A Fuzzy Logic Approach for Intelligence Analysis of Actual and Simulated Military Reconnaissance Missions

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Abstract— **Over the past decade the role and focus of the Army has changed drastically. The days of the Cold War are gone and with the recent cutbacks in the military budget, efforts must be refocused on building the Army of the future. Today's leaders believe the future of the Army is in information and digital technologies. Many challenges face the Army as they venture into the information technology world. Full exploitation of information and digital technologies will present major challenges for developers of these systems. Fortunately, technologies have arisen in the computer science field that will contribute to solutions to many of the problems these developers will face. One specific technology, fuzzy logic, which has been applied only to a very limited degree in military systems, holds great promise. The information used in the planning and conduct of military operations has very high levels of uncertainly and ambiguity. Fuzzy logic technologies provide an effective means to address, and even exploit, this uncertainty and ambiguity. This paper shows the applicability of fuzzy logic technologies to a specific military application by automating a specific intelligence analysis task. The task involves evaluating the suitability of various locations for the conduct of a reconnaissance mission. The positive results produced through this effort underscore the overall desirability of applying fuzzy logic technology to problems in the military domain.**

Keywords— **Fuzzy Logic, Simulation and Modeling**

I. Introduction

With modern advances in the computing industry, the Army has committed to fielding an automated force by the turn of the century. General Gordon Sullivan, former Army Chief of Staff, stated his views of the future Army as: *"[In the] Army of the 21st century, rapid technological developments in information management and process are ushering in what many believe to be the beginning of a post-industrial age; the Information Age. The microprocessor is revolutionizing the way that we live our lives as individuals, the way that society functions, and the way that we are likely to fight our future wars ... . These powerful developments are leading society toward an uncertain but interesting future; a future which it is just beginning to explore [1]."* In accordance with this vision, the Army of the 21^{st} century will be organized into combat units which are driven by information and information technologies. These networked units will possess the capability to rapidly and effectively react to the volatility associated with the modern battlefield. The Army's tactical operations center (TOC) will evolve into an information warehouse consisting of numerous command and control (C^2) systems which will provide decision-makers with access to a high-fidelity conceptual view of the battlefield.

These new systems will undoubtedly create new challenges for future commanders and their staffs. Specifically, systems which merely increase the amount of data the staffs must *process* are likely to have deleterious effects on their performance. With the expected increased information flow, the challenge becomes the staffs' ability to decipher the information that is critical, and to effectively apply this information in the decision process. Unfortunately, unless future systems can help analyze and synthesize this data, the tendency will be for staffs to become overwhelmed with small details, thus losing sight of the "big picture."

To meet the requirements of the Army of the 21^{st} century, future C^2 systems must go beyond the capabilities of today's information systems. These systems must incorporate artificial intelligence (AI)-based decision support tools so that they become a part of the staff, rather than just a tool used by the staff. This will enable commanders and their staffs to generate, modify, and analyze complete, consistent, and robust plans in real-world, resource-constrained environments.

This paper describes a technology – fuzzy logic – that could have a significant impact on the Army's many automation initiatives. Fuzzy logic was introduced over 20 years ago as an approach to generalize classical two-value logic for reasoning under uncertainty [2]. The environment in which military operations are planned and executed is fraught with uncertainty and imprecision. Noted military theorist Carl von Clauswitz once stated that "many intelligence reports in war are contradictory; even more are false, and most are uncertain [3]." Even though these words were written over 160 years ago, they still ring true today. Based on the statements above, technolo-

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0-7803-4053-1/97/$10.00

gies that handle uncertainty and imprecision should play an important role in the development of future C^2 systems. Fortunately, systems which are based on fuzzy logic technologies are inherently able to tolerate uncertainty [4]. Specifically, the uncertain and imprecise knowledge that military planners use can be effectively represented using fuzzy linguistic variables. These variables use *linguistic labels* which are readily understood by the domain experts and are useful for communicating concepts and knowledge with human beings [5]. Additionally, they have a well-defined quantitative component that allows for interoperability among other non-fuzzy Army systems. Representing knowledge in this manner simplifies the knowledge acquisition process, thereby providing a more consistent result among multiple users. Conventional rule-based or statistical approaches are other possible solutions to this problem. However, a fuzzy logic approach provides an alternative technology that alleviates many of the difficulties conventional approaches have in handling uncertainty, imprecision, and ambiguity. Secondly, by using fuzzy logic techniques the system can readily represent and reason with both explicit information *and* the various types of uncertainty that are implicit in much of this knowledge. Finally, fuzzy logic methodologies provide a "communication bridge" between domain experts and the system through fuzzy linguistic variables.

