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The Imagery Exploitation System/Balanced Technology Initiative (IES/BTI) is a first phase near-real time image exploitation system to support Army Corp intelligence and electronic warfare (IEW) situation development, target development and target and target acquisition. IES/BTI exploits synthetic aperture radar (SAR) and infrared (IR) imagery and annotates the presence and type (artillery, armor, etc) of military units (company size and above).

IES/BTI employs a coarse-to-fine hierarchical reasoning paradigm, using Bayesian inference for hypotheses management and belief propagation to solve the complex force/terrain/military situation image understanding problem. Military forces are modeled at multiple levels of abstraction representing force hierarchy, situation and formation. Evidence gathering actions evaluate the closeness of data supporting the hypotheses to the force models using statistical metrics and/or expert system rules. Some rules are complex dynamically adapting a static force model to the local terrain and threat situation. A uniform certainty calculus defines how evidence from the model match is applied to the hypotheses.

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ESCH

Imagery Exploitation System/Balanced Technology Initiative (U)

ABSTRACT

The Imagery Exploitation System/Balanced Technology Initiative (IES/BTI) is an automated first phase near-real-time image exploitation system to support Army Corps intelligence and electronic warfare situation development, target development and target acquisition. IES/BTI exploits synthetic aperture radar (SAR) and infrared (IR) imagery and annotates the presence and type of military units (company size and above).

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IES/BTI has processed data from two military theaters and IES/BTI has learned lessons concerning which methods have worked well and which ideas haven't met expectations. These lessons learned are presented.

BIOGRAPHY

Frederick H. Esch is a senior engineer working on IES/BTI and has worked on AI applications since coming to TEC in 1987. He has previously worked as a geodesist and co-authored MIL-HDBK-600008, *Datums, Projections, Grids and Common Coordinate Systems, Transformation of*. Mr. Esch holds an M.S. in Geodetic Science from the Ohio State University and a B.S. in Geology from the University of Utah.

Imagery Exploitation System/Balanced Technology Initiative (U)

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1. INTRODUCTION

The Imagery Exploitation System/Balanced Technology Initiative (IES/BTI) is a automated first phase near-real-time image exploitation system to support Army Corps Intelligence Electronic Warfare situation development, target development and target acquisition. IES/BTI's speed, efficiency, ability to perform force analysis, and ability to use *low-resolution imagery* will allow *timely* exploitation of imagery covering hundreds of square kilometers allowing commanders to see much larger portions of the battlefield.

IES/BTI exploits synthetic aperture radar (SAR) and is integrating infrared exploitation capabilities. IES/BTI locates the presence and type of military units (artillery, armor, etc.) within imagery and prepares either graphic overlays of results and/or an ASCII file of results. Currently, experiments using IES/BTI results as input to Flying Carpet (Simnet) and using IES/BTI results as input to the Demons imagery displays at TEC and the imagery analyst (IA) workstation at the imagery analyst school at Ft Hauchuca are being conducted. IES/BTI is also being considered for incorporation in the Imagery Processing and Dissemination System (IPDS) architecture at Corps.

The focus of this paper is the Artificial Intelligence (AI) aspects of IES/BTI, the conditions that influenced the chosen implementation and the lessons learned in evaluating IES/BTI in two military theaters.

Section 2 provides a background on IES/BTI functions, and the conditions, constraints, and requirements placed on IES/BTI. Section 3 briefly addresses the functionality included in IES/BTI. Section 4 describes the lessons learned in the process of building, testing and migrating an AI system to a second military theater.

2. BACKGROUND

This section provides a brief background on the role IES/BTI is designed to play in the image analysis process and the conditions, constraints and requirements placed on IES/BTI.

The envisioned role of IES/BTI in the Image Exploitation Process is to automatically perform exploitation before an IA receives the imagery (see Figure 1). IES/BTI performs vehicle detection, force aggregation, force typing, false hypotheses rejection and merging of various evidence sources. The IA is presented the IES/BTI results along with the imagery. Guided by the results graphic (see Figure 2), the IA can quickly focus on the potential forces and can efficiently eliminate major areas of search. With this tool much larger amounts of imagery can be processed by the Corps level analyst and the analyst's task shifts away from vehicle level detection to unit level analysis/verification.

