A Fail-Safe Motion Planner for Autonomous Vehicles

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Introduction

In recent years, advanced driver assistance systems have seen a real increase in the automobile industry. Within the next twenty years, it is estimated that autonomous vehicles will become the most viable form of transportation and will account for more than 75% of all cars on the road [1]. These vehicles offer many advantages, both to the driver and to other traffic participants (e.g. pedestrians). Among the most important advantages are of course the improvement of safety, traffic flow and comfort. However, like many other rapidly evolving technologies, the development of such vehicles faces many challenges. One of them concerns the safety they are supposed to bring us. Today, the world of robotics is still being debated, and even more so with the emergence of ever more advanced methods. For example, society is not prepared to tolerate road accidents caused by machines. Therefore, a guarantee of safety is essential for the acceptance of these vehicles. Furthermore, since a fully autonomous vehicle must be able to relieve the driver of all tasks, it must also be able to guarantee safety in a fast-moving environment. These requirements obviously complicate their arrival on the market. In order to guarantee this safety, it is necessary to start by working on motion planning methods. The first step is to generate the vehicle trajectory by considering the most probable trajectories of the surrounding vehicles. The second step is to make sure that an emergency maneuver remains possible at all times, otherwise, if the surrounding vehicles perform unexpected maneuvers, a collision may be inevitable. Silvia Magdici and Matthias Althoff have addressed this issue in their paper ”Fail-Safe Motion Planning of Autonomous Vehicles” [2]. In this paper, they develop a fail-safe motion planner that generates optimal trajectories while guaranteeing safety at all times.

1 Motivations

1.1 Need for Fail-Safe Motion Planning

Generating host vehicle trajectories based on the possible trajectories of other traffic participants is obviously a key element in ensuring the safety of autonomous vehicles. However, relying solely on the most likely trajectory of other surrounding vehicles is not always safe, as unexpected maneuvers can lead to collisions. Fail-safe motion planning is therefore necessary to be able to react safely in any traffic scenario. The idea is as follows:

- The trajectory of the host vehicle is firstly generated for a given time horizon, taking into account the most probable trajectory of the other vehicles
- Then, an emergency maneuver considering all possible actions of the surrounding vehicles is kept available at each time step.

If no feasible trajectory other than the emergency trajectory is found, then the emergency maneuver is applied until the host vehicle stops or a new feasible trajectory is found.

1.2 Ensuring both safety and comfort

Ensuring safety and comfort when planning movement in a dynamic environment is a complicated problem due to the infinite number of possible trajectories of other traffic participants. Furthermore, comfort and safety are very often conflicting requirements. For example, it is quite conceivable that a sudden (and therefore uncomfortable) maneuver could be useful to avoid a collision (and therefore safety). Although there are already many works on emergency maneuvers and optimal trajectory generation, the paper by S. Magdici and M. Althoff is the first to address motion planning with simultaneous consideration of safety and comfort. In the following, we first give an overview of the approach proposed by Silvia Magdici and Matthias Althoff, and then describe the fail-safe motion planner. We will then discuss the effectiveness of their approach by considering real traffic data on a highway.

2 Overview, Definitions, and Modelling

2.1 General definitions

The "host vehicle" is defined as the vehicle that is controlled by the safe-fail motion planner. Other traffic participants that are located in front of the host vehicle, in the same or adjacent lanes, and whose direction of travel is similar to that of the host vehicle are called "leading vehicles" or "surrounding vehicles".

2.2 Definition of the road network

The road network is defined by adjacent roads with arbitrary curvatures. The roads are denoted $lane_i$ and are defined by left and right boundaries ($b_{L,i}$ and $b_{R,i}$) defined as polygonal lines. The destination lane is the lane to which the leading vehicle is heading.

2.3 Modeling definition

Each vehicle is uniquely described by its position (s_x, s_y) in a global coordinate system. To model the vehicle, S. Magdici and M. Althoff use the paper by Moritz Werling and Darren Liccardo "Automatic Collision Avoidance Using Model-predictive Online Optimization" [3]:

$$\begin{aligned} \dot{s}_x &= v\cos\theta, \\ \dot{s}_y &= v\sin\theta, \\ \dot{\theta} &= \frac{v\ \delta}{l\left[1+\left[\frac{v}{v_{\text{ch}}}\right]^2\right]}, \\ \dot{\delta} &= u_1, \\ \dot{v} &= u_2, \end{aligned} \tag{1}$$

where (s_x, s_y) and v represent the reference position and velocity of the vehicle, respectively, θ denotes the direction of travel (or yaw angle) and δ is the wheel steering angle. The wheel steering rate u_1 as well as the acceleration u_2 serve as inputs to the system. Two other parameters are also used: the length l of the car and the characteristic velocity v_{ch}, which depends on the mass and the cornering stiffness, and characterizes the steady state dynamics of the model.

