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AN URBAN TERRAIN ABSTRACTION TO SUPPORT DECISIONMAKING USING RECURSIVE SIMULATION

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ABSTRACT

Recursive simulation is the technique of having simulated decisionmakers themselves use simulation to inform their decisionmaking. Issues of efficiency require that the recursive runs, especially if extended over multiple levels to represent adversarial planning, be at a relatively simple and abstract level of detail. However, the nature of urban terrain is that it is dominated by particulars that drive up the level of detail and make automated decision representations difficult. The proposed terrain abstraction is intended to address these issues, and support low resolution embedded simulation used for recursive decision support for entities in a higher fidelity simulation.

1 BACKGROUND

Recursive simulation is the use of a simulation within a simulation to inform decisions made by the simulated decisionmakers. An example of this has been demonstrated with a military simulation “eaglet.” Headquarters units at the brigade and division levels used the same “eaglet” simulation, called recursively, to project the possible outcomes when a decision needs to be made. The eaglet simulation was intended to be a much simplified surrogate for the U.S. Army's “Eagle” simulation (Gilmer and Sullivan 2000).

Figure 1 illustrates the recursive simulation concept. Here the simulation initiated by an analyst (or as an embedded decision tool within some system) is referred to as the “base” level simulation, which is initiated at some initial simulated time t0 and runs to some final time. There may actually be many trajectories to allow statistical analysis of results. Now we suppose that at some particular time t1 an entity within one of the simulation trajectories needs to make an important decision. A simulation may be used by that entity to perform a simulation run to study the issue, having some number of states (at least one per possible choice) out to some t3 in the decision making entity’s future. The called simulation may use the same simulation engine (recursive simulation) or another (nested simulation), but in either case would probably be at a lower resolution, more limited scope, and limited information, compared to the “Base” simulation. Within that simulation run, entities may also initiate simulation analyses, using recursive calls to the same simulation engine.

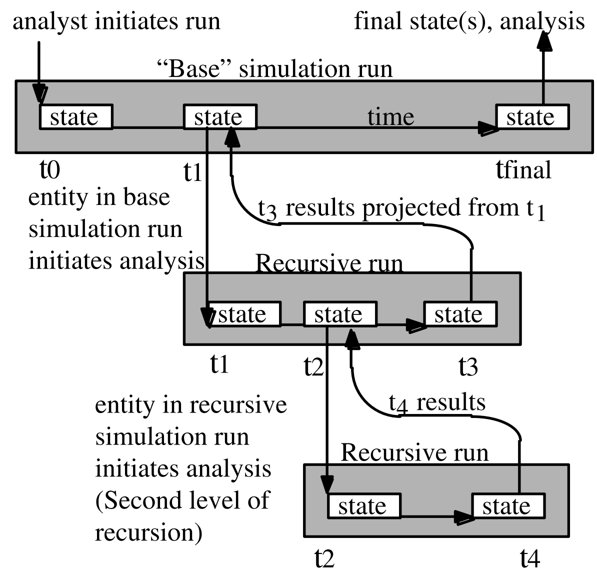

Figure 1: Recursive Simulation Illustration

The simulation “eaglet” used military units of nominally battalion resolution and terrain characterized by woods, ridges, heights, and roads. Thus, the context was conventional warfare of the type of primary interest during the Cold War rather than the smaller unit and urban context that is of such concern today. The urban battlefield presents a much more difficult problem to computer representation of the command control process. The terrain dominates decisions down to the individual level, and the particulars can vary so greatly that developing templated approaches is difficult. Furthermore, the vertical dimension is important. Entities may be at any of several different levels in a given building simultaneously, even when on opposite sides, so movement and combat must be represented as taking place in a more complex space than a surface having a single elevation at each point in the (roughly) horizontal plane. The "AI" seen in commercial computer games (first person shooters) has been largely focused at the individual level, which is not much help in representing a realistic command process. Using the level of detail of such simulations in recursive calls would be prohibitive in its expense, even if a satisfactory decisionmaking within a richly detailed level typical of these games is achieved.

Meanwhile, computational capability has exploded. Multiprocessor computers with clock speeds well into the GHz range are common and inexpensive, making it possible to consider modeling a large area down to the individual soldier or vehicle level. This would seemingly be a useful goal for the base level of a simulation (the level of simulation initiated by the analyst). In a base level simulation with only one trajectory, human intervention may also be practical as a way of either making corrections to the automated C2 (Command Control) representation to improve the fidelity of the process. A "person in the loop" may even be an explicit part of the C2 representation. However, in recursive simulation, human involvement is not practical. Whatever representation is used must be fully automated. If multiple levels of recursion are to be used to give an adversarial planning capability, the recursive simulation must be fast running as well. This implies that some resort to a more abstract representation of the terrain and the decision context is needed.

