Integrated Multiple-Hypothesis Nonlinear Tracking

Eric Tollefson, Warren Eldredge,
Daniel D. Sternlicht, Donald W. Pace
ORINCON Defense
4770 Eastgate Mall, San Diego, CA 92121

Stephen L. Anderson
Metron, Inc.
11911 Freedom Drive, Suite 800
Reston, VA 20190

ABSTRACT

Technologies for adaptive data fusion, multiple-hypothesis fusion management, and nonlinear tracking have, over the years, matured along separate lines of research and development. In this paper, we introduce an extendable, multi-source acoustic tracking system architecture for undersea C4ISR applications, which integrates a multiple-hypothesis tracking (MHT) paradigm with a Monte Carlo particle tracking paradigm. The former approach models target state probability densities with a Gaussian sum Iterated Extended Kalman Filter (IEKF), whereas the latter method employs non-linear probability state distributions. The prototype system, designated MultiStar, is being designed to apply the tracking methodology best suited to the estimated state probability of the targets being tracked. Preliminary analyses indicate that this integrated data fusion architecture will produce significantly better tracking estimates than either of the methods implemented separately.[1]

1. INTRODUCTION

Technologies for adaptive data fusion, multiple-hypothesis fusion management, and nonlinear tracking have, over the years, matured along separate lines of research and development. In this paper, we introduce a multi-source acoustic tracking system architecture that integrates a multiple-hypothesis tracking (MHT) paradigm with a Monte Carlo particle tracking paradigm. The former approach models target state probability densities with a Gaussian sum Iterated Extended Kalman Filter (IEKF), whereas the latter method employs non-linear probability state distributions. The prototype system, designated MultiStar, is being designed to apply the tracking methodology best suited to the estimated state probability of the targets being tracked. Integration of these disparate technologies within a single system is intended to increase the Navy's ability to solve difficult problems in Command, Control, Communications, Computers, and Intelligence, Surveillance, and Reconnaissance (C4ISR).

The object-oriented MultiStar system, illustrated in the block diagram of Fig. 1, provides JAVA and C++ based interfaces in a COTS development environment that allows multiple supplier modules to function as part of an open data fusion system. The Fusion Input Processor (*FIP*) provides measurement scans from the reporting sensors. The Fusion Output Processor (*FOP*) provides the interface to output tracks, e.g., to the display system. The multiple-hypothesis fusion engine (*MHFE*) performs the fusion management functions within the multiple-hypothesis environment, including: contact data clustering, hypothesis generation and management, and direction of evaluator processing. *Evaluators* (modules to the right of the MHFE in Fig. 1) perform domain-dependent state estimation and track-measurement association scoring, as directed by the MHFE. To allow for relatively easy incorporation of various evaluators, a standardized application programmer interface (API) was established between the MHFE and the evaluators. This flexible design allows the addition of other state estimation and correlation domains into the system.

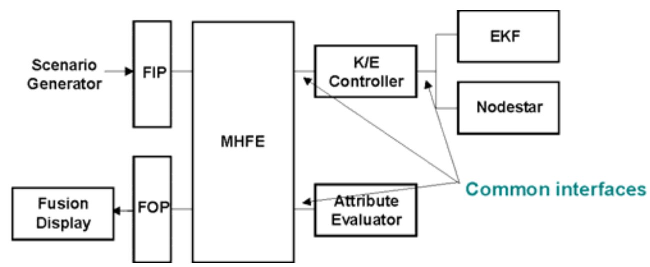


Figure 1. MultiStar Open Architecture:
Integration of Gaussian sum-based extended Kalman filter and
Nodestar particle filter kinematic evaluators.

The kinematic evaluator (KE) estimates each track's kinematic state (position and velocity) and computes kinematic association scores among measurements and tracks. The MultiStar technology presented here combines ORINCON's multiple-hypothesis tracking system (the Automatic Localization and Field Processor – ALFP) and IEKF kinematic evaluator with Metron's Nodestar Bayesian tracking paradigm.

Sections 2 and 3 of this paper describe the ALFP, IEKF and Nodestar systems. Section 4 describes the prototype controller used to integrate the ALFP IEKF and the Nodestar kinematic evaluators. Section 5 uses simulated data to compare the performance of the MultiStar paradigm with that of the ALFP IEKF and Nodestar systems operating solo. Section 6 summarizes the research.