II. Background

The research described in this paper extends work that was initially performed by members of the faculty at the United States Military Academy. Their approach used fuzzy logic to model visibility factors which were then used to categorize the suitability of potential areas for observer locations in a military reconnaissance mission.

In their system, the analysis is performed over a region surrounding the target which is bounded by an annulus. The analysis involves evaluating a partitioning of the annulus which is based upon the underlying elevation data [6]. The system applies a set of fuzzy rules to assign each area to one of five fuzzy sets (unacceptable, poor, neutral, good, excellent). These sets describe the suitability of each partition. The limitation of this approach is that it is based on the minimal amount of input used in the model. No consideration is given to the impact of vegetation, weather, or additional operational knowledge that should affect the results. This research extend their approach by using fuzzy logic to combining additional spatial information and operational knowledge in the reasoning process which determines the suitability of each region. This extension should improve the overall quality of the categorization process when evaluating potential areas for observer locations.

The resulting system will provide an assessment of possible locations for use as observer positions. Fuzzy logic is a viable means to perform reasoning using a combination of spatial information (vegetation, roads, etc.) and operational knowledge in locating potential observer positions. Since much of this operational knowledge is subjective, a fuzzy approach is a very natural mechanism for representation and reasoning.

III. Concept

The reconnaissance mission is one of the most challenging missions that a small unit is required to perform. Many of the intelligence analyses performed in support of this type of mission are accomplished under a great deal of uncertainty. Additionally, the manner in which the various underlying aspects of the intelligence analysis problem interact is very complex. Also contributing to the difficulty of planning a reconnaissance mission is the great risk to the well-being of the personnel who make up the recon team. The risk involved is attributable to the fact that in order to successfully accomplish a reconnaissance mission, a team must normally occupy a position that is in close proximity to an enemy force. The reconnaissance planner therefore has two conflicting goals to consider when he selects positions for a reconnaissance mission. On one hand, he must select potential positions which are close enough for the team to gather all required information. On the other hand, he must select a position which does not expose the recon team to undue risk.

These opposing goals can be seen clearly in the doctrinal fundamentals of reconnaissance missions as articulated in the in the Army Training Manual, ST 21-75-3, Dismounted Patrolling [7]. The first two fundamentals are:

- Gain all required information.
- Avoid detection.

This trade-off between potential for information-gain versus risk is the most important consideration that the operational planner must take into account when selecting potential positions from which to conduct a recon. If the planner can successfully balance these two competing goals, there is a far greater likelihood that a particular mission will be successful. The importance of this trade-off had a significant effect on the overall design of this application.

IV. Design considerations

After an extensive review of the military literature concerning the intelligence analysis process, commonly referred to as Intelligence Preparation of the Battlefield (IPB), the recon process was subdivided into three main modules. The first two modules model risk and information gain associated with the recon locations. Each location is assigned a rating describing the risk and information gain potential of that location. The final module evaluates these ratings in combination with the commander's willingness

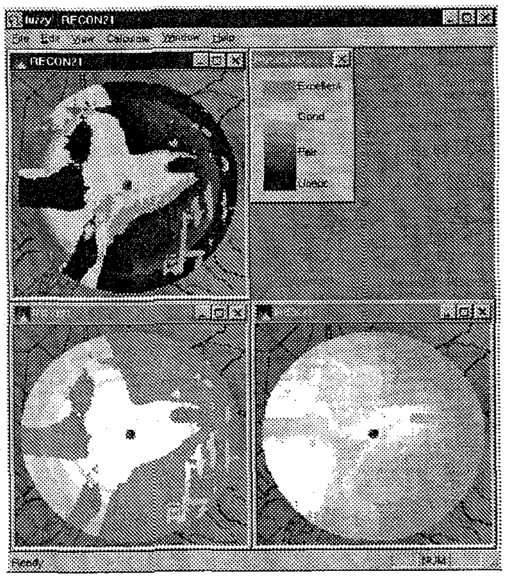

Fig. 1. Graphical output of reconnaissance analysis

to accept risk. Using this paradigm, the system design is based on this decomposition. Furthermore, the analyst bounds the search space by defining a minimum and maximum radial distance allowed for potential locations, which results in a doughnut-shaped area (annulus).

