ARTICLE IN PRESS

Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Moving scanning emitter tracking by a single observer using time of interception: Observability analysis and algorithm

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Received 20 May 2016; revised 3 August 2016; accepted 19 December 2016

KEYWORDS

Cramer-Rao lower bound;
Least squares;
Observability;
Scanning emitter;
Target motion analysis;
Time of interception

Abstract The target motion analysis (TMA) for a moving scanning emitter with known fixed scan rate by a single observer using the time of interception (TOI) measurements only is investigated in this paper. By transforming the TOI of multiple scan cycles into the direction difference of arrival (DDOA) model, the observability analysis for the TMA problem is performed. Some necessary conditions for uniquely identifying the scanning emitter trajectory are obtained. This paper also proposes a weighted instrumental variable (WIV) estimator for the scanning emitter TMA, which does not require any initial solution guess and is closed-form and computationally attractive. More importantly, simulations show that the proposed algorithm can provide estimation mean square error close to the Cramer-Rao lower bound (CRLB) at moderate noise levels with significantly lower estimation bias than the conventional pseudo-linear least square (PLS) estimator.

1. Introduction

Determining the position and velocity of a moving source by a single or multiple observer(s), which is also referred to as target motion analysis (TMA), is essential for many applications such as radar, sonar, reconnaissance, and wireless networks.[1–4] For a non-cooperative source, the TMA can be based on the direction of arrival (DOA), frequency of arrival (FOA), time of arrival (TOA), time difference of arrival (TDOA) or their combinations.

The DOA-based TMA has been a classical estimation problem.[4–8] However, estimating DOA requires multiple receiving channels, which increases the system complexity and leads to high cost. In addition, the direction finding accuracy is vulnerable to the amplitude/phase unbalance between receiving channels. On the other hand, the FOA-based TMA which uses the Doppler effect[9,10] needs only a single receiver channel. This technique requires relatively high frequency estimation precision and therefore it is more suitable for tracking emitters with simple modulation types and with known carrier frequency, which cannot always be satisfied for non-cooperative source.

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.03.006

The TOA-based TMA requires only a single receiver channel as well. However, it is mainly used for tracking emitters with known pulse repeat interval (PRI) pattern.[11,12] The TDOA-based TMA needs at least two observers and requires accurate time synchronization among obsevers.[13,14] For the scanning emitter, such as the mechanically scanning radar, which covers the surveillance area in a periodic manner using a narrow beam antenna,[15] the TMA problem can be resorted to the time of interception (TOI), which is the time when the peak location of the main lobe of the scanning emitter reaches the observer. Unfortunately, the TMA methods mentioned above cannot be directly used for the scanning emitter tracking using TOI measurements.

The origin of the scanning emitter localization technique can be traced back to locating mobile robots from landmark bearings,[16–18] where the difference of directions to the landmarks are explored to determinate the robot position. By transforming the TOI measurements into the direction difference of arrival (DDOA), the same idea can be used in the considered problem of the scanning emitter passive TMA. To obtain the target position and velocity from the DDOA measurements, the existing estimation methods,[15,19–23] nevertheless, all assume multiple observers and the static scanning emitter. In this work, the TOI-based tracking of a moving scanning emitter using a single observer is investigated.

By a single observer, the TOI measurement can be obtained at most once in one scan cycle. As a result, measurements should be accumulated over multiple scans for parameter or state estimation. Fewer literatures have been devoted to this topic. The static emitter localization method using a single observer has been studied,[24] and the performance of the geometric solution[15] with 3 measurements is compared at different noise levels.[24] However, this solution cannot be directly used in the TMA for a moving scanning emitter. Therefore, new solutions to such a TMA problem are needed. They would be nontrivial solutions because of the strictly high nonlinearity between TOI and the position and velocity of the emitter. In addition, insights into the least number of measurements required for unique identification of the scanning emitter trajectory are highly desirable, as they are indeed the observability conditions for the TMA problem in consideration.

