (targeting to support higher level goals) • Environmental model shows targets of opportunity
When/where is IED reconnaissance occurring?	• Process model indicates steps in IED reconnaissance • Environmental model forecasts actual activity in space and time
What is happening across the IED process (e.g., the bomb making)?	• Process model indicates the range of options available to factions • Environmental model forecasts activity across process and space/time dimensions
How are tactics, targets, and resources likely to shift and propagate over time?	• Leadership model goal, target, tactics sharing over time • Environmental model generates gradual shifts using evolutionary model

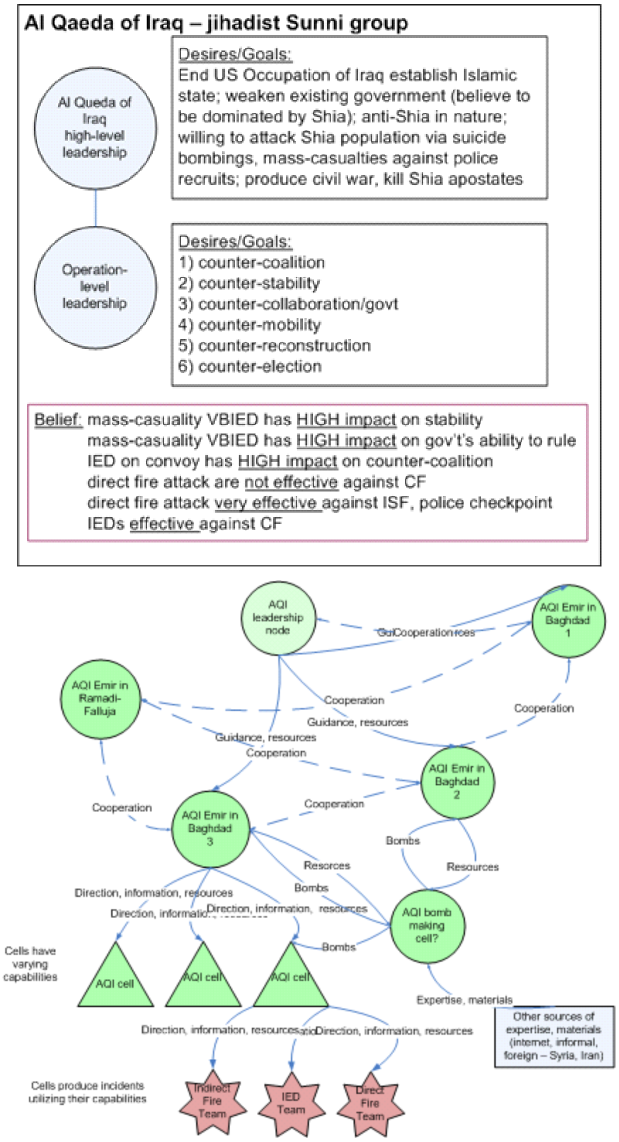

Figure 2 - Example models for faction leadership

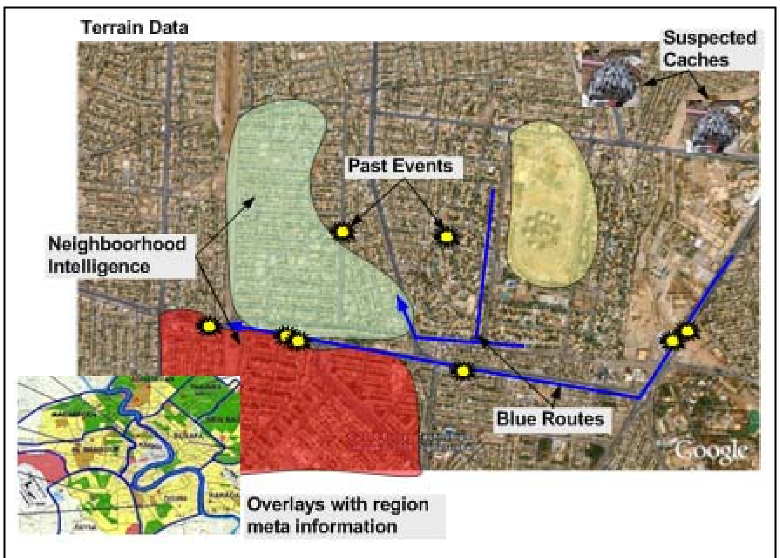

Figure 3 - Example of Environmental Model

Figure 2 shows an example leadership model for Al Qaeda of Iraq (AQI). On top is the structured knowledge used to build the goals and strategies of the group, including general desires (e.g., "End US Occupation") and specific lines of operation (e.g., counter stability operations). These goals and strategies are combined with group beliefs (e.g., "VBIEDs have a high negative impact on stability") to derive actions that have are likely to achieve the group's desires, using the approach detailed in [13]. The bottom shows a network diagram of a portion of the AQI infrastructure. These models were developed by an expert in faction structure and behavior. In fielded operations, similar models would be generated by analysts and experts with knowledge (e.g., www.tkb.org) and intelligence data (mostly classified).