2.4 Constraints definition

$$0 \le v \le v_{\max}, \tag{2}$$
$$a_{min} \le u_2 \le a_{max}. \tag{3}$$
$$(s_x, s_y) \in \textit{lanes}, \tag{4}$$
$$\delta_{\min} \le \delta \le \delta_{\max}, \tag{5}$$
$$\dot{\delta}_{\min} \le u_1 \le \dot{\delta}_{\max}. \tag{6}$$

The above constraints must be satisfied. The first two inequalities (2) and (3) indicate possible values of speed and acceleration and thus refer to physical constraints. (4) is a safety constraint such that the vehicle stays within the lane boundaries. Finally, the inequalities (5) and (6) are comfort constraints, such that the generated trajectory is smooth.

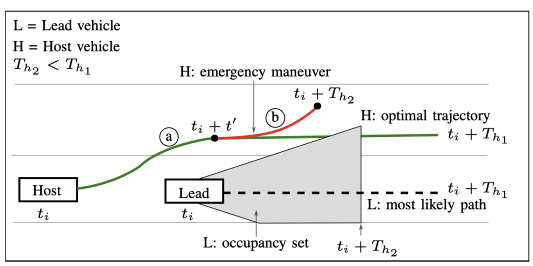
3 Fail-Safe Motion Planner

The main idea of the ”fail-safe motion planner” is based on three steps:

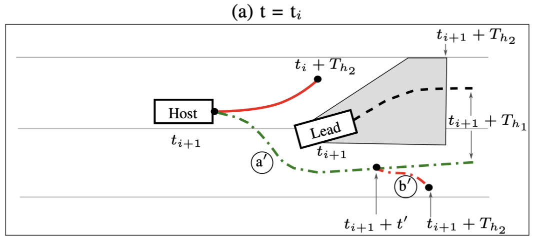
1. The most probable trajectory L of the leading vehicle is calculated, and from this an optimal trajectory H of the host vehicle is generated for a given time horizon Th_1, so that no collision occurs on this horizon.

2. Then, all possible trajectories of the leading vehicle are considered by computing the set encompassing all possible occupations of this vehicle for a given time horizon Th_2. From this set, an emergency maneuver that can bring the host vehicle to a stop is generated. To ensure that there is an emergency maneuver that can bring the host vehicle to a safe stop regardless of the trajectory of the leading vehicle, it is sufficient to consider the fail-safe trajectory determined by concatenating the segments (a) and (b) such that: (a) is the segment of the optimal trajectory H calculated for a time interval $[t, t + t]$ and (b) is a generated emergency maneuver. The fail-safe trajectory determined by this concatenation does not intersect the occupancy set of the leading vehicle, for any intermediate time interval up to the time horizon Th_2, which means that the host vehicle is safe.

3. Finally, after receiving the new traffic measurements, it is evaluated whether the optimal trajectory H should be continued or abandoned in favor of the safety trajectory (a)+(b). If there is another safety maneuver obtained by connecting an optimal trajectory (a’) with an emergency maneuver (b’) that does not cut through the newly calculated occupancy set, then the optimal trajectory (a’) is followed. If several feasible trajectories are found, the optimal trajectory is chosen. Otherwise, if there is no other collision-free trajectory, then the previously calculated emergency maneuver (b) is applied.



(a) t = t_i



(b) t = t_{i+1}

Figure 1: Emergency maneuver kept available.

We will now describe in more detail the generation of the optimal trajectory H as well as the emergency trajectory (b).

3.1 Optimal trajectory

In order to generate the optimal trajectory H for the host vehicle, the most likely trajectory L of the leading vehicle must first be calculated. For this purpose, there are different approaches: assuming constant yaw rate and acceleration (CYRA) [4], or using a maneuver recognition module (MRM) [5]. In their paper, S. Magdici and M. Althoff use the MRM approach because it is more accurate for longer term prediction. The idea is to predict the most likely trajectory L based on the detection of the destination lane, i.e., by comparing the current trajectory of the leading vehicle with the centerline of a given lane. For this purpose, only three basic maneuvers are considered: (1) keeping the lane, (2) changing lanes and (3) turning. It is assumed that for any maneuver execution, the target position of a vehicle remains on the centerline of a lane. Once the most likely trