Unscented Kalman Filtering for Visual-Inertial Navigation with Applications to Small Unmanned Aircraft Navigation

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April 1, 2017

Abstract

Acknowledgments

Five years ago, when I first took an interest in robotics, I went with several of my friends to ask a professor for support in starting a design team. We entered the professor's office with no money, no experience, and no plan. That professor bet on us when we had nothing but curiosity and optimism. Years later, that same professor became my adviser and continued to support me in my research endeavors. It is my pleasure to thank Dr. Kevin Kochersberger for opening so many doors. Thank you.

Contents

Chapter 1

Introduction

Throughout this document, there are several sections whose titles have been placed in parentheses. These sections have been included to give added context to the work, but are not strictly necessary to the reader's understanding.

1.1 (Personal Motivation)

I first took an interest in unmanned aircraft in the fall of 2012, my sophomore year of college. In search of an exciting engineering challenge, several of my friends and I founded the Cooperative Autonomous Robotics Design (CARD) team at Virginia Tech. Our core team consisted of a dozen students devoted to designing and competing with drones and other robotic vehicles. Our team, guided by my future graduate adviser Kevin Kochersberger, entered a number of design competitions and brought home several awards for the university. My early experiences with the team brought me into contact with microcontroller programming, Proportional-Integral-Derivative (PID) controller design, mechatronics, and computer-aided design (CAD) modeling.

After two years of involvement with the CARD team, I applied for an internship at the National Institute of Aerospace[1] (NIA). In the summer of 2014, I was part of a team of NIA researchers working on the Flying Donkey Challenge[2], an international engineering competition centered around the idea of "flying don-

[1] http://www.nianet.org

[2] http://www.flyingdonkey.org

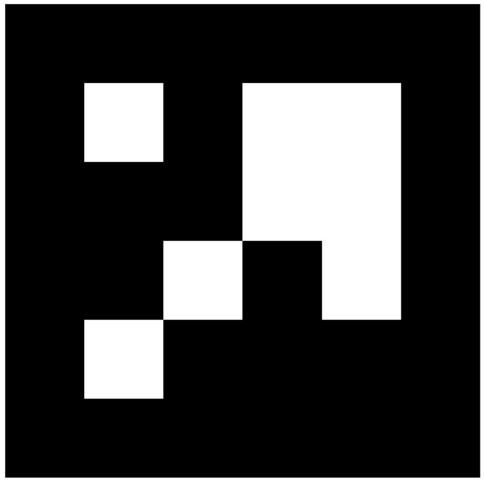

Figure 1.1: Example of an April tag from the `apriltags_ros` ROS package.

keys," full-sized autonomous airplanes capable of quickly carrying cargo between small airports in rural Africa. This competition, unfortunately now defunct, was divided into a number of sub-challenges focusing on different technical objectives such as precision landing and collision avoidance. Our team's goal was to design an inexpensive system for GPS-denied navigation that could reliably guide unmanned aircraft during a GPS blackout. This project introduced me to many of the technologies and techniques that would later become my major research interests, particularly the Robot Operating System[3] (ROS), Kalman filtering, and sensor fusion.

My internship at the NIA brought me into contact with Dr. Danette Allen, head of the NASA Langley Autonomy Incubator. During the 2014–15 academic year, Dr. Allen sponsored the CARD team to design and build two autonomous multirotor delivery drones. These aircraft were capable of delivering 5-lb packages to distances of up to 2.5 miles (or 5 miles, round trip). In addition, these vehicles were able to land precisely on 1 m^2 April tags such as that found in Figure 1.1[4]. Following the completion of this project, I worked as a summer intern at the Autonomy Incubator.

During the summer of 2015, I began the research that eventually evolved into

[3] http://wiki.ros.org

[4] http://wiki.ros.org/apriltags_ros

my thesis project, studying Visual-Inertial Navigation (VIN) and the unscented Kalman filter. In reading up on the unscented Kalman filter (UKF), I took a serious interest in the design of the algorithm. Unlike many other formulations of the Kalman filter, the UKF has a notably limited dependence on information about the system whose state is being estimated (this *system agnosticism* is discussed in detail later on in Chapter @@@@@). In learning about the UKF, I became excited by the idea of taking advantage of this trait to build a minimalistic software interface by which a wide variety of disparate systems could one day be tracked and studied in a ROS framework. I envisioned a kind of "one-stop shopping" experience for massively reusable and customizable filtering profiles that could fulfill the needs of a great many researchers and roboticists with little overhead in the way of state estimation knowledge. This vision eventually drove my development of the `kalman_sense` ROS package and cemented my interest in state estimation and controls.

1.2 Project Overview

1.3 Organization of this Document

Prior Work

In Prior Work, we explore recent contributions to loosely coupled filter-based navigation and estimation. We focus primarily on a number of impactful publications coming from ETH Zurich's Autonomous Systems Lab (ASL) and the University of Pennsylvania's GRASP Lab. We define the current state of the art in filter-based navigation and establish the research context in which this work exists.

