Motion Planning and Decision-Making for Autonomous Systems: From Quadrotors To Autonomous Vehicles

by

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This is to certify that I have examined the above Ph.D. thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
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Abstract

Autonomous systems have been widely deployed in various field applications, such as inspection, exploration, and aerial videography using micro aerial vehicles (MAVs), and highway pilot (HWP), rush-hour pilot (RHP), robo-taxi in field of intelligent vehicles. For accomplishing such missions in challenging environments, navigation functionality is essential.

In this thesis, we study practical and efficient planning methods for autonomous systems, which can achieve full autonomy in real-world complex environments. Our study covers both low-level motion planning problems and high-level decision-making (i.e., behavior planning) problems, targeting for safe and smooth autonomous navigation with minimum user intervention. We investigate the navigation problem for two different platforms, namely, quadrotors for MAVs, and autonomous vehicles (AVs), which have significant practical impacts while illustrating different focuses and functionalities.

We start with a novel kinodynamic motion planning method for quadrotors, which achieves safe and efficient replanning in unknown cluttered 3-D environments. Leveraging the knowledge of motion planning for quadrotors, we further study the planning problem for autonomous vehicles in highly dynamic environments. Different from the motion planning for quadrotors, planning for AVs requires reasoning about other dynamic traffic participants and social compliance. To this end, a novel behavior prediction method is proposed to understand the behaviors of

other traffic participants in the real world. The behavior prediction is then tightly incorporated into our proposed decision-making framework which generates robust decisions efficiently. The output decision is subsequently utilized by our novel motion planning module to generate a smooth and safe trajectory for closed-loop execution. We assemble all the individual modules into a complete and robust planning system which is validated in real-world dense city traffic.

CHAPTER 1

INTRODUCTION

The development of mechanization and autonomy has always been the source of the industrial revolution. New machine tools have boosted production efficiency in a wide range of field applications, such as industrial machines, automobiles, etc. Unlike robots that work in simple and dedicated environments (e.g., manipulators in the industry), mobile robots need to work in fast-changing environments. There are numerous kinds of mobile robots emerging nowadays, such as micro aerial vehicles (MAVs), micro-ground vehicles (e.g., sweeping robots), autonomous vehicles (AVs), etc. Onboard perception and planning capabilities are essential for mobile robots to ensure their general applicability.

In this thesis, we focus on planning for *fully* autonomous navigation in complex environments. Specifically, we focus on two typical autonomous systems, namely, MAV and AV. The problem which planning needs to solve can be concluded in one sentence: how to accomplish the user-input task *safely*, *smoothly* and *optimally* with *minimum intervention*? For example, we may require MAVs to inspect some narrow, confined environments for us. Or we input our destination and require AVs to take us to the destination without any human intervention. The first term “safely” is straightforward: the robot should not collide with any obstacle even faced with unknown, cluttered, or changing environments. The second term “smoothly” can be interpreted differently depending on the application. For example, in autonomous driving, this term poses comfort constraints, while for micro aerial robots this term represents that the planned trajectory should be smooth enough so that the controller can follow. The third term “optimally” requires an elegant plan. For instance, the trajectory for MAVs should be energy-efficient, while the decisions of AVs should illustrate enough intelligence (e.g, automatically overtakes when appropriate). The fourth term “minimum intervention” means that the planning system should handle all the circumstances which the robot will potentially encounter in the operational design domain (ODD). This is the ultimate goal of using an autonomous system, namely, “click, go and done”, and this is exactly where the working efficiency and user-experience come from.

To this end, we target at building complete planning systems for MAV and AV to approach the goal of fully autonomous navigation. To build such systems, several research problems are raised and solved in this thesis. Specifically, navigating quadrotors smoothly in unknown

