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Cascaded Kalman and particle filters for photogrammetry based gyroscope drift and robot attitude estimation

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ABSTRACT

Based on a cascaded Kalman–Particle Filtering, gyroscope drift and robot attitude estimation method is proposed in this paper. Due to noisy and erroneous measurements of MEMS gyroscope, it is combined with Photogrammetry based vision navigation scenario. Quaternions kinematics and robot angular velocity dynamics with augmented drift dynamics of gyroscope are employed as system state space model. Nonlinear attitude kinematics, drift and robot angular movement dynamics each in 3 dimensions result in a nonlinear high dimensional system. To reduce the complexity, we propose a decomposition of system to cascaded subsystems and then design separate cascaded observers. This design leads to an easier tuning and more precise debugging from the perspective of programming and such a setting is well suited for a cooperative modular system with noticeably reduced computation time. Kalman Filtering (KF) is employed for the linear and Gaussian subsystem consisting of angular velocity and drift dynamics together with gyroscope measurement. The estimated angular velocity is utilized as input of the second Particle Filtering (PF) based observer in two scenarios of stochastic and deterministic inputs. Simulation results are provided to show the efficiency of the proposed method. Moreover, the experimental results based on data from a 3D MEMS IMU and a 3D camera system are used to demonstrate the efficiency of the method.

1. Introduction

Knowing the orientation of robotic vehicles is a prerequisite for control purposes in any robotic application such as territorial, airborne, industrial and surgical robots. With attitude we refer to the robot's orientation relative to a fixed coordinate system [1]. Generally, three-axis gyros are used on board to provide data (angular rate) for attitude estimation. Especially, after the evolution of small silicon based ones (MEMS), their usage has become more widespread. It is because these sensors are small, light, inexpensive, and at the same time they consume less power and have short start-up time [2]. In the presence of precisely measured angular rate data, the exact kinematic model can be used in order to estimate the attitude of a moving body. However, gyros' measurements suffer from sensory faults and errors. These faults and errors are in the form of bias, drift, scale factor and hard faults which cannot be identified and detected in a standalone use [3].

1.1. Sensor fusion, attitude representation and estimation

To overcome the disadvantage of MEMS components in terms of accuracy and stability stemmed from their errors and faults, they are typically used in combination with aiding sensors. Inertial sensors are typically used in combination with vision, Ultra-Wide Band (UWB) and Global Positioning System (GPS). The aiding sensor is chosen depending on application. GPSs and UWBs are normally fused with inertial sensors to navigate autonomous vehicles for outdoor and indoor applications, respectively. They are used to stabilize the platform and follow a predetermined path. The combination of inertial sensors (gyroscope in this paper) and vision is very suitable for applications in robotics and virtual reality (VR) [2]. Photogrammetry is a classical tool for mapping where sequence of stereo images is captured and self oriented. It has been recently replaced with traditional LASER scanners for indoor robotic

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localization problems fusing with inertial sensors [4] and [5]. We also employ visual sensor in this paper comprising three cameras combined with three light sources (LEDs). The attitude of object is determined using close range Photogrammetry.

Similar combination of Photogrammetry and gyroscopes as an inertial sensor for attitude estimation has also been used for spacecraft attitude estimation such as the ones presented in [6–12] where star trackers are employed as vision sensors to measure spacecraft attitude using far range Photogrammetry.

The combination of gyroscope with star tracker and GPS has been employed in [6] for attitude determination in which GPS and star tracker are used for attitude determination. Star tracker uses Photogrammetry to give information about attitude. Then, states are propagated using linearized attitude dynamics and gyro measurements while other sensor measurements are utilized to provide state updates. In [7] interacting adaptive multiple models are employed for stereo-imagery satellite attitude estimation. The first 6-state model considers satellite kinematics whereas both kinematic and dynamic models are considered in the second 12-state model. EKFs assuming different noise levels for star sensors are designed for each model. Euler angles (roll, pitch and yaw) are employed for attitude representation in this paper.

The main drawback concerns with this attitude representation is singularity problem of estimated parameters. To overcome this problem, other research studies such as Crassidis et al [8] and Kim et al. [9] use quaternions as constrained parameters to describe the attitude kinematics. We also employ quaternions to avoid singularity in this paper. Other parameters for attitude representation are Rodrigues parameters and modified Rodrigues parameters (MRPs) employed in [10] and [11]. They are also unconstrained parameters and suffer from singularity problem.

