Ad Hoc Networks 34 (2015) 196–210

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Real-time collaborative tracking for underwater networked systems

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ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form 12 October 2014
Accepted 13 October 2014
Available online 4 November 2014

Keywords:
Underwater networks
Real-time tracking
Acoustic networks

ABSTRACT

Localization is a crucial requirement for mobile underwater systems. Real-time position information is needed for control and navigation of underwater vehicles, in early warning systems and for certain routing protocols. Past research has shown that the localization accuracy of networked underwater systems can be significantly improved using inter-vehicle collaboration. More specifically the Maximum Likelihood (ML) position estimates of a mobile collective can be computed from measurements of relative positions and motion, albeit in a non-real-time fashion. In this work we extend this solution to compute the position estimates of a network in real-time and in a distributed fashion. We first describe a centralized approach to identify key factors that fundamentally limit the performance of a real-time solution. Using the centralized approach as a benchmark, we arrive at a real-time distributed solution that additionally computes the location of vehicles using information obtained locally by them. We address practical considerations in the implementation of our algorithm and propose solutions to mitigate computational errors. With this proposed implementation, we provide insight on how to appropriately plan a deployment of nodes when collaborative tracking is to be utilized. Lastly, we shed light on situations where implementing collaborative tracking can hinder the localization performance of the network so that these can be avoided.

1. Introduction

There has been a growing interest in operating groups of autonomous underwater vehicles in a networked fashion, using short to medium range acoustic modems [1]. Location information is critical to such networked mobile underwater systems for correctly annotating data samples, control and navigation and in certain data routing protocols. However, since GPS is not available underwater, the position of vehicles has to be estimated over time.

Most existing solutions based on Kalman or particle filters are designed for tracking vehicles individually [2,3]. This is achieved by combining measurements of relative position with respect to known landmarks or beacons together with estimates of the vehicle's motion obtained from on board sensors. These *non-collaborative* tracking methods perform poorly in underwater networks where vehicles have short to medium acoustic communication range. This is due to the fact that a vehicle may not be within the communication range of a sufficient number of beacons or it may move out of range of beacons from time to time. A solution to this problem involves using additional measurements for localization, which can be obtained from communication between vehicles. Such a *collaborative* approach has been employed by a number

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http://dx.doi.org/10.1016/j.adhoc.2014.10.008
1570-8705/

of localization techniques such as multi-dimensional scaling and iterative multi-lateration. However, these techniques have been proposed for stationary networks. They typically use relative position information (distance, proximity or direction) as geometric constraints on the unknown location of devices. Since devices are stationary, the constraints can be considered concurrently to solve for the unknown locations. In principle these algorithms can be extended to mobile underwater networks by localizing time snapshots of the network as suggested in [4–6]. However this requires measurements of relative position to be obtained concurrently. Further, position estimates for each snapshot must be computed before there is significant displacement in the vehicle positions. In reality, due to practical communication constraints, the use of such techniques for underwater networks would be severely limited when deployments are sparse and vehicles are moving.

Our prior work has shown that in sparse mobile underwater networks, localization accuracy can be significantly improved when vehicles collaborate [7], compared to both individual tracking and collaborative static localization. We proposed a collaborative solution that tracks a group of vehicles as a collective by jointly computing the trajectories of all vehicles using non-concurrent estimates of inter-node distances together with measurements of motion from on-board navigational sensors. While there exist a few collaborative tracking methods that also loosely follow the same idea, our solution is optimal as it jointly computes the Maximum Likelihood (ML) positions of all vehicles over time.

The drawback of this optimal ML solution is that it is centralized and can only be applied offline, after all measurements are available at a single location. It serves applications where position information is only needed post-facto, but cannot solve the problem of real-time localization. Creating a real-time tracking solution for mobile underwater networks is a difficult task due to the power required for inter-node communication and the band limited acoustic channel of the ocean. Despite these challenges, our work in [8] modified our existing ML solution to compute positions in real-time. In this work we first propose a centralized real-time algorithm which computes all position estimates at a central location albeit in real-time. We use this solution to highlight the inherent loss in localization performance when we go from a non-real-time to a real-time solution. More practically, we propose a localized distributed solution for our real-time tracking that minimizes the communication overhead by strategically sharing information between vehicles, yet achieves localization accuracies close to the best case. The essential problem that we address to this end is to determine what information to share between vehicles and when, as well as how to encode information to minimize the communication overhead.

While the work of [8,7] only considered one set of trajectories in their analysis, in this work we provide additional analysis of these techniques by applying them to different motion models. We find that there are cases where the collaborative framework for localization does not perform best, but often it can alleviate many different sources of error in an underwater network and provide results that are superior to the non-collaborative case. Ultimately, we propose that careful consideration of the motion models of the vehicles as well as the positioning of the beacons must be taken into account when planning a deployment of vehicles who are collaborating to determine their position. We provide insight on how these parameters affect the location accuracy of each vehicle so that an informed decision can be made on whether or not to collaboratively localize as well as how to set up a network to reduce localization error when collaborating. Before we can delve into this analysis, we will describe our prior work on non-real-time centralized tracking as well as centralized and distributed real-time tracking. This knowledge forms the basis of later analysis on deployment considerations.

2. Related work

A detailed discussion of how our factor-graph framework relates to other estimation techniques that are traditionally used for underwater navigation, in robotics as well in terrestrial sensor networks can be found in our prior work [7]. A number of real-time and distributed localization techniques have been proposed for underwater networks [4,9,5,6]. Among these DNRL [4] and LSL [6] use multi-lateration while USP [5] applies iterative bilateration. To improve the localization accuracy, DNRL proposes the use of mobile beacons. In LSL a hierarchical (infrastructured) approach is proposed for localization [6]. These techniques essentially estimate positions for time snapshots of the network using only spatial constraints (estimates of inter-vehicle distances) and do not account for vehicle motion. The main drawback compared to our solution is that they would not work well in sparse networks and need more frequent signaling. A more in depth survey is available in [10]. A comparative performance evaluation of some of these schemes has been done in [11].

AUV navigation using a single mobile beacon is proposed in [2,3]. Here measurements of vehicle motion are combined with non-concurrent distance estimates to the beacon. In addition path planning is done to improve the tracking performance [3]. A collaborative solution has been proposed for under-ice AUV tracking where inter-vehicle estimates of distance and relative velocities (from measurements of Doppler shifts) are used for localization [12]. Vehicle positions are estimated using a least squares approach. To minimize the position uncertainty, a subset of neighbor vehicles are selected as position references via an exhaustive search method.

3. Non-real-time centralized solution

Our centralized ML solution estimates the position of vehicles by simultaneously capturing a number of spatial and temporal constraints. These constraints are the result of the measurements that the vehicles collect to help them determine their positions. A first set of measurements, yielding the ‘spatial’ constraints, are inter-vehicle distance estimates with neighbors within communication range,