Figure 3 shows some of the modeling elements that the environmental model can incorporate, including data from past IED explosions, including location of attack, type of munition, and trigger mechanism. Other important information includes blue force patrol routes, neighborhood overlays indicating ethnicity, resources (e.g., power, water), and government/military locations. DEFUSE converts these overlays into digital pheromone maps that the swarming simulation uses to explore multiple possible futures.

Figure 4 shows a fragment of an IED process model. A library of these models is created using knowledge engineering techniques. As IED processes change relatively slowly over time (e.g., you must always make a bomb before you can detonate it), the core of these process models is relatively static. However, the analyst is able to modify parameters and resources available within the model, such as access to EFPs or other specific types of IEDs.

Computing Forecasts and Outcomes

Once the analyst configures the models to fit her requirements, they are executed to generate a time sequence forecast of IED activity in the area of interest. Simulations are fast, on the order of minutes to generate hundreds of futures and prepare probability distributions and event forecasts from these futures. By contrast, manual wargaming or planning takes hours or days it takes to generate a similar forecast.

Output is generated by agent-based simulation,

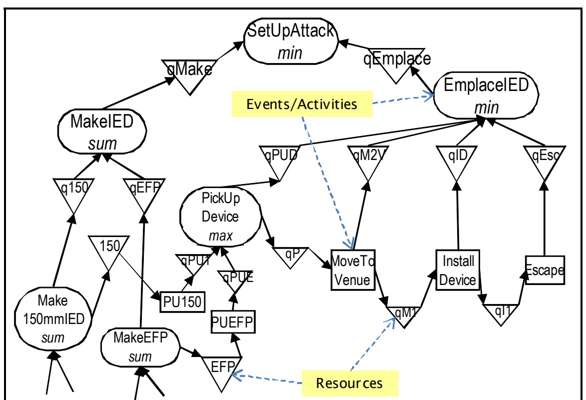

Figure 4 - Fragment of a process model hierarchical network.

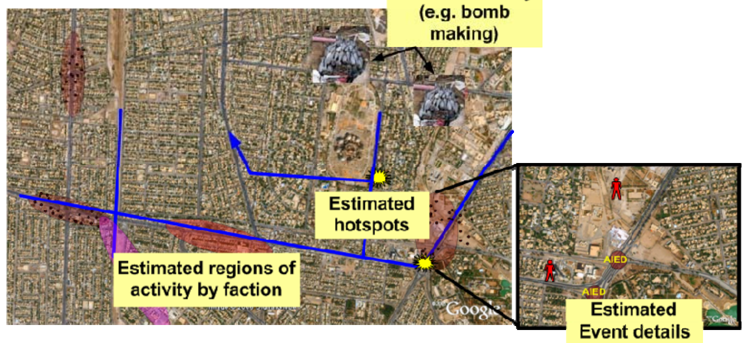

Figure 5 - Example of DEFUSE outputs.