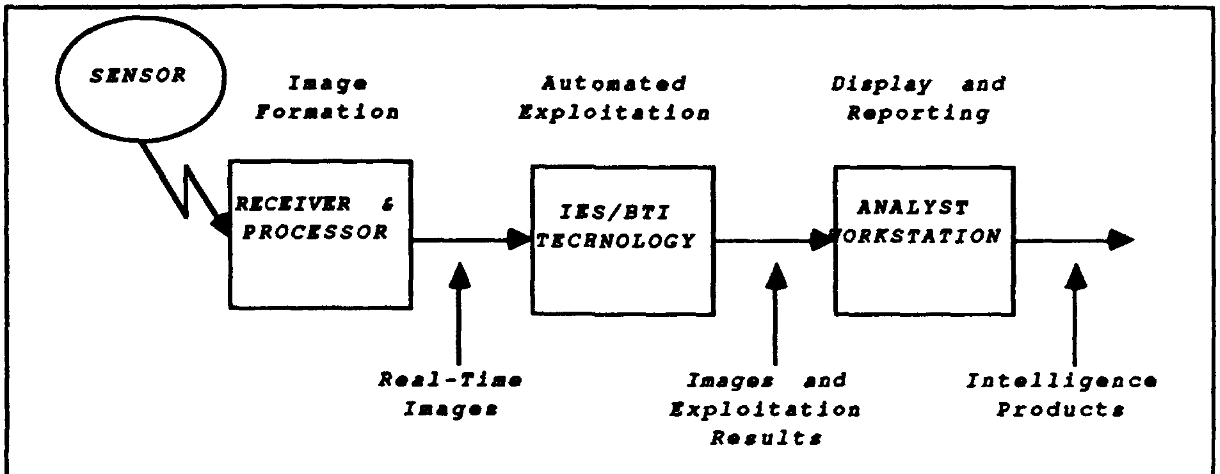

Figure 1. Exploitation Process Data Flow

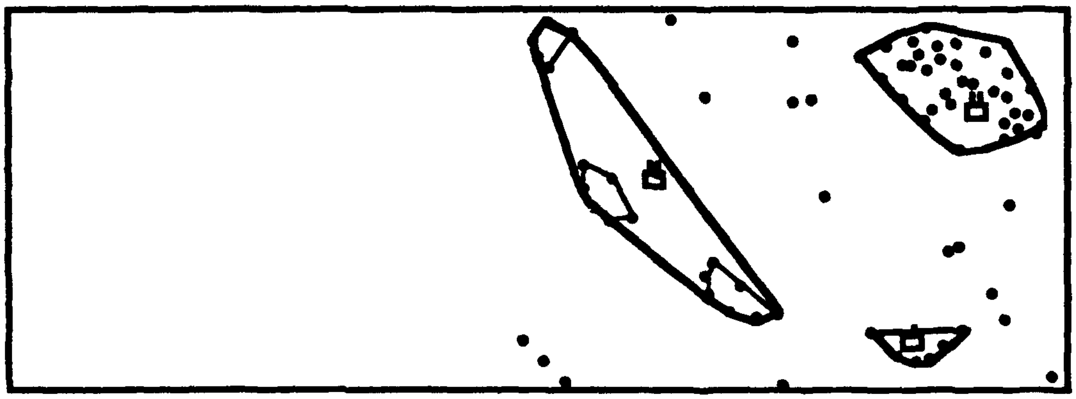

Figure 2. Example results graphic. Potential vehicles are shown as dots. Companies and battalions are shown as hulls and icons.

To illustrate how an IA uses IES/BTI results an example image exploitation event is presented. Gil, an IA, has been asked to exploit an image. Gil calls up the image and the IES/BTI results graphic on his workstation. Gil sees the result graphic, Figure 2, draped over the image. Gil notices the left side of the image contains no activity and being a pessimist quickly scans the left side of the image. Gil knows that the results graphic contains over 90 percent of the vehicles present so unless something catches his eye, he can feel comfortable ignoring the left side of the image. Satisfied the left side is empty, Gil focuses his attention on the right side of the image. Gil then verifies the forces presented on the results graphic. Gil asks himself are all the units real? Did the machine miss any units? Is the lone company part of either of the battalions? Believing that the lone company is part of one of the battalions, Gil adjusts the interpretation to Figure 3 and generates his report.

