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A process and representation for modeling expert navigators

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ABSTRACT: *This paper describes both the knowledge elicitation process we have used and the representation we have built as a result of our study of expert navigators. The first step was to recognize and characterize expert navigation behavior. We interviewed a focus group of Army Ranger School instructors to determine how they evaluate tactical dismounted navigation expertise. The second step was to characterize the mental processes that lead to this expert behavior. We identified a group of expert navigators and interviewed them using a variation of Naturalistic Decision-Making methodology. The results of these interviews provide our initial representation of expertise, which we will refine, validate, and extend to an executable cognitive model. This model will provide realistic control of force navigation for military simulations and will also be used as a feedback mechanism for military navigation training.*

1. Motivation

Our goal is the construction of a computational model to approximate expert navigator behavior. Toward that end, we define land navigation expertise, use this definition to identify experts to study, and then determine how these experts make navigation decisions. Ultimately, we intend to model all navigation activities, but we focus present efforts on the route-planning segment.

Such a model could be used to train navigators. Also, it could aid in developing realistic and valuable models of small-scale military operations. For example, if an analyst wished to evaluate the possible consequences of using an elite squad or a conventional squad for a given mission, he might use this model. Let the elite squad use the expert route planner, reflecting the higher level of navigation expertise in the unit, and let the conventional squad use a less proficient version that plans intermediate routes. In another application, the expert route planner could be used to control the movement of elite enemy forces, or enemy forces that are operating on familiar terrain. In short, any scenario that calls for expert navigation behavior could use this model.

2. Progression of the Research

As our involvement in this project has grown, so has our understanding of many related topics. The main focus of this paper is to document this growth, and we choose to structure the discussion chronologically and topically. Chronologically, the progression spans four phases. During the "Project Preparation" phase, we formed our team and developed our initial plan. Then, we interviewed a group of Army instructors. Phase II, "Focus Group Analysis," documents our analysis of the results. During Phase III, "Preparation for Interviews," we synthesized what we learned into our preparation for a round of individual interviews. Next, we conducted the individual interviews. We end this progression with Phase IV, "CDM Analysis," where we analyzed the interview results.

2.1 Topics

For each phase, we categorize the elements of the progression into five topics: domain analysis; knowledge elicitation; knowledge representation; knowledge conveyance; focus issue.

2.1.1 Domain analysis

We describe the domain to be tactical, dismounted infantry land navigation, within which there are two relevant sub-topics. The first is the characterization of navigation skill; exactly how do skilled navigators perform this task? The second sub-topic concerns the differences between sport navigation and tactical navigation. Are the skills required for expert sport navigation the same or different than those required for tactical navigation?

2.1.2 Knowledge elicitation

Two main issues emerge when considering the knowledge elicitation efforts. First, we must identify the correct sample of the domain population. Who are the right people and how do we access them? Assuming access to the correct population sample, we want to elicit knowledge from them. What knowledge elicitation methods should we employ?

2.1.3 Knowledge representation

Our intermediate-goal is a knowledge representation that will drive skilled CGF (Computer Generated Force) navigation. Mindful of this, which of the available representations is best-suited? We are aware of numerous cognitive architectures that are available for such modeling, so we would ideally like to select one of these standardized, developed representations rather than building our own from scratch.

2.1.4 Knowledge conveyance

Our end-goal is a system for training students to become better navigators. One approach to such a system involves the use of virtual environments. Although DoD agencies are investigating the use of VE's for training [1], currently traditional methods provide satisfactory training. Thus, our approach is to investigate opportunities for applying VE interventions while respecting the traditional methods.

2.1.5 Focus issue

Between phases, we directed our efforts to focus on the single most critical issue facing us at that time. The description of that issue and how it each to the four topic areas will be addressed by phase.

3. Phase I: Project Preparation

The beginning of this phase is marked by the assembly of the research team and covers the weeks spent planning our first contact with navigators external to our team.

3.1 Domain Analysis

Members of our research group have tactical navigation experience. Largely based upon that experience, we thought that we could describe skilled performance; indeed, we regarded ourselves as subject matter experts. Although we thought we could describe our own performance, we were not sure if we could or how we would recognize other skilled navigators.