using two classes of agents that interact across modeling levels. *Leadership agents* in the leadership model, guided by their goals, select strategic and high-level tactical actions such as sharing goals, tactics, and targets. Leaders bias the environment by setting and adjusting constraints such as the number of entities active in the environmental simulation and the targets and tactics favored by the IED teams. *Polyagents* [8] operate at both the process and the environmental levels. Processes constrain and order agent activities. Agents called *ghosts* move from node to node in the process graph taking simple actions, such as making or installing a device. For nodes in the process graph requiring spatial activity, ghost agents swarm through the spatial environment (i.e., over an annotated map) executing actions such as placement, detonation, and escape. Hundreds of ghost agents explore alternative futures for each polyagent, producing a probability distribution of possible futures.

The outcome (Figure 5) is a spatio-temporal map of IED activities such as blasts, bomb-making, and transportation. For each IED deployment region details of IED locations are also provided including triggermen, ambush locations, and munition type. IED effectiveness (e.g. potential casualties) is reported to both the analyst and the leadership models, driving future strategic activity.

Modeling Workflow and Answering the Questions

The analyst examines the simulation results for answers to her questions. Because the simulation explores hundreds of futures, she begins with trends in the statistical distributions, and can explore specific events (e.g., a hotspot). Environmental outcomes are tied to leadership decisions through leadership actions, so one can see why certain activities occurred, down to the individual goals and beliefs that drove a particular decision. The leadership model provides biases and direction, but does not drive individual entities in the environment. Thus one can see where ties between leadership and IED cells are strong or weak by looking at differences between leaders' directions and regions of high activity.

The results of one simulation run typically lead to further questions and changed assumptions. Figure 6 show how an analyst iteratively expands and deepens her understanding by varying previous configurations or data and re-running the simulation. Some variations try different COAs, while others use different assumptions of faction goals and resources. The end result is a family of related simulations that forecast future activity across a broad range of situations. These forecasts can inform decision making, and details of the IED activities can be supplied to tactical units.

IV. DEFUSE ARCHITECTURE

DEFUSE extends the ARM with a "dynamic network layer" for modeling faction leader interactions. The architecture contains three layers: a leadership layer, a process layer, and an environmental layer. DEFUSE is a hybrid architecture, applying the structure and technology that best solves the problems represented in each layer [11].

While simple to configure and use, single technology systems cannot solve the range of problems required to model complex IED processes and factions. Environmental models, for example, tend to be good for forecasting IED blasts and low-level physical activities in a steady state situation (where the strategies, goals, and tactics are not changing rapidly), while leadership models tend to be good for understanding the effects of changes to network structure and resources on high-level trends, but cannot produce specific details on how activity on the ground will change.

DEFUSE enhances these individual layers with additional advantages from their interaction.

- It can convert high-level leadership decisions into forecasts of specific IED activities.
- It can model the effects of different levels of cohesion between leadership and IED teams (e.g., strong chain-of-command factions vs. loose networks).

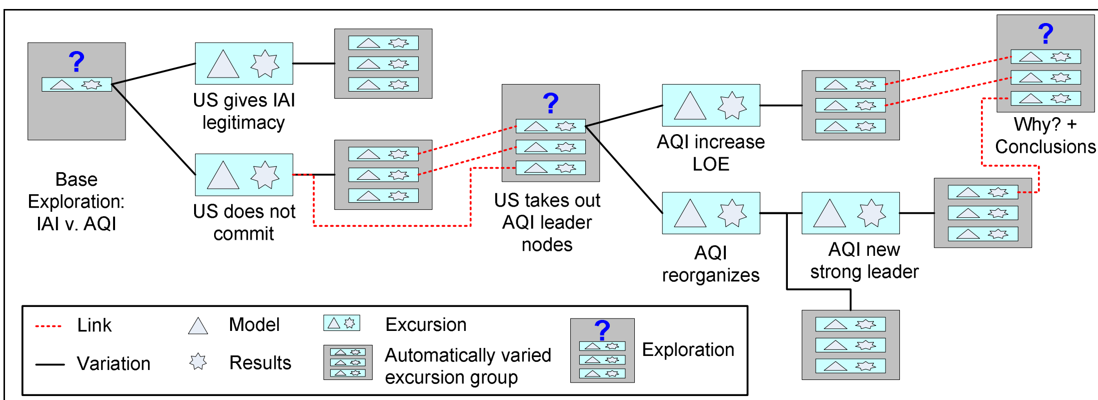

Figure 6- Workflow showing exploration of futures using multiple simulation instances.