2. AUTOMATIC LOCALIZATION AND FUSION PROCESSOR (ALFP)

ORINCON's ALFP multiple-hypothesis tracker employs an iterated extended Kalman filter (IEKF) for tracking, scoring, and associating submarine and surface contacts across

[1] This work was sponsored by the Office of Naval Research under contract # N00014-02-C-0517.

multiple sensors and platforms. Figure 1 provides a block diagram and the relationship of the different processes.

Target state probability density functions are approximated with a sum of Gaussian density functions. The Gaussian sum approximation [1] is an attractive means of modeling target state within a sensor array's bearing wedge, as a bank of Kalman filters can be employed to model the terms representing the sum. An arbitrary density function *f* can be approximated arbitrarily close by the finite sum:

$$f_k(x) = \sum_{k=1}^{K} \alpha_k \ N(x - \mu_k; \Sigma_k)$$

where N is the Gaussian density function with mean μ_k and covariance Σ_k , and α_k specifies the weights for component densities. By selecting α_k , μ_k , Σ_k , and K, f_K can approximate *f* to an arbitrary degree of closeness [2].

Figure 2 graphically illustrates single-target state and multiple-target state representations of measurements originating within a single bearing wedge. An analysis was conducted that substantiated the use of inverse weighting of the Gaussian sum terms. As part of this R&D effort [3], ORINCON transitioned its baseline ALFP architecture from single-state Gaussian track initialization/processing to multistate Gaussian track initialization and processing, thus implementing a more comprehensive representation of nonlinear target state densities within the bearing wedge.

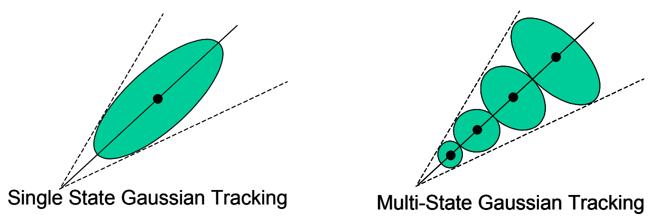


Figure 2. Bearing Wedge Representation via Gaussian Sum Approximation

The ALFP processing technique can fuse data from fixed deep water acoustic sensors – approximating conically projected bearings (Fig. 3) using multiple Gaussian states – with multiple sensors from a submarine platform, thus enhancing a submarine's tactical control system performance in real time. Examples of ALFP tracking outputs are shown in Sec. 5.

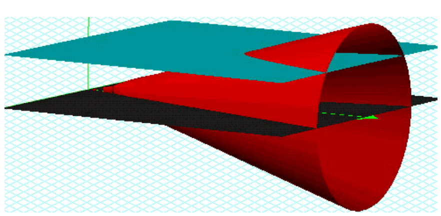


Figure 3. Single Line of Bearing Measurement Interpreted as a Cone in three Dimensions

3. NODESTAR

The Nodestar Bayesian tracking system is designed to run aboard submarines for processing measurements made by onboard acoustic sensors; however, it can use information from any onboard sensor. A specific example is the conic angles that are estimated from broadband acoustic data received by a linear array of towed hydrophones. Nodestar tracks several dozen targets using broadband and narrowband information. "Tracks" are assigned Sierra numbers (such as "S1," "S2," etc.) by the sonar operator, and bearing estimates and time information associated with these tracks constitute the Nodestar "measurements."

The output of a Bayesian tracker is a nonlinear probability distribution on the state of each target being tracked [4]. The NodeStar system employs a five-dimensional target state space: three dimensions in position (x, y, d) and two in velocity $(\dot{x}, \dot{y})$. The posterior probability on a discrete target state space is the Bayesian tracking solution. Point estimates derived from this distribution, such as the mean, can be computed and displayed when appropriate.

