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Path planning for two unmanned aerial vehicles in passive localization of radio sources

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ABSTRACT

This paper studies the trajectory control problem for a pair of unmanned aerial vehicles (UAVs) equipped with time of arrival (TOA) sensors to measure the time difference of arrival (TDOA) of the transmitted radio signal to localize the source. The extended Kalman filter (EKF) is applied to estimate the source's position. The proposed trajectory control strategy encompasses three optimum experimental design criteria based on the position error covariance produced by the EKF. The control strategy steers the UAVs to the positions to minimize the uncertainty about the location of the source. The effectiveness of the proposed approach is illustrated through simulation examples.

1. Introduction

Passive localization of radio sources (emitters) has several civilian and military applications in electronic warfare systems, search and rescue scenarios, indoor environments, wireless mobile telecommunication systems and so on. Although, the source could be localized by stationary sensors mounting the sensors on moving vehicles can greatly enhance the localization performance [1]. Aerial localization of radio sources is an appropriate alternative for a large number of applications. The speed, flexible steering ability, and wide vision of the aerial vehicles may improve the localization accuracy and speed. Flying above the ground level reduces the uncertainty about the transmitted signal caused by obstacles and improves the detection of the position related parameters of the radio signal.

Optimal trajectory control for a pair of UAVs in radio source localization is tackled in this paper. The localization scenario in this paper estimates the location of a stationary radio emitter recursively based on a sequence of noisy measurements obtained by TOA sensors. To eliminate the uncertainty about the signal transmission time TDOA measurements are applied for source location estimation. According to the measurement equations the estimation accuracy is a function of the relative sensor-source geometry [2,3]. Therefore, in the case that the sensors are mounted on the UAVs the localization performance depends heavily on the UAV trajectories. Sensor platform motion planning has many applications in search and rescue scenarios [4,5], target tracking [6,7], environmental monitoring [8], surveillance systems [9,10], as well as defense applications [11]. The objective of the UAV trajectory optimization is to determine the UAV waypoints in order to maximize the emitter location estimation accuracy. Since the emitter position is unknown, the relative geometry is optimized based on the last emitter position estimation. Consequently, the location estimation accuracy and the trajectory selection effectiveness have mutual impact on each other.

A vast amount of work has been performed in the area of optimal UAV trajectory control in radio source localization over the last decade. Doğançay [12] has developed online receiver trajectory optimization algorithms for AOA/scan-based emitter localization. Doğançay et al. [13] have considered a multisource environment and have allocated a UAV team for localization of each source. In the work presented in [14] the path planning problem for multiple UAVs with heterogeneous payload sensors has been studied. The proposed steering algorithms in [12–14] control the UAV trajectories based on maximizing the determinant of approximated fisher information matrix (FIM). The active target-tracking problem for a team of UAVs equipped with 3-D range-finding sensors has been studied in [15]. A path planning approach has been proposed in [16] for the limited number of UAVs in the RSS based localization of a single source. In the present paper a gradient-based waypoint optimization for a pair of UAVs equipped with TOA sensors applying D-, A- and E-optimality criteria based on the estimated position error covariance produced by the EKF is studied.

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The TOA is a sensor-source range based parameter which has been consistently applied for localization of the radio emitters [17–19]. However, a single TOA does not have any sensor-source range information when the signal emission time is unknown. In the case that there are two such measurements subjected to the same signal the TDOA observation is obtained. TDOA eliminates the need to know the emitter emission time that is required for TOA based localization. A noise free TDOA measurement in two-dimensional space specifies the location of the emitter on a hyperbola. N TOA sensors generate $N-1$ non-redundant TDOA measurements subjected to an identical transmitted signal. In the absence of measurement noise the emitter is located at the intersection of $N-1$ hyperbolae. For two-dimensional noise free localization at least three TDOA measurements are required to find the emitter position [20]. Generally, the measurements are noise corrupted and the hyperbolas will no longer intersect exactly at the emitter location and an estimation algorithm should be applied.

Applying an additional sensor (UAV) increases the localization accuracy. However, in addition to the cost of the UAVs applying an additional UAV intensify the complexity of path planning and localization processes and suitable low bandwidth communication network provision for transferring the measurements. Therefore, some applications may require to apply the minimum number of UAVs and increase the target location estimation accuracy through geometry optimization; e.g. in the search and rescue scenarios when there are a large number of sources in a large search area which require to appoint a UAV group to each source. For TDOA localization at least two sensors are required to form at least a single TDOA measurement at each time step and estimate the source location based on the sequence of observations. In this paper a trajectory control strategy is proposed for the minimum number of UAVs in TDOA localization.