- It can use results from the environmental simulation to drive future decisions at the leadership level (thus accounting in part for tactic and target diffusion).
- It can generate top-down (goal driven) behavior to model shifts in activity as well as bottom-up (constraint driven) behavior to understand local interactions and trends (between tribes, resources, and civilians).

The leadership layer is a network of actors, each representing a leader or a group. These networks can be hierarchical (with commanders and subordinates) or flat. Connections between actors indicate their relationships, which can be friendly or hostile. A relationship in the model indicates some form of interaction between those actors, e.g., transfer of orders, requests for aid, or declarations of threat. Given just these features, the leadership layer is simply a social network. Next, we associate a computer agent with each actor, creating a "living network" in which the nodes communicate and act to achieve their goals [13]. Outcomes emerge,not from top-down global optimization as in traditional SNA, but as agents seek to optimize local success criteria.

Agent decision making is based on the computational theory of beliefs, desires, and intentions [12]. Each agent's goals indicate desired states in the world. For example, an Al Qaeda agent might have a goal to eliminate US forces from Iraq. Each agent also holds a set of cause and effect beliefs, or rules about how activity in the world impacts the state of the world. For example, an Al Qaeda agent might believe that high casualty rates will cause US withdrawal and that IED blasts cause high casualty rates. Each agent uses these goals and beliefs to select actions that increase its expected utility (the extent to which its goals are met). In our very simple example, an Al Qaeda agent would decide to place IEDs that it believes (by belief chaining) will increase US casualties and thus cause the US to withdraw. Thus, agents take actions that are consistent with their own beliefs and goals. Because each agent can have its own beliefs and goals, these actions do not have to be consistent with the goals and beliefs of other agents (including the US). This approach provides a computational mechanism for generating major shifts (or tipping points) in action, because agent decisions are non-linear (e.g., an agent may dramatically shift its activities when a goal switches between met/unmet states). Furthermore, agent decisions are rational computationally, so analysts can understand the reasons for decisions.

The process layer consists of a hierarchical task network (HTN) in rTÆMS, an extension of TÆMS [6] that supports coordination and interaction between computational agents. Figure 4 shows an example rTÆMS network for a fraction of an IED creation and emplacement process. An rTÆMS graph is bipartite, made up of *task* nodes (ovals and rectangles) and *resource* nodes (triangles). Resources indicate constraints on activities (e.g., amount of munition available to be made into an IED) and include virtual resources that enforce ordering constraints as well as physical resources. Tasks indicate activities that are either abstract (not represented in our environmental model) or concrete (represented in the environmental model). For example, "Make 150mm IED" is abstract, since the environmental model does not simulate processes such as picking up two parts and putting them together. "MoveToVenue" is concrete, since the environmental model does support moving from one point on a map to another.

Two rTÆMS constructs are useful for modeling coordinated behaviors. First, resources form a natural coordination point. Though agents may execute tasks in parallel, resource nodes serve as points of coordination and competition, constraining agent activity to physically possible levels. Second, the the links between tasks and nodes form a set of constraints on ordering and hierarchy. Agents must do certain tasks before others, while they can do other tasks in parallel. Supporting this process is the *quality accumulation function* (QAF) for each hierarchical (top-down) task decomposition (see "Emplace IED"). A QAF is a rule that controls how execution of the subtasks is aggregated. Example QAFs are *logical AND* (all subtasks must complete to complete the top-level task) and *logical OR* (just one subtask must complete to complete the top-level task).