In some of our prior work, we have studied land navigators, and we have suspected that there exists a significant difference between sport and tactical navigation. While most of our participants have been military personnel, frequently with some tactical navigation experience, most of the experimental tasks have emphasized sport navigation skill rather than tactical skill. Our observations are that an experienced tactical navigator uses a specific tactical strategy. Some elements of that tactical strategy may transfer directly into a sport navigation task, but other elements must be adapted to create a different sport strategy. Because the two tasks require different types of strategies, proficiency in either sport or tactical navigation does not necessarily transfer into the other. Since our objective is the study and training of tactical navigation, we are directing our efforts away from sport navigation to focus on the tactical.

3.2 Knowledge Elicitation

During this phase, our goal was to be able to learn from expert instructors how they recognize skilled navigators. We decided to first approach the instructors at the U.S. Army Ranger Course. Both the fine reputation of the school for producing skilled infantry patrol leaders and our association of navigation skill with patrol leadership skill led us to believe that the students were representative of expert navigators. Expert instructors observing expert navigators should be the correct sample population.

We expected to observe navigators directly while they patrolled in their natural environment; but we did not know what behavior to watch for during this direct observation. We justified focus group interviews as preparation for the real knowledge elicitation of expert navigators, which would follow at some future point in time. Because we had both only had a few hours to meet with the instructors and assumed that the interviewees would be able to clearly articulate their expertise, we thought a focus group would be appropriate. The focus group was planned as a preparatory step for the future knowledge elicitation that would be done by direct observation.

3.3 Knowledge Representation

In parallel with our planning of the knowledge elicitation, we had been assessing many cognitive architectures. Working from the list of architectures announced by Pew and Mavor [2] we had whittled the candidates down to a handful: iGen™ or Cognet™; ACT-R; Soar. Clearly, we felt that with more research into the field, we would be able to select one of these architectures and represent our CGF expert navigator using it.

3.4 Knowledge Conveyance

We cannot envision a training system in which VE's replace live, physical training; what we can envision are ways for virtual environments to enhance live, traditional training investments. Our envisioned system mediates the training intervention via a virtual environment that immerses the student in a three-dimensional model of the natural terrain, provides the student with intuitive interactions and compares student performance to the

CGF expert as one source of instructional feedback. The knowledge representation of the cognitive architectural would drive the CGF behavior, and the knowledge elicitation would provide content for the training scenarios.

3.5 Phase Focus: NDM as our theoretical framework

Given our desire to understand the details of expert navigation, we searched for a theoretical framework that matched the domain characteristics. Ideally, we wanted to use this framework as a guide through each step of system development - knowledge elicitation, representation and conveyance. Our literature search produced references to a relatively new framework, Naturalistic Decision-Making (NDM) [3, 4].

We were attracted to NDM because it respected the influence of the environment on performance and emphasized study of performance out in the field, in the environment in which it naturally takes place [4]. Previously, our group had studied military navigators performing score orienteering tasks in a non-tactical environment [5, 6, 7, 8]. Military navigation is inherently different from civilian orienteering. It incorporates elements of small unit tactics, group leadership, and military mission planning that do not exist for the civilian orienteer. While the orienteer simply gets from point to point as quickly as possible, the tactical military navigator must conserve his patrol's energy for its mission, avoid detection by enemy forces, and maintain control over several soldiers. None of these vital considerations can be measured on a standard navigation course. This implies that, to properly evaluate navigators, the evaluator must observe them in the context of a tactical mission.

Furthermore, the NDM framework emerged from the field of psychological inquiry into domains that were rather impervious to more traditional methods [4, 9]. The profile of such domains defines properties of task and environment: the task is performed in dynamic, uncertain environments; the performer has to adapt to shifting, ill-defined, competing sub-goals; the performer must continuously monitor and integrate environmental feedback from his or her actions; the performance conditions are high-tempo and high-stress; there are high stakes placed on performance quality [4, 9]. These properties matched our domain properties quite closely.

Dynamic, uncertain environments

After departing friendly territory, the patrol's environment is uncertain, and the navigator must monitor the terrain and dynamically update the patrol's location. Although the patrol labored to create an operational order and its travel route to the objective, changes to the plan happen and are not under the navigator's control: the patrol may move more quickly or slowly than planned; enemy contact or its avoidance can disrupt planned movements. Furthermore, weather, visibility and seasonal factors naturally change the appearance of terrain and landmarks.