Thesis Statement

Algorithm Design and Implementation

Because of the naturally computational nature of this work, we explore in detail the design and implementation of the `kalman_sense` ROS package. We discuss plant model abstraction as well as code organization and data flow. We summarize the process by which one could extend `kalman_sense`'s functionality and the advantages of system-agnostic algorithm design.

Experimental Design

In this section, we first establish the goals of the testing regimen and then discuss the real-world execution of these goals. We discuss important statistical methods for characterizing the system's effectiveness as well as data collection procedures and post-processing. Physical testing infrastructure is explored in detail.

Experimental Results

In Experimental Results, we evaluate the system's performance during testing and seek out any limiting factors that influence estimation accuracy. We probe for possible improvements to the algorithm and provide a notional understanding of the system's theoretical effectiveness in real-world scenarios.

Conclusions

We briefly summarize the contributions made by this work, the effectiveness of the `kalman_sense` package, and any miscellaneous insights acquired during programming and testing.

Future Work

In Future Work, we expand upon the possible improvements proposed in Experimental Results and also offer a number of applications for this work. Specific examples of heterogeneous fleet management and unmanned traffic management (UTM) are explored.

Chapter 2

Prior Work

2.0.1 Unscented Filtering and Nonlinear Estimation

In [1], Julier and Uhlmann discuss the application of the extended Kalman filter (EKF) as an estimation algorithm and the associated difficulties. The EKF contains inherent problems and works best with linear systems. These limitations led to the development of the unscented transformation (UT) for nonlinear applications. In this paper, Julier and Uhlmann describe the unscented transformation (UT) and its benefits including easier implementation and improved accuracy. UT offers greater accuracy and reliability by applying higher order information using sigma points to the traditional mean and covariance information associated with linear applications. The authors provide examples, which may be tailored, that show how UT overcomes the limitations of the EKF.

2.0.2 A Multi-State Constraint Kalman Filter for Vision-aided Inertial Navigation

In this paper, Mourikis et al. expand investigation of the familiar topic of Vision-aided Inertial Navigation, with particular emphasis on small, low-cost, low-weight systems, including unmanned aerial vehicles (UAVs) using a monocular camera. Because technical advances have been made in the manufacture of inertial sensors, these robotic systems are capable of producing high precision state estimations even in uncontrolled urban environments, without utilizing a 3D feature position in the filter state vector of the Extended Kalman Filter (EKF). The exceptional accuracy produced in this real-time, real-world pose estimation model is highly desirable because it produces images that are rich in high-dimensional measurements. This robustness, however, invariably comes at a cost of computational complexity in the EKF-based algorithm, a trade-off that is unavoidable in the present state-of-the-art for vision-aided inertial navigation systems.

2.0.3 Monocular-SLAMâĂŞBased Navigation for Autonomous Micro Helicopters in GPS-Denied Environments

Autonomous micro aerial vehicles (MAVs) provide access to environments that are difficult to access. Further, they mitigate the risk to people and the environment. For many applications, the MAV must navigate in a GPS-denied environment. This paper presents an approach to navigation that relies on a micro helicopter, a single camera, and onboard inertial sensors. A monocular simultaneous localization and mapping (SLAM) framework stabilizes the vehicle, which is used to overcome the issues with drift. This research is important because urban canyons limit GPS availability. The authors, in this paper, show that autonomous navigation in a GPS-denied environment is achievable.

2.0.4 Autonomous Multi-Floor Indoor Navigation with a Computationally Constrained MAV

In this paper [2], Shen et al. extend the work of other authors on the topic of autonomous MAV navigation, particularly as it relates to stable indoor flight and GPS-denied localization in constrained multi-floor environments. The research distinguishes itself by emphasizing the use of onboard sensors only, as well as fully autonomous, real-time internal computational capabilities, with no hands-on user interaction beyond basic high-level commands. The research extends to multi-floor MAV operation with loop closure. It also addresses specially designed controllers to help compensate for sudden changes in wind velocity and air flow as the MAV traverses constrained low-clearance areas with potentially strong aerodynamic disturbances.

2.0.5 Real-Time Metric State Estimation for Modular Vision-Inertial Systems

Stephan Weiss and Roland Siegwart developed an algorithm that provides a metric scale to estimate that estimates monocular visual odometry or monoSLAM approaches. The authors accomplished the development of the metric scale by the addition of an inertial sensor with a three-axis accelerometer and gyroscope. Stephan Weiss and Roland Siegwart created a modular solution that is based on an Extended Kalman Filter (EKF) and provides both simulated results and data-based results. In this paper, the authors discuss their unique approach, its applications, versatility, and reliability of their estimating algorithm for visual odometry, such as visual SLAM, in real-time.

