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Unattended ground sensor situation assessment workstation

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ABSTRACT

Advancements in both sensor hardware technology and in software systems and processing technology have enabled the development of practical realtime situation assessment capabilities based upon information from unattended ground sensors. A decision support workstation that employs rule-based expert system processing of reports from unattended ground sensors is described. The primary goal of this development activity is to produce a suite of software to track vehicles using data from unattended ground sensors. The situational assessment products from this system have stand-alone utility, but are also intended to provide cueing support for overhead sensors and supplementary feeds to all-source fusion centers. The conceptual framework, developmental architecture, and demonstration field tests of the system are described.

Keywords: unattended ground sensors, UGS, data fusion, situation assessment, expert system, tracking

1. INTRODUCTION

1.1 Background

Effective utilization of unattended ground sensors (UGSs) in a theater reconnaissance, surveillance, target acquisition, and kill assessment environment requires that a human operator be able to interpret, and collectively assess, the significance of realtime data obtained from UGS emplacements over large geographical regions of interest. The products of this UGS data interpretation and assessment activity can then be used in the decision support process for command level evaluation of appropriate courses of action.

The basis for the development activity described in this paper evolved from Sandia National Laboratories technical support to the Ballistic Missile Defense Organization's POET organization in the early 1990s. During this time, Sandia participated in a three year study focused on the prosecution of theater ballistic missile defense operations. One of the concepts which came out of the study was the potential for using inexpensive unattended ground sensors spread over the battlefield to provide increased situational awareness back to a field command center.

Following our experience in the BMDO study, Sandia began a series of activities to try to determine the feasibility of using a reasonable number of inexpensive unattended ground sensors to gain knowledge about remotely monitored events. Two of the activities included testing the utility of implementing ground sensors at the Department of Energy's Nevada Test Site and developing data analysis and display software to intelligently process the data coming from fielded sensors. Specifically, the purpose of this software suite is to build and maintain track files from vehicle movements based on information from unattended ground sensors which reside along the road network.

1.2 USAW development

This paper describes a two-year Sandia internal research and development program, the goal of which has been to apply modern data processing technologies to the automation of converting the data from field ground sensors to knowledge about what is transpiring on the battlefield. The product of this effort has been labeled the Unattended Ground Sensor Situation Assessment Workstation (USAW). The end result of this effort is intended to be a portable workstation platform, and/or portable software, that can be fielded in either a command center or distributed simulation environment. The software has been designed to interface with simulated ground sensor inputs from a variety of scenario generators, or to be

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interfaced to process incoming sensor data from fielded remote sensors. In addition to application to the active theater and battlefield, this technology should be readily applicable to surveillance and situation assessment for intelligence preparation of the battlefield (IPB), proliferation response, treaty verification, underground facility monitoring, drug enforcement, and installation security applications.

The paper describes the context surrounding the interpretation of ground sensor data, covers the functionality of the software being developed, and gives several examples of how the software has been used with both simulated UGS scenarios and live field tests.

Preliminary work for USAW began in FY93 but the bulk of software development activity occurred in FY94 and FY95. The system was used in live and simulated test environments at Sandia and the Nevada Test Site in FY94, FY95, and FY96.

2. CONCEPT DESCRIPTION

2.1 The operational context

The tactical battlefield ground environment will be characterized by very complex and target-rich circumstances -- having both civilian and military vehicles; columns, convoys and single vehicles; convoys merging and splitting; traffic meeting and passing, overtaking and passing, stopping and reversing, going into hide sites, etc.; that is further complicated by road junctions, road crossings and alternate routes. The overlaying UGS sensor environment will be characterized by relatively sparse sensor densities, with limited sensor classification and identification capabilities, and autonomous sensor operations; which will be further complicated by noise induced and/or irrelevant (e.g. air traffic) sensor activations.

Regardless of the design robustness of a suite of UGS sensors, their utility when fielded in such a battlefield context will be minimal to nil without some means of interpreting and assessing the sensor outputs in a collective and integrated manner over the entire region of interest.

