

Using Target Range Rate Data in Distributed Data Fusion Systems

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ABSTRACT

Current data fusion architectures are evolving from single-platform, standalone systems to multi-platform, integrated systems. By taking advantage of the favorable geometry of a distributed data fusion system, target tracking performance can be greatly increased. Sensors can typically provide an estimation of a target's position, but only the radial component of the target's velocity. The target's velocity is typically obtained by tracking a target over time and estimating both position and velocity by putting the correlated sensor reports through a kalman filter. This filtering can take on the order of minutes (depending on sensor update rates) in which time the target may have maneuvered, possibly causing the filtering process to restart. If the range rate information from multiple platforms is combined, target velocity can be estimated quicker and with greater accuracy. This velocity information can then be fed back to the individual platforms, allowing smaller correlation gates which will enable tracking in higher density scenarios. The drawback to this approach is an increase in the amount of data that needs to be communicated among the platforms. This paper considers the performance implications of four different multi-platform architectures: sharing the best track, fusing all of the tracks, fusing all of the sensor reports, and fusing sensor reports that contain range rate information. The metrics that will be analyzed are: track initiation time, velocity accuracy, and communication message bandwidth.

1. Introduction

With the advent of high speed computers, taskable electronically scanned antenna (ESA) radars, high bandwidth communication links, and advanced data fusion algorithms, new approaches to distributed data fusion can be considered. The concept that will be explored in this paper is to share target range rate information among participants in a communication link. Some possible uses are: improved velocity estimation, reduced track initiation time, smaller correlation gates, maneuver detection, determination of Doppler notch conditions, and detection of low cross section targets. Section 2 of this paper will define the variables and develop the necessary relationships to investigate the effects of engagement geometry

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and noisy range rate measurements on estimating target speed and heading. Section 3 will present the results of Monte Carlo simulation runs to verify the results in section 2. Section 4 will compare performance effects of sharing sensor reports versus tracks in distributed data fusion systems.

2. Problem Description

2.1. Calculation of a Target's Range Rate

A target's range rate is the component of a target's speed in the direction of a particular platform. Typically, the platform's radar measures a Doppler frequency shift (see [1]) brought about by the relative motion between the target and the platform. The relative range rate is calculated by:

$$\dot{R} = -f_D * \frac{\lambda}{2} \quad (1)$$

where f_D is the Doppler shift and λ is the transmitted wavelength. The target's range rate is then calculated by removing the contribution of the platform motion in the direction of the target.

From [2], the one sigma range rate error is calculated by:

$$\sigma_{\dot{R}} = \frac{(\lambda/2) * \Delta f}{\sqrt{12}} \quad (2)$$

where Δf is the Doppler resolution of the radar system. For a high PRF radar, typical values of $\lambda = 0.1\text{ft}$ and $\Delta f = 100\text{ Hz}$ yield a range rate error of approximately 1 knot.

For most sensors, the cross-range speed is not observable so that a target's speed cannot be accurately estimated with a single sensor report. In fact, targets with the same position and range rate can have vastly different speeds. However, with sensing platforms at different viewing angles to the target, an accurate estimate of a target's speed and heading can be made.

2.2. Estimation of Target Speed and Heading

Consider the case of a single target observed by two platforms as shown in Figure 1. The target's range (R), bearing (θ), and range rate (D) are measured from each platform with errors σ_R , σ_θ , and σ_D respectively. Assuming that both sensor measurements occur at the same time, the target's velocity (speed and heading) can be calculated as follows. The speed S of a target can be calculated by:

$$S \cos(\alpha_i) = -D_i, \quad i = 1, 2 \quad (3)$$

where α_i is the angle between the target's velocity vector and line connecting the target and platform (the minus sign defines range rate as negative for closing targets). Now, define:

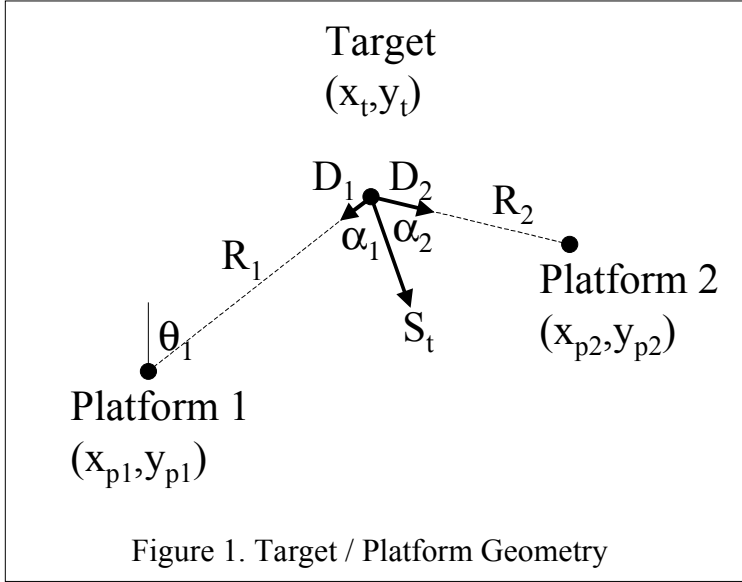
$$\phi = \alpha_1 + \alpha_2 \quad (4)$$