4. KINEMATIC EVALUATOR CONTROLLER (KEC)

The Kinematic Evaluator Controller (KEC) evaluates the context of each track and selects an appropriate evaluator. In the integrated MultiStar system, we have implemented a simple prototype controller that selects either the multistate MHT extended Kalman Filter (EKF) or the Nodestar Bayesian tracker to process incoming measurements. A simple rule delegates single-array, bearing-only tracks to the Nodestar subsystem, whereas the extended EKF is used for all other cases; based on these criteria, the MultiStar system transfers solutions from the Nodestar subsystem to the EKF subsystem, and vice versa.

Converting Gaussian states to non-linear representations is straightforward. In the other direction, approximation conversion algorithms are used to convert a contact's solution from a Bayesian representation to a set of Gaussian states. A combination of the Gaussian expectation maximization (GEM) and K-Means algorithms enables the kinematic controller to receive a set of Gaussians that are based on a Nodestar distribution consisting of several thousand sample points. An example of this process is shown in Fig. 4, where the color raster image represents the non-linear state densities for the Nodestar subsystem, and the ellipses represent a number of Gaussian state approximations with associated goodness-of-fit measures.

The ORINCON and Metron team is continuing R&D of the kinematic controller to identify methods that identify Gaussian or non-Gaussian-like approximations of a contact solution. Those contacts with a Gaussian-like distribution will be processed in the IEKF, whereas the Nodestar evaluator will process non-Gaussian-like contacts.

5. SIMULATION

Simulations illustrated in Figs. 5 and 6 demonstrate the functionality of MultiStar. A 10-minute scenario simulates target tracking carried out by a submarine sensor suite where, in the first five minutes, bearings-only measurements from an unknown surface target are collected using the ownship's towed array (Fig. 5), and, in the final five minutes, measurements from both the ownship's towed array and sphere array are collected and processed (Fig. 6). The ownship (P2), transiting 120° at 3 kts with a TB-16 line array towed 0.66 kyd astern (POS1), tracks target T0 as shown by the complete track chart of Figure 6. Target T0 starts at range-from-ownship 2.60 kyds, ends at range-from-ownship 1.46 kyds, and transits 20° at 6 kts.

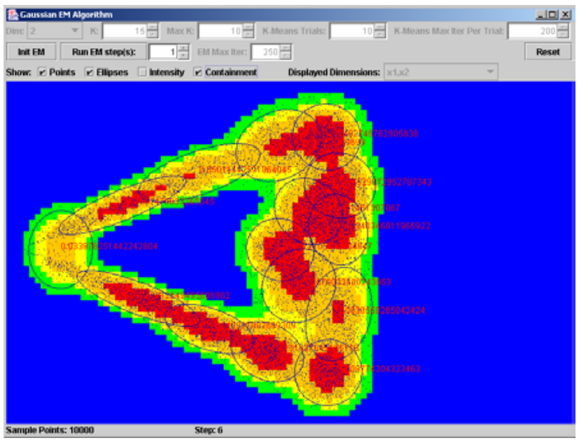
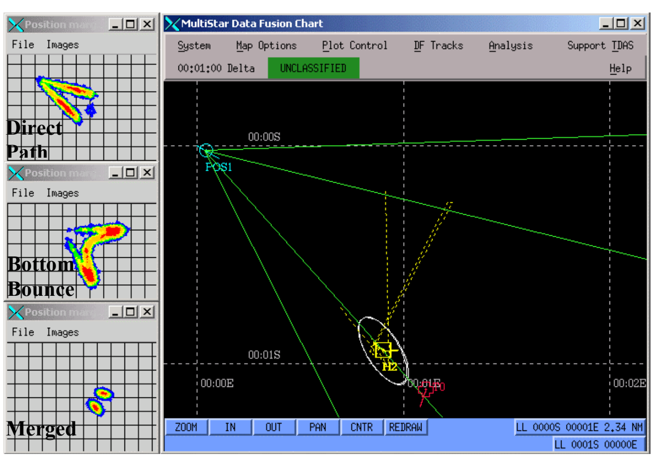


Figure 4. Conversion of Nodestar State Representation to Multiple Gaussians

Bearing measurements are processed at 10-second intervals that contain a bearing uncertainty to account for the observation errors. The yellow square symbol and dotted line represent the position and history of the MultiStar tracking solution. As evident from Fig. 6 and from the truth-track miss distance plot of Fig. 7, the MultiStar system initiates the scenario with a miss distance of approximately 2 kyds and, by the close of the 10-minute interval, converges to a miss distance of less than 100 yds. The final H2 solution state registers the target traveling at a speed of 6.3 kts and a course of 30.2 degrees.



