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An optimization based Moving Horizon Estimation with application to localization of Autonomous Underwater Vehicles

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HIGHLIGHTS

- A novel localization method for Autonomous Underwater Vehicle is proposed.
- Moving Horizon Estimation is designed for 3D single beacon based localization.
- Connection between filter- and optimization-based methods is explicitly studied.
- Observability is analyzed in the context of nonlinear discrete time systems.
- Simulation verifies the observability and performance of proposed method.

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ABSTRACT

Localizing small Autonomous Underwater Vehicles (AUVs) that have limited payload and perception capability is of importance to promote popularization of underwater applications. Two different methodologies, filter and optimization based methods, can both be used to address the localization problem. But they are seldom rigorously compared and their relative advantages are rarely established. This paper presents a rigorous investigation on the relationship between these two methods. Based on this examination, a novel cooperative localization algorithm for the scenario where AUVs are localized by using range measurements from a single surface mobile beacon is proposed. The main contribution of this paper is threefold. First, major difference and close connection between filter based method and optimization based Maximum a Posteriori method are explicitly clarified by analytically solving optimization problems. Second, a novel localization algorithm combining a filter based extended Kalman filter and an optimization based Moving Horizon Estimation is developed for three-dimensional underwater localization in real-time and long-term applications. The algorithm allows data fusion of multiple sensors, imposes physical constraints on states and noises, bounds computational complexity, and achieves a compromise between better accuracy and lower computational requirement. Third, observability analysis of single beacon based localization algorithm is conducted in the context of nonlinear discrete time systems and a sufficient condition is derived. The observability and improved localization accuracy of the proposed localization algorithm are verified in a customized underwater simulator by extensive numerical simulations.

1. Introduction

Recently, localization problem of Autonomous Underwater Vehicles (AUVs) has been attracting enormous attention because localization is acknowledged as an essential capability for an AUV. The traditional techniques, such as dead-reckoning and acoustic baseline system with arrays of pre-deployed static beacons, suffer from unbounded localization errors, costly setting up, restricted operating area, etc. In addition, in order to decrease the costs and simplify the design complexity of AUVs, the small and simple AUVs are increasingly adopted. This makes the conventional underwater localization systems unsuitable due to the limited size, power and payload of AUVs and the high cost of localization systems in terms of hardware complexity and energy consumption. Therefore, a new underwater localization scheme based on the cooperation between AUVs and a single mobile surface beacon has been studied in recent years [1–4].

In a cooperative localization system shown in Fig. 1, a mobile surface vehicle and a number of underwater AUVs cooperate with each other to realize accurate localization. The surface vehicle can obtain its absolute position in real-time, and then broadcast it

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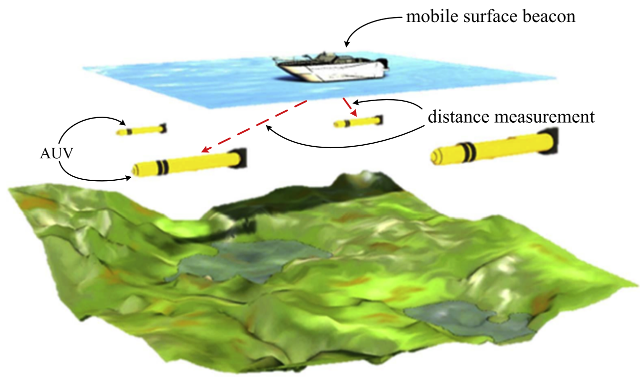

Fig. 1. Architecture of underwater cooperative localization.

to AUVs. The AUVs measure the distances to this mobile surface vehicle in order to use them to bound the localization errors accumulated by dead-reckoning. Because the surface vehicle and AUVs are moving as a team, their operating area is dramatically enlarged compared with the static beacon scheme.

It is well known in the robotics community that multi-sensor data fusion is an effective solution to robot localization problem [5], and a generic framework for multi-sensor fusion based underwater localization is proposed in [6]. Two different types of methodologies, filter based and optimization based methods, are frequently used. The filter based methods, such as Kalman filter (KF) and extended Kalman filter (EKF), recursively estimate the position of a robot. The series of KF based filtering methods are the most classic and widely used techniques for robot localization since they are easy-to-use and low-computational. In [4,7], the centralized EKF and decentralized extended information filter are proposed for off-line and on-line cooperative localizations of AUVs with highly accurate sensors, such as Doppler Velocity Log (DVL). In order to perform the cooperative localization of AUVs in the absence of DVL, algorithms based on EKF and particle filter (PF) are proposed in [1,3]. On the other hand, optimization based method, as an alternative to its filter based counterpart, formulates the localization problem into an optimization problem. In [3], the nonlinear Least Squares (NLS) optimization, a Maximum a Posteriori (MAP) method, is designed for underwater localization.