Another common drawback of the methods proposed by Chiang et al [6] Bolandi et al [7] and Crassidis et al. [9], is sub-optimality of linearization based estimators (such as EKF) leading to slow convergence or even divergence. To overcome this problem it has been proposed in [8,12] to use filters that propagate and update a discrete set of sigma points rather than using linearized equations for the mean and covariance. These approaches are all based on the Gaussian assumption so that the probability density function is adequately specified by its mean and covariance. Therefore, it has been proposed in [10,11] to use particle filtering approaches that do not require the Gaussian assumption and can also handle any functional nonlinearity in system and measurement models. In this paper particle filters are also employed to estimate quaternions kinematics.

1.2. Decentralized architectures in inertial navigation systems

Assuming bias as a known parameter, we augment sensory drift dynamics to attitude kinematics and angular velocity dynamics resulting in a nonlinear high dimensional state space model. This leads to a slow estimation process when PF is employed for a precise estimation. Furthermore, Rao–Blackwellization [13] has been proposed to reduce state vector dimensionality; however, a special structure of the system is required [14]. Although the system model does not meet the required structure, it is an inspiring approach in this paper.

Additionally, considering the limitations of current processors in serial execution and fast updating rate, parallel computation approaches have been proposed more recently in Inertial Navigation Systems (INS) [15–18]. The idea of Rao–Blackwellization and parallel computations in reducing the number of particles and computation time, motivate us to decompose the augmented model to linear and nonlinear subsystems connected in a cascaded architecture. A cascaded KF–PF based algorithm is then proposed for estimation. This algorithm is suited for a cooperative modular system with noticeably reduced computation time. Besides, it also provides easier tuning, more precise debugging and more possible verifying from the perspective of programming. In the modular implementation, each module has the task of observing one of the subsystems, possibly using different methods (some linear and some non-linear according to the subsystems' dynamics), and relying on its own measurements and the information gathered from its neighboring subsystems [19] and [20].

As reviewed in the literature, the idea of gyroscope error estimation is not new. Moreover, a scenario of decentralized attitude estimation has been proposed by Crassidis et al. [21] in a sensor network architecture. The decentralized estimation approach has been developed for a spacecraft system equipped with two redundant star trackers. Each star tracker is exploited in an EKF together with a common gyro measurement. However, the novelty of our proposed method resides in the way the architecture is designed and in the application of decomposition methods to gyroscope error estimation in the framework of robot attitude determination. This leads to a PF design in a cascaded architecture where both stochastic and deterministic inputs (outputs of other filter in cascaded architecture) are assumed.

This paper is organized as follows. Section 2 provides some backgrounds about quaternions, sensor fault models, vision and gyroscope measurement models as well as a preliminary introduction to Kalman and Particle Filtering (KF and PF). Section 3 presents system mathematical formulations, cascaded decomposition and cascaded KF–PF based estimation. Simulation results are presented in section 4 to demonstrate the efficiency of the proposed method. The experimental results based on data from 3D MEMS IMU and 3D camera system are provided in section 5.

2. Background

In this section, we present basic concepts about quaternions and different types of sensor faults. After that, we concentrate on gyroscope and vision measurement models. Then, a preliminary introduction to Kalman and Particle Filtering is provided.

2.1. Quaternions

In this section in order to represent an attitude, we review attitude kinematics using quaternions. For attitude representation, quaternions have been most widely used. Quaternions are given by a four-dimensional vector defined as

$$q=\begin{bmatrix}\cos(\delta/2)\\ \sin(\delta/2)n\end{bmatrix}=\begin{bmatrix}q_0\\ \overline{q}\end{bmatrix},\quad \overline{q}=\begin{bmatrix}q_1\\ q_2\\ q_3\end{bmatrix} \tag{1}$$

where n is the unit Euler axis and δ is the rotation angle around n [22] and q is presented as a two-part vector. The first part is scalar part, q_0, and the second part is vector part, $\overline{q}$.

In linear algebra terms, any two Cartesian coordinate systems with a common origin are related by rotations about some fixed axes which can be represented in the form of quaternions. The associated quaternions are obtained using the quaternions' product which is defined as follows:

$$q=q^1\otimes q^2=\begin{pmatrix}q_0^1q_0^2-\overline{q}^1\overline{q}^2\\ q_0^1\overline{q}^2+q_0^2\overline{q}^1+\overline{q}^1\times\overline{q}^2\end{pmatrix} \tag{2}$$