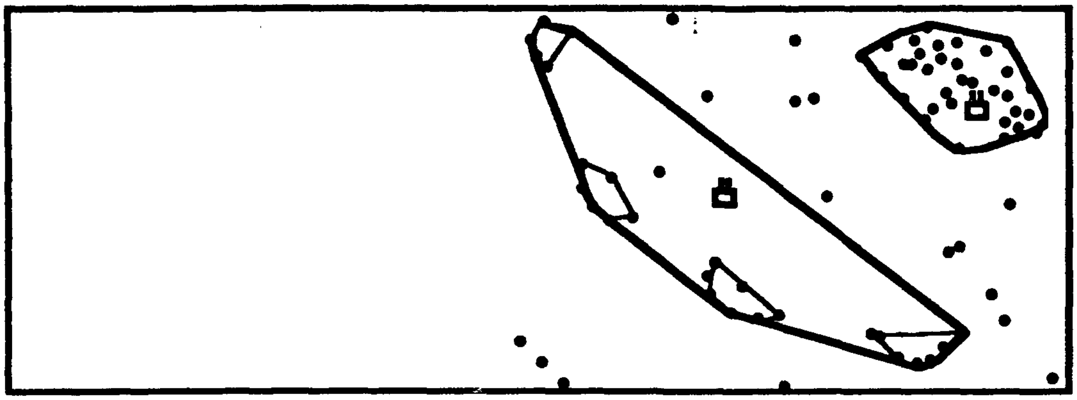

Figure 3. Gil's results.

IES/BTI's system requirements are oriented for a tactical environment. IES/BTI will be used by IAs rather than computer scientists so the results and supplemental information must be clear. IES/BTI will be used in many military theaters and will use standard DMA products as a basis for terrain reasoning. IES/BTI requirements include timing, accuracy, multi-sensor considerations, software standards, compliance with commercial off the shelf policy (COTS) and theater of operation portability requirements. Additionally, IES/BTI will be constrained to two 19 inch racks of computer equipment. Top level requirements are given in Table 1.

Table 1. Top Level IES/BTI System Requirements

Requirement
Provide multi-sensor capability (SAR, IR)
Complete processing of image in less than five minutes for images up to 100 sq nm
Process in a operational (tactical) setting
Provide 100 m vehicle location accuracy
Provide graceful migration between theaters of operation
Use DMA products for terrain information

The system requirements, especially coverage, speed, theater portability, and data sources, put constraints on the AI methods and representations that IES/BTI could use. Being designed as a field deployable system also constrains AI methodologies by not confining the problem and creating indirect requirements of being well behaved and having results that degrade gracefully. Thus it is possible for IES/BTI to be asked to analyze imagery from a new military theater, against a new force in a matter of days! Coping with this scenario presents a difficult task for an AI based system.

3. IES/BTI FUNCTIONALITY

IES/BTI performs five functions: vehicle detection, terrain reasoning, force aggregation, force evaluation/conflict resolution and force typing. Functions within IES/BTI have three notable characteristics: 1) functions are actually large sets of evidence-gathering actions that have been abstracted to a function; 2) functions may be split between several software components that may be widely separated in the reasoning chain; 3) boundaries between functions blur at higher levels of reasoning especially when using multiple sources of evidence. These characteristics are important as they allow us to meet several of our requirements and influence the AI methodology chosen. A brief discussion of each function and Bayesian inference is given below.

An inference system is needed to knit the functions' results together and arrive at an answer. Within IES/BTI we chose Bayesian inference using a Bayes network of hypotheses and Pearl's algorithm for belief propagation.

Bayesian inference has several properties which we found beneficial: a basis in probability, a well defined method of propagating evidence, a single belief value for a hypotheses, a hierarchical network that relates well to force structure and allows efficient management of hypotheses, a model that estimates the utility of future actions, and independence of belief and order of evidence aggregation.

