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Multistatic pseudolinear target motion analysis using hybrid measurements

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ABSTRACT

This paper presents a new hybrid pseudolinear estimator (PLE) for target motion analysis of a constant-velocity target in the two-dimensional plane using angle-of-arrival, time-difference-of-arrival and frequency-difference-of-arrival measurements obtained from spatially distributed stationary passive receivers. The hybrid PLE is developed by linearizing the nonlinear measurement equations in the unknown target motion parameters. The resulting estimator is not only closed-form and has low computational complexity, but is also free from nuisance parameters, therefore avoiding the problems arising from the dependence of the nuisance parameters on the target motion parameters. However, the noise injected into the PLE data matrix causes biased estimates. To address this, a bias-compensated PLE is proposed based on an asymptotic bias analysis of the hybrid PLE. This estimator is then incorporated into a weighted instrumental variable (WIV) estimator to obtain asymptotically unbiased estimates of the target motion parameters. The WIV estimator is shown to be asymptotically efficient both analytically and through numerical simulation examples. Furthermore, it is observed that the WIV estimator performs similar to the computationally demanding maximum likelihood estimator, closely achieving the Cramér–Rao lower bound and producing negligible bias at moderate noise levels.

1. Introduction

Target motion analysis (TMA) has been an area of intensive research for many years with plenty of applications in both civilian and military domains including wireless sensor networks, acoustic source localization, and radar and sonar systems, to name a few. The objective of TMA is to estimate the position and velocity of a moving target (i.e., the target trajectory) from noisy sensor measurements collected by a moving receiver or a number of spatially distributed stationary receivers. In passive TMA, the receivers "listen" for the signal emitted by a target or exploit an "illuminator of opportunity" from a nearby transmitter station as their sources of signal transmission. A passive system offers significant advantages over its active counterpart such as capability to counter stealth technology, much less vulnerability to electronic countermeasures as it emits no radio energy, and lower cost in terms of system implementation and maintenance as no transmitter hardware is required [1,2]. In this paper, we focus on passive multistatic TMA in the two-dimensional plane where the position and velocity of a moving target with constant velocity are estimated using angle-of-arrival (AOA), time-difference-of-arrival (TDOA) and frequency-difference-of-arrival (FDOA) measurements obtained from spatially distributed stationary receivers.

Estimating the target position and velocity from AOA, TDOA and FDOA measurements is not trivial because of the nonlinear relations between the AOA, TDOA and FDOA measurements, and the target position and velocity. Several TMA estimation algorithms have been developed in the literature. The extended Kalman filter (EKF) [3] is widely used to tackle the nonlinearity. However, the EKF requires a good initialization to avoid potential divergence. Moreover, it has no optimality properties and its performance is strongly dependent on the accuracy of the linearization of the nonlinear measurement models [3]. More sophisticated nonlinear filters such as particle filters can also be considered, but their high computational complexity [4] makes them less attractive for the TMA problem at hand. Maximum likelihood (ML) estimators were developed for different TMA problems (see e.g., [5–8]). Although the ML estimator is asymptotically unbiased and efficient, it does not have a closed-form solution and is often

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computed using iterative numerical search algorithms that are computationally demanding. In addition, the iterative ML estimator is vulnerable to divergence problems if a good guess on the target position and velocity is not available for initialization.

An attractive alternative to nonlinear TMA solutions is a linear least squares solution which results in a closed-form estimate, requires low computational complexity and does not suffer from divergence problems. For the bearing-only (AOA) TMA problem, this kind of estimator is commonly referred to as the *pseudolinear estimator* (PLE) [7–9]. A disadvantage of the PLE is that it suffers from severe bias problems [5,10]. To overcome the PLE bias problems, a bias-compensated PLE was developed based on instantaneous bias estimation in [7]. Furthermore, an asymptotically unbiased weighted instrumental variable (WIV) estimator was proposed in [7], which was shown to be asymptotically efficient in [11]. For stationary target localization, a two-stage closed-form solution using TDOA measurements was proposed in [12], where a nuisance parameter is introduced to linearize the TDOA equations. Based on this idea, a closed-form solution for target localization using multistatic time-of-arrival (TOA) measurements was developed in [13].

Using heterogeneous sensor measurements in the boarder context of target tracking and localization has recently attracted great attention in the literature [14–21]. Two main motivations behind using hybrid sensor measurements are (i) a smaller number of distinct sensor stations are required to attain the desired level of estimation performance, and (ii) ambiguous solutions, i.e., the ghost targets, which may arise from using one particular type of sensor measurements, can be eliminated [14]. Focusing on linear closed-form solutions, a hybrid TDOA/AOA localization algorithm for a stationary target was developed in [18] based on the two-stage approach presented in [12]. In [19], three closed-form algorithms were developed for localizing a stationary emitter using AOA and Doppler-shift measurements collected by a single moving sensor platform based on the pseudolinear estimation techniques in [7]. Much less attention has been given to moving target scenarios. In [16], a two-stage algebraic solution was presented to estimate the target position and velocity of a moving target using TDOA and FDOA measurements. Here, the authors turned the tracking problem into a localization problem (i.e., estimating the target position and velocity from TDOA and FDOA measurements for each single time instant).

