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# 主　論　文　の　要　旨

論文題目　Occlusion-aware speed and road position planning for autonomous vehicles
（自動運転のためのオクルージョンを考慮した速度および走行位置計画）

氏　　名　　NARKSRI Patiphon

## 論 文 内 容 の 要 旨

Widespread utilization of autonomous vehicles is expected to bring multiple benefits to society, such as more efficient use of energy, less traffic congestion, and most importantly, fewer accidents, injuries and fatalities. As a result, there has been increasing research and investment in the development of these vehicles. Efforts to accelerate the mass adoption of autonomous driving technology have led to the rapid broadening of the operational domains of autonomous vehicles in recent years, i.e., autonomous vehicles are no longer expected to operate only in simplistic driving environments.

Surrounding structures and other objects often prevent autonomous vehicles from fully observing the driving environment, a phenomenon known as “occlusion”. In complex driving environments such as urban areas, partial occlusion of the driving environment by buildings, walls, foliage, etc. is inevitable, however, most autonomous driving systems do not explicitly take this limitation of their sensing modules into account during their motion planning stage, and only consider detected observable obstacles. This failure to consider occlusion while planning an autonomous vehicle’s motion can lead to catastrophic accidents at critical locations such as low visibility intersections, for example, where the vehicle can mistakenly assess that it is safe to enter the intersection as no obstacles are currently detected, while there is, in fact, a vehicle rapidly approaching from an occluded area of the intersection.

One approach commonly used in occlusion-aware motion planners to deal with the risk imposed by occlusions is to explicitly assume that there are virtual obstacles approaching at high speed from outside of the visible areas of the roadway, on a path that will intercept the ego vehicle’s trajectory. By

assuming the worst-case scenario, and treating these virtual obstacles as if they are real, the motion of the ego vehicle can be efficiently and safely planned. However, approaches that are based on the assumed presence of virtual obstacles have two main drawbacks: excessively conservative movement due to the worst-case assumption, which can result in deadlock, i.e., the inability to move forward, and a lack of road position adjustment by the ego vehicle, which prevents it from obtaining a better vantage point by moving to the side of its lane.

In the context of navigation, "deadlock" is sometimes used to refer to a situation where multiple traffic participants are waiting for the others to pass through a conflict zone, e.g., an intersection, a merging area, or a narrow one-lane road, such that none of them can actually proceed. However, the meaning of "deadlock" in the context of this dissertation is slightly different, as it does not refer to an encounter between actual vehicles but between the ego vehicle and virtual vehicles assumed to be approaching at high speed from occluded areas. By assuming that such hypothetical vehicles are always approaching at high speed, the ego vehicle is forced to stop and wait indefinitely when visibility is severely limited.

The lack of road position adjustment is a more straightforward problem. Most occlusion-aware motion planners mainly consider the longitudinal motion of the ego vehicle, i.e., its speed, and ignore lateral motion, i.e., a movement toward the vehicle's lane boundaries. In other words, it is commonly assumed that the ego vehicle will always travel along the center of the lane. While this assumption simplifies the planning process, driving in the lane's center does not always yield the best visibility of the driving environment.

In this dissertation, we attempt to solve these two main weaknesses of occlusion-aware motion planning approaches which are based on assumptions of approaching virtual vehicles. To solve the deadlock problem, we proposed using the hypothetical visibility of approaching, hidden vehicles, as well as potential changes in their behavior after observing the ego vehicle, to plan the ego vehicle's speed. Our proposed speed planner first estimates visibility from point of view of the ego vehicle and potential hidden vehicles, using a 3D LiDAR scan and a road network map. The speed planner then predicts the states of occluded vehicles using a particle filter algorithm which supports possible changes in the behavior of approaching hidden vehicles based on their ability to see the ego vehicle. The behavior model for the hidden vehicles which is used to predict their states is based on an analysis of real driving data. An experiment confirms that our proposed speed planner can generate deadlock-free crossing motion at a blind intersection of two narrow roads, a maneuver that a baseline planner was not able to execute since the ego vehicle stopped indefinitely before entering the intersection.

Regarding road position planning, we proposed predicting and quantifying the visibility conditions of driving environments using high-definition 3D point cloud maps and road network maps. The quantified visibility conditions are then used to plan road positions for the ego vehicle that will result in minimal occlusion (i.e., maximum visibility). Our proposed visibility estimation method first approximates a 3D scan of a specified viewpoint using a 3D point cloud map. The approximated scan and 3D points representing the area of the relevant surrounding lanes are then projected onto depth images, which are consequently compared to identify the visible and occluded regions of the relevant parts of the driving environment from the specified viewpoint. This visibility estimate is then quantified by calculating the ratio of the visible areas of the driving environment to the total area of the relevant driving environment, to determine an area’s visibility ratio. Candidate trajectories for the ego vehicle, with different lateral offsets from the reference path, are then generated, and visibility ratios along each candidate trajectory are calculated. Finally, a visibility cost derived from the visibility ratio is used along with other planning costs to determine the optimal output trajectory. The proposed planner was tested in various simulated traffic scenarios while using live localization and object detection results. Our experimental results show that the ego vehicle was able to effectively minimize occlusions, and consequently discover occluded vehicles earlier, in most cases, when the proposed road position planner was used, in comparison to a baseline planner.