2 THE RECURSIVE C2 CONTEXT

Planning by a decisionmaker in a military simulation is assumed to involve two basic processes: construction of courses of action, and evaluating those courses of action. Construction of courses of action, "planning," is largely a matter of searching structures for a good fit to the resources of the planner, goals given (usually in orders from above), and what is known of the environment (including friendly and enemy forces). For a search process to be practical, the number of alternatives to be examined needs to be bounded either by well developed heuristics such as the use of templates, and / or abstractions that represent the search space with relatively few discrete choices.

It is assumed that the understanding of a decisionmaker's situation is represented by a structure (a frame, or script) that has "roles" that represent objects or features of particular importance to the operation that the decisionmaker is attempting to carry out.

An example of such a frame is shown in Figure 2 below, as used in "eaglet." The structure for a unit's "course of action," or "plan" once adopted, includes a list of "roles" that specify entities important to the execution of the plan. These would be filled by particular subordinates, identified supporting units, or particular enemy units that may present a threat or opportunity. The planning process

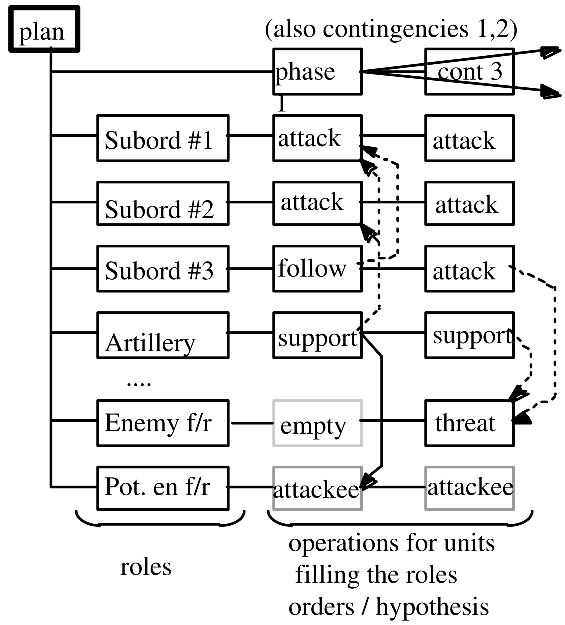

Figure 2: A Role Based Representation of a Decisionmaker's Understanding of the Situation

begins with selection of a concept for the operation that is a template with specified but empty roles. As the plan is developed, units or other entities are assigned to the particular roles. Template orders from the concept for the operations to be assigned to the units having subordinate roles (under the control of the decisionmaker) are then detailed. There could be a series of these orders, with rules for transitions. The phase structure provides the decisionmaker defined transitions from one distinct set of operational conditions to another, with the transitions of subordinates to other orders being conditioned on the phase. This allows both sequential phases and a choice of contingency responses. The "orders" for enemy units or other friendly units would represent hypotheses about their actions and selection criteria used for filling the role. In a sense this structure is just an expansion of the "execution matrix" to include known or hypothetical enemy units, and hypotheses about what they may be doing. The structure may also include roles for key terrain, such as barriers and chokepoints. Some roles may initially be empty, if there is no assigned unit. For example, a particular enemy unit presenting a threat to the plan may not yet be identified.

The importance of the role structure is its ability to represent relationships among the objects of importance to the decisionmaker. Some of these are shown by dashed lines in Figure 2. For example, the subordinate given a "follow and support" role will have an explicit spatial goal in relation to the unit it is to follow, which is the unit in a particular other role. In this case, subordinate 3 is assigned to follow subordinate 1 as long as the operation is in Phase 1. A force filling an "enemy unit role" may become the target for fire for the supporting unit, in order to suppress a danger to the attacking unit. The same enemy unit would also become a target for other supporting assets, which might need to create new roles in order to carry out their required missions under the relationship. For example, some forms of direct fire support would necessitate a line of sight to the enemy, so a new role for the position of the supporting unit would need to be created if that location is not where the supporting unit already is.

For all of this to be useful for recursive simulation, the process of searching for terrain objects to fill roles relevant to a military operation in urban terrain must be relatively simple and straightforward. Yet, the objects must be relatively large and abstract. The kinds of things that need to be represented are described below.