so that

$$\cos(\alpha_2) = \cos(\phi - \alpha_1) = \cos(\phi) \cos(\alpha_1) + \sin(\phi) \sin(\alpha_1) \quad (5)$$

and using

$$\sin(\alpha_1) = \sqrt{1 - \cos^2(\alpha_1)} \quad (6)$$



yields

$$S = \csc(\phi) \sqrt{D_1^2 + D_2^2 - 2D_1D_2 \cos(\phi)} \quad (7)$$

To solve for the target's heading, note from Figure 2 that, for each platform, there are two solutions for the target's heading. This is because $\cos(\alpha) = \cos(-\alpha)$. Therefore,

$$\alpha = \pm a \cos(D/S) \quad (8)$$

and so the heading (denoted H) is:

$$H = \theta \pm (180 - \alpha) \quad (9)$$

The ambiguity is removed by comparing the possible headings calculated from the two platforms. Only two of the possible headings will match (the bold arrows in Figure 2) to produce the correct heading estimate.

2.3. Speed and Heading Error Analysis

An error analysis was undertaken to determine the speed and heading errors. Since speed is a function of the range rate measurements, the speed error is calculated by using the propagation of uncertainty techniques described in [3]. Assuming negligible error contribution by ϕ , the speed error is:

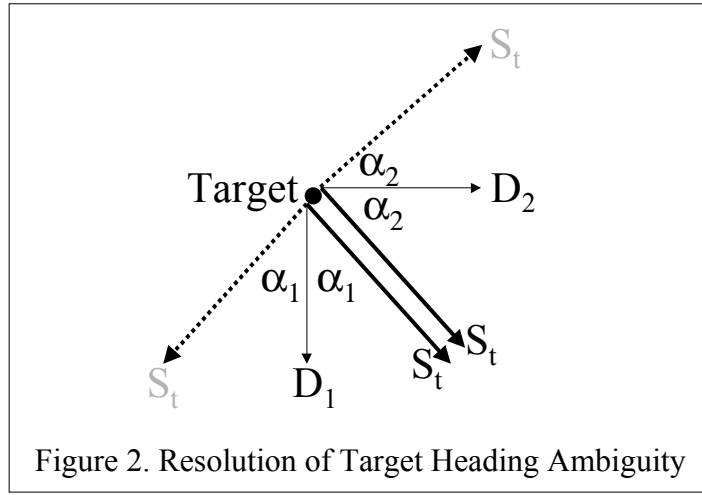
$$\sigma_s = \sqrt{(\partial S / \partial D_1)^2 (\sigma_{D_1})^2 + (\partial S / \partial D_2)^2 (\sigma_{D_2})^2} \quad (10)$$

Assuming $\sigma_{D_1} = \sigma_{D_2} = \sigma_D$, and using equations (7) and (10), after some algebraic manipulation, the speed error is:

$$\sigma_s = \left(\frac{\sigma_D}{S}\right) \csc^2(\phi) \sqrt{(D_1 - D_2 \cos(\phi))^2 + (D_2 - D_1 \cos(\phi))^2} \quad (11)$$

In a similar manner, the heading error is calculated as:

$$\sigma_H = \left(\frac{\csc(\alpha)}{S}\right) \sqrt{(\sigma_s \cos(\alpha))^2 + (\sigma_D)^2} \quad (12)$$