Neither sensorscape visualization techniques nor sensor fusion alone is adequate to achieve this objective, but together they provide reason for optimism. Existing UGS data visualization techniques provide effective tools for supporting operator assessment of relatively straightforward ground activities that are occurring over relatively small geographical areas. However, the effectiveness of these techniques begins to break down as the size of the geographical area increases, along with greater numbers of emplaced sensors, and increased situational complexity as described above. Further ambiguity is introduced given that sensor reports for each individual target arrive over a period of from minutes to hours. As a consequence, the operator begins to be unable to grasp the significance and retain the context of the UGS data that is appearing. Something is needed to permit the operator to extract essence from excess.

In addition to advanced visualization techniques, at least two levels of sensor fusion are required to achieve the assessment objective: *Low-level fusion* is necessary to interpret raw UGS data at the individual sensor level and/or within local fields of closely spaced sensors. *Higher-level fusion* is necessary to assess and interpret the low-level fusion products, collectively, over the entire region of interest (ROI). The latter, generally labeled Level II fusion by the data fusion community, along with sensor/geoscape visualization, has been the intended scope of the USAW program.

2.2 Design considerations

Ultimately, subject only to the design-inherent performance limitations of the available UGS hardware, the USAW system will be expected to be able to exploit all available UGS-provided information to maintain target and track files on all vehicles of interest, along with their classification and identification, within a geographical region of interest. The baseline restriction of the program has been to force the solution of this problem to within the constraints of "UGS-space" only, *i.e.* permitting no advantage to be taken from information contributed by external non-UGS sensor platforms; under the conviction that this will force the most robust possible system architecture for USAW. Later, provision will be incorporated to take advantage of such additional external information -- and to provide USAW situation assessment output products back to those external platforms for cross-cueing and all-source fusion.

To force further design robustness the initial USAW design was restricted to accepting only the very limited information obtainable from non-intelligent sensors (seismics, magnetics and infrared break-beams). Initial success has already been proved using these sensors; however, the real power of the system will become apparent when processing of information from extended phenomenology sensors and sensors with classification and identification capabilities can be incorporated.

The USAW supports three modes of operation: Simulation, Realtime (using live reports from fielded sensors), and Playback (using captured sensor reports from previous live exercises). In simulation mode, the USAW will accept sensor data messages from a simulated scenario environment. A scenario generator was developed as part of USAW to allow for testing the USAW analysis and display software without having to input realtime sensor data. The scenario generator itself proved to be a very useful tool which was used extensively in planning field sensor emplacements and in planning the scripted movement of vehicle traffic in the live field tests.

2.3 The geometry of sensor based tracking

The issues of target tracking, classification, and where possible, identification, through the use of UGSs entail unique challenges that are not faced within other sensor system contexts, and they must, therefore, be handled with unique approaches. Figure 1 leads into the discussion of the differences inherent in tracking ground vehicles with UGSs versus tracking them with more conventional overhead sensor systems. The figure shows two views of the same swatch of a road network, one for each context. From the perspective of overhead systems, the upper diagram of Figure 1 is intended to convey the perception of relatively large sensor fields of view, shown as elliptical "footprints" on the ground, and also, implicitly, the sense of both sensor and footprint "agility"; all of which provide a significant robustness to overhead sensors in a tracking context that is inherently unavailable to UGSs.