The process layer relates strategic decisions to IED team activity. Leadership agents direct lower level activities by changing the properties and structures of these graphs. For example, a leader agent might put a preference on a particular node to indicate direction to use a particular tactic (e.g., EFPs), or might set the parameters for a task (e.g., "MoveToVenue") to bias IED team behavior toward particular targets. Environmental agents move within the graph to execute various aspects of the IED process such as bomb making and deployment.

The environmental layer includes a terrain database and a collection of "active terrain overlays" called *digital pheromones*[1], scalar fields that represent the distribution of a particular environment property (e.g., threat to the OPFOR) in both space and time. Digital pheromones form the virtual landscape over which the entities within the environmental model make decisions and move.

Entities representing individuals (e.g., bomb makers) and teams (e.g., deployment teams) are represented as *polyagents* [8]. Polyagents have two components. An *avatar* represents an entity or team in the world. It generates a stream of *ghosts,* which project that entity's activities into the future[2]. Polyagents generate dozens of ghosts in a single simulation run. Each ghost moves and acts in the world based on its *personality,* a set of scalars that indicate the ghost's attraction or repulsion to a given digital pheromone. Thus, the decision process for ghost agents is computationally very efficient (roughly equivalent to a dot product), and thousands of ghost entities can swarm and interact in real time. When real world data is available, these personality vectors can be automatically configured via genetic algorithms.

Ghosts operate in both the process and environment models. The process layer's coordination constraints guide the ghost's activities (telling the ghost what task comes next), while the environmental model provides the physical space within which spatial activities occur.

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[1] Digital pheromones are used in the process layer as well.

2 Sometimes ghosts move and act in the past as well; for example, when polyagents are being trained on historic data.

As ghosts move, they deposit digital pheromones of their own and react to pheromone deposits of other ghosts. This results in a complex, dynamic interaction between ghost agents in a high-speed simulation of many possible futures, resulting in interesting effects such as the "bandwagon effect" where ghosts accumulate and act in places where other ghosts are successful. A probability distribution of activity emerges. This distribution can be aggregated in various ways to form conclusions about activities such as the likely IED blast threat in an area or regions likely to support bomb-making processes.

V. CONCEPT DEMONSTRATION

A demonstration of DEFUSE illustrates this CONOPS.

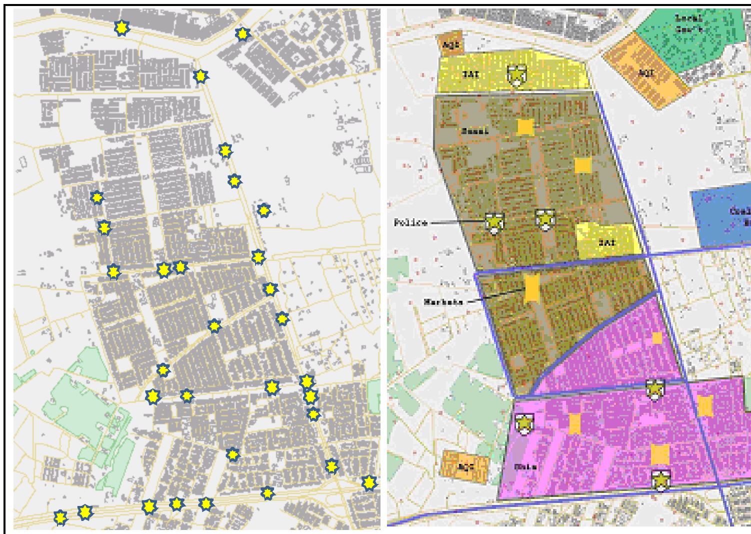

Figure 7 - Base terrain and past IED events (left) and neighborhood overlay (right)

Constructing the Models

We work with expert consultants to construct high-level models of two Iraqi factions: Al Qaeda of Iraq (AQI) and the Islamic Army of Iraq (IAI). Both factions are Sunni and have many similar goals and beliefs. However, IAI consists of former regime leaders and supporters, while AQI consists of jihadists connected with the global Al Qaeda group, leading to key differences in their goals and methods.

