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Doppler-aided localization of mobile nodes in an underwater distributed antenna system

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ABSTRACT

In this paper, we consider a problem of localizing a moving object in the context of an underwater distributed antenna system. All the distributed nodes record the time-of-arrivals of a single message from the moving object and obtain the Doppler speed estimates used in the decoding process. Conventional methods have relied only on the time-of-arrival measurements to obtain position estimates, on top of which filtering methods can be further applied for tracking purposes. In this work, we explore the usefulness of Doppler speed information. The combination of time-of-arrival measurements and Doppler speed estimates associated with a single message enhances the accuracy of position estimation and provides an estimate of the velocity of the mobile object. A Kalman Filter (KF) and a Probabilistic Data Association Filter (PDAF) are further implemented processing the point estimates. Simulations show that the proposed Doppler-aided methods improve both the point estimation and tracking filter performance, which is verified using data from pool tests.

1. Introduction

In underwater acoustic communications there has seen a growing interest in one system architecture: Distributed Antenna Systems (DAS). This differs from the common Central Antenna System (CAS) in that multiple antennas are distributed throughout a wireless network and connected via some outside links (either cabling or in the case of underwater acoustic networks a surface link connecting nodes via radio). The advantages of DAS in terms of throughput, outage performance, coverage area, and other properties are well discussed elsewhere [1–5]. What is of note for this particular topic is the notion of fusing data from multiple antennas in the network to enable near-instantaneous location estimation for highly mobile network elements, such as fast-moving AUV's, gliders, or other non-tethered nodes in relatively sparse networks.

Localization is a key part of any wireless network or vehicle navigation scheme, and is a particularly challenging task in the realm of underwater acoustic communications. Much work has been done with regard to underwater localization in recent years, as summarized in [6,7]. Most works focus on using ranging or angle estimates as the primary methods of location estimation, and perform multilateration using information from multiple anchor nodes [8–15]. Other methods have been developed from a network perspective, working largely to extend the multilateration technique to cover large areas or exploit the broadcast nature of wireless transmissions to reduce the communication overhead [16–18]. In our previous work, we had developed a system that used scheduled

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periodic broadcasts from time-synchronized anchors [19] and another system with asynchronous anchors that can react to a localization demand [20].

When several messages are required for time-of-flight multilateration or similar methods, there arises an important issue when localizing mobile elements. The nature of the underwater acoustic channel forces these messages to have a large temporal delay. Consequently, as the mobile elements are moving, there would be non-negligible position changes in the data collection process. This typically must be dealt within the estimation itself, either by using non-linear tracking or measurement conversion methods or supplementing with measurements from inertial navigation systems (INS).

In this work, we consider the localization of a mobile unit via a distributed antenna system which only requires one message to be sent from the mobile unit. Note that Doppler speed estimation is used often as a tool to improve messaging capabilities in underwater communications. The modems used in our research have the capacity to estimate the channel during receiver processing and also provide an estimate of the Doppler scaling factor present in the received signal [21,22]. With a received message, all the distributed nodes in a DAS record the time-of-arrivals and obtain the Doppler speed estimates used in the decoding process. Conventional methods have relied only on the time-of-arrival measurements to obtain position estimates, on top of which filtering methods can be further applied for tracking purposes. In this paper, we explore the usefulness of Doppler speed information. The combination of time-of-arrival measurements and Doppler speed estimates associated with a single message enhances the accuracy of position estimation and provides an estimate of the velocity of the mobile object. A Kalman Filter (KF) and a Probabilistic Data Association Filter (PDAF) are then further implemented processing the point estimates.

This Doppler estimation along with an estimation of the time-of-flight for a message from a target node to several anchor nodes constitutes what can be considered a range and range-rate measurement. The use of range-rate to supplement range measurements has been studied in the radar and sonar literature, and generally it would appear that it can affect the localization and tracking accuracy both positively and negatively. The primary factor in whether the effect is an improvement in accuracy or a reduction is based on the uncertainty of the range-rate estimate. We look at experimental data where the Doppler speed estimation capability of a modem is analyzed, and determine if the uncertainty is low enough to offer performance improvement.

The primary contribution of this paper is to derive an instantaneous position and velocity estimator for a mobile node in a distributed antenna system based on both the time-of-arrival measurements and the Doppler speed estimates, perform simulated analysis to determine the performance improvement due to the Doppler information, and then validate the assumptions and simulations with tests using acoustic modems that enable this capability.

The paper is organized as follows. Section 2 describes the general protocol and algorithm to determine the position of a moving unit. Section 3 describes the trackers adopted. Sections 4 and 5 present the simulation and test results, respectively. Section 6 features discussions of alternative methods and scenario-specific concerns, and finally we conclude our work in Section 7.

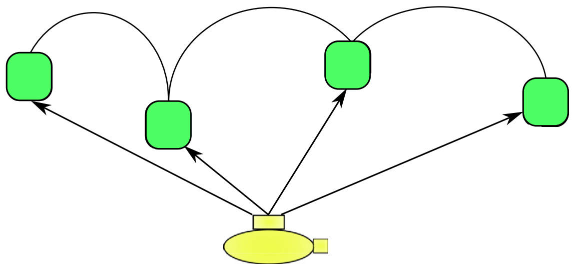

Fig. 1. A brief overview of the transmission protocol in a sample network. The AUV sends a burst message received by all nearby antenna nodes, which then collaborate among each other to localize the AUV.

Notation. Bold upper case and lower case letters denote matrices and column vectors, respectively; $(\cdot)^T$ denotes transpose of a vector or a matrix.

2. Localization protocol

We consider a scenario of AUV navigation, wherein we have one cooperative target attempting to navigate with the aid of several listening beacons deployed over an area of interest. An AUV, denoted as the active node s, is located at an arbitrary position $[x_s, y_s, z_s]$ within a known area. We assume that N antenna nodes are deployed at positions $[x_n, y_n, z_n]$, $n = 1, 2, \ldots, N$.

There are several assumptions we must explicitly make with regard to the node properties. First, the active antenna nodes can all communicate perfectly in the respective frames of localization and there are no interference nor collisions (discussion on communications failure is deferred to Section 6). Second, all antenna nodes have perfect knowledge of their position and they share a globally synchronized clock. Third, the antennas are capable of collaboratively sharing information such that one arbitrary node can collect all measurements before either localizing the active node at the antenna and relaying that to the node, or transmitting the collected information back to the active node for it to self-localize. This can either be handled through messaging among antenna nodes, or more elegantly via DAS networking with a secondary communication link (see Fig. 1).

The procedure would then be as follows:

- At some time t_0, the active node transmits a single message requesting localization be performed by all listening nodes, as well as the local time t_0 at which the message was transmitted. Each node n then receives that message at local time $\hat{t}_n$.
- Each node obtains a Doppler speed estimate $\hat{v}_n$ based on the received waveform.
- After collecting all information, a master node obtains all estimates and performs the localization procedure and transmits the full state estimate back to the active node. Alternatively, the information could be collected and relayed to the active node where localization is then performed.