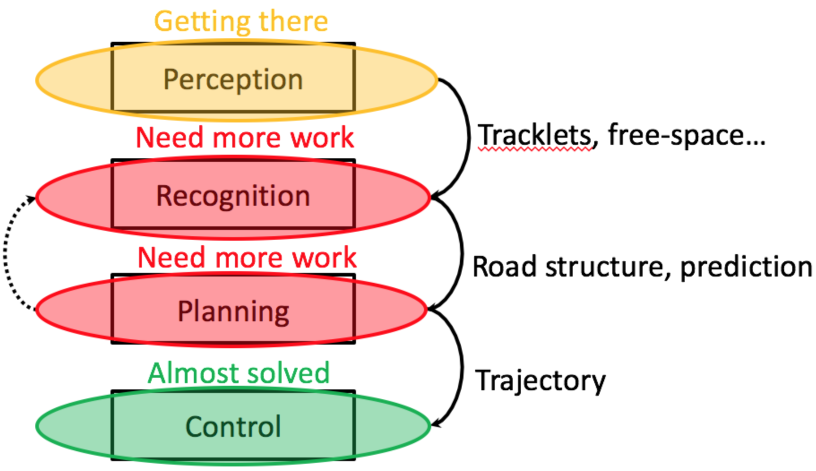

Figure 1.1: Illustration of the typical hierarchical structure of an autonomous system. For quadrotors, the perception layer includes depth sensing (i.e., static obstacles) and 3-D map reconstruction, while the recognition layer may include trajectory prediction for tracked objects. For autonomous vehicles, the perception layer may further include free-space detection, traffic signal detection, etc, while the recognition layer includes behavior and trajectory prediction for traffic participants. The control layer for both quadrotor and autonomous vehicle has the same meaning, namely, tracking the output trajectory of the planning layer as accurate as possible.

cluttered 3-D environments requires an efficient motion planning system. While for AVs, the planning system is more complex and consists of prediction, decision-making, and motion planning modules to adapt to dynamic multi-agent environments. In the following, we first discuss the related research problems and our solutions are elaborated in the following chapters.

1.1 Research Problems

We start with the motion planning system for MAVs, which has a straightforward goal. Specifically, the planning system is required to constantly generate smooth and dynamically feasible trajectories for quadrotors in unknown 3-D environments. When encountering unforeseen obstacles, the planning systems should replan timely and automatically to avoid the obstacles in a safe and optimal manner. The abovementioned system is a typical motion planning system, which can serve as a good starting point for this thesis.

As far as autonomous vehicles are concerned, other traffic participants are involved. These traffic participants can be stochastic and nosily rational while perceiving these participants also suffers from noises and errors. To understand the behaviors of other participants, prediction is required. Moreover, apart from motion planning, decision-making is more critical for AVs, since competing and cooperating with other participants are required. To this end, we divide the whole planning system into several components, namely, behavior prediction, decision-making, and motion planning. We specify the research problems for these aspects one by one and finally we integrate these modules into a complete planning system for autonomous vehicles.

At a high level, although quadrotors and autonomous vehicles may seem quite different, they share a similar hierarchical structure as shown in Fig. 1.1. For quadrotors, the perception layer mainly focuses on sensing static obstacles and reconstructs accurate 3-D map for the environments, while the planning layer basically focuses on the low-level motion planning. On the other hand, for autonomous vehicles, the perception layer may includes broader categories including perceiving the traffic signals, road structures, dynamic objects, etc. At the same time, since autonomous vehicles need to drive in social environments, they require a recognition layer to identify and understand complex social behaviors. For example, the recognition layer may include behavior and trajectory prediction for other traffic participants. Moreover, since autonomous vehicles need to accomplish complex user-input tasks (e.g., highway pilot, rush-hour pilot, shared control), their planning system requires high-level behavior planning to facilitate accomplishing the high-level goals specified by users.

Generally speaking, the perception layer is “getting there”. The reason is that from algorithmic perspective, the perception algorithms are becoming mature in terms of accuracy, latency and robustness. However, how to guarantee the perception quality with low-cost sensor suites remains a challenging problem. For example, with high-end lidars, depth sensing and object tracking can be extremely accurate. However, high-end lidars are too expensive to be deployed widely in industrial products. Perception with low-cost sensors such as cameras and noisy inertial measurement units (IMUs) is the current research direction. Honestly speaking, the recognition and planning layer are quite preliminary in the current stage. The algorithms are far from becoming mature and no consensus is reached. As a result, autonomous vehicles nowadays still seem “stupid”. The control layer is mature since the control algorithms have been mature for decays. The remaining challenges mainly involve controlling complex systems such as a truck with payload.