As a consequence, two questions of significance have arisen. What are the essential differences between filter based method and optimization based MAP method?[1] How can we choose the one that is more suitable for a specific application? To find solutions to these questions, it is necessary to clarify the characteristics of these two methods and the connection between them. Although these two methods both have been well known and widely used for many years, they are seldom rigorously compared and their relationship is rarely established except that a pioneering study on this is proposed in [8]. But this work specializes on visual simultaneous localization and mapping (SLAM) without considering optimization constraints and is mainly conducted by evaluating the experimental performance. In fact, KF produces a recursive solution to the unconstrained MAP in the context of linear systems subject to Gaussian noise (see Section 4.1). In other words, KF is identical to MAP when the system is linear, the noise is Gaussian and no constraint is imposed. In such cases, it is not necessary to use optimization based method because additional computation is needed to solve the optimization problem. However, there are two cases in which the optimization based method is appealing. First, the optimization based method can handle nonlinear dynamics more elegantly than filter based method. This is because the optimization framework allows the explicit use of nonlinear system models, and it iteratively calculates the optimal value by multiple linearizations, achieving higher accuracy than EKF. Second case is that constraints on states and noises can be easily introduced into the optimization based method, while it is difficult to incorporate them into the classic filter based method. Therefore, this paper is dedicated to explicitly clarifying the filter and optimization based methods and rigorously building a bridge between them.

From the computational complexity perspective, the optimization based approach is usually unsuitable for real-time or long-term application, which seriously hiders its widespread use in robot localization. The computational complexities of optimization based methods grow over time since all the previously calculated states and observed measurements are incorporated into every computation. Meanwhile, the required time to iteratively solve a general optimization problem greatly depends on an initial guess, the number of iterations, etc., which means the total time for solving the problem is almost unpredictable. Some techniques can be adopted to reduce or bound the computational complexity. Sliding window filter (SWF) is proposed in [9] for vision based landing by using Schur Complement to marginalize out old data. However, none of the previous algorithms considers the importance of constraints on state variables and process uncertainties. In fact, the constraints, which are usually derived from prior knowledge, are of importance. For example, it is useful to employ the constraints on noises to precisely and realistically model the system noises as truncated normal distribution since physical quantities are almost always bounded. In [10,11], Moving Horizon Estimation (MHE), the dual of Model Predictive Control [12], is used to formulate the robot localization problem into a fixed window optimization problem incorporating the constraints. The MHE is designed for two-dimensional localization problem with the aid of several static beacons or landmarks.

Our localization method is also based on MHE, but it combines with EKF for real-time implementation and only uses a single mobile beacon for three-dimensional cooperative localization. Since only range measurements from a single mobile beacon are used to bound the localization error for a group of AUVs, the observability, which can determine the robot localizability, should be investigated. By considering a nonlinear system as a linear time-varying system, observability Gramian is adopted in [13,14] to analyze the observability of a single range based localization system. In [15–17], the rank of observability matrix is proposed for observability analysis of linear systems or linearized nonlinear systems. However, the original localization systems are usually nonlinear and the linearization might an over confident estimation result [3]. Therefore, the observability rank condition derived from Lie derivative for nonlinear continuous time system is used in [3,18,19] to study the observability of robot localization. However, all the studies mentioned above transform discrete time systems into continuous time systems for observability analysis with the assumption that the sample time is small enough, and no research has considered the observability of robot localization using a nonlinear discrete system directly. Since most of the localization systems are discrete time system, it is worth analyzing the observability of localization in the context of its discrete representation. There is another challenge in our proposed system. The propagation speed of underwater acoustic communication is much slower than that of wireless signal in air, which results in the low frequency of underwater ranging. This high latency degrades the localization accuracy or even makes the estimator divergent if no special care is taken.

In this paper, the relationship between two classic methodologies, filter and optimization based methods, of robot localization is investigated. According to this examination, a cooperative

[1] Unless otherwise stated, the optimization based method refers to the optimization based MAP method throughout the remaining paper.

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