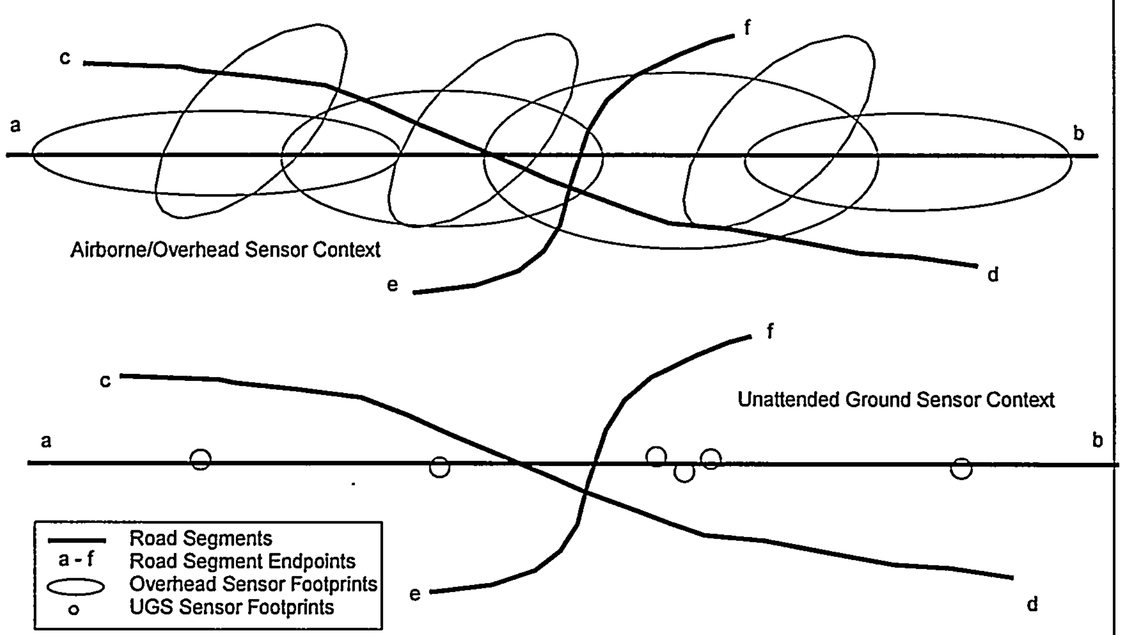

Figure 1: THE GEOMETRY OF SENSOR BASED TRACKING

In the more conventional overhead sensing context, advantage may generally be taken from the fact that relatively broad area sensors will be observing a target, that the footprints of several sensors will frequently be simultaneously overlapping, and that the sensor processing systems will be intercommunicating and cross-cueing regarding simultaneously common targets. The sense of this is illustrated in the top view of the figure, where again the large ellipses represent the ground footprints of the overhead sensors. Thus, it is comparatively difficult (when compared with UGSs) for a target to disappear from the field of view of an overhead sensor; and, more so yet, from a suite of such sensors. If a target vehicle or convoy is observed at Point a, it is relatively easy (again when compared with UGSs) to ascertain that target's same identity when it arrives at Point b; even though there may have been opportunities (*viz.* c-d, e-f) for it to have gone elsewhere, and/or for other targets to have arrived and intermingled with the original target.

In the UGS system context, however, with the smaller UGS detection ranges, much can happen outside the fixed sensing footprints of the UGSs. This is apparent in the bottom diagram of the figure, wherein the small circles represent the UGS footprints. As a target travels from Point a to Point b, there is much less certainty that it is the same target when "it" arrives at Point b. Or conversely, if it does not arrive at Point b, there is also much less certainty where, in fact, it went. Thus, there is clearly less frame-to-frame continuity when attempting to track and classify targets with UGSs than when tracking with sensors that have larger and overlapping footprints. This loss of continuity is very detrimental to the situation assessment process, and it must be recaptured to the greatest extent possible. This loss of continuity strongly suggests the need for the UGS sensors to work together, cooperatively, each taking advantage of whatever clues that all the other sensors can provide, together, to assemble the best possible overall picture of what is happening. The critical frame-to-frame continuity, enjoyed within the conventional broad area overlapping sensor footprint contexts, but lost in the UGS sensor context, must be recaptured with some sort of integrated wide area UGS sensor fusion to enable situation assessment over the entire region of interest.

The USAW system attempts to recapture this loss of continuity by building, incrementally, target and track files based upon all available information that can be collected from isolated individual and local fields of UGSs as the targets move through the sensor emplacements. This information is interpreted by, and inferences produced from, rulesets within an expert system. Target and track continuity is developed by evaluating consistencies and inconsistencies in target velocities, courses of travel, and target classification characteristics, as collected from all of the sensors in an ROI.