To summarize, in this thesis we mainly focus on the two layers we mark as “need more work”, as in Fig. 1.1, namely, the recognition layer and planning layer. For the recognition layer, we study the behavior prediction problem for autonomous vehicles in Chap. 3. For the planning layer, we study the high-level decision-making problem in Chap. 4 while the low-level motion planning problems in Chap. 2 and Chap. 5.

1.1.1 Motion Planning for Quadrotors in Unknown 3-D Environments

Consider a typical application that we need the quadrotors to complete an inspection task with full autonomy. We can derive two basic requirements for this problem. First, the environment is probably unknown beforehand. Second, the quadrotor may need to deal with narrow and confined 3-D environments such as inspection during disaster response. Considering these two problems together, the quadrotor is required to *replan* constantly when encountering unforeseen obstacles. To this end, we focus on trajectory replanning for quadrotors. However, replanning is a challenging task. First of all, the replanning should be highly efficient especially during fast autonomy. As such, heavy-weight motion planning methods can not be adopted. Second, replanning typically starts from nonstatic initial states, i.e., the quadrotor is not static for replanning. This poses additional feasibility constraints for planning. Many previous works [5–9] may be problematic when faced with nonstatic initial states. To this end, kinodynamic replanning is proposed in this thesis to accomplish efficient dynamically feasible replanning.

1.1.2 Behavior Prediction for Autonomous Vehicles

When coming to the problem of autonomous driving, we have to consider other traffic participants. However, traffic participants are known to be stochastic, noisily rational, and hard to predict. Therefore, it is essential to build behavior models for traffic participants. During online execution, through the inference process based on past observations, we can interpret the future motions of other traffic participants. However, building such behavior models is complex due to the multi-modal nature of the problem (e.g., thinking about predicting a vehicle in a uncontrolled intersection). Moreover, the uncertainty of the model increases dramatically as the prediction horizon increases. The problem is that, for planning purpose we need long-term prediction up to 5 to 10 s, while prediction is only accurate for short term (less than 3 s) in many existing works [10–13]. To this end, we require accurate long-term prediction while accounting for the multi-modal nature of the behaviors. And in this thesis, we work towards extending the prediction horizon by modeling additional multi-agent interaction information and build a learning-based behavior prediction pipeline.

1.1.3 Decision-making for Autonomous Vehicles

After building up the understanding of other traffic participants, the remaining problem is how to make intelligent decisions to interact, cooperate, or even compete with them. This problem can be characterized as decision-making in a multi-agent setting. When considering onboard autonomous driving, the problem becomes more complex. Since for onboard driving, all the observations come from onboard sensors, while sensing is hardly perfect. Various restrictions (e.g., occlusion, shading) impose errors in perception, which will be then propagated to prediction. As a result, from the decision-making perspective, the prediction received may be uncertain. The core problem is how to efficiently conduct safe decision-making in uncertain and multi-agent environments. In this thesis, we propose an efficient uncertainty-aware decision-making framework to tackle the above challenges.

1.1.4 Motion Planning for Autonomous Vehicles

The difference between decision-making and motion planning is that decision-making cares about a rough course of behavior plan which can be typically represented by a preliminary sequence of states, while the role of motion planning is to generate a smooth and safe trajectory in the local feasible solution space surrounding the initial guess provided by the decision-making. Unlike quadrotors which typically operate in static or semi-static environments, the challenge for motion planning of autonomous vehicles is to deal with dynamical obstacles. To this end, it is essential to take temporal information into account. Moreover, constraints or cost engineering has been a headache for motion planning, since there are various constraints imposed by the semantics of the environments such as lane geometry and traffic rules. We require a unified trajectory generation process which is easy to tune and seamlessly adapt to diverse environments. In this thesis, we propose a spatio-temporal semantic corridor structure to achieve this goal.

1.1.5 System Integration for Autonomous Vehicles

Based on our studies on individual components, it is time to assemble these modules into a complete planning system. In academia, a lot of planning systems have been proposed claiming various kinds of novelties. However, few of them are validated on a real autonomous vehicle. In industry, various demos are presented showing promising autonomy, but few technical details are published. For autonomous driving, the applicability of a planning system cannot be verified without onboard experiments. The reason is that real-world driving is constantly different from simulation and dataset, no matter how multi-modal and accurate the simulation or dataset is. To this end, we require verifying the whole planning system on a real autonomous vehicle with purely onboard sensors, and achieve closed-loop driving in dense city traffic. In this thesis, we achieve this goal leveraging all the advances made in this thesis.