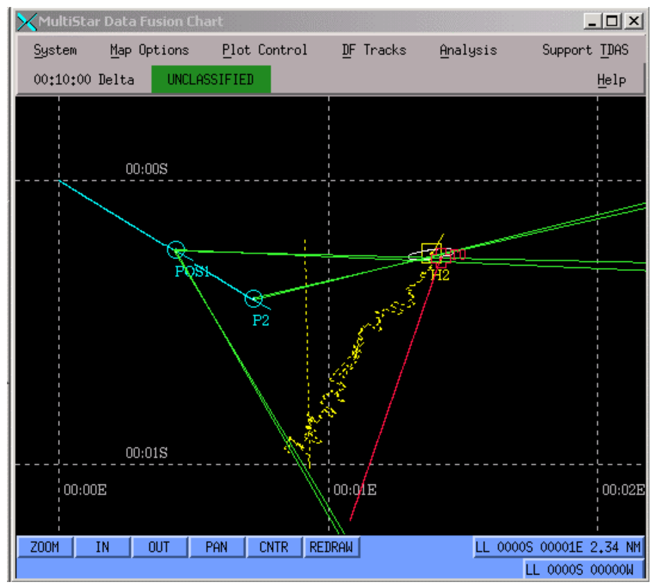
Time Elapsed = 1 minute. Individual bearing measurements shown in green.
Ownship: Traveling 120 degrees; POS1 = towed TB-16 array.
Target: T0 truth with associated track H2.

Figure 5. Cartographer Display for Single Sensor Phase

5.1 SINGLE-SENSOR PHASE

The MultiStar tracker operation for a single towed array measurement (Fig. 5) makes use of tagged data, which denotes direct path and bottom-bounce bearing measurements. Each measurement consists of a bearing vector pair symmetric about the axis of the array, identifying azimuth ambiguities inherent to line arrays. The inner vector pair represents the direct path measurement, while the outer pair represents bottom bounce.

The raster plots to the left of Fig. 5 show the marginal position densities corresponding to the direct path measurement, the bottom bounce measurement, and the merged representation (direct path and bottom bounce corresponding to same target). MultiStar maintains both single target and multiple target hypotheses corresponding to these measurements.



Time Elapsed = 10 minutes. Individual bearing measurements shown in green.
Ownship: Traveling 120 degrees; P2 = sphere array; POS1 = towed TB-16 array.
Target: T0 truth with associated track H2.

Figure 6. Cartographer Display for Two-Sensor Phase

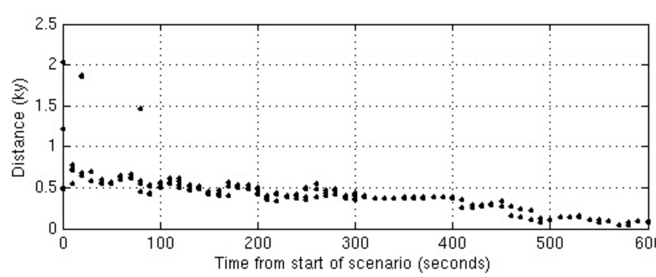


Figure 7. MultiStar Performance for Track H2 re: Truth T0

5.2 TWO-SENSOR PHASE

At five minutes into the simulation, sphere sensor measurements are collected, complementing measurements from the towed array and inducing the KEC to switch from the Nodestar tracker to the extended Kalman filter. A review of the MultiStar performance graphs reveals that at and past the five-minute mark (300 seconds), measures of miss distance and area of uncertainty continue to decrease with time, demonstrating a near-seamless transition between the Nodestar and IEKF kinematic evaluators. Figure 6 shows the Cartographer display at 10:00 minutes into the simulation. Here, the two sets of bearing vectors concentric about the towed array (POS1) represent two consecutive direct-path measurements, where the spherical array measurements (P2) are represented by a single (unambiguous) bearing vector.

