Max Rudolph
Advisor: Dr. Jennifer Hasler
AutoQuads
Review of Simultaneous Localization and Mapping (SLAM) for uses on autonomous multi-rotors

Introduction

As drones become more ubiquitous in modern society, they must be designed with more autonomy and safety as to smoothly integrate them into people's everyday lives. There are several main components of multi-rotors that have an effect on autonomy and safety: flight controller and navigation computer, state-estimating sensors, power system, and the motors/propellers. This paper will discuss the navigation computer and sensors as they are the only components used by SLAM algorithms. SLAM, otherwise known as Simultaneous Localization and Mapping, is the creation and usage of map of an unknown environment. Applying SLAM to a multi-rotor gives the robot the ability to know where it is in space and act appropriately. SLAM is an essential part of any autonomous agent and this paper will discuss the various methods of SLAM applicable to autonomous quadrotors.

Current Work in the Field

Autonomous drones have been researched and implemented for several years. A majority of the publicly available literature done on autonomous drones has been conducted by universities and commercial research labs. For example, Draper Labs has designed a quadcopter with the ability to navigate unknown terrain going at speeds of up to 45 mph [1]. This project was developed for emergency responders (soldiers, firemen, policemen, etc…) to quickly learn about a GPS-denied environment as a part of the DARPA Fast Lightweight Autonomy (FLA) program. DARPA has expressed interest in technology that "could reduce the amount of processing power, communications, and human intervention needed" for drone flight [2]. They have given grants to research organizations and published the organizations' flight autonomy in several videos [3].

Additionally, there has been some research into SLAM for commercial purposes. Most of the work done for corporations has been for the purpose of automating warehouse functions typically conducted by humans. For example, Amazon Robotics has a fleet of robots that retrieve and organize large pallets of merchandise in certain Amazon warehouses. The robots are advanced line followers with swarming capabilities. Furthermore, in 2016, engineers from Walgreens and University of Pennsylvania filed a patent documenting the process to autonomously map store layouts. The document outlines the system architecture necessary to map the shelves and products in a large retail store [4]. Bergstrom et al. macroscopically describe the algorithm necessary to optimally map the store.

It is clear that there are commercial, research, and governmental applications of autonomous robots and SLAM. Unfortunately, most products in this space are not available to everyday consumers; and thus, prices are often not public and not applicable. However, the world's largest drone company, DJI, has a fleet of drones that use localization technology similar to that discussed in this paper. The DJI Mavic Platinum Pro can stabilize itself using SLAM and it costs $1149. The typical price range for consumer drones using SLAM is between $100 and $5000.

How SLAM Works

SLAM is a general term for the overarching action of a robot mapping its surrounding and localizing itself. It can be achieved through many algorithms and methods. Typically, a robot will use data from sensors and apply algorithms to it. Sensor data can include acceleration measurements, gyroscopic measurements, camera images, and GPS data [5].

At a high level, SLAM algorithms will take in sensor data from the robot's current state and try to do two things; 1) update its state with regards the robot's previous states and 2) use the current state to add information to its internal state map. The term 'state' can refer to any variables that are being tracked by the system. In the context of autonomous drones, state often includes location, orientation, and in the case of multi-agent autonomy, the robot's connection to other robots.

Common SLAM algorithms often implement a special kind of filter called a Kalman filter. Kalman filters are ubiquitous tools used in state-estimation. As inputs they take in sensor data and statistical models of those sensors. With this real time information and knowledge of a system's pervious states, a Kalman filter can accurately predict its current state or extrapolate its next one.

In the case of Draper's FLA Program drone, the researchers use a novel method of visual navigation by method of smoothing and mapping [6]. The system (deemed SAMWISE) takes in sensor information (inertial and camera) and smooths it using Bayesian filters in order to do real time processing.

It is easy to validate SLAM algorithms as there are many technologies that can map 3D spaces to a high degree of accuracy and precision. Because of this, in post processing, a researcher can compare a robot's generated map with that of the baseline map created prior to experimentation.

Implementation of SLAM

As discussed in this paper, in order to achieve SLAM, a robot must have a stream of sensor data and appropriate algorithms to handle the data. Key sensors will include cameras, inertial measurement units, and 2D depth sensors. Because SLAM algorithms work better the more information they have, most algorithms take in several data types and fuse them. As for computing power, most drones will require a flight controller to interface with the motors and a computing unit (such as a Raspberry Pi) to perform all the state estimation and forecasting.

Kalman filters and other SLAM algorithms are often available on Github and other software repositories. For example, when using a depth camera like the Xbox Kinect or Intel RealSense, libraries for manipulating the sensor data come with the product. There are also open source tools like the Point Cloud Library (pcl) that help use these sensors' data.

Key points to consider when implementing sensors and algorithms for SLAM are processing time. Because SLAM is performed in real time, the robot must be able to process all its data in a time frame such that its state does not change significantly from time step to time step.

Most of the technologies required to perform SLAM on a drone are already developed but not synthesized. It will be necessary to take all the hardware and software necessary for SLAM and synthesize them together into a platform that can achieve autonomous navigation.

[1] "Drones Reporting for Work at 45 MPH," *Draper*, 03-Aug-2017. [Online]. Available: https://www.draper.com/news-releases/drones-reporting-work-45-mph. [Accessed: 29-Sep-2019].

[2] "FLA Program Takes Flight," *Defense Advanced Research Projects Agency*, 12-Feb-2016. [Online]. Available: https://www.darpa.mil/news-events/2016-02-12. [Accessed: 29-Sep-2019].

[3] DARPAtv, *YouTube*, 12-Feb-2016. [Online]. Available: https://www.youtube.com/watch?time_continue=4&v=LaXc-jmN89U. [Accessed: 29-Sep-2019].

[4] J. Bergstrom, et al. "Autonomous Vehcile for Mapping Store Layout," United States Patent 10318907, Jun. 11, 2019

[5] S. Perera, N. Barnes, and A. Zelinsky, "Exploration: Simultaneous Localization and Mapping (SLAM)," in *Computer Vision: A Reference Guide*, Springer, 2014, pp. 268–275.

[6] T. J. Steiner, R. D. Truax, and K. Frey, "A vision-aided inertial navigation system for agile high-speed flight in unmapped environments: Distribution statement A: Approved for public release, distribution unlimited," *2017 IEEE Aerospace Conference*, 2017.