Action/Feedback loops

Especially when reacting to unplanned deviations from the route, the navigator must monitor feedback from the environment caused by earlier decisions and actions.

High Tempo, High Stress

Of all the phases, the navigator normally has the most control over the tempo and stress level of the task during mission planning. Still, even in ideal cases, the navigator rarely has enough time to fully visualize and memorize before planning ends. Field and security conditions often add stress to an already difficult task. Once the patrol begins movement toward the objective, the tactical tempo and stress rise as the navigator has less and less control over the situation.

High Stakes

Poor navigation can mean trouble for the patrol. Wandering off course into enemy territory or inaccurate reports to friendly operating units can compromise the patrol's security. In less extreme cases, patrol morale itself is quite sensitive to navigation performance; a lost patrol is a frustrated patrol.

4. Conduct and Critique of the Focus Group Interview

Our same reasons for adopting the NDM framework imply that to properly evaluate navigators the evaluator must observe them in the context of a tactical mission. Instructors at the U.S. Army Ranger Course do exactly this several times each month.

We conducted a focus group discussion with ten Ranger Instructors, identified by the 4th Ranger Training Battalion chain of command as its most knowledgeable and experienced. These men had, at the time of the meeting, an average of 9 years of Army service and an average of 25 months as Ranger Instructors. The Army's Ranger Course is a demanding small-unit leadership course in which units of seven to ten soldiers routinely navigate several kilometers, under stressful conditions, to conduct small-unit missions. Ranger Instructors are all course graduates who give detailed feedback to students on a daily basis. They routinely evaluate students with a wide range of experience and aptitude, and thus can clearly describe the differences between novices and experts.

During the focus group, we asked the participants to put themselves into a situation in which they were evaluating a patrol leader's navigation skill. We structured the interview to match the chronological progression of a patrol: we began by discussing evaluation of the navigator's route selection and planning; next, we directed discussion toward activities during the movement from the start point to a point just short of the objective (where patrols begin preparation for actions on the objective); finally, we discussed navigation activities that take place between this halting position and the objective itself. To prompt discussion, for each phase of the mission, we presented specific activities that a typical navigator might follow. We also opened the discussion to cover topics we had not formally presented.

After the session, we had a series of behaviors associated with expertise, and clearly contrasting sets for novice and competent performance. This information provided a working model of navigation expertise.

4.1 Critique and evaluation

From this experience, we learned that the group interviews are not an appropriate setting for eliciting detailed information. Also, the time efficiency was low for the instructors – if each individual had spent the time that he spent in the group setting with us individually, the efficiency would have increased. Additionally, some members were very vocal while others remained relatively silent. On the positive side, the group dynamic helped to spawn unanticipated threads and provided immediate recognition of areas of agreement or disagreement. The greatest value of the focus group is that it helped us know which sub-skills contribute to expert navigation by phase. This structure would help us organize future study.

5. Phase II: Focus Group Analysis

The description of Phase II highlights our analysis of the data gathered from the Focus Group Interview.

5.1 Domain Analysis

The focus group data corroborated what we, as SME's (Subject Matter Experts), already thought we knew about expert navigation. Although our personal navigation skills are not as current as the instructors', we know how to navigate as experts; later, we would learn otherwise.

One particularly strong contribution of the interviews was our ability to describe navigation skill by associating certain behavior with relatively expert or novice performance levels. Our description is provided in the Phase II Focus section.

Particularly noteworthy is that we added two elements to our skill characterization. Our previous efforts to isolate the skill for analysis artificially stripped the task from its context; both new elements served to reintegrate navigation into its natural context. First, we recognized that in most cases individuals do not navigate alone. While most infantry schools do train individually and test navigation proficiency of individuals, post-graduation navigation is universally performed by members of teams and not individually. Second, we were reminded that navigation performance is important only in the context of the tactical mission; in essence, navigation is a means to locate the unit at the mission objective. The ability to integrate mission and navigation is essential.

The results confirmed our position regarding the differences in navigation types. Sport strategies bear little resemblance to the complex strategies employed by the tactical navigator.