1. Locations: Geographic places in which military units may be said to be, with enough specificity to be useful, and yet, extensive enough that in most cases a unit does not need to be spread across a number of such locations. In an urban area, some (perhaps many) locations may be defined by a vertical dimension in the sense that they are "over" other locations. A unit might be on "floor 1 or a higher floor of a building, or under or on the top of a bridge.
2. Routes: Paths by which military units may move from one location to another. The most obvious are roads and paths, but some routes may lie across open spaces that are more like a continuum, such as an open field. Others may be normally blocked but can be created (or opened) by military action. A "route" may transverse a number of locations, so it may be more appropriate to think of a route "link" as the fundamental object.
3. Barriers: These are things like walls which obstruct the use of a route or a possible route. (Some barriers may be harder to characterize as they could also serve as a route, for example an empty drainage ditch.) A barrier need not be absolute. For example, a floor in a large multi-story building with few connections to adjacent floors acts as a barrier to units that would want to move vertically from one level to another. Similarly, a wall barrier may have door or window penetrations, but still present a discrete problem to movement (or fires) between locations it may separate. The set of potential barriers forms a dual to the set of potential routes; any given route link could need to traverse a barrier.
4. Aggregations of the above: Some important features are structured combinations of the above abstract objects. For example, a field of fire might encompass many locations. A route to be followed may consist of several links. A particular barrier may block various links crossing it at several points.
5. Lines of sight: Connections between regions may not just be important for movement but also for fires. The abstraction of a "field of fire" may be useful for some purposes, especially short range direct fire weapons. But for longer ranged devices and weapons, such as a laser designator, a discrete test of a line of sight, and a representation of that line of sight as a represented connection, will be necessary. This is especially true if one is to explicitly represent creation of a barrier, such as a visual barrier of smoke, that intersects the line of sight.

Since the purpose of recursive simulation is to address decisionmaking issues, it is most important that the terrain representation be responsive to processes that support decisionmaking: role filling, logic concerning occupation status by military forces, the existence of paths or fields of fire, and such. Obviously the terrain representation must also support models of movement, combat, and other physical processes as well. Often terrain modeling starts with the physical processes and only later is found to present difficulties when support decisionmaking. This was the case with "eaglet." So, the focus in this paper is on the support of decisionmaking.

3 THE PROPOSED REPRESENTATION

The proposal is that terrain be abstracted into a link-node representation, or graph. This facilitates searching. The abstract objects are, as listed above, nodes representing locations, connections by links, and a barrier or potential barrier that intersects each link. A simplified example is shown in Figure 3 that shows several of the different features represented in this graph. The nodes of the graph represent locations. A given location may span a fairly large area. For example, the ground level of the building in the upper right corner is much larger than the area of the adjacent street intersection. The assumption is that at a given location, co-occupation by opposing forces would be untenable over an extended period of time. Entry of a force into a location occupied by an enemy would result in elimination or flight by one or the other force in a period of time that is relatively short from the perspective of the automated decisionmaker using this representation.

The links shown connect adjacent locations, and represent potentially practical paths for movement. The locations are representing areas as shown, but for representational purposes in planning and executing movement are a node where two or more links meet. Some links, such as the links following the center of a street or across open areas, present no barrier to movement. Other links cross walls separating a building level from the street or adjacent buildings. Some of these may be solid with no penetrations, and others may have penetrations such as doors, and yet others may be open (e.g. a destroyed wall) while retaining some military significance, such as cover. Note that