The above discussion has addressed the aspects of UGSs that render them comparatively difficult to work with in a tracking application. UGSs do, however, also have several very definite positive features for this application. First, they are inherently much closer to their targets. This confers upon UGSs an intuitive robustness for target classification and identification that is relatively more difficult to achieve with conventional overhead sensors. Secondly, since the UGS footprints are relatively small, their capability for positional resolution is relatively good, (granting that the resolution of certain overhead sensors is even better). Thirdly, once emplaced, the UGSs always remain on station. And finally, UGSs can be emplaced in areas that are inaccessible to, or are masked from overhead sensors. At this point it must be emphasized that this paragraph (or the entire document, in fact) is not intended to draw value judgments regarding the relative merits of UGSs versus overhead sensors in a tracking and situation assessment application. On the contrary, it is the firm conviction of this writer that the two approaches are very complementary; and that together they can provide a product that far exceeds that which either can provide independently.

To summarize then, tracking and situation assessment based upon UGSs is a different problem from tracking and situation assessment based upon conventional overhead sensors; and for success, different perspectives, different expertise, and different algorithms are required. But the two solutions however can, and should, be employed together.

3. SYSTEM DESCRIPTION

3.1 Functional schema

Figure 2 shows the USAW system functionally, in terms of its three primary processing subsystems.

A *scenario generator* was created to provide a driver for USAW during its developmental phases, to create time-sequenced files of simulated sensor reports that would result from a scenario of vehicle movements within an ROI. In order to produce a sensor report output file, however, it is first necessary to create the driving scenario. The scenario generator does this, interactively with the operator, based upon input convoy characteristics (*i.e.* number of vehicles, types of vehicles), starting locations, starting times, routes, etc. But before this can be done, however, the ROI must first be described to the system. The scenario generator again does this, interactively with the operator, by overlaying a road network upon a digitized map of the ROI. Sensors are then interactively placed onto this road network, with the scenario generator effecting logical accessibility to each of the sensors and its location. When the driving scenario is then initiated, the scenario generator creates its simulated output sensor report file based upon the responses of its internal sensor models to the vehicle movements as they approach the sensors' emplacement locations.

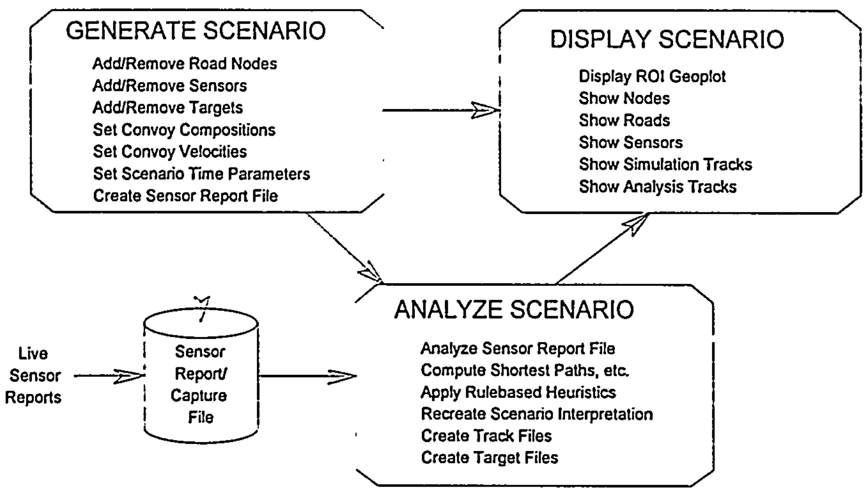

Figure 2: FUNCTIONAL SCHEMA

In addition to simulation mode, USAW also operates in realtime and playback modes. During realtime and playback operations, the output sensor report simulation feature of the scenario generator is circumvented to allow for, respectively, realtime reports from actual fielded sensors operating against actual vehicles; or in the case of playback operations, replay of a sensor report capture file from a previous live operation. The scenario generator's sensor report simulation feature will, however, continue to be used throughout the remaining USAW developmental process to permit testing of diagnostic scenarios of increasingly stressing complexity.