5.2 Knowledge Elicitation

Clearly, our participants are highly skilled navigators and expert evaluators. Perhaps we asked the wrong questions to the right group. Unintentionally, we were asking them to draw from their wealth of experience evaluating patrol leaders, to answer our questions concerning the evaluation of patrol navigators. During the patrol phase of the course, the instructor's mission is to evaluate students in leadership positions; their mission is not necessarily to evaluate navigators. In many cases, the patrol leader and the patrol navigator are not the same person. Navigation success leads to mission success, and the patrol leader is responsible for mission success. It follows that the patrol leader is responsible for navigation, but this responsibility is indirect. The instructors report that typically, the patrol leader delegates navigation responsibility to other members of the patrol; from the point of delegation forward, the leader monitors navigation but is routinely not actively involved in its execution.

Poor navigators are weeded out of the school in an earlier phase, and the majority of students evaluated in the patrol phase are competent. Many of the strong Ranger School student-navigators are associated with the Army Special Forces units, so we began to lay plans for connecting with the Special Forces community.

Studying navigators in the natural mission setting will be a challenge. In addition to the common difficulties cited in the literature [10], direct observation in this domain is particularly thorny for many reasons, as we will discuss in a later section. We began to reconsider other methods.

5.3 Knowledge Representation

At this point, we first tangled with two difficulties regarding the knowledge representation. First, we began to appreciate the importance of situation assessment skill to expertise. A large component of situation assessment involves highly-attuned perceptual sensitivity to the environment. The candidate architectures are not particularly well suited for modeling this type of situational assessment sensitivity [2]. Second, we found evidence that while a portion of the skill could be represented by rules, our attempts to use rule-based representations left significant gaps in adequate description of the skill. Since most of the architectures were based upon rule-based production systems, we began to question their suitability to our domain.

5.4 Knowledge Conveyance

For this community to adopt a computer-based trainer, especially extremely high-tech training intervention like VE's, a clear-cut demonstration of its value is imperative. So began our attempts to identify leverage points where we could target the technology to maximize overall training investments. We were confident that our growing understanding of both the technology and the domain would benefit our target selection.

We suspected that we could apply relatively low-end VE technology to train the critical skill of mentally switching perspective from egocentric to geocentric and geocentric from egocentric. When studying a map, the navigator views the terrain from a geocentric perspective; when looking at the real terrain, the navigator views from an egocentric perspective. The ability of interest concerns how navigators can study a map and visualize how the terrain will actually appear when the navigator will walk across it. A similar ability concerns how a navigator can look at the terrain as he walks and visualize how it would look represented by a contour map.

5.5 Phase Focus: Focus Group's Expert Characterization

As we discussed in a previous section, the focus group discussion covered the three stages of the mission – route planning, long-distance navigation from the starting point to a control point, short-distance navigation from the control point to the mission objective. The characterization that follows applies to the route planning stage only.

Route selection involves selecting a navigation technique and check points, to include identifying specific terrain features to aid navigation, selecting boundary features, and adjustments for suspected enemy locations. Novice navigators select straight-line routes and use azimuth and pace count to dead reckon their way from point to point. Routes are characteristically the shortest possible distance, regardless of terrain or the tactical situation. The novice tries to compartmentalize navigation as the first phase of his mission instead of something to be done throughout. Intermediate navigators incorporate terrain association, and their routes include check points on identifiable terrain features and boundary features to indicate errors. Typically, the intermediate navigator uses roads as boundaries, and man-made features as check points. Additionally, they neglect to factor suspected enemy locations into their routes, as they also try to navigate first, then conduct the mission after navigation is done.

Experts heavily rely on terrain association as their navigation technique. They use natural features as check points and boundaries, and structure their routes to avoid known or suspected enemy locations. The expert's route is typically longer than the novice's, but can be executed faster. The expert can deduce facts about the terrain that escape the competent, such as places the vegetation is likely to be thicker. By avoiding these places, his route again may be longer, but can be executed faster. Critically, the expert always limits his possible error by identifying natural boundary features along his route. His route thus becomes a corridor of movement, bounded by elevation changes which allow him to detect deviation from the route. He plans to use the compass and pace count as guides and checks within the corridor, but only in a rough sense, relying on his skill in terrain association to navigate precisely. Most importantly, the expert does not try to decouple navigation from his mission. He realizes that navigation is woven into every aspect of the mission and cannot be isolated, checked off a list of things to do, then forgotten.

