A Hardware-Minimal Unscented Kalman Filtering Framework for Visual-Inertial Navigation of Small Unmanned Aircraft

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Acronyms

AR Augmented Reality

EKF Extended Kalman Filter

GPS Global Positioning System

KF Kalman Filter

IMU Inertial Measurement Unit

PTAM Parallel Tracking and Mapping

SLAM Simultaneous Localization and Mapping

ROS Robot Operating System

UAV Unmanned Aerial Vehicle

UKF Unscented Kalman Filter

UT Unscented Transform

UTM Unmanned Traffic Management

Chapter 1

Introduction

In this document, there are several sections containing titles that have been placed in parentheses. These sections have been included to give added context to this thesis, but are not strictly necessary to the reader's understanding of the material being presented.

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

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

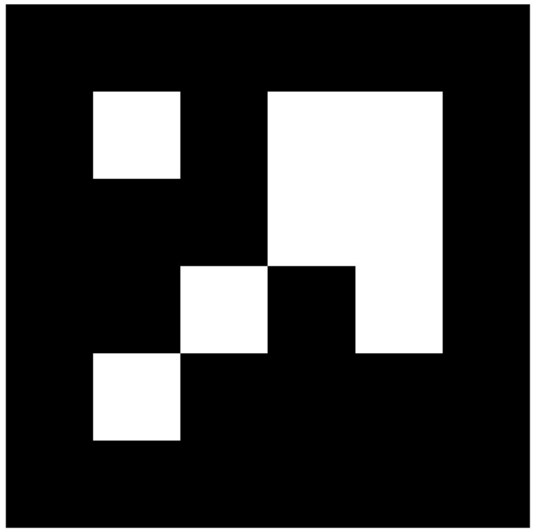

Figure 1.1: Example of an April tag from the `apriltags_ros` ROS package.

researchers working on the Flying Donkey Challenge[2], an international engineering competition centered around the idea of "flying donkeys," 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

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

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

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 my thesis project, studying Visual-Inertial Navigation (VIN) and the Unscented Kalman Filter (UKF). In reading up on the 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 under scrutiny (this *system agnosticism* is discussed in more 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 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 researchers and roboticists with little knowledge of state estimation techniques. This vision eventually drove my development of the `kalman_sense` ROS package, cementing my interest in UAV 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 state 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 thesis exists.

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

Algorithm Design and Implementation

Because of the algorithmic nature of state estimation processes, 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 and then 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. The system's 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 in this thesis, the effectiveness of the `kalman_sense` package, and any 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 the algorithm and processes developed herein. Specific examples of heterogeneous fleet management and unmanned traffic management (UTM) are explored.

Chapter 2

Prior Work

2.1 Development of the Unscented Kalman Filter

In [1], Simon Julier and Jeffrey Uhlmann presented a nonlinear estimation approach for the Kalman Filter. Recognizing that most applications for autonomous navigation are fundamentally nonlinear in both their dynamics and their observation models, Julier and Uhlmann proposed the use of a set of discretely sampled "sigma points" to determine the mean and covariance of a probability distribution. By recasting the prediction and correction steps of the Kalman Filter in the form of unscented transforms (UTs), this new filter eliminates the need to calculate Jacobian matrices. Julier and Uhlmann argued that for this reason their formulation was easier to implement than the EKF and went on to suggest that its use could supplant the EKF in virtually all applications, linear or nonlinear.

In [2], Julier acknowledges that the (linear) Kalman Filter has been used successfully in many nonlinear scenarios, but notes that the use of only the first two moments of the state estimate sigma points results in the neglect of all higher order information (that is, third-order moments, or "skew"), a potentially rich source of new and useful information relating to symmetry of the state estimate. By extending the sigma point selection scheme of the conventional unscented transform, Julier was able to present a tractable but computationally complex extension of the Kalman Filter that could predict not only the first two moments of a sigma point distribution but also the skew. Though formulated initially for unimodal distributions, Julier stated that the approach could, with additional mathematical considerations, be generalized for use with multimodal distributions. Julier's contention was that the use of higher order information could promote better performance levels in autonomous vehicle navigation. The utility of maintaining and utilizing higher order information through the use of skewed filtering was assessed by the authors in a realistic tracking scenario. However, the results turned out to be somewhat disappointing as the change in performance turned out to be minimal, presumably due to the linearity of the filter's update rule. Accordingly, research in this area continues, including examination of the use of nonlinear update rules in the filtering process.