Within IES/BTI, we use the hierarchy of the Bayes network to correlate with force echelon. Each Bayes node contains the current set of conflicting hypotheses (at the same echelon) with each hypothesis linked to its supporting evidence, child nodes and parent nodes. The number of hypotheses within a node is controlled by pruning hypotheses with beliefs below a minimum belief threshold and by pruning the weakest hypotheses when the number of hypotheses within the node exceeds a threshold[1]. Controlling the number of hypotheses is performed to limit combinatoric explosion and allow quicker processing.

Vehicle detection within IES/BTI is based on window operators and does not have a AI implementation. However, it should be understood the role of vehicle detection is to detect greater than 90 percent (>90%) of the vehicles present regardless of false alarm rate. In the speckled SAR environment more than 50 percent (>50%) of detections may be false alarms! We prefer a high detection rate rather than a low false alarm rate as we do not want the IA to have to search the image for missing vehicles and therefore defeat the purpose of giving him an IES/BTI! Secondly, when detection and false alarm rates are lowered, entire units may be lost or rejected in early processing causing the analyst to search the imagery for missing units.

Therefore, other functions must perform rejection of false alarm detections, perform rejection of false unit hypotheses and reason about units that may include false vehicle detections. This means most reasoning in IES/BTI is geared toward separating the real units (with noise) from the phantoms.

Terrain reasoning is performed at several stages within IES/BTI. The coarser reasoning of rejecting detections in prohibited (No-Go) areas and mobility/emplacement value calculation is based on military order of battle, terrain analysis and heuristic models. The coarse generic reasoning is precompiled and saved as encoded data layers for each military theater. At run-time local operations calculate a generic (non-unit specific) terrain likelyhood ratio value with the emphasis on providing a rank ordering of clusters based on the mobility/emplacement value of the terrain underlying the cluster. The

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[1] Null (no unit) hypotheses are never culled.

importance of rank ordering clusters is to allow subsequent processing to focus on the most promising clusters and to start rejecting clusters with low belief values.

Later stages of terrain reasoning are divided into two categories: reevaluation of mobility/emplacement value or as expert system rules utilizing conceptual terrain objects (hill, city, avenue of approach, etc). Reevaluation of mobility/emplacement potential can be performed to obtain mobility/emplacement potential for a specific type of unit (such as artillery) or as part of an inter-force/terrain evaluation. Force/mission/terrain evaluation and inter-force/terrain evaluations are often encoded as expert system rules. Within IES/BTI terrain expert system rules are generally Army and military theater specific and terrain objects used by the expert system are regionally defined.

Force aggregation consists of two types of actions: an initial clustering phase where vehicle detections are clustered into potential company or battalion sized units and a second phase aggregating (hypothesized) units into a higher echelon unit. Clustering attempts to form all real units while limiting the number of non-real units. Clustering eliminates built-up areas and high speckle areas by density screening detections, and then clustering aggregates detections that are related both spatially and by detection belief. Clusters are evaluated on image derived evidence and the underlying terrain (mobility/emplacement value). Clusters form the basis of the initial hypotheses formed in the Bayes network.

A natural method of force aggregation is inherent in Bayesian inference using a Bayes network. As part of building a Bayes network, Bayes nodes are created and linked hierarchically. Within IES/BTI, we use the hierarchy of the Bayes network to correlate with force echelon. Force aggregation is simply building the next level of the network and applying the appropriate force evaluation actions.

Force evaluations are actions that can generate new hypotheses, add evidence to hypotheses and produce or alter Bayes network evidence nodes. Force evaluations evaluate hypotheses features and/or beliefs with hierarchical models of forces. The evaluated features often include features of the child hypotheses. Double counting of evidence is avoided by adding or altering evidence nodes at the appropriate echelon/Bayes network level and propagating all other evidence up or down the Bayes network. Evaluation criteria are stored in a knowledge base organized hierarchically by force level, force type and evidence granularity. Evidence gathering actions evaluate the closeness of data supporting the hypotheses to the force models using statistical metrics and/or expert system rules. Some rules are complex dynamically adapting a static force model to the local terrain and threat situation. Expert system and other high cost rules are applied only if more coarse evidence evaluations and action utility calculation support proceeding with the action.