6. Phase III: Preparation for Interviews

Phase III marks three major changes to our knowledge elicitation approach. First, we switched from the Ranger School to the Special Forces School. Second, we conducted individual, rather than group, interviews. Third, rather than discussing all three stages of the mission equally, we emphasized actions of the second stage, long-range navigation from the start point to the control point.

6.1 Domain Analysis

We still considered ourselves to be worthy navigators and suitable SME's. Integrating what we had recently learned, we now regarded navigation to be a collaborative secondary task, performed to support the primary task of tactical mission accomplishment.

Very little changed regarding our position about sport orienteering, and we regained a respect for the complexities of tactical navigation and a heightened sensitivity to the differences in navigational strategies. We expected that the next phase would shed more light on these strategy differences and the different skill-sets that enable the tactical navigation strategies.

6.2 Knowledge Elicitation

The Ranger Instructors identified the Special Warfare Instruction Center at Camp Mackall, NC as a good source of experts. The average Special Forces Qualification Course student is more experienced in both small unit operations and land navigation than his counterpart at the Ranger Course. Those candidates with insufficient small unit experience or leadership ability are not admitted.

This time, our goal was to investigate expert navigators. We attempted to convey to the school liaison that we wanted to interview the navigators themselves. As we did with the Rangers, we would rely on the school's instructors' cooperation and support, but our goal was not to interview the instructors. Rather, we wanted the instructors to screen the students and select their very best navigators. We specified that we did not want to speak with patrol leaders; we asked for the person whose primary responsibility was navigation.

We thought of ourselves as being respectful SME's; but we knew we were visitors. As much as we wanted to walk with the patrols and directly observe them, we could not prove that the benefits outweighed the costs. Plus, our study of the NDM literature pointed us to the Critical Decision Method (CDM) [11]. For the reasons outlined in the Phase III Focus section, we once again favored interviews over observation. These interviews would mark our first opportunity to both use the CDM and test how well it fits our needs.

6.3 Knowledge Representation

Aware of the potential limitations of existing cognitive architectures regarding perceptual sensitivity and reliance on rule-based structures, we prepared ourselves to sensitize to these issues during our visit. How important is perceptual sensitivity? To what extent do experts rely on rules for decision making?

6.4 Knowledge Conveyance

We still felt that we could make significant training gains by precisely targeting specific sub-skills for virtual interventions. One promising sub-skill candidate was the visualization ability to switch between egocentric and geocentric perspectives.

6.5 Phase Focus: the CDM as the elicitation method

Initially, we thought we would directly observe the navigators while patrolling. As we learned more about the task and the culture, we decided to find another approach. In the natural patrol setting, especially in a school, we judged that observation would be too obtrusive and organizationally disruptive. The CDM is one knowledge elicitation method that was developed from the NDM framework. We chose it because we wanted to maximize the quality of information elicited from each interview. While the CDM provides enough flexibility for its adaptation to specific needs of the researcher, it also provides the structure necessary for getting the most out of each interview

At the heart of this method is the Critical Decision itself [11]. The interview is structured to first identify an appropriately critical decision and then probe deeply into the cognitive operations that resulted in the decision. As described by Hoffman, Crandall, & Shadbolt [12] , the procedure is structured as follows. During interview preparation; the elicitor learns about the domain and gains access to the participants. Once the specific interview begins, the first step is to select the incident; the elicitor works with the participant to identify a situation in which the expert's skills were challenged and it stands out in the decision-maker's mind as being critical. Once identified, the elicitor guides the participant through progressively deeper and more detailed retellings of the incident. Typically, the interview is tape or video recorded.

7. Conduct and Critique of the Individual Interviews

An instructor accompanied each student-led patrol. Immediately after the patrol finished its mission, the instructor would evaluate the leaders and critique the overall conduct. Depending upon the instructor's preference, we planned to interview the patrol navigator either during the instructor's critique or immediately following its conclusion.

7.1 Planned Protocol

Our two-member team planned to begin the interview within an hour of its end and conduct it in 75 minutes according to the following protocol:

1. Meet with instructor to identify key difficulties, key decision points. 2. Elicitor orients participant to the patrol just completed as the patrol of interest. 3. The participant recounts the entire patrol. 4. Elicitor retells the story back to the PL. This allows both PL and interviewer to arrive at a common understanding of the sequence. 5. Elicitor and participant build a time line of the sequence of events. The timeline will include decision points, inputs to each decision point and actions taken as a result of each decision. 6. Elicitor asks probe questions to deepen his understanding of the navigation.