In [3], Julier describes a novel approach to modifying the unscented transformation state estimation method. In the new approach, Julier takes the additional step of introducing a framework for scaling sigma points as part of the state estimation process. The general framework of the new methodology allows preservation of the first two moments of any set of sigma points, thus providing a construct for limiting values to either the conventional unscented transform or the modified (scaled) transform. Providing detailed mathematical validations, the author shows that the new scaling algorithm is computationally manageable in that it is, in essence, little more than the conventional unscented transformation algorithm with the addition of a simple post-processing step, the only difference being the inclusion of an extra correction term. Thus, the new algorithm's computational and storage costs are similar to that of the non-scaled transformation. The performance level of the scaled UT is thus demonstrably superior to the unscaled UT for propagating the two lower-order moments of a sigma point distribution.

In [4] Julier and Uhlmann discuss the application of the EKF as an estimation algorithm and the associated difficulties in doing so. Because the EKF is fundamentally a linearizing approach to estimation, its effectiveness is thus tied to the veracity of the local linearity assumption for the system under scrutiny. These limitations led to the development of the UT for nonlinear applications. In this paper, Julier and Uhlmann describe the UT and its benefits, including easier implementation and improved accuracy. The 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 to various process and observation models, that show how the UT overcomes the limitations of the EKF.

2.2 Visual-Inertial Navigation (VIN)

In [5], Georg Klein and David Murray proposed a method for tracking a handheld camera in unknown environments for use in small augmented reality (AR) workspaces. In contrast to many previous SLAM-based approaches to camera tracking, Klein and Murray split the tracking and mapping functions into two separate computational tasks. They performed these tasks on a dual-core computer utilizing parallel threads, with one thread directly tracking erratic motion of the hand-held camera and the other thread constructing a 3D map of the environment. Through the use of this Parallel Tracking and Mapping (PTAM) algorithm, Klein and Murray were able to take advantage of computationally expensive batch-optimization techniques for map reconstruction which were rarely ever used in real-time applications previously. This, in turn, allowed Klein and Murray to forego the common approach of creating a sparse map of high quality features in favor of a much denser map whose features could vary widely in quality. The resulting system could produce detailed maps tracking thousands of features at frame-rate and could recover gracefully from a variety of intermittent tracking failures. That being said, the researchers made certain relaxing assumptions regarding the scenes which would be tracked. PTAM, by nature of its orientation toward AR applications, operates best in small, static, planar environments (such as on the surface of a desk or the floor of an office). PTAM's value to the robotics community quickly became obvious due to its independence of *a priori* knowledge of the scene and its minimal initialization procedure (explored in Chapter tk).

Four years later, Stephan Weiss et al. presented a VIN system for autonomous UAV navigation which employed PTAM [?]. The researchers presented the results of several experiments in which a UAV equipped with only a monocular camera and inertial sensors navigated through unknown environments without the aid of GPS satellites or other external sensing infrastructure. All calculations were performed online in real time using an EKF framework, proving that this minimalist combination of sensors could be employed in real-world GPS-compromised flight scenarios to great effect. At approximately the same time, Shen et al. [6] conducted similar experiments aimed at stable indoor flight and GPS-denied localization in constrained multi-floor environments with 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 UAV operation with loop closure. It also addresses specially designed controllers to help compensate for sudden changes in wind velocity and air flow as the UAV traverses constrained low-clearance areas with potentially strong aerodynamic disturbances.