2.0.6 Versatile Distributed Pose Estimation and Sensor Self-Calibration for an Autonomous MAV

The authors present a versatile framework to enable autonomous ïňĆights of a Micro Aerial Vehicle (MAV). The MAV has only slow, noisy, delayed and possibly arbitrarily scaled measurements available. The use of these measurements directly for position control is not practical since MAVs exhibit great agility in motion. In addition, these measurements often come from a selection of different onboard sensors, hence accurate calibration is crucial to the robustness of the estimation processes. In this article, Weiss, et al address the problems using an EKF formulation which fuses these measurements with inertial sensors. The authors not only estimate pose and velocity of the MAV, but also estimate sensor biases, scale of the position measurement and self (inter-sensor) calibration in real-time. The authors show that it is possible to obtain a yaw estimate from position measurements only. The authors demonstrate that the proposed framework is capable of running entirely onboard a MAV performing state prediction at the rate of 1 kHz. Their results illustrate that this approach is able to handle measurement delays (up to 500ms), noise (std. deviation up to 20 cm) and slow update rates (as low as 1 Hz) while dynamic maneuvers are still possible. Stephan Weiss et al present a detailed quantitative performance evaluation of the real system under the inïňĆuence of different disturbance parameters and different sensor setups to highlight the versatility of our approach.

2.0.7 Real-time Onboard Visual-Inertial State Estimation and Self-Calibration of MAVs in Unknown Environments

In this paper, Weiss et al. explore the advantages of utilizing a high-performance navigation algorithm on a low-cost, low-weight micro aerial vehicle (MAV) equipped with a single camera and an inertial measurement unit (IMU) capable of both onboard processing and real-time operations, with focus on a speed estimation module to help control the speed of the MAV, all within an Extended Kalman Filter framework. The system was shown to be useful for real-time self-calibration of the sensor suite—critical to ensuring the robustness and flexibility of any state estimation process—and as a potential solution to some of the tracking failures common to keyframe-based modules.

2.0.8 A Quadratic-Complexity Observability-Constrained Unscented Kalman Filter for SLAM

In this paper, Huang et al. explore solutions to two Unscented Kalman Filter (UKF) limitations that exist in current state-of-the-art Simultaneous Localization and Mapping (SLAM) systems. Specifically, the authors address the problems of cubic complexity in the number of state pose estimates, and the inconsistencies in those estimates caused by a mismatch between the observability properties of statistically-linearized UKF systems and the observability properties of nonlinear systems. To address the problem of cubic complexity, the authors introduce a novel sampling strategy which produces a constant computational cost which, while linear in the propagation phase, is quadratic in the update phase. Although this new sampling strategy was primarily proposed for resolving the above-referenced SLAM problem, it also has potential usefulness in other nonlinear estimation applications. To address the problem of inconsistency in state estimations, the authors propose a new UKF algorithm which, due to the imposition of observability constraints, ensures that the linear regression computations of the modified UKF system produce results similar to those of nonlinear SLAM systems and, in the process, provide improved accuracy and consistency in state estimations. Importantly, these results have been validated with both real-world and simulation experiments. While the paper focused on 2D SLAM, the authors contend that their proposed methodology is also useful for robot localization in 3D, using inertial sensors.

Chapter 3

Algorithm Design and Implementation

We begin by defining the state vector $\mathbf{x} \in \mathbb{R}^n$:

$$\mathbf{x} \triangleq \{x, y, z, q_x, q_y, q_z, q_w, \dot{x}, \dot{y}, \dot{z}, p, q, r, \ddot{x}, \ddot{y}, \ddot{z}\}^T . \tag{3.1}$$

The covariance associated with each state $\mathbf{x}$ is a matrix $\mathbf{P} \in \mathbb{R}^{n\times n}$. A set of $2n+1$ sigma points is then derived from $\mathbf{x}$ and $\mathbf{P}$:

$$\begin{aligned}
\chi^0 &= \mathbf{x} \\
\chi^i &= \mathbf{x} + \left(\sqrt{(n+\lambda)\,\mathbf{P}}\right)_i, \quad i = 1, \ldots, n \\
\chi^i &= \mathbf{x} - \left(\sqrt{(n+\lambda)\,\mathbf{P}}\right)_{i-n}, \quad i = n+1, \ldots, 2n
\end{aligned} \tag{3.2}$$

Bibliography

[1] S. Julier and J. Uhlmann, “Unscented Filtering and Nonlinear Estimation,” in *Invited Paper Proceedings of the IEEE*, vol. 92, pp. 401–422, March 2004.

[2] S. Shen, N. Michael, and V. Kumar, “Autonomous Multi-Floor Navigation with a Computationally Constrained MAV,” in *IEEE International Conference on Robotics and Automation*, pp. 20–25, 2011.