After the user inputs all the necessary information, the analysis process is initiated. Using the default distance constraints (100-1500 meters) the computational time on a Pentium platform is approximately 10 minutes. After the analysis is complete, the results can be overlaid on any of the base maps supported by the system. The color assignments are based loosely on the standard military color scheme of black, red, amber, and green where green locations are the most favorable and the black areas are the least favorable. An example output is illustrated in figure 1. This figure contains the results of the three modules. The top image is the overall assessment and the bottom two are the results from the information gain and risk modules, respectively. The information gain image uses dark shades of gray in areas that are not conducive to acquiring the needed information. The risk module uses lighter shades of gray to indicate areas of high risk.

V. Architecture

This section provides a technical description of the modules which were implemented in the development of this system.

Fuzzy assessment modules

During the decomposition process it was determined that the fuzziness of this problem can be represented by comparing risk against the possibility of acquiring information. Dividing the problem along these lines allowed for the development of three modules. The first two modules model the risk and information gain while the third module evaluates the resulting assessments against the objectives of the mission.

Risk assessment module

During the planning process, commanders consider risk as a key attribute in the creation of a course of action. Risk is a measurement that describes the likelihood of loss-of-life occurring during the execution of a mission. The level of acceptable risk is dictated in the overall mission statement. Risk assessment is accomplished in the system by analyzing each location (represented by a single pixel) and assigning a rating characterizing the risk at a given location. A combination of factors including known enemy positions, their detection capabilities, and the geographical characteristics (surface contour, vegetation, etc.) of the area all play a role in the evaluation of risk. Risk is modeled considering the threat associated with a position and how visible a position is relative to the enemy. Positions that are unobservable by known enemy locations are assumed to be less risky. The objective of this module is to assign low ratings to locations that are far from known enemy locations and which allow minimal observation by the enemy. Areas that are close to known enemy positions or that are considered highly visible are assigned high ratings. Environmental factors such as fog or precipitation, canopy cover provided by vegetated areas, terrain obscuration, and darkness all synergistically lower the risk of a specific location. Conversely, enemy positions with higher security and more elaborate detection devices will increase the overall risk. The result of the risk analysis is the rating of each pixel in a continuum of 0-1 based on all factors influencing risk. The lower bound implies minimum risk and the upper bound implies maximum risk.

Information gain module

A commander must consider the potential of acquiring required information from surrounding locations when he selects positions from which to conduct a reconnaissance mission. Information gain is a measure of the degree to which a specific location supports the acquisition of critical information in a reconnaissance mission. The degree to which a specific location supports information gathering is a complex function which takes into account many factors. These factors include distance to the target, terrain *masking* (concealment due to terrain features), weather and astronomical data, vegetation, target illumination, and friendly observation capability. The assessment of the information gain potential of a given position is determined through the process of analyzing each location (represented by a single pixel) and assigning a rating which characterizes the degree to which required information can be acquired from that location. This module will assign a high rating to locations that support the recon team's ability to acquire information on a specific target area. Low ratings are assigned to areas that do not readily support the team's ability to gain information.

The system models information gain by taking into account the visibility of the target and the observation potential from each specific location.

The visibility of the target is determined by considering the weather, the terrain and vegetation masks, the target and the ambient illumination, and the obscuring effects of the weather. The observation potential of a given location is a function of the distance to the target and the equipment that the recon team will employ to enhance their ability to observe the target. The weather obscuration is determined by the amount of fog and/or precipitation that is expected at the time of the mission. The results of the information gain analysis are ratings for each pixel in a continuum from 0 to 1. The upper bound implies maximum information gain, while the lower bound implies minimum information gain. The process of combining the inferences associated with each graph produces an assessment of the degree of information gain from each location.

Mission Assessment Module

In order to perform a complete analysis of the suitability of each of the locations that surround a particular reconnaissance target, a commander must take into account the competing goals of minimizing risk while maximizing the potential for information gain. His assessment of how to reconcile these two goals is largely dependent on the amount of risk that he is willing to accept. Consequently, the overall assessment of each of the locations is a function of the risk assessment, the information assessment, and the commander's risk acceptance threshold. For example, if the information that will be acquired during the mission is highly critical, then the commander would be more likely to accept a higher degree of risk. However, if there might be serious negative ramifications associated with a compromised mission, then he would be less likely to accept a high level of risk.

The overall results of the mission assessment are ratings for each pixel in a continuum from 0 to 1. The upper bound implies maximum suitability for a given location. The lower bound implies insuitability for a given location. The inference surface which characterizes the inferencing process for this assessment is shown in figure 2. Note that the surface has an intuitive appeal in that the most suitable locations provide the greatest potential for gaining information, while the least suitable locations have great risk and little likelihood of gaining information.