7.2 Critique of the actual protocol

Ideally, we would like to have met with the instructor immediately before we conduct the actual student interview; we hoped that the instructor's comments would help us focus the interview on the key decision areas of that particular patrol episode. In practice, this was not practical and we were unable to meet with the instructors. The window between the end of the patrol and the beginning of our interviews was quite narrow and the instructors were busy enough preparing themselves for their own critiques.

We intended to generate two artifacts during each interview. The first was the participant's sketch of the patrol; the second was a timeline, with key decision points indicated on it. After attempts to produce both artifacts, we dropped the timeline and focused effort on the patrol sketch. It seems that the sketch afforded a focal object for the discussion, while the timeline served to scatter the discussion too much.

After reviewing the results of the interviews, we recognized that the probes did not go deeply enough into the participants' expertise. Details of most of the important cues were helpful but not adequate to fully describe the critical components of expertise. In the future we may be able to probe more deeply, but this will require lengthier interview sessions and more effective probing methods.

8. Phase IV: CDM Analysis

During Phase IV, we analyzed the data gathered from the interviews and prepared to build the executable model.

8.1 Domain Analysis

The interviews humbled our team. In the presence of true expert navigators, we had to admit that we were not SME's. Perhaps we are competent, but clearly the soldiers were interviewed here were head-and-shoulders above our best performances. It was a honor and pleasure to interview these experts, and we learned a tremendous amount from them. Our updated expert characterization is discussed in the Phase IV Focus section.

We also qualified our position regarding our previous assertions that characterized the navigation context. Perhaps from the patrol leader's perspective, navigation is both collaborative and secondary to mission accomplishment, but at some point the leader delegates the navigation duties to the navigator. The patrol's navigation success rests solely on that soldier's ability. Although during planning and movement he will consider the specifics of the mission situation, navigational concerns are the navigator's primary responsibilities. Furthermore, while the patrol as an organization does collaborate and divide navigation duties across its members, the navigator routinely does not collaborate. He plans the route, walks it and the patrol follows him.

Regarding sport and tactical strategies, the interviews both confirmed the differences and emphasized the similarities. Regardless of whether the task is for sport or military mission, expert navigators can quickly and accurately build a mental map from map study; they can also quickly and accurately reconcile their egocentric perspective to a geocentric representation.

8.2 Knowledge Elicitation

We found an excellent pool of participants. Our ability to clearly express the qualities of the experts we wanted to interview and convey this description to the squad instructors was our most significant challenge. The school chain of command was extremely supportive and we feel that the instructors made every effort to sent us what we asked for – expert navigators.

As effective as the CDM was, we failed to tap into the details of expertise as deeply as we had hoped. Our experience taught us that an ideal approach would probably combine the CDM with direct observation.

8.3 Knowledge Representation

We can describe the process that experts use through rules, but such description does not penetrate deeply enough. It is unlikely that rule-based representations can adequately describe real expertise. We can draw the boxes but we cannot use rules to describe what happens inside the boxes. Similarly, we found evidence that expert navigators are able to quickly assess the situation. Hence, the representation must include a strong situation awareness component.

8.4 Knowledge Conveyance

The interviews confirmed out opinion that we could use VE's to train visualization skill. We also learned one critical distinction between trainers and mission rehearsal systems. Spatial awareness and navigation on the mission objective is qualitatively distinct from that spatial awareness and navigation in movement. They are quite different and expertise in one may or may not transfer to the other.

8.5 Phase Focus: CDM Expert Characterization

During the interviews, we bounded the participants' account to the enroute navigation phase of the mission. Thus, we did not directly probe the details of their route planning activity. Nonetheless, their responses referenced many of their route planning activities. The resulting characterization of expert navigators emphasizes several common attributes: experts develop extremely detailed "mental maps" of mission areas; experts rely on a blending of several cues instead of just one; they can adjust the tools they use quickly during execution; and experts are highly adept at visualizing three dimensional terrain from a two dimensional map.