In [?] Weiss and Siegwart went on to tackle the problem of metric scale in monocular VIN systems. The researchers developed a general algorithm that provides metric scale to monocular visual odometry and monocular SLAM systems using IMU data. The authors accomplished the development of the metric scale by the addition of an inertial sensor with a three-axis accelerometer and gyroscope. Weiss and Siegwart created a modular solution that is based on an 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.

In 2012, Weiss et al. built upon this metric scale algorithm to present a versatile sensor fusion framework for autonomous flight. Due to latency, noise, and arbitrary scaling within the output of a UAV's sensors, it is impractical and ill-advised to incorporate this sensor output without calibration or post-processing for position control. In this article, Weiss et al. address these problems using an EKF formulation which fuses these measurements with inertial sensors. The authors not only estimate pose and velocity of the UAV, but also estimate sensor biases, scale of the position measurement and self (inter-sensor) calibration in real-time. The research shows that it is possible to obtain a yaw estimate from position measurements only. In addition, this demonstrates that the proposed framework is capable of running entirely onboard a UAV, performing state prediction at a rate of 1 kHz. Their results illustrate that this approach is able to handle measurement delays (up to 500 ms), noise (with positional standard deviation up to 20 cm), and slow update rates (as low as 1 Hz) while dynamic maneuvers are still possible. Weiss et al. present a detailed quantitative performance evaluation of the system under the influence of different disturbance parameters and different sensor setups to highlight the versatility of their approach.

[Weiss, Achtelik 2012] Weiss et al. explore the advantages of utilizing a high-performance navigation algorithm on a low-cost, low-weight UAV equipped with a single camera and an IMU capable of both onboard processing and real-time operations, with focus on a speed estimation module to help control the speed of the UAV, all within an EKF framework. This system employed a pose estimator based on PTAM which was found to be robust to in-air loss of tracking.

[Huang 2013] Huang et al. explore solutions to two UKF limitations that exist in current state-of-the-art 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.

[Lynen 2013] Simon Lynen et al. report on the development of a generic framework to overcome known limitations in fusing information transmitted from multiple sensors in the navigation of robots, focusing mainly on the navigational needs of rotor-based UAV which can more easily traverse from indoor to outdoor domains. The authors demonstrate that their Multi-Sensor-Fusion EKF framework is capable of processing various measurements from an unlimited number of sensors, as well as sensor types, while simultaneously performing online self-calibrations of the overall sensor suite. Designed to be modular, the framework allows seamless handling of sensor signals during operation while performing other complex, iterative calculations to achieve near optimal linearization points for state updates.

[Engel 2013] Engel et al. propose a novel direct monocular SLAM algorithm unlike that of existing direct approaches which embrace pure visual odometry. The novelty of the authors' approach is that it permits the building of consistent, accurate, large-scale 3D maps of the environment while simultaneously tracking camera motion, incorporating any scale-drift in the environment and allowing for the detection and correction of any accumulated drift. The system is capable of running real-time on a central processing unit and as visual odometry on a modern smartphone.

[Rogers III 2014] Rogers et al. presented a methodology for overcoming some of the constraining conditions encountered in a GPS-guided autonomous robotic system, such as occlusion (blocking of GPS signals) and multipath (reception of indirect signals due to environmental reflections) and potentially to ameliorate the effects of jamming or spoofing resulting from adversarial activities. Specifically, the methodology incorporated GPS measurements into a feature-based mapping system, thus providing geo-referenced coordinates allowing for better execution of high-level missions and providing the ability to correct accumulated mapping errors over the course of long-term operations in both indoor and outdoor environments.

[Faessler 2015] Faessler et al. report on the development and demonstration of a low-cost, low-weight, vision-based quadrotor UAV with onboard sensing, computation, and control capabilities. These onboard capabilities eliminated reliance on external positioning systems such as GPS or motion capture systems. This development moves the UAV from its current line-of-sight control state to wireless communications with the ability to execute intricate processes autonomously and to transmit live feedback to a user. Reporting on both indoor and outdoor experiments, the authors believe that such a vehicle potentially would be a great enhancement in search-and-rescue missions, disaster response, and remote inspection of terrain.

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