System level conflict resolution consists of deciding which actions to perform and deciding when to stop processing and report results. System level conflict resolution is supported by the inherent ability to monitor the state of the Bayes network and therefore propose actions based on that state and the ability to calculate the utility of the proposed actions.

Within the Bayes network, hypotheses conflict resolution is not necessary except to ensure efficiency. All conflicting (mutually exclusive) hypotheses can be kept in a single Bayes node and all hypotheses can be carried indefinitely. This feature combined with the ability to estimate the utility of future actions and the ability to monitor the state of the Bayes network, allows timely low-cost belief-based dynamic hypotheses pruning.

Force typing actions are actions which attempt to identify a force's type (armor, artillery, etc) and thus refine the hypotheses. Figure 4 shows the hierarchical organization of force types used within IES/BTI. Competing hypotheses differing in force type exist within the same Bayes node. Force typing actions are quite variable and try to seize on the distinction between the force types. Force typing actions often generate new competing hypotheses within the Bayes nodes and may internally generate and prune hypotheses as part of the action. Force typing are generally hierarchical actions.

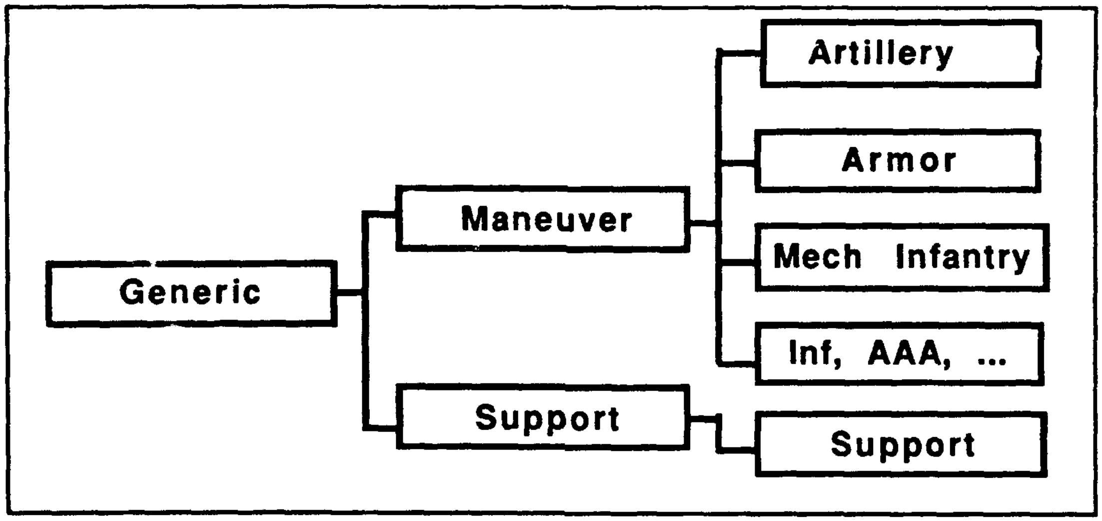

Figure 4. Hierarchical organization of unit type within IES/BTI.

Methods for identifying unit type within IES/BTI are: *using vehicle* level information, using deployment and formation information, using terrain considerations and using intelligence cues.

4. LESSONS LEARNED

Within the IES/BTI development team there have been several ideas that influenced the success of IES/BTI that are applicable to a wide range of AI applications. These ideas proved their value in two military theaters, Europe and South West Asia, even though the scenarios are much different. These winning ideas are given in Section 4.1.

There were also ideas within IES/BTI that fell short of our expectations. These ideas failed to mature in our environment and we provide observations or suggest alternate methods. Some of these ideas may work out for you and time and technology will eventually bring about their success. Nevertheless, our failure may be your savings so they are included. Our ideas that fell-short are given in Section 4.2 and include: image-to-map-registration, formation pattern matching and automatic target recognition.

4.1 WINNING IDEAS

Within the IES/BTI development team there have been several ideas that worked out well and are applicable to a wide range of AI applications. The winning ideas are flexibility, reasoning in real-world coordinates, Bayesian inference and hierarchical reasoning.