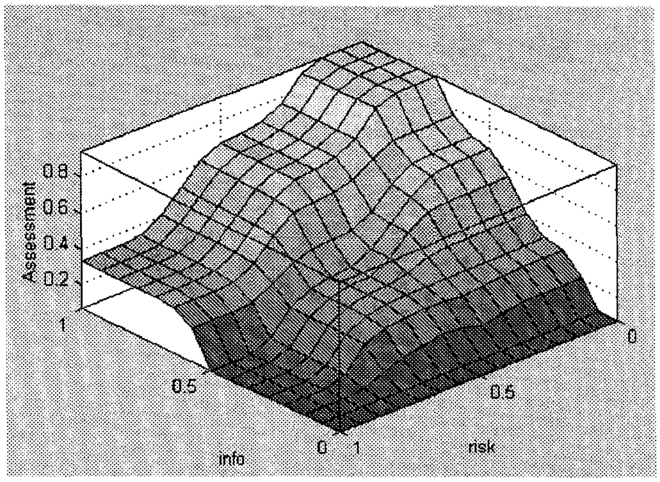

Fig. 2. Inference surface for mission assessment

Inference Process

The previous section subdivides the problem into three modules: risk, information gain, and mission assessment. This section describes the process that was used to model these modules using a fuzzy logic framework. It was discussed earlier how fuzzy linguistic variables bridge the gap between the qualitative information that captures domain knowledge and the quantitative information that the system requires to perform the inferencing process. The linguistic variables are used in conjunction with fuzzy *if-then rules* to represent domain knowledge and provide the means to perform fuzzy reasoning.

The user interface was constructed to allow the user to characterize the scenario through linguistic variables. Each fuzzy input is represented utilizing a standard slider bar. Each slider bar is labeled by using the linguistic terms as references that are placed along the top of the bar. This allows the user to position the slider relative to the set of possible terms allowed for the variable. For example, an input characterizing the condition of a unit would use the standard black, red, amber, green convention. A non-fuzzy approach would require the user to select only one of the four. If a unit condition borders on red and amber, then one user may characterize it as red where the other describes it as amber. Such a conflict could make a substantial difference in the resulting analysis. However using a fuzzy approach, a slider bar can represent a continuum and the terms black, red, amber, and green are placed along the top of the bar as a reference. Now the user can position the slider bar between red and amber to represent the uncertainty in their judgment of unit's status. This approach allows for a smoother transition among differing states of the input, thereby decreasing the sensitivity of the results based on subjective information.

Once the linguistic terms are identified, the next

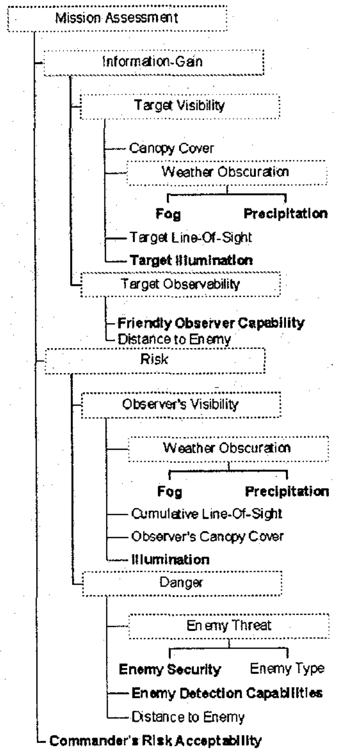

Fig. 3. Inference Hierarchy

step is to determine the inference mechanism used in the prediction process. The approach taken in this research involved the modeling of a problem through creation of a series of fuzzy rule-based models. Each of these fuzzy models map system inputs (or intermediate conclusions) to outputs. The fuzzy inference engine employs *fuzzy if-then* rules to perform this mapping. The combination of fuzzy rules generates an inference surface like the one illustrated in figure 2. The theoretical foundation of this type of fuzzy model is Zadeh's *fuzzy graph* [4]. The Mamdani Model [8] was selected instead of the two other popular fuzzy graph-based models: TSK [9] and SAM [10]. Mamdami was chosen because it supports fuzzy variables in both the premises and conclusion of the fuzzy rules.

The strategy used in the development of this system was to subdivide each module discussed above into sets of various components where each component would consist of a fuzzy graph. Once the components are built, they are assembled into a hierarchical structure based upon required inputs. A component whose inputs are not dependent on the output of any other component is placed in terminal or leaf position of the tree. A component becomes *executable* once all of its dependent components are completed. The component representing the root of the hierarchical structure produces the final result that rates the overall quality of a location on an interval of 0 to 1.