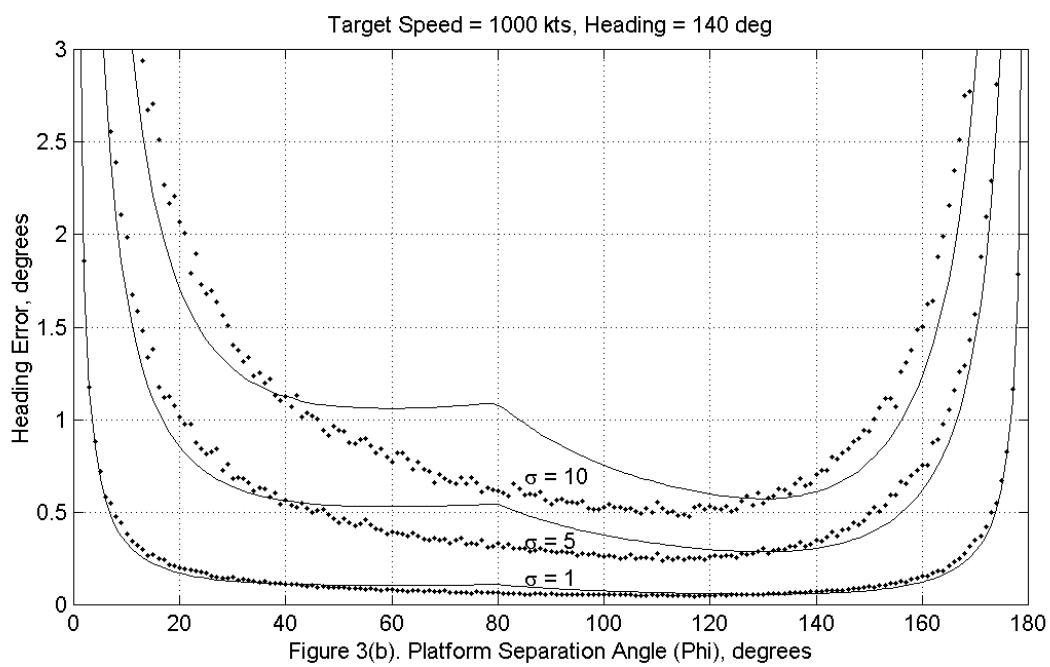
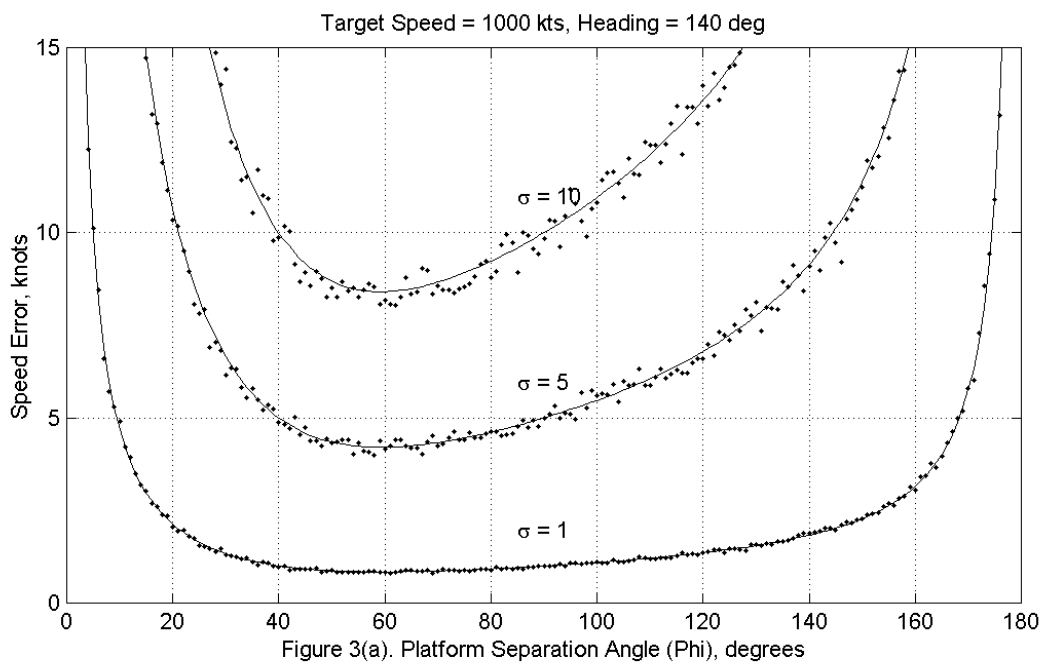


3. Monte Carlo Simulation

Simulation experiments were conducted to verify the results from section 2. For each simulation, the target and platform 1 starting positions were fixed at 200 nmi apart. The position of platform 2 was varied so that the separation angle between the platforms (denoted as ϕ) varied from near zero to near 180 degrees, yielding a total of 179 simulations. Within each simulation, the target's speed was held constant at 1000 knots, but the target's heading was varied from 1 to 360 degrees, yielding a total of 360 sub-scenarios. Within each of these sub-scenarios, 500 Monte Carlo runs were made, with gaussian random draws on the range rate errors. Each sub-scenario was run with $\sigma_D = 0, 1, 5,$ and 10 knots. Perfect knowledge of ϕ was assumed.