Flexibility is the single most valuable asset for a military AI system. A comparison of the relative evidence value provided by IES/BTI functions for the European and the South West Asia Theaters demonstrates this point, see Table 2.

Table 2. Relative Value of Evidence Sources by Military Theater

Function	Europe	S W Asia
Detection	Low	High
Terrain Reasoning	High	Low
Force Aggregation		
Clustering	Medium	High
Up Echelon	High	Medium
Force Evaluation	High	Medium
Force Typing	Medium	Low

As shown in Table 2, the relative value of evidence sources are not constant from theater to theater. A system that requires consistent behavior may perform poorly outside the theater used in designing it. Secondly, flexibility is required as expected behavior and reality are not exact matches and dynamic adapting to doctrine must occur.

Abstracting to high-level functions increases flexibility in definition and implementation which is crucial when changing military theaters, adding sensors or adding additional evidence sources. Using knowledge bases also promotes theater portability as does parameterizing any heuristics. Overall the less functions are hard-coded the more portable they become.

Symbolic reasoning in real-world coordinates (latitude/longitude or Universal Transverse Mercator (UTM)) allows a AI application to be sensor independent. Leaving the image domain as soon as possible allows other processing to be sensor independent and maximizes symbolic reasoning and code reuse. Within IES/BTI, adding sensors only requires adding the appropriate detection and registration code.

Neural networks, Dempster-Shafer, cluster analysis and decision trees were among the methods considered for use in IES/BTI. However, no other method contained the combined features, power and flexibility of Bayesian inference. Bayesian inference insensitivity to small errors in belief and the ability to re-calibrate evidence belief values are needed in real-world applications. An AI system without the ability to economically recalibrate evidence may be left fighting the last war. Furthermore, Bayesian inference behaves well regardless of activity level. Bayesian inference neither forces you to keep hypotheses nor forces you to prune hypotheses, allowing you to correctly reflect the activity level as shown in Figure 5. Other useful features such as: a probabilistic basis, a well defined method of propagating evidence, a single belief value for a hypotheses, hierarchical organization, utility estimation of actions and independence of belief, and order of evidence aggregation were pointed out in Section 3. Not all applications will benefit from Bayesian inference, but systems that require symbolic logic across several evidence domains, have potential combinatorial problems, need to be portable across military theaters or that can take advantage of hierarchical reasoning may benefit from Bayesian inference.