Several works have addressed the problem of localization of radio sources with limited number of sensors. Okello et al. [21–23] have applied TDOA measurements received by two UAVs as they traverse the predefined trajectories to localize a stationary or moving emitter. Three nonlinear filters: a Gaussian mixture measurement integrated track splitting filter, a multiple model filter with unscented Kalman filters, and a multiple-model filter with extended Kalman filters have been compared in [21]. The researchers in [21–23] have studied the TDOA based localization performance applying two UAVs in the case that the UAV trajectories are predefined.

There are not enough studies about the optimal trajectory control for limited number of UAVs in radio source localization with the objective of minimizing the estimation uncertainty. Doğançay [24] has proposed a trajectory control algorithm for any number of UAVs equipped with AOA sensors. The UAV paths are optimized by minimizing a cost function comprising the mean-squared error (MSE) of predicted target position estimates produced by the EKF. A trajectory control for two UAVs in DRSS localization of multiple stationary RF emitters is proposed in [25]. In the latter research the path optimization is performed based on the determinant of the approximated FIM.

In this paper the localization of a stationary emitter by two UAVs measuring the TOA of the radio signal has been investigated. In order to eliminate the uncertainty about the transmission time the TOA observations at each specified time step form a single TDOA measurement. The sequence of measurements coupled with the emitter motion model is essential to estimate the emitter location over time. An updated estimate of the target location is required in each measurement instant. The interest of the present study is not in deriving the position estimators but rather in optimization of the UAV trajectories that could be achieved applying any unbiased estimator. Since the TDOA is a nonlinear measurement the EKF which is a nonlinear filtering technique is applicable for the proposed problem of this paper.

In the trajectory control problem the UAV waypoints should be selected to optimize an objective function, i.e. the path length, the localization accuracy, and so on. The objective of this study is to select the waypoints which increase the source location estimation accuracy. The position error covariance produced by the EKF measures the estimation uncertainty and also is related to the localization geometry. Therefore, minimizing some real-valued functions defined on the position error covariance may find the waypoints that increase the localization accuracy. In this research three most popular optimum experimental design criteria, D-, A- and E-optimality, based on the position error covariance produced by the EKF have been applied for UAV trajectory optimization.

This paper is organized as follows. The next section provides the source localization problem description and the EKF design for TDOA localization with two TOA sensors. Then the proposed path-planning approach for two UAVs is described in the presence of geometric path and movement constraints. Three optimum experimental design criteria based on the position error covariance are presented. Extensive simulation examples for the proposed UAV steering algorithms are provided and conclusions are drawn afterwards.

2. Source localization

2.1. Problem description

Consider a stationary radio source at unknown three-directional Cartesian position. The emitter is a radio source with omnidirectional propagation. Two UAVs at known Cartesian positions equipped with omnidirectional antennas are tasked to localize the emitter. The location of the UAVs could be achieved by the Global Positioning System (GPS). Both UAVs are equipped with electronic support measures (ESM) to observe the TOA of the propagated signal. The TOA measurements subjected to an identical transmitted signal at the UAVs are estimated at known time steps. The interval between two consecutive time steps (measurements) is T seconds.

The signal trip time (TOA minus the time of transmission) is a linear function of the sensor-source range. Furthermore, the altitude of the UAVs and the source are known for the system; the source is located on the flat ground. Accordingly, without loss of any information a two-dimensional model could be applied for the localization and path planning scenarios. However, the observed three-dimensional TOAs could be converted to the two dimensional measurements through Pythagorean Theorem. The unknown two-dimensional Cartesian position of the source and the known Cartesian positions of the UAVs are denoted by $\mathbf{x}=[x,y]^T$ and $\mathbf{u}_k^i=[u_{x,k}^i,u_{y,k}^i]^T$, $i=1,2$ respectively. The superscript ^{T} denotes the matrix transpose operator and k refers to the instants when the measurements are formed. The TOAs and the UAVs' positions are transmitted to a processing unit to perform the calculations. The processing unit is located in one of the UAVs.

Each UAV measures the time of arrival of the transmitted signal with additive zero-mean white Gaussian noise with a standard deviation of σ_t. The TOA measurement at the UAV i formed at time step k is given by:

$$t_k^i=t_k+r_k^i/c+n_k^i \qquad (1)$$

where t_k is the source transmission time, $r_k^i=\|\mathbf{x}-\mathbf{u}_k^i\|$ is the Euclidean direct distance between the emitter and UAV i at time step k, c is the signal propagation speed, and $n_k^i\sim N(n;0,\sigma_t^2)$ is the TOA measurement noise where $N(n;m,P)$ is the probability density function (pdf) of a Gaussian distribution of variable n with mean m and variance P.