Analyses of the top two target state hypotheses at 7:30 minutes into the simulation are displayed in Figure 8. The left pane shows that a hypothesis that fuses measurements from the sphere array with those of the towed array (H2) generates a dominant score (1.000), whereas the score associated with separate targets for each sensor (0.000) is negligible to three decimal places. For these EKF solutions, the tagged bottom bounce messages were turned off, as the ALFP tracker does not yet utilize this information.

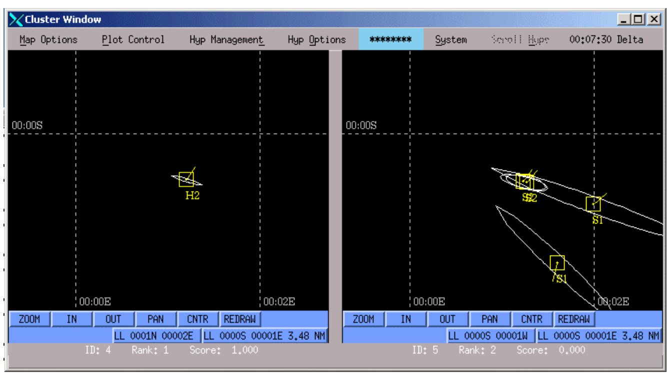


Figure 8. Hypothesis Analysis Window for MultiStar Simulation at time 7:30 min.

5.3 DISCUSSION

To evaluate the MultiStar target-tracking paradigm, we tested the scenario with both the Nodestar Monte Carlo particle filter and ALFP IEKF evaluators operating solo. In general, the Nodestar system provides a tighter distribution of solutions during the first five minutes of the simulation; however, as the second sensor is brought to bear, the IEKF converges to a more precise solution (miss distance consistently less than 50 yds). Comparisons of the tracking paradigms for this and other scenarios demonstrate the potential improvements of informed switching between kinematic evaluator functions.

In addition to increased tracking accuracy, MultiStar solutions were better contained than solutions for the solo NodeStar or IEKF implementations, where *containment* refers to the percentage of available truth times that the target is contained in at least one of the track state error ellipses. For the solo IEKF operation, the bottom bounce measurement components were not used. Currently exploitation of bottom bounce measures is being added to the IEKF subsystem.

6. SUMMARY

Initial testing of the MultiStar Kinematic Evaluator Controller (KEC) was completed in late 2002. A simulation was created, wherein a single-sensor Nodestar Monte Carlo particle filter tracking solution was transitioned to a dual-sensor ALFP IEKF tracking solution, upon target contact with a second sensor. Making effective use of bottom-multiple messages, the NodeStar subsystem effectively tracked the target's trajectory during the initial single-sensor stage of the simulation. During the dual-sensor stage of the simulation, the IEKF subsystem produced a tracking solution that more closely converged with the truth information for the simulated target. This test of the MultiStar architecture illustrates the utility of combining the Monte Carlo particle filter tracker and the iterated extended Kalman filter in a single multiple-hypothesis tracking system.

Multiple evaluators and information from disparate on-board and off-board sensors can be incorporated into MultiStar's extendable object-oriented data fusion architecture. We, thus, anticipate that the MultiStar approach will improve situational awareness for submarine drivers and other ASW assets. In the next year ORINCON and Metron will demonstrate MultiStar with submarine data in conjunction with the Office of Naval Research (ONR) and the Navy's Advanced Systems and Technology Office (ASTO).

REFERENCES

[1] D. Alspach, "A Gaussian sum approach to the multitarget identification-tracking problem," *Automatica*, B11, pp. 285-296 (1975).

[2] D. Klamer, T. Zadra, R. Brouillard, E. Frangione, J. R. Miller, J. J. Onderisin, M. W. Owen, and P. J. Shea. "An overview of tracking and data fusion at ORINCON," *U.S. Navy Journal of Underwater Acoustics*, (50) 1, pp. 27-54 (2000).

[3] ORINCON Phase I SBIR Final Report, "Integrated Multiple-Hypothesis Nonlinear Tracking," July 2002.

[4] L. Stone and S. Anderson, "Bayesian Tracking for Submarine Towed Arrays," U. S. Navy Journal of Underwater Acoustics, Vol. 50, No. 1, January 2000.