Particularly relevant to our present focus is the reemergence of the ability to study a map and then visualize how the terrain would look. During route planning, navigators do not have the opportunity to physically traverse the land or the routes under consideration. In most cases, the only tool available is the two-dimensional map. Of the features depicted on the map, experts most often referenced attending to contour lines, vegetation and bodies of water. Combining their study of the combinations of these features with their general and location-specific navigation experience, they are able to assess the quality of potential routes. This assessment takes place in the context of the navigator's knowledge of the patrol leader's tactical intent of the mission.

9. From Paper to Executable Model

Ideally, our virtual navigators would perform each of the tasks that their real counterparts perform, across all three stages of the mission, from planning through arrival at the objective. For a computer construct, however, the distinction between planning and execution is meaningless. An icon or avatar simply moves through the environment, and the important distinction is in the output. A planning model would output a route that an expert would plan, while an execution model would output a route that an expert might actually execute, with appropriate random errors. We decided that we wanted a virtual route that would closely match the planned route of a human expert. Thus, our model is focused on route planning. Consideration of three other factors reinforced this focus: route selection requires visualization skill very similar to enroute navigation visualization skill; a computer can acquire spatial knowledge from a map more easily than it can from direct exploration; route planning is less dynamic than en route navigation.

The results of both interview sessions converge on the criticality of the navigator's visualization skill. This ability to transform perspectives to 3D from 2D and vice versa is dominant in two cases: the visualization of considered routes from map study alone; the transformation of the egocentric environmental scene to 2D map representation. So, both cases are measures of navigation expertise. The first is instrumental to the task of route selection. The second is instrumental to en route navigation.

Since our goal was an executable model, the computer would have to acquire the pertinent information from the simulation. We judged that attempts to model computer visual perception of a 3D space would be very difficult. So, we chose to build a 3D model but provide the elevation and terrain data through direct database queries rather than visual search. From the database, elevation, vegetation and water features could be directly calculated, hence relieving the need to model visual perception. This abstraction more closely matches how humans plan the route than how humans execute it.

Finally, since the database queries have been abstracted, it is easier to control the simulation. In the real task, route planning is much more controlled than the route execution. This allowed us to simplify the modeling requirement by selecting a task that is naturally less dynamic.

10. Route Planning Model

With an understanding of how experts plan routes, we were ready to begin constructing the expert route planner. Rule based artificial intelligence approaches, such as A* search algorithms, are unsuitable for this domain. They require a clear definition of the problem and a specialized database to represent the terrain. Our goal is to create a portable tool useful on any terrain model that supplies basic elevation and terrain data. With this in mind, we chose to program the model using adaptive agents in Java and Java3D. This allows it to execute on any platform that can run the Java Virtual Machine, and operate using any terrain database that is properly organized (and loadable into a Java3D scene graph). For this project, we used a terrain database constructed with MultiGen Creator™ in the OpenFlight™ format.

The adaptive agent technique assigns multiple agents the task of planning a route between two points. Each agent uses a set of very simple rules, taking selected inputs from its environment, to plan a route. A "mover manager" then scores each agent's performance, and implements a genetic algorithm to discard poor agents and combine the rule sets of successful ones into new agents.

The adaptive agent approach gives us three important advantages over more traditional techniques. First, it allows us to explore several different types of environments, on different terrain databases, without changing the parameters input. As long as the terrain database is loadable into a Java3D scene graph, and is organized by types of terrain (e.g. thick woods, water, roads, open areas), this model can plan routes on it. In a classic A* search, the database would need to be divided into nodes, and agent movement would be limited to these nodes. Our approach requires no such organization; the agents can move freely throughout the database.

Second, the genetic algorithm automatically adjusts the agent's rule set to fit the environment [13]. It does what, we have found, human experts actually do: adjusts its navigation technique to fit different environments and conditions. A traditional method would require the programmer to rewrite different rule sets for each new environment.

Third, it allows the user to adjust the agent's goals through the scoring system. If the user wants faster movement and is less concerned with security, he can change the scoring system through a dialog box and reward different types of performance.