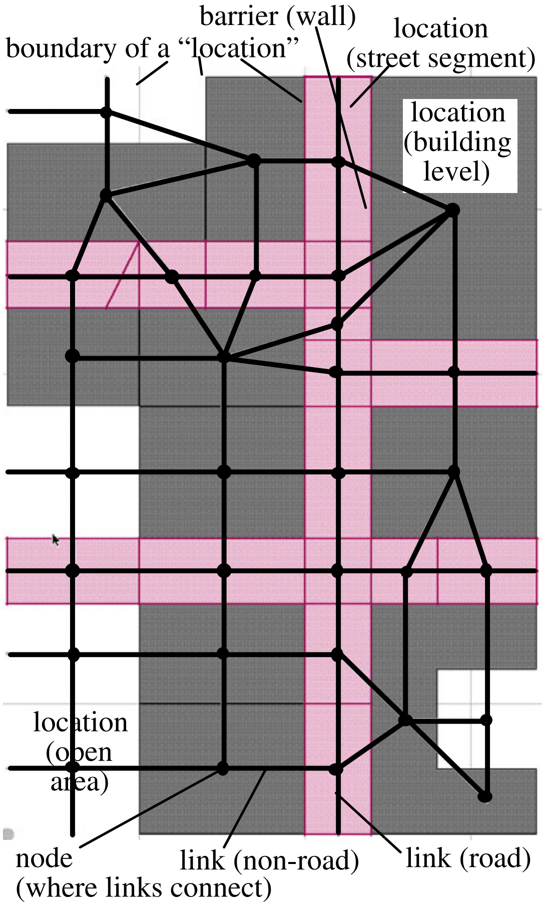

Figure 3: An Urban Terrain Representation

the barriers (and potential barriers) constitute a dual graph, that has barrier links potentially intersecting each movement link between locations. This is useful in recognizing and planning barrier objects, such as a line of resistance under a defensive concept of operation.

There are some representation challenges, such as the building in the lower right corner of the figure. Such a concave structure can present problems that must be solved, for example, by further partition into multiple locations that are not concave.

In addition to the features shown In Figure 3, each building would have additional levels stacked on top of the ground level. These would be connected to the (roughly) equal height levels of adjacent buildings. At least the first upper level would be also connected to adjacent open areas, since escape (or entry) by windows is a possibility. An example of the vertical representation of terrain is shown in Figure 4, which is a cross section across the middle of that shown in Figure 3. Basement levels are also a possibility.

4 APPLICATION OF THE REPRESENTATION

The question remains of how this abstraction helps decisionmaking. This section will offer some examples. The

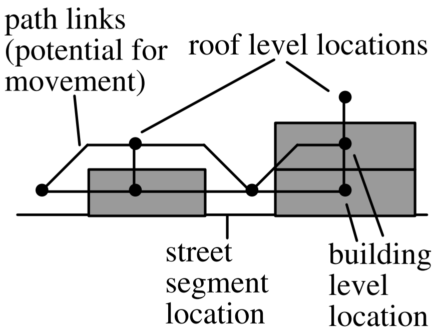

Figure 4: Vertical Terrain Representation

assumption is that these examples occur in simulation at the base level in applications for which low resolution is sufficient, or at recursive levels when the base level simulation has a higher fidelity but for which a lower fidelity recursive simulation is used as a tool for evaluating courses of action or other decisions.

4.1 Route Selection

An infantry leader has a mission to attack and seize the ground floor of the building between the two streets on the right hand side of the example terrain in Figure 3, with options shown in more detail in Figure 5. The leader and his unit are currently in the building across the street to the left (they occupy that location in the graph). An enemy force is assumed to occupy the objective. A route to the objective must be planned. One potential route is the link to the street segment in between, and from there to the objective (Route #1, shown in black). Another is to exit to the street segment below, move along the street to the intersection, and continue to the street segment on the other side, and from there enter the objective from the lower side through that wall (Route #2, shown in white). There are a number of additional choices and variations, but they are relatively small in number (dashed lines). The route planner algorithm is assumed to generate a list of possible routes, and using a relatively simple heuristic (for example, length modified by consideration of barrier difficulty and exposure) to score each possible path. A small number of paths having the highest scores, such as the two routes identified, are selected for more serious consideration.

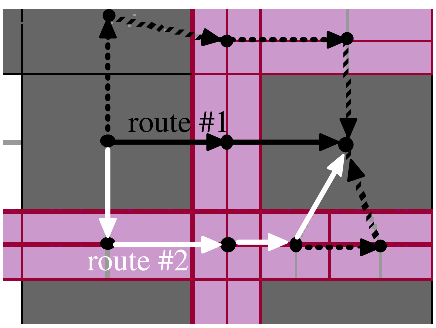

Figure 5: Alternative Routes

That consideration consists first of creating an initial simulation state for a recursive simulation run. This initial recursive state is a subspace of the base simulation (in which the leader is an object) limited to the geographicarea local to the decisionmaker (the infantry leader), and possibly modified to reflect limited intelligence. The initial state is duplicated. In one copy, the leader chooses Route #1, in the other he chooses Route #2. The simulation (with both trajectories) is then run from this initial state for the duration needed to carry out the operation. At the end of the recursive run, the final states of these trajectories, having simulated the consequences of the decision for the two different routes, will be assessed, and the preferred one selected. Now, this decision will be implemented in the base simulation, which is still back at the time prior to executing the operation. In this use, the most important aspect of the terrain representation is its link-node characteristic that allows path planning with a relatively small discrete set of choices.