Based on the idea of the pseudolinear algorithms in [7], a hybrid linear estimator using AOA and TDOA measurements has been developed for 3D TMA in [22]. This algorithm cannot be applied to the passive multistatic TMA problem considered in this paper as it assumes a very specific system configuration with one moving receiver and two stationary receivers. Moreover, TDOA measurements cannot be estimated accurately without taking into account the Doppler-shift effect (FDOA) on the received signals caused by the relative motion between the target and the receivers. In the radar literature, TDOA and FDOA measurements are jointly estimated by computing the cross-correlation between received signals using a bank of matched filters in which each matched filter corresponds to a particular value of hypothesized FDOA [23]. Therefore, FDOA measurements are always available parallel to TDOA measurements. Incorporating the FDOA measurements into TMA rather than ignoring them will enhance the estimation performance. Compared with AOA and TDOA measurements which both provide information about the target position, FDOA measurements provide additional information about the target velocity. To the best of our knowledge, no hybrid linear closed-form solution for TMA has been proposed to date using AOA, TDOA and FDOA measurements.

The main objective of this paper is to develop a hybrid multistatic PLE for constant-velocity target with high performance and low computational complexity. As different from [6,12,18,16], to avoid the creation of undesirable nuisance parameters that are dependent on the target motion parameters, the TDOA equations are linearized using the AOA and TDOA measurements jointly, and the FDOA equations are likewise linearized using the AOA and FDOA measurements jointly. In [12,18,16], a two-stage process is required to tackle the dependence of the nuisance parameter on the target position and velocity. However, since no measurement information is involved in the second stage, this may result in inferior accuracy [20]. An enhanced two-step estimator was proposed in [20], but it requires more computation. In this paper, we eliminate the nuisance parameters by exploiting the AOA measurements in the linearization process, thereby avoiding the problems arising from their dependence on the target motion parameters. To overcome the PLE bias problem, an analysis of the asymptotic bias of the proposed hybrid PLE is presented and a bias compensation technique is developed based on instantaneous bias estimates. An asymptotically unbiased WIV estimator is then developed for the hybrid TMA problem utilizing an IV matrix and a weighting matrix constructed from the bias-compensated PLE. An analysis of the efficiency of the proposed WIV estimator is also provided, in which the WIV estimator is analytically shown to be asymptotically efficient, attaining the Cramér–Rao lower bound (CRLB) at low noise levels.

The paper is organized as follows. Section 2 introduces the passive multistatic TMA problem using hybrid AOA, TDOA and FDOA measurements, and describes the assumptions made throughout the paper. Section 3 derives the ML estimator and the CRLB for the hybrid TMA problem. The hybrid PLE is developed in Section 4. An asymptotic bias analysis for the hybrid PLE along with a bias compensation method is covered in Section 5. Sections 6 and 7 present the WIV estimator and its analysis of asymptotic efficiency, respectively. Section 8 provides a comparison of the computational complexities of the proposed estimators and the ML estimator. Comparative simulation studies are presented in Section 9. The paper concludes in Section 10 with a brief summary.

2. Hybrid multistatic target motion analysis

Fig. 1 depicts the two-dimensional TMA problem using AOA, TDOA and FDOA measurements obtained by a passive multistatic TMA system with N stationary receivers. In Fig. 1, $\mathbf{p}_k = [p_{x,k}, p_{y,k}]^T$ and $\mathbf{v}_k = [v_{x,k}, v_{y,k}]^T$ are the unknown target position and velocity at discrete-time instant $k \in \{0, 1, ..., M-1\}$, and

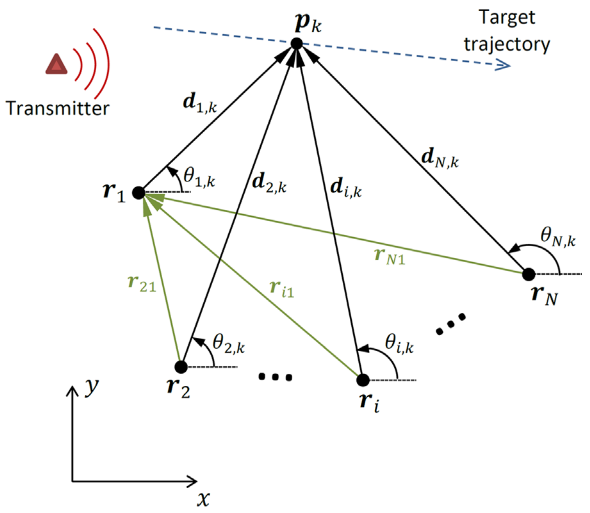

Fig. 1. Two-dimensional hybrid passive multistatic TMA geometry.