IAI seeks return to power and governmental legitimacy. AQI seeks an Islamic state under its control. Thus IAI is less inclined to mass casualty events that alienate the population, while AQI favors mass casualty to spread fear and gain attention. IAI is more hierarchical and rigid, reflecting its government/military roots. AQI is more fluid and less centralized, depending more on activity within local cells.

Next, we construct an environment model of a region of Baghdad (Figure 7, left). Notional IED events appear in Figure 7 as small yellow blast indicators. The terrain and past IED events are used to train the system. Regions deemed generally attractive to IED attacks are shaded green.

We then construct a neighborhood overlay shown in Figure 7 (right, data is notional). We generate a Sunni region, a Shia region, various government and market facilities, and "hotbed" centers where members of the IAI and AQI are expected to live and from which they are likely to operate.

Given just this information, the system will produce a generic IED forecast but will not distinguish the factions. Next, we create a high-level strategy for each faction based on its goals (Table 3). These strategies are mapped to attractiveness levels (target region biases) for the underlying environmental model. Negative values indicate a reluctance to attack, and positive values indicate a desire to attack.

This simple demonstration does not include a process model.

Running the Base Case

Generating an IED forecast (Figure 8) requires about 60 seconds on a standard desktop computer. The left panel shows the region biases for each faction. Both are biased toward similar regions, but AQI is much more biased toward centers of Shia activity. However, many of these attack regions overlap with US supply and patrol routes (along the roads surrounding the neighborhood regions.

IAI focuses much of its attack on government installations (e.g., the government center to the northeast). However, it also has several forecasted attacks against US supply and patrol routes. In general, IAI avoids market regions, as they do not like mass casualty events.

Forecasts for each faction differ based on different high-level strategies. However, both factions share the same training/configuration data, so they both favor IED deployment reflecting historic data such as along roads and in US patrol routes.

Exploring Possible Futures

To demonstrate model exploration, we hypothesize that IAI is given a small role in the Iraqi National Government. In exchange, IAI agrees to denounce AQI and stop attacks on Iraqi government installations. We constructed a new IAI region bias manually, then repeat the simulation. AQI remains the same. We are enhancing DEFUSE so that

Table 3 - Leadership Biases for IED Activity by Faction

Neighborhood/Region Type	IAI	AQI
Sunni Neighborhoods	-2	-2
Sunni Market	-2	0
Sunni Police	1	2
IAI Area	-2	-1
AQI Area	-1	-2
Shia Neighborhoods	1	2
Shia Market	2	3
Shia Police	2	3
Government Office	2	3
US Base	-2	-2
US Patrols	3	3

Figure 8 - IED Forecast for Initial Simulation.

leadership agents can update their strategic direction and output new target biases automatically.

Figure 9 shows updated region biases (lower left). The forecast (right) shows heavily reduced IAI activity, with no more attacks on Iraqi government facilities. However, we still see a few attack regions along US patrol routes, and one very small IED incident to the south west on a police station in the Shia area. Though the leadership has biased IAI cells against attacking government sites, there is strong low-level dislike of Shia, and a local cell made the attack anyway. Environment models do not blindly follow higher-level commands. They seek to maximize their own utility, leading to emergent effects similar to those that occur in the real world for large organizations.