4.2 Resource Requirement Identification

The above example is continued and extended to identify a second order planning issue. In addressing the direct route, let us suppose, the measure of effectiveness shows excessive and unacceptable losses, and possibly mission failure, because the open street is part of a field of fire not only of the enemy forces known to inhabit the objective, but those believed to occupy the level above. As part of the enemy decision structure in the recursive run, this street segment is identified as a field of fire. A mechanism called "circumstance descriptors" (Gilmer 2000) is used. It is an elaboration of rules that make reference to specific roles and create other new roles in the operation structure. Figure 6 illustrates a circumstance descriptor applied in this example. This mechanism makes the association between the planner's roles for the course of action (potential plan) and the roles in the enemy's structure for the enemy force causing the problem and its field of fire when the latter

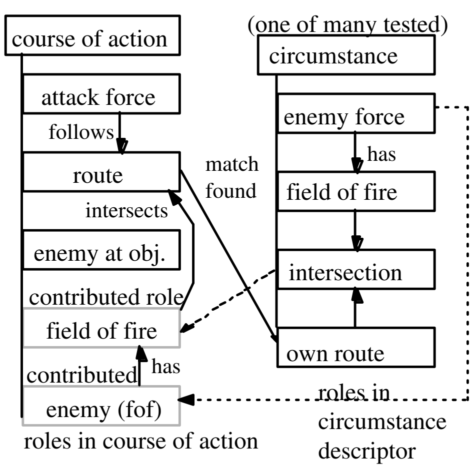

Figure 6: Example of Field of Fire Problem Circumstance

contains the same object (the street segment) as the route. Another (currently unfilled) role in the circumstance is a barrier to the link connecting the enemy force to the field of fire (or, more properly, blocking observation of the field of fire, and hence the effectiveness of such fires). This is a desirable role to fill, since it significantly changes the hazard associated with moving through the street segment. There may be several circumstances that could apply to this situation, but the number should be relatively small and discrete. A possibility is to generate smoke using smoke grenades. Figure 7 shows the recognition of such a circumstance that may be applicable to this situation.

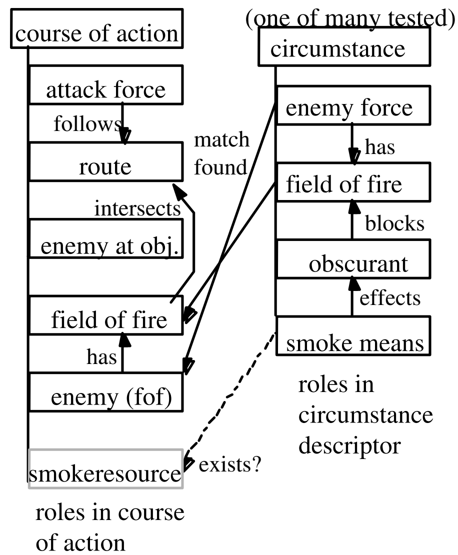

Figure 7: Obscurant Circumstance Example

For this example, the important aspect of the terrain representation is that it supports spatial reasoning necessary (intersection, in this case) to determine that the adjacent street is not just a location along the proposed path, but also a field of fire. The reasoning in this case is quite simple, but could be more complex in other cases since a field of fire could include multiple locations. In contrast, the open terrain model in "eaglet" constructed "field of fire" objects which were typically quite convoluted, that then had to be intersected with paths to produce additional nodes and regions having different characteristics (exposed or not), greatly complicating the reasoning. The representation proposed here is be lower in resolution, in having a location either be or not be part of the field of fire with no attempt to further partition the terrain locations.

If the leader has a sufficient supply of such smoke grenades, that resource (and the role they fill) becomes part of the structure of the course of action, which is then re-simulated as a part of the course of action development process to assess whether this modification makes the course of action (in this case a route selection) acceptable or preferred. Note that the circumstance itself merely suggests the remedy, it does not assess it. That is done by the recursive simulation call. This means that such circumstance descriptors (rules that add structure to a plan) do not need to be rigorously correct, since a simulation mechanism rather than a rule system is responsible for the physics, causality, countermeasures, and other intricacies that may make even a reasonably sure concept fail in a particular situation.

(Note that in Figures 6, 7 and 8 only the roles and not the phases or operations are shown in the interest of simplicity. The operations being conducted by candidate entities to fill various roles, and the template operations attached to the unfilled roles, may need to match to some degree, depending on the role filling criteria. However, it is the presence of and the filled or not filled status of the roles that are important to this example. For similar reasons the phase structure of Figure 2 is also omitted here.)