The purpose of the *analysis subsystem* is to sequentially analyze the incoming sensor reports, and from these produce target and track files. In simulation mode, the goal of the analysis subsystem is to reconstruct the driving scenario from which the scenario generator created its time-sequenced simulated sensor report file. In realtime and playback modes, the goal of the analysis subsystem is to interpret actual incoming sensor reports and produce its best assessment of the vehicular movements that were responsible for those sensor reports. The analysis subsystem does this by interpreting the reports against each other and against information that it has previously accumulated regarding its interpretation of the unfolding scenario. This process is supported by automated reasoning that is governed by both kinematical and behavioral rulesets within an expert system. All of the USAW sensor fusion is accomplished within the analysis subsystem.

The nature of the task that USAW addresses requires processing at higher levels of abstraction than is normally accomplished with conventional, numerical-based computation. This is particularly significant when considering the geographical sparsity of data that is provided by UGSs on individual targets. To accommodate the need for inferential processing, USAW employs a rule-based expert system as a central element.

The *display subsystem* provides the man/machine visual interface for USAW. It displays all the salient features of the ROI, at variable scales, during both scenario generation and analysis subsystem processing. It also provides the displays of individual target files and track file histories, the latter both tabularly and graphically. At present, the ROI is displayed only in 2-D; later enhancements are planned to provide 3-D display.

3.2 Implementation environment

The USAW system is currently implemented on a SPARC Station 20 ZX dual-CPU host platform with 64 MB of main memory and a 1GB hard drive, and the system is running under Solaris 2.4. The scenario generator and display subsystem are coded in "C" language, operate under the X Window System and MOTIF, and run on one CPU; while the expert system modules, including the character-based Version 3.0 of EXSYS, run on the other CPU.

3.3 The expert system component

As noted in Section 2.1 above, two levels of sensor fusion are required to accomplish UGS situation assessment processing. Low level fusion, which operates on and at the raw data level, at low levels of abstraction, can be thought of in terms of numerical signal processing, with high mathematical content, and is normally accomplished by numerically-efficient procedural languages such as FORTRAN, BASIC, "C", *et al.* Level II fusion, on the contrary, with which the USAW development is concerned, operates at higher levels of abstraction that can be thought of in terms of inferences, deductions, hypotheses, etc. This kind of material is not readily amenable to numerical, procedural, algorithmic processing; but rather to symbolic processing, generally associated with languages such as LISP, PROLOG, *et al.*; the languages of artificial intelligence (AI). In short, although Level II fusion *has* been addressed with numerical processing, the only significant recent successes that have been achieved have been with symbolic processing, as implemented within the AI disciplines of expert systems and templating. A commercially-available expert system developmental shell, EXSYS, has been acquired and interfaced for this purpose. EXSYS is a state-of-the-art shell that employs both forward and backward chaining and supports fuzzy logic and confidence assessment.

4. TESTS AND EXERCISES

4.1 Initial test in a simulated environment

A proof-of-concept demonstration scenario was developed over a 43,000 square kilometer ROI within Iraq. The scenario included some 3700 kilometers of roads, 250 road segments, 70 seismic sensors, and 20 simultaneous and separate but interacting target vehicle tracks. The scenario was developed using the USAW scenario generator. The vehicle interactions included near-simultaneously crossing vehicle tracks, meeting and passing tracks, and overtaking and passing tracks. All tracks of the scenario were successfully resolved by the USAW analysis module. This proof-of-concept demonstration scenario was shown at the December 1994 Sandia UGS Symposium and it appeared to be very well received.

4.2 Use with an independently developed simulator

This effort was conducted under DATSD/AE-CP sponsorship, in conjunction with Sandia developers of the UGS Sensor Evaluation Model (SENSEM). The purpose of this work was to assess the ability of USAW to construct tracks of vehicles operating in a North Korean ROI, based upon: 1) the Global Protection Against Limited Strikes (GPALS) 92-2 and BMDO North East Asia (NEA) II campaign scenarios, and 2) classifying UGSs capable of distinguishing vehicles of interest. Five North Korean UGS scenarios were developed, based upon sensor reports generated by a Monte Carlo simulator within SENSEM; which was, in turn, initialized with parameters from the GPALS and NEA II scenarios.