11. Agent Structure

11.1 Decision Vector

Agents in the model are based on the ISAAC agents first developed by Andrew Ilachinsky [14]. Agents contain a decision vector consisting of six elements which assign weights to the agent's propensity to take certain actions. Decision vector values are in effect the relative importance the agent places on its different, and often competing, goals. These goals include minimizing time of movement, minimizing distance traveled, minimizing total cumulative change in elevation, maximizing cover and concealment, avoiding enemy contact, and minimizing linear danger area (road and stream) crossings. The decision vector elements are:

ω_1: move to goal (shortest distance)
ω_2: move to least elevation change
ω_3: move to avoid enemy
ω_4: move along the fastest route
ω_5: move to cover/concealment
ω_6: move to avoid road/stream crossing

11.2 Perception Vector and Penalty Function

Agents move, in five meter increments known as steps, in one of eight directions based on the calculations of a penalty function for each possible movement. Penalty function values can be expressed as the scalar product of the decision vector stored inside the agent and a perception vector which changes based on the agent's location in the environment. It is calculated for each pairing of current and proposed locations. The perception vector is:

α_1: dist to $\text{goal}_{\text{proposed}}$/ dist to $\text{goal}_{\text{current}}$
α_2: | $\text{elevation}_{\text{proposed}}$ - $\text{elevation}_{\text{current}}$ |
α_3: 0 if not in enemy sensor range, else dist to $\text{enemy}_{\text{proposed}}$/ dist to $\text{enemy}_{\text{current}}$
α_4: time to move from current to proposed
α_5: $\text{cover}_{\text{proposed}}$ - $\text{cover}_{\text{current}}$
α_6: 0 if proposed location is not an LDA, penalty value if it is

The agent calculates the penalty function for each of the eight possible locations to which it can move, then moves in the direction with the lowest penalty function value.

11.3 Scoring and Genetic Algorithm

Agents begin with randomly selected decision vectors. For the genetic algorithm to operate, the agents must have some variation in their decision vectors, and be evaluated on their performance during a "warm-up" phase [13]. During this phase, the mover manager randomly selects route start and end points. All agents use the same start and end points, but different decision vectors will cause them to select different routes [15] After they complete the route, the mover manager assigns each agent a score based on how well the agent satisfied each of the six goals.

The relative weights of the six goals (minimizing time of movement, minimizing distance traveled, minimizing total cumulative change in elevation, maximizing cover and concealment, avoiding enemy contact, and minimizing linear danger area crossings) are defined by the user. They reflect the relative importance the user places on each aspect of route planning, and can be modified based on mission requirements.

After the agents complete, and are evaluated on, five routes, the mover manager uses the genetic algorithm to discard the decision vectors of the worst performers, then replace them with new vectors based on combinations of the decision vectors of the best performers. Additionally, a random draw determines whether or not a mutation occurs, which assigns a randomly selected value to one element of the new decision vector. For our model, we used a mutation rate of 1%. The new agents (and the survivors from the last iteration) then complete five more randomly generated routes, and the mover manager applies the genetic algorithm again. The warm-up phase continues for a minimum of 100 routes.

When an agent occupies the top performance position in the cumulative standings for ten consecutive routes, it has approximated expert performance. Once an agent achieves expertise, the system prompts the user to enter desired start and end points, and the agent will return the expert route between the two.

12. Future Work

We will extend this work in four ways: build a prototype training system; develop elicitation methods for more detailed probing; continue to build working relationships with the infantry community; continue to develop the agent model.

Through these studies, we have identified the navigator's visualization ability as one possible area for applying VE technology. We will build a prototype of such a trainer and test its training effect.

Although the CDM proved to be a valuable elicitation tool, our probes did not elicit the level of detail required to fully describe navigation expertise. We will refine our CDM approach so in an effort to tap this detailed knowledge.

The level of cooperation demonstrated by the dismounted infantry community is tremendous. It is critical that we build and maintain strong relationships with them. Any data analyzed and presented to improve navigation training will be most valuable to them; therefore, we must work closely to direct our efforts so that generated data serves their needs.

This iteration of the model will be complete when it is tested against the routes planned by human experts. We will have five human experts plan a total of fifty routes in the framework of a tactical scenario. The model will then plan the same fifty routes on a database of the same terrain. Statistical analysis will show how closely the computer generated routes match actual human expertise.

Future work on the agent model will center on improving the agent rule sets to minimize the warm-up period (if desired) and to extend the model beyond route planning to model actual enroute navigation. Then, we will focus on building an interface to training and mission rehearsal tools to allow the expert navigator to offer advice to human users. Improving the genetic algorithm to allow the agents to dynamically generate their own rules, improving the terrain databases to look like the actual three dimensional terrain, and adding a human avatar to the simulation are longer-term project goals.

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