4.3 Supporting Relationship Development:

To extend the example still further, let us suppose that the leader planning this operation has no organic capacity to block or sufficiently mitigate the enemy force's field of fire into the street segment. Another circumstance that is applicable is suppressive fire from another friendly force. Figure 8 illustrates this.

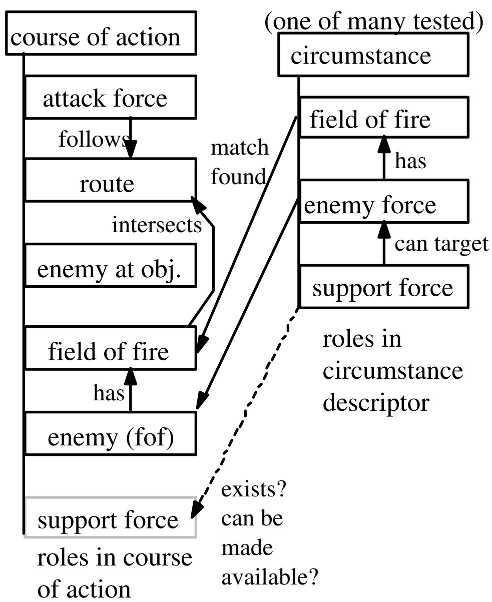

Figure 8: Support Circumstance

Currently there is no friendly force with that role. But perhaps one can be arranged. The circumstance is added to the course of action representation, and the roles for the supporting force and for the target needing suppressive fires are added. But the role for the supporting force is empty for now. But this does lead to recognition of a further circumstance that applies to an unfilled supporting role. This is a circumstance that generates a message requesting such support from the planning leader's superior. If within the time period allowed for course of action development a response is received, and is positive, a friendly force is identified that fills that role. When the course of action is again evaluated (using recursive simulation), the effect of that support will be reflected in the resulting measures of effectiveness for this course of action. (Presumably the rule for requesting the support is restricted to a course of action that would be preferred should the support be available. One would not want to request such support only to select a different course of action in which the support is not needed, hence imposing an opportunity cost on the leader's superior.) As in the previous example, the important aspect of the terrain representation is to support reasoning about spatial relationships, in this case whether a potential supporting force can target the enemy force presenting the danger.

As in the earlier developments to the course of action, recursive simulation would be used to examine how this particular solution to the problem would play out. The number of refinements and iterations through the recursive simulation process to support planning may need to be bounded in practice to limit the use of resources.

4.4 Intelligence Tasking

Returning to the supposed existence of the enemy force in the second floor of the objective building that led to the developments in sections 4.2 and 4.3 above, it may be that the threat does not actually exist. If the second floor is vacant, the field of fire peril from that supposed unit is removed. The importance of determining whether this threat exists or not should to be determined, if possible. An initial event for the recursive simulation run, "2nd level threat exists" together with the two candidate routes, gives 4 trajectories (given that the combinations are deliberately populated in the state set of the recursive run). When all four trajectories end, it is possible to establish an effect from not only the route choice, but from the existence of this threat unit. Assuming that the event "2nd level threat exists" and is indeed important, then this fact is reflected in the concept of operation structure in a way that brings an appropriate circumstance descriptor into play by defining the supposed threat role as an intelligence target. Then one or more circumstance descriptors for different means of determining the threat's existence can be invoked. These might include reconnaissance by fire, or requests that a supporting organization make a determination. It should also be possible (with a larger trajectory set) to detect other important but unanticipated events through event analysis to see which may be important, and target intelligence collection or suppression on the entities involved. Details for intelligence tasking circumstances have yet to be developed. Again, recursive simulation allows a mechanism to examine the consequences of such refinements incorporated into the course of action.

5 CONCLUSIONS

The proposed representation of terrain is designed to facilitate planning in a context where limiting search space is an important objective. The approach has not yet been fully developed, though some work has been accomplished as a new variation of the "eaglet" simulation. The real test of value cannot occur until both the terrain representation is developed and also the decision support structures (template plans and circumstance descriptors) and the software mechanism to simulate decisionmaking is complete and operational. Both the recursion and circumstance methods have been used before in "eaglet, but not in a combined manner. These techniques have been used together, but only in a very simple cats chasing mice context (Agarwal and Gilmer 2004). The terrain representation illustrated here and the circumstances and methodology described above are only a start toward bringing this method for decisionmaking in the urban context to a demonstrable level.

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