This was effectively a "double-blind" test for USAW, in that the individual that developed the sensor laydown was not given the vehicle movements, the individual that developed the vehicle movements was not given the sensor laydown, and the third individual that operated USAW was given only the sensor activation times and locations, and had no knowledge of the number of vehicles operating nor their routes, starting or ending times or locations.

A description of USAW's performance in satisfying detail would require several pages of text and as many additional figures. In summary, its "effectiveness" in reconstructing the vehicle tracks was about 65-75 percent, depending upon the measures used. All of the tracks correctly identified the areas of operation. About half of the track segments were reconstructed correctly end-to-end, given the ambiguities of that measure -- for example, an actual ground truth track, though already underway, cannot become apparent to USAW until a sensor report is received by USAW on that track; and, the association of two goal-oriented track segments, one arriving at, and the other departing from the same location, after a significant layover time, cannot be other than probabilistic without unit identification information from the sensors.

4.3 Initial live exercises

The first live exercise of USAW was conducted at the DOE-sponsored non-proliferation and regional security Cooperative Monitoring Center (CMC) facility at Sandia on 30 July 1995. In this test, real vehicles were successfully tracked, using real sensor reports, in realtime. The CMC ROI was modest in scope compared with the previous scenarios, but proved adequate for a first live test. It included an area of 0.9 square kilometers, 2.1 kilometers of roads, 24 road segments; and 9 seismic, magnetic and infrared (IR) breakbeam MIDS sensors.

Even in the face of sensor activation problems (false reports and failures to report), and considerable extraneous traffic, the performance of USAW exceeded expectations. All of the tracks uncorrupted by sensor problems and unsolicited external traffic were constructed without flaw; and, in fact, tracks of several of the extraneous vehicles, though unplanned, were acceptable. The CMC test provided the first empirical critique of seismic UGSs as employed in a tracking environment.

A second live test was conducted at the CMC facility on 3 November 1995 *within* the CMC office building. Although USAW was conceived for application to ROIs on a theater to battlefield scale, an opportunity arose for testing it at the opposite extreme. This test was related to Sandia's programs in U.S. and international treaty verification and monitoring of production and storage facilities for weapons of mass destruction. The issue that was addressed was whether USAW could provide a useful contribution in the tracking and situational assessment of personnel and critical materials movements within a facility, by using already installed simple monitoring and intrusion detection devices such as passive IRs, IR breakbeams, door switches, weight scales, strain gauges, radiation detectors, etc. To provide a first-order test surrogate for such devices, the single-floor CMC building was instrumented with 24 IR tag sensors for movement monitoring. Three simple walking scenarios were tested. On two of these, in which the movements were continuous and straightforward, USAW was able to construct the tracks perfectly. On the third, as was anticipated, when the tracks included participant interactions, lingering, and random movements within individual rooms, USAW's ability to resolve the tracks broke down.

4.4 NTS live exercise

USAW supported a live field exercise that was conducted at Nevada Test Site (NTS) on 14-15 September 1995. During this test, live UGS reports of traffic operating at NTS were transmitted to Albuquerque and were processed by USAW in realtime.

The prescribed purpose of the NTS exercise was to demonstrate the test range capability for collecting and transmitting realtime sensor data from NTS to Albuquerque, in anticipation of future application in distributed interactive simulation exercises at the Air Force's Theater Air Command and Control Simulation Facility (TACCSF) in Albuquerque. This objective was clearly achieved, as USAW was able to process the transmitted sensor data. The objectives for USAW in the exercise were to evaluate its current processing capabilities in a fairly realistic realtime environment, and to capture all live sensor data from the exercise for use in its continuing development.

The NTS ROI included 74 square kilometers of area, 41 kilometers of roads, 58 road segments; and 28 seismic, magnetic and IR breakbeam MIDS sensors. (For strict accuracy, 50 sensors had been emplaced, but only 28 were used by USAW during the test).