3.1. Results of Error Analysis

Figure 3 shows the results of these experiments. The dots represent the calculated errors (standard deviation of error over the 500 Monte Carlo runs) and the lines represent the estimated error (mean error from equation 11). The graphs in Figure 3 are the results for a target heading of 140 degrees; The results are similar for other target headings, especially for good platform separation angles (20 to 160 degrees).



3.2. Conclusions

The results of the above analysis confirm two things. First, very accurate speed and heading estimates can be obtained from just two sensor reports with moderately advantageous (non-collinear) viewing angles. Second, accurate error estimates can be obtained from the equations developed above.

4. Tracks vs. Sensor Reports for Distributed Data Fusion

This section of the paper will briefly look at the performance impacts of sharing sensor reports vs. tracks in the areas of track velocity accuracy and track initiation time.

Consider again a simulation consisting of one target and two platforms, similar in geometry to Figure 1. The target starts at $(x,y) = (0,0)$ and moves at a speed of 1000 knots and a heading of 165 degrees. Platform 1 is located at $(0,-200)$. Platform 2 is located at approximately $(128.6, -153.2)$, so that the platform separation angle ϕ is initially 40 degrees. Both platforms detect the target at times $t = 0, 10, 20, \dots$ (i.e. every 10 seconds). Both platforms use a 4 state kalman filter $(x, \dot{x}, y, \dot{y})$ and rotate the sensor measurement errors from range/bearing into x/y . No use is made of the range rate information in tracking the target.

Three different cases for data distribution will be considered: (1) sending out sensor reports, (2) sending out the best platform track and (3) sending out all tracks (for fusion).

4.1. Description of Scenario Time History

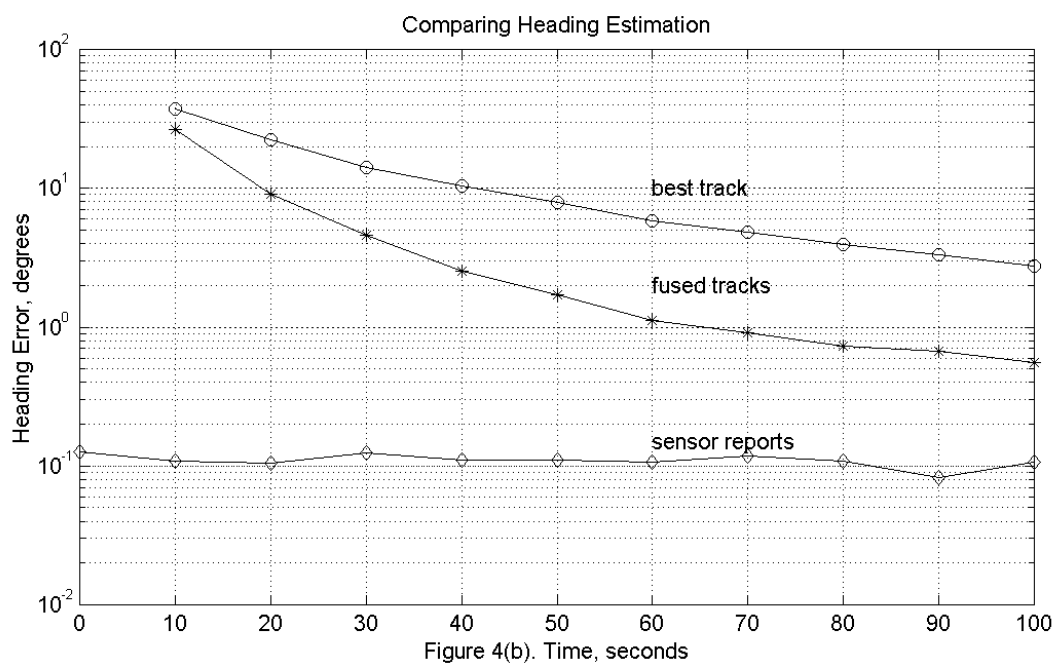
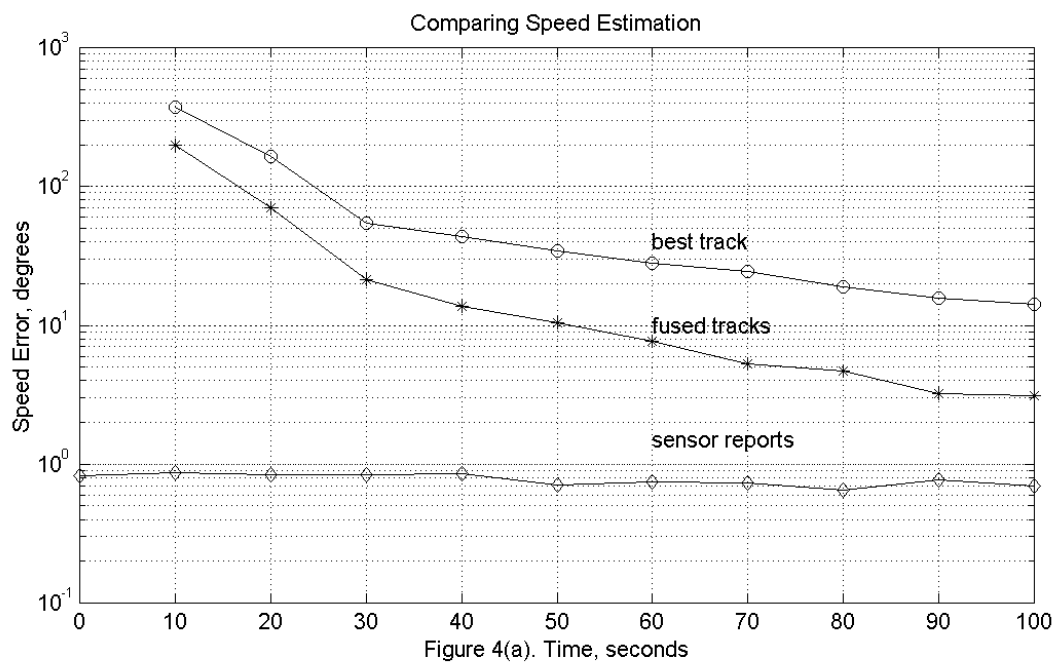
At time $t = 0$, both platforms generate a sensor measurement (or report) on the target. These two reports can be combined to estimate the target's velocity (as well as improve the target position accuracy). No tracks are formed yet by either platform.