The process of subdividing the modules was performed by first identifying the necessary intermediate linguistic variables. Then the input variables necessary to infer these intermediate values were identified. This process produced inference chains which are represented in the hierarchical structure shown in figure 3. Each box in the figure represents a fuzzy graph and fuzzy inputs are represented in bold type. During the the subdivision process, the number of input variables to each component was minimized in order to reduce the number of required rules. After the subdivision process, the information gain module was represented using four components, the risk module uses five components, and the mission assessment module is represented using a single component. To represent these 10 components, a total of 731 rules were encoded.

VI. Data

The majority of data used in this system were digitized representations of geographical features. Since the objective was to categorize potential reconnaissance positions based on a combination of situational and geographical information, an accurate representation of the terrain was vital to the process. A study of the types of feature information required for this analysis indicated that elevation and vegetation data would suffice. The elevation data contained a series of elevation postings describing the height of the terrain in meters above sea level. This feature information is primarily used by the line-of-sight module to determine visibility. The elevation feature is supplemented by the vegetation feature which provides information describing height and type of vegetation at each location. The height of the vegetation is added to the elevation value at each location to determine the its relative height. The vegetation type attribute allows the system to vary the concealment potential of the vegetation based on seasonal changes.

The digital feature data, acquired from an Army source, covered an area in the state of New Mexico. The size of the area covered was approximately 25 kilometers^2 with an estimated resolution of 30 meters (between elevation *postings*). Both features are represented in a raster format (Arc Info's Arc/Grid), where each pixel covers a 30 meters square area in both the x and y directions.

VII. Results and Conclusions

Although no formal verification procedure was implemented for this prototype system, an effort was made to insure that the results were both intuitive and adhered to Army doctrine related to the conduct of reconnaissance missions. To perform an informal validation of the system a number of trials were performed in which the reconnaissance target location and other system inputs were varied. The results of these numerous trials were then evaluated by the authors, one of whom is a US Army Infantry officer with sixteen years of service who served as the domain expert throughout this research.

The initial results produced by this prototype system look very promising. In all trial cases the results were intuitively satisfying, and did not appear to violate the doctrinal principles for the reconnaissance mission. For example, all *tree-line* areas in the vicinity of the target were assessed to be very suitable recon locations. This adheres to conventional wisdom for conducting a reconnaissance in that these locations provide maximum observation of the target (i.e, high information gain) while minimizing the chances of being detected by the enemy (i.e, low risk). In addition, all densely vegetated areas, regardless of their proximity to the target were assessed to be unsuitable. This result is intuitive since dense vegetation normally minimizes the area that can be observed from a given location (i.e., low information gain) and as a result, these locations are generally unsuitable for recon locations.

The initial results produced by this prototype reveal that applications of fuzzy logic technologies in the military domain have the potential to increase the overall quality of automated systems. For this reason, fuzzy logic technologies should be considered for integration into existing and future military C^2 systems.

This system performs an intelligence analysis in support of a reconnaissance mission, and the results of the analysis are graphically represented. However, the resulting knowledge gained through this analysis can be readily shared among existing C^2 and simulation systems which require reconnaissance information.

The transition of the Army into the information age will require fielding systems beyond the capabilities of traditional information management systems. Just having access to vast amounts of information will result in a small payoff. Military users need software systems that will assist in distancing them from the details, thus allowing them to capture the higher-level knowledge they need in the decision process. The technology used in developing these systems must be compatible with the environment in which it is designed to operate. Many obstacles face developers in this environment, especially in dealing with the uncertainties that must be considered during planning operations. Design considerations must center on the cost/benefit ratio of such systems. More complex models typically require a finer description of the state space for prediction. In the context of military applications, time is truly an asset that must be used wisely. Performing an in-depth analysis of a situation requires an abundant amount of information and substantial processing time.

VIII. Future Work

There are a number of areas in which this system could be extended and improved. First, a more rigorous and structured verification and validation procedure should be implemented. Specifically, the validation should involve multiple domain experts and, if possible, the actual terrain on which the target locations are placed should be evaluated to determine the utility of the assessments produced by the system. Secondly, the system could be extended by incorporating additional terrain feature data (i.e, built-up areas, transportation, and mobility potential) in the assessment of the terrain surrounding a given reconnaissance location. Taking into account additional factors is certain to improve the quality of the results produced by this system.

The system could also be extended to perform additional intelligence analyses and planning tasks. For example, the risk assessment module could be used in conjunction with additional user inputs to provide an assessment of the suitability of projected movement routes. Integration of additional capabilities will increase the system's utility, and make it a potentially valuable component of future military planning and C^2 systems in both simulated and actual environments.

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