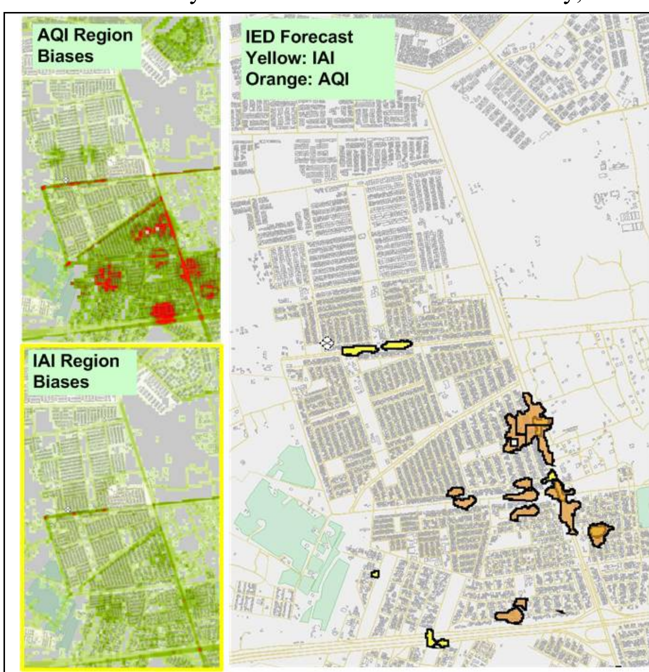

Figure 9: IED Forecast for IAI shift in strategy

AQI's activity has shifted as well, though its strategic region biases have not changed. Activity is still centered in the Shia region but is more concentrated along the eastern boulevard and neighboring markets/police stations. This shift is due to the dynamic interactions of polyagent ghosts. The faction entities interact with each other, not just the environment, and activity from IAI entities affects the activity and distribution of AQI entities and attacks.

Finally, we explore AQI retaliation against the IAI by generating a new high-level strategy and translating it to a region bias map (Figure 10, upper left). Now AQI leadership biases cells to attack regions where IAI supporters are known to live and operate. The results (on the right) show much less activity in the Shia regions. AQI does not have the resources to attack both Shia-centered targets and IAI targets to the levels previously forecasted. We also see some IED threat areas further to the north in and around IAI regions.

For both factions, attack forecasts remain heavy along US supply and patrol routes. However, now IAI's activity picks up slightly along the eastern US patrol route as AQI moves out of that region. Still, IAI's threat is mainly to the US, away from Iraqi government installations.

This demonstration shows how DEFUSE can forecast IED attacks for multiple factions, using realistic terrain and event data and guided by higher level strategic direction modeled by leadership agents. These strategic influences can have significant effects on the quantity and distribution of IED attack forecasts. Thus DEFUSE can forecast tipping points that are difficult to produce in steady state statistical models. DEFUSE's speed in forecasting multiple, related events allows an iterative analytic workflow, helping the analyst answer key questions about IED activity such as intensity and target distribution and type.

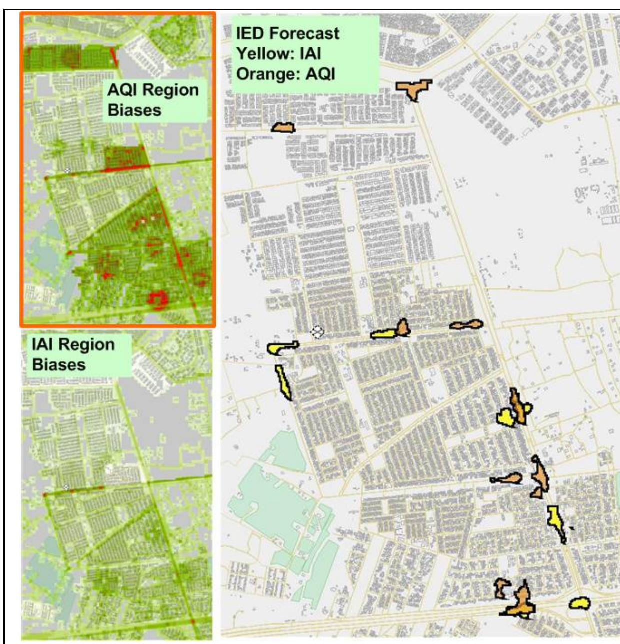

Figure 10. IED Forecast for AQI retaliation.

VI. CONCLUSION

Prediction of terrorist actions such as IED planning, manufacture, emplacement, and detonation is vital to security. To push this capability "left of the blast" requires reasoning across multiple domains, including the social structure and dynamics of the groups mounting the attacks, the process constraints that they must negotiate, and geospatial constraints imposed by the environment. DEFUSE integrates advanced simulations of each of these domains to provide a tool that analysts can use to do realistic "what-if" planning in support of security operations.

VII. ACKNOWLEDGMENTS

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