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Distributed localization using acoustic Doppler

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ABSTRACT

It is well-known that the motion of an acoustic source can be estimated from Doppler shift observations. It is however not obvious how to design a sensor network to efficiently deliver the localization service. In this work a rather simplistic motion model is proposed that is aimed at sensor networks with realistic numbers of sensor nodes. It is also described how to efficiently solve the associated least squares optimization problem by Gauss–Newton variable projection techniques, and how to initiate the numerical search from simple features extracted from the observed frequency series. The methods are evaluated by Monte Carlo simulations and demonstrated on real data by localizing an all-terrain vehicle. It is concluded that the processing components included are fairly mature for practical implementations in sensor networks.

1. Introduction

The motion of a passing acoustic source can be estimated from the observed Doppler shift. We consider an acoustic sensor network with two or more synchronized nodes with known positions. It is assumed that the Doppler frequency of a passing acoustic source can be detected and measured by each sensor. It is further assumed that the source motion obeys a parameterized model. We address the problem of identifying the model parameters, from which the source trajectory is deduced.

The problem of localizing moving acoustic sources based on Doppler shift observations has received fairly much attention in the literature, especially during a period around 1990. Still, there are aspects within the area that are not entirely covered, and today it would be particularly interesting to revive the interest for the acoustic Doppler phenomenon with the background of both the last decade of advances in wireless sensor network technologies and new opportunities to solve the associated numerical problems with state-of-the-art algorithms.

A number of authors have considered the case with a single sensor by which the source passage distance and assumed constant speed are estimated [1–4]. It appears, however, that the estimation problem is inherently nonlinear in the parameters, and a rather wide range of different numerical approaches are proposed to pursue the, in various senses, optimal estimate. Most commonly, the parameters are given by minimizing some variation of a least squares criterion.

A complication in the acoustic case is the *retardation*; the effect that, when the sound reaches the sensors, the source has already moved to a new position, see [5]. To avoid any misunderstanding regarding our terminology, note that the retardation effect is unrelated to any source velocity retardation. It is the phenomena that follow from retarded signals; signals that are delayed due to finite propagation speed. In the radar case, this effect can usually be disregarded since the propagation speed of the electromagnetic waves is many orders of magnitudes larger than

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the speed of most sources of practical interest (the "stop-and-go approximation"), see [6, p. 97]. Disregarding the retardation in the acoustic case may, depending on geometry and source speed, however result in significant estimation bias.

The approximate retardation-free model can be parameterized with only two nonlinear parameters (instead of three or four), for instance, an x and a y coordinate on the source trajectory. This low parameter dimension facilitates an exhaustive grid search for the (least squares) minimum, which avoids otherwise problematic local minima. This is elegantly demonstrated by [2]. By also using the frequency time derivative as a measurement, the grid search can be conducted in only one dimension, see [7]. Actually, by disregarding the retardation, an exact solution based on a deterministic model and three frequency measurements can be found by calculating the roots of a third order polynomial, see [1].

Another estimation technique is to match an observed frequency series with a library of precomputed Doppler shift profiles. This way, a complex retardation model may be used as a basis, and the estimation step can be implemented on a simple platform (wireless sensor) with computational limitations, as showed by [4].

The validity of a retardation model has been demonstrated by having a single sensor estimating the distance to, and speed of, a passing propeller-driven aircraft, see [3].

There are also examples of sensor networks with multiple sensors that use Doppler shift for source localization. A way to do this is to model the measured frequency difference (in effect of the Doppler shift) among every sensor pair in the network. This rich set of measurements may then be informative enough to identify more complex motion models, for instance ballistic trajectories, see [8]. Another (suboptimal) way to configure the network is to have each sensor make a local estimate of the passage distance and speed, and then transmit the results to a fusion node that in turn aggregates the individual estimates to a more informative output in terms of global trajectory coordinates. This was demonstrated by [2] and later by [9]. If the state of the source is *a priori* known at some instant, Doppler based source tracking can be accomplished by calculating a frequency stretch factor between pairs of distributed microphones. This technique is proposed in [10], where the authors demonstrate aircraft tracking with a network of seven microphones. The aircraft state may then be assumed known at take-off or touch-down by means of ground control cameras.

There are many reasons for keeping the number of sensors in a network moderate, such as purchase, deployment, and maintenance costs. Balancing costs, in terms of sensor count, with performance is an essential part of the sensor system design that requires careful analysis. For instance, with as few as five Doppler sensors (with a non-degenerate geographical distribution) it is possible to uniquely and instantaneously determine the source position, see [11].

The scientific contribution of this work includes the analysis of a new circular motion model for acoustic Doppler measurements that accounts for acoustic propagation delays. It is not sensitive to retardation effects since the propagation delay is explicitly modeled. The model is more general or flexible than the frequently proposed linear motion models, but also more complex to identify. Most models in the literature referenced above are based on linear motion. We have also studied linear models to confirm the results of earlier works and to investigate how these can be extended to sensor network settings. Parts of these studies we published in [12], but since the linear motion is just a special case of the model we propose here, we have however chosen not to include these studies in this paper. The linear models are not appropriate at all for the non-linear motion used in the numerical experiments.

The estimator will here be developed as the solution to a least squares problem which is pursued by numerical minimization. However, the objective function is not generally convex. Particularly, when an acoustic source is observed for only a few seconds by a limited number of sensors operating at low signal-to-noise ratio, it is challenging to find a robust initialization that yields a successful minimization. We recently proposed the new model in [12]. The news in this work is (1) a robust solution to the initialization problem and (2) error analysis which is based on extensive Monte Carlo simulations.

The identification is formulated as a batch processing problem, which means that the source has more or less passed the sensors before the parameters are estimated. This is suitable for implementation on lightweight platforms (wireless sensor nodes) in applications where a delay of a few seconds is acceptable. This does not necessarily restrict the method to off-line uses. All on-line system solutions are in fact associated with various degrees of response delays attributable to processing time, transmission time and so forth. The point is that the proposed method could very well be used in on-line systems, but may not be the best choice in situations where the response delay is critical. An application could be a ground sensor network that from a limited set of alternatives decides which way passing vehicles take. Another application is a sensor that can determine the trajectory of passing aircraft [3,9,10] or rockets [4]. Also passive sonar has been mentioned in the literature. Moreover, we presented a tracking application for multiple ground vehicles with a probability hypothesis density (PHD) filter using Doppler measurements in an acoustic sensor network, see [13]. For more references on Doppler-based tracking we refer to that work.

The paper is organized as follows. Next, in Section 2, the estimation problem is formalized and modeled, and the general assumptions made are described. Then a method to efficiently initialize the resulting optimization problem is detailed in Section 3, followed by a tailored Gauss–Newton method to solve the estimation problem in Section 4. Section 5 then briefly discusses implications in the context of sensor networks, before the suggested method is validated, in Section 6, using both Monte Carlo simulations and experiments on real data from an all-terrain vehicle. Finally, conclusions are provided in Section 7.

2. Signal model

The Doppler model is based on the source–observer *propagation delay*, $\Delta(t)$, which leads to a comprehensive