Derivation of the observability conditions of the TMA problem is intractable due to the nonlinear characteristic of the problem. Two methods, the nonlinear differential equation method[25] and the linearization-based method,[26] have been applied to the observability analysis for the nonlinear system. These methods are mathematically complicated and do not provide useful insights as well. When the emitter is fixed, the observability condition can be derived easily using simple geometrical method since the observer and the emitter are located on a positioning circle defined by the TOI measurement.[15] However, it becomes more complex for the moving emitter because it is hard to determine the positioning circle non-uniquely, due to the emitter motion. To analyze the observability in presence of the high nonlinearity between the measurements and the target state, a re-parameterization method is introduced in this work in order to obtain an equivalent analytic model. Some necessary observability criteria are established on the basis of this model and physical interpretations for the obtained conditions are given.

A possible approach for the scanning emitter TMA is to recast it into a nonlinear least square (NLS) problem by using the maximum likelihood (ML) solution.[21–23] However, NLS estimation requires a proper initial guess close to the true solution, which may not be easy to find in practice. To make use of the geometrical characteristic intrinsically in the measurements, we transform the TOI into DDOA measurements.[19] A pseudo-linear least square (PLS) estimator is then proposed by considering the first DOA as a nuisance parameter to be identified jointly with the emitter motion trajectory. However, it is known that the PLS estimator suffers from the presence of significant bias.[5,8,19] To reduce the estimation bias caused by the correlations between the regressor and regressand, an instrumental variable (IV) method is proposed. A weighted IV (WIV) estimator is also developed to reduce the estimation variance. The proposed method attains performance very close to the Cramer-Rao lower bound (CRLB) at moderate noise levels.

The rest of this paper is organized as follows. Section 2 establishes the DDOA model for the scanning emitter TMA using TOI only with multiple scans. Section 3 conducts the observability analysis and gives the physical interpretations. Section 4 presents the closed-form PLS estimator as well as the WIV estimator. Section 5 presents the simulation results to verify the proposed estimators. Finally, conclusions are drawn in Section 6.

2. Problem formulation

Without the loss of generality, we consider the TMA problem in a 2D plane. As shown in Fig. 1, an emitter is moving at a constant velocity $\dot{\boldsymbol{x}} = [v_{Tx}, v_{Ty}]^{\mathrm{T}}$. There is a mechanically scanning antenna with a known constant scan rate ω at the emitter. Its main beam periodically sweeps across a single maneuvering observer, which intercepts the signals and records the interception time of the beam peaks.[15] It is assumed that at time t_k, the observer, located at $\boldsymbol{s}_k = [x_{ok}, y_{ok}]^{\mathrm{T}}$, intercepts the main beam signal, which was transmitted by the emitter at $\boldsymbol{x}_k = [x_{Tk}, y_{Tk}]^{\mathrm{T}}$.

According to Fig. 1, the TOI measurement of the scanning signal is

$$\hat{t}_k = t_k + \eta_k = \frac{\beta_k - \beta_0}{\omega} + (k-1)T_n + \frac{r_k}{c} + t_0 + \eta_k \tag{1}$$

where $k = 1, 2, \ldots, N$. N is the total number of the interceptions. c is the speed of light. $T_n = 2\pi/\omega$ is the scanning period, which is known because ω is known. t_0 and β_0 are the initial

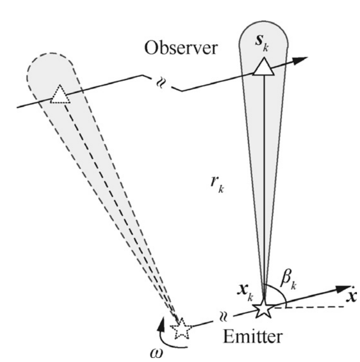

Fig. 1 Illustration of tracking a moving scanning emitter via a single observer.