At time $t = 10$, both platforms generate a second report. Also, this would be the first opportunity to create a track. If the platforms were in a communication link with reporting responsibility rules similar to Link 16, only one of the platforms would transmit a track over the link. In this case, a very crude estimate of the target's velocity would be made. If the link supported distributed track fusion, both platforms would transmit their track information. The tracks are then fused, yielding a more accurate velocity estimate.

The scenario continues through time $= 20, 30$, etc., with the resulting velocity estimates collected for the three case listed above.

4.2. Description and Results of Monte Carlo Experiment

Fifty Monte Carlo runs were performed for this scenario with gaussian random draws on the range, bearing, and range rate errors ($\sigma_R = 0.1$ nmi, $\sigma_\theta = 0.5$ degrees, and $\sigma_D = 1$ knot respectively). The results are presented in Figure 4 which show superior velocity estimation (over the first 100 seconds) and reduced track initiation time. Track fusion shows reasonable performance after about 1 minute but it may be slow to respond to target maneuvers whereas the sensor report case will continue to produce accurate velocity estimates during target maneuvers.



5. Future Work

This paper has outlined the basic concept of using target range rate information in a distributed data fusion system and has applied the results to improved velocity estimation and reduced track initiation time. Other applications exist and many real world issues need to be investigated and resolved.

5.1. Other Applications

As mentioned in the introduction, the use of the concept developed in this paper can be extended to provide smaller correlation gates, maneuver detection, determination of Doppler notch conditions, and detection of low cross section targets. These will be addressed in future papers.

5.2. Details to Investigate

The key to real world deployment of this concept is the ability to correctly correlate and quickly communicate the offboard sensor reports. Communication link loading in particular needs to be investigated to determine if this approach will be feasible. The details would include sensor false alarm rates and update rates, number of platforms and targets, and the communication system architecture. Advanced correlation algorithms that use velocity hypotheses need to be developed. Techniques for removal of biases, gridlock errors, and communication latency need to be studied and incorporated. Also, larger, non-gaussian range rate errors (e.g. due to multipath or jet engine modulation) will need to be identified and corrected.

The simultaneity of sensor reports was assumed in this paper but the results can be extended to include non-simultaneous reports. Also, with the development of ESA radars, high bandwidth communication links, and advanced sensor management techniques, nearly simultaneous measurements can be obtained with coordinated resource allocation efforts.

6. References

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3. John Taylor, *An Introduction to Error Analysis*, University Science Books, Mill Valley, CA, 1982.