The test consisted of four runs of a two and one-half hour scripted scenario, with the following variations:

- ten vehicles with extraneous traffic
- ten multiple-vehicle convoys with extraneous traffic
- ten vehicles without extraneous traffic
- ten multiple-vehicle convoys without extraneous traffic

Each of the four scenario runs followed the same start/stop location and time scripting, as closely as was practically achievable. Each of the ten vehicles, (or the lead vehicle in the case of convoys), was equipped with a GPS receiver to permit determination of ground truth. All of the sensor reports and the GPS interrogations were time-tagged and recorded for later analysis.

During the test runs most of the tracks appeared, visually on the operator's screen, to be developing properly at the expected locations and times. Several flaws in the constructed tracks were apparent as well, however. These included several gaps in the tracks, track reversals, and unscripted additional tracks. Unfortunately, as of this writing, a thorough analysis of the test results has not yet been completed. Initial examinations of the data indicate that a number of the sensors behaved erratically, either false alarming or missing alarms.

The degree to which the sensor anomalies will explain the flaws in the constructed tracks is yet to be determined. Expectations are that they will explain most of them. This expectation is supported by the fact that pre-exercise simulations of the same scenario were analyzed perfectly by the system. Conversely, if flaws are found that cannot be explained by the sensor anomalies, then they will provide realistic empirical criteria for improvements to the rulesets -- which is exactly what was hoped for.

In summary, USAW's performance during the NTS tests, as viewed from the operator's screen, and especially in view of the sensor anomalies, exceeded expectations. Whether this appraisal will prove to be excessively charitable will be determined during the remaining post-test analyses.

5. CONCLUSIONS

5.1 Findings

The above demonstration scenarios and live exercises have proved that a few good rules go a long way toward reconciling a large fraction of the well-behaved, purposeful, goal-oriented traffic operating within an ROI. The developers are harboring no illusions however, that traffic in an unscripted field environment will always be that polite. USAW has yet to be confronted with non-well-behaved traffic, high densities of interacting civilian and military vehicles, convoys merging and splitting, and large ratios of noise reports and false alarms. On the other hand, USAW is still a developmental system. The successes that have already been demonstrated provide intuitive confidence that such complexities can be addressed with equal success -- given some time to work on them.

The higher the information content of the sensor data, the more utility it has in the USAW fusion process. The seismic sensors that were used in the CMC and NTS tests provide little more information than an indication that "something just went past here." The magnetic and IR breakbeams are just as stingy. This is not a revelation. The initial USAW design was, in fact, intentionally constructed around non-intelligent sensors to force greater rigor into its architecture -- it must first be able to track with non-intelligent sensors,.then help from smarter sensors will be allowed. As higher phenomenology sensors are introduced, up through those with classification and identification capabilities, for example acoustic and IR classifiers and imagers, the expanded robustness of the information content that will be introduced into the fusion process will be, hopefully without fatally rupturing the term, phenomenal. And USAW's ability to track will increase accordingly.

5.2 Continuing development

Additional enhancements are planned, including improving the fuzziness of the existing rulesets, extending the existing sensor models -- which are at present quite simple, improving false alarm handling, incorporation of sensor reliability assessment capabilities, and the extension to 3-D visualization.

Completion of most of the above capabilities will then permit cost/benefit balancing studies to be conducted, regarding the necessary ratios of intelligent to non-intelligent sensors. Tracking can be done with either; but although non-intelligent sensors are less expensive, they cannot classify or identify; and while the intelligent sensors can, they are much more expensive. The necessary ratios will vary from area to area within an ROI, again depending upon the anticipated scenario complexity within each area.

5.3 Applications and interfaces

Although USAW was originally conceived for application to domains on the order of theater to battlefield size, as the development progressed it became increasingly apparent that its range of application is largely a matter of scale -- in principle, USAW should perform from a theater scale, to a battlefield, to an urban sector, to an installation perimeter, to within a facility. At one end of the spectrum it can provide tracking and situation assessment of military time-critical-targets in a TMD environment; while at the smaller scales it can be applied to, for example, tracking of critical materials movements and attempts at covert device emplacement in a proliferation response environment.

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