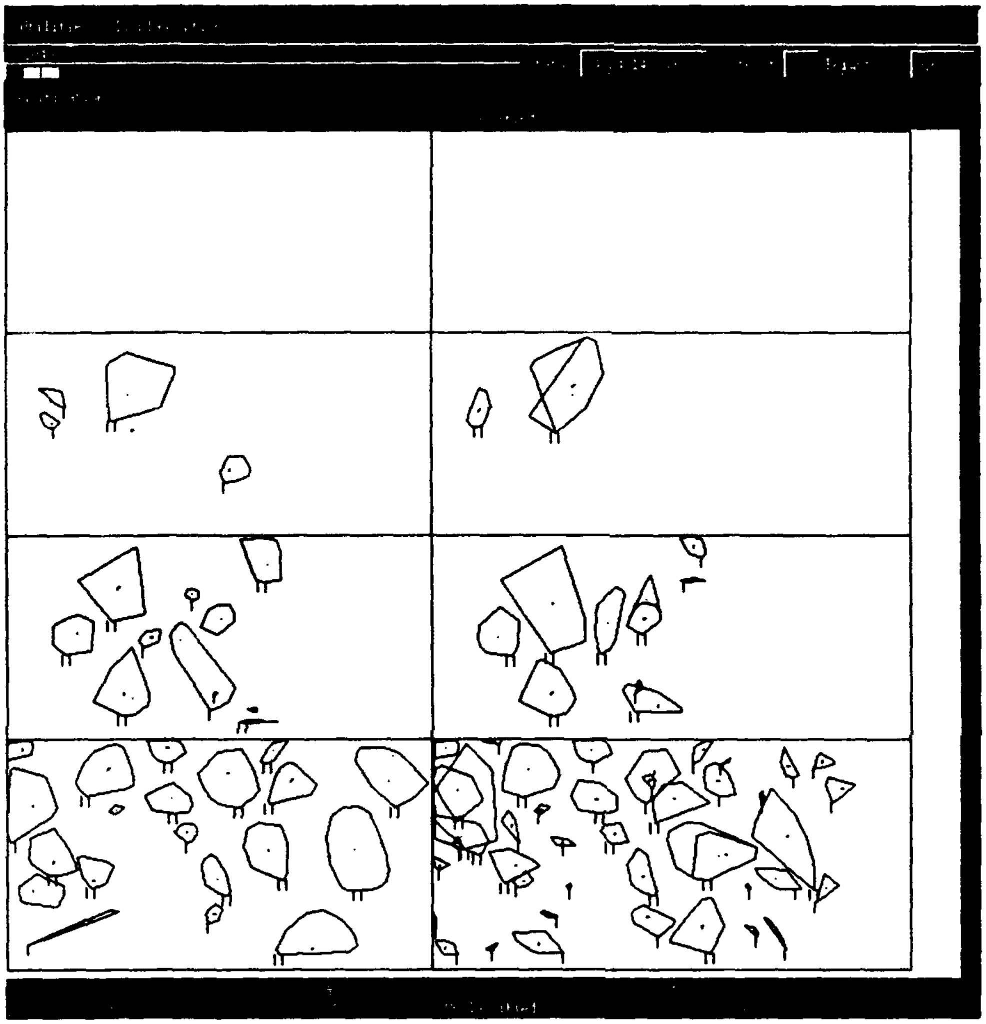

Figure 5. Truth (left) compared with IES/BTI results (right) for four different levels of unit activity (strength). Hulls with two "legs" are the convex perimeter of a battalion. Hulls with one "leg" are the convex perimeter of a company. Hulls with no "legs" are the convex perimeter of a element. Note for IES/BTI results overlapping hulls indicate competing hypotheses with similar belief and the IA is left to resolve the unit extent.

Hierarchical reasoning was another big winner. Hierarchical reasoning matches well with Bayesian inference and is necessary in near-real time systems to quickly produce results as exhaustive evaluation is too costly. Hierarchical reasoning is needed in the high speckle SAR environment where applying detailed models against hypotheses without prior coarse evaluations leads to phantom matches. Hierarchical reasoning avoids rejection of true units by allowing the hypotheses to be kept and confirmed at a coarse level even if it fails to successfully refine into a more detailed hypotheses, while allowing pruning of poor hypotheses as evidence against them builds up.

4.2 IDEAS THAT FELL SHORT IN IES/BTI

Our ideas that fell-short include: image-to-map registration, formation pattern matching and automatic target recognition.

Image-to-map registration failed as it misuses map derived data. Maps were never meant to serve as a basis of photogrammetric control but people need to register imagery to the earth, and maps are often the only terrain product available. Maps contain "cartographic licence" which alters the metric relationships between features, thus introducing registration errors. Cartographic licence is needed in map making to produce clear maps. Thankfully, DMA is producing image derived products (video point positioning data base (VPPDB) and some interim terrain data (ITD)) which do not contain the cartographic licence inherent in maps. Anyone contemplating image-to-map registration might pursue image-to-VPPDB as a more likely candidate for success.

Formation pattern matching did not meet our expectations in both military theaters for two different reasons. In Europe, forces moved a lot and didn't reflect classical formations (V, line, six up one back, etc) when in movement, halted near a road or in assembly. In South West Asia all units tended to have similar patterns or no pattern regardless of forces present. Finally, regardless of theater, missing vehicles within the pattern greatly reduces the value of the "match". However, pattern matching is effective for units such as artillery, where physics encourages them to form regular patterns.

Automatic target recognition (ATR) also fell short of expectations. ATR promises accurate unit typing and accurate unit verification. IES/BTI does not currently use an ATR for two main reasons: ATR is currently to slow to meet IES/BTI timelines and ATR rarely discriminate against all the vehicle classes/types needed in a real-world battlefield environment. As ATR matures IES/BTI will surely include them.

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