1.2 Thesis Overview

The whole thesis is devoted to answer the following question:

> How to accomplish the user-input task *safely*, *smoothly* and *optimally* with *minimum intervention*?

This question is repeatedly raised throughout this thesis and will be answered in detail in the following chapters.

We start this thesis by introducing our motion planning framework for quadrotors in unknown complex 3-D environments (Chap. 2). The planning system is implemented on a quadrotor with only one monocular camera and one IMU. The system is extensively validated in both simulation and real-world experiments.

Based on the understanding of motion planning for quadrotors, we turn to the planning system for autonomous vehicles. Unlike planning for quadrotors, motion planning module is only one particular component for the planning system of autonomous vehicles. Before stepping into the motion planning for autonomous vehicles, we first introduce behavior prediction for autonomous vehicles (Chap. 3) which is employed to model traffic participants for driving. This behavior prediction module is further incorporated into the decision-making module (Chap. 4) which provides high-level decisions for the ego (controlled) vehicle in interactive driving environments. The interesting part is that our decision-making module (Chap. 4) can account for uncertain predictions provided by (Chap. 3), which is critical in real-world driving. Since in real-world, perfect prediction never exists. A robust decision-making system has to take the responsibility of tolerating uncertainties of upstreaming modules while still being able to ensure safety.

Given the decision, the remaining problem is to generate a smooth and safe trajectory which faithfully follows the decision. A motion planning module for autonomous vehicles is then introduced in Chap. 5. Having all the individual components, in Chap. 6 we assemble them into a complete planning system, and conduct field tests in real world to verify its effectiveness. The story is then finished and conclusions are drawn in Chap. 7, where we also point out promising future directions for the planning community.

1.3 Thesis Contributions

This thesis contributes to several aspects of motion planning and decision-making for two autonomous systems, i.e., MAV and AV. The contributions are not only algorithms but also complete system designs and extensive real-world validations.

In Chap. 2, we propose a complete and efficient kinodynamic replanning for quadrotors. This framework is designed to overcome the problem that traditional methods often generate non-smooth or even infeasible trajectory under non-static initial states. The kinodynamic search we propose provides superior performance in terms of the optimality and efficiency tradeoff compared to several state-of-the-art methods. Moreover, we implement the whole framework on two different vision-based platforms: one quadrotor with one camera and one IMU (monocular) and the other with dual-fisheye vision. Although the perception quality and field of view are quite different for two platforms, our planning framework consistently provides safe and smooth performance in real-world unknown 3-D environments.

In Chap. 3, we illustrate our first step into the field of autonomous driving. Before considering planning for autonomous vehicles, we have to understand the driving environments at the first hand. In this chapter, we propose a learning-based behavior prediction method for autonomous vehicles. This method is dedicated to solving the problem that the prediction horizon of existing methods is insufficient. However, planning requires long-term prediction. To this end, we propose utilizing interaction information among agents to introduce an additional clue for prediction and achieve extending the prediction horizon. Our method has superior accuracy and a longer prediction horizon compared to several state-of-the-art methods. We validate the method using a real-world highway driving dataset.

In Chap. 4 and Chap. 5, we finally approach the problem of planning for autonomous vehicles after obtaining the understanding of other traffic participants. In Chap. 4, we propose an efficient uncertainty-aware decision making (EUDM) framework. EUDM is designed to be robust to uncertain predictions while being highly efficient, which addresses two key concerns of decision making (i.e., efficiency and uncertainty). In Chap. 5, we introduce how to realize a particular decision to an executable trajectory. We propose a unified abstraction which wraps various constraints and obstacles in the driving scenario, i.e., the spatio-temporal semantic corridor (SSC). With the help of SSC, the trajectory generation problem boils down to a straightforward optimization formulation. Moreover, the SSC makes the formulation free of tuning, which is the key challenge for motion planning for autonomous vehicles.

In Chap. 6, we assemble a complete planning system for autonomous vehicles, based on our accumulated contributions. The key feature of our system that we not only have a systematic and consistent design but also validate our system in real-world city traffic. Although many existing works have been published on the planning for autonomous vehicles, few of them are validated in the real world. In this Chap. 6 we validate the real-world impact of our planning methods.