1 Abstract

With the current pace of development in autonomous vehicles, the demand for a high-intelligent collision avoidance system is increasing. Due to the inability to determine inner state of tracked vehicles from Lidar, GPS (Global Positioning System), and radar sensors, researchers have utilized state estimation methods to converge available measurements to the true state of the system. The purpose of this thesis is to review and implement different algorithms of set-based state estimation, using zonotopes as domain representation, on existing datasets of real traffic participants (approx. 10,518 entities). Set-based methods are used to enclose the true state of the system in a set, in contrast to stochastic methods which give a point-estimate close to the true state. Encapsulating the true state in a set is important to forbid tolerance in any divergence from the true state for safety-critical tasks in autonomous vehicles, . The algorithms implemented are segment intersection methods (using F-radius, P-radius, and volume) and interval observer (using H-∞ observer) and are compared in terms of computation time, time to converge, tightness of bound and accuracy. H-∞ interval observer has performed better in terms of computation time but starts with a wider initial bound. Segment intersection minimization using P-radius is faster than using F-radius, but compromises on the bounds and accuracy. Of all the methods compared, the segment minimization using F-radius gives the most desirable estimates for this use-case.

2 Introduction

There is a steep progress in research and development of autonomous vehicles. The race to the top of the automobile industry, participated by companies like BMW (Bavarian Motor Works), Tesla, Waymo/Google, requires fast development and vigorous testing of novel technology. One of the many challenges of this field is to ensure collision avoidance. With no human behind wheels for Level 5 [**SAE2014**] cars, the vehicle must keep track of roads, surrounding traffic participants (like vehicles and pedestrians) in different circumstances, including rain and fog, to ensure the safety of its passengers. Current collision avoidance systems based on sensors, radar, and camera will be overwhelmed with high computation demands for this purpose. Tolerating error in such a system can cause accidents; such errors in vehicles have already caused real-life accidents, including one resulting in death [1].

The collision avoidance system in a car consists of two parts: sensing and tracking, and motion planning. The sensing and tracking part is done by sensors like radar, camera, and GPS (Global Positioning System). With advancement in technologies in image processing, image analysis, and object detection and the decline in the cost of cameras, the sensing and tracking is developing fast. Although cameras can classify vehicles, it cannot guarantee measurement in a low-light environment (e.g. night) [**Hirz2018**]. On the other hand, radar guarantees robustness to weather in exchange for a higher cost. Similarly, there are disturbances in GPS. Thus, one uses sensor fusion to compensate for shortcomings of specific sensors . After detecting all relevant elements in the environment, a motion planner has to find a collision-free path. The probable location of the tracked vehicle, is thus also important to calculate a predicted trajectory. However, all the data to predict the vehicle's location is not measurable using just sensors. Furthermore, the sensor data are not 100% accurate, and hence solely cannot be relied on to carry on a maneuver to avoid a collision.

Due to the lack of quality and availability of sensors, researchers have used state estimation algorithms to determine the state of the tracked vehicle. One of the widely applied techniques is the Kalman filter, that requires a probability distribution of perturbation in the measurements. Such statistical data required for this method is not always derivable for all situations. Moreover, the Kalman filter provides point

[1]https://www.theguardian.com/technology/2018/mar/19/uber-self-driving-car-kills-woman-arizona-tempe

estimation, which is not favorable for the automobile scenario. This motivates to use set-based state estimation methods.

The set-based state estimation technique provides a set of state enclosing the true state of the system considering the bounds of the noise in the measurement and process. The skeleton of every set-based state estimation method is similar to the Kalman filter, consisting of a prediction step and a correction step. The prediction step is comprised of computing the state estimation using a previous estimation and a model to define the transition. The correction step differs across algorithms and has been solved by Single Value Decomposition, computing Gain Matrix, solving LMI (Linear Matrix Inequality), etc. Three distinguishable segment minimization methods and one Luenberger observer are implemented and evaluated in this paper.

Comparing different domain representations of the sets enclosing the possible state of the system, zonotopes are chosen for this paper as opposed to ellipsoid and polytopes due to higher accuracy for a lower computation cost. Furthermore, zonotopes have gained fame for state estimation because of wrapping effect(i.e. not increasing in size due to accumulated noises over time) and Minkowski sum(i.e. the sum of zonotopes is also a zonotope). We used CORA in Matlab® for the functionalities in zonotope required for state estimation.

To utilize the state estimation algorithms, the first prequisite step is to define the tracked vehicle in a linear model. Although there are complex models that can be used to represent a vehicle state [**Althoff**], not all can be used due to the unavailability of parameters like wheelbase, velocity, etc. as it is unlikely to be acquired in run-time from a tracked vehicle. Hence, the models used in this paper to compare are the simplest, yet complete enough to determine the properties of the tracked vehicle for trajectory prediction: Constant Velocity, Constant Acceleration, and the Point-Mass Model.

A high degree of accuracy and guarantee is the necessity of the collision avoidance system, hence we chose to compare the set based state estimation algorithms for different scenarios involving dynamic traffic participants from a dataset collected from intersections using drones and fixed cameras. [**Rath**] has encouraged many sections in this paper and compares a superset of algorithms covered here; however, the algorithms were compared on simulated data, in contrast to this paper.

The paper is organized as follows. Chapter 2 presents the vehicle localization problem to be solved by state estimation algorithms. The following chapter 3 discusses the zonotope-based state estimation algorithms to be compared. Chapter 4 gives the evaluation of the algorithms, with extended results in chapter 6. Finally, chapter 5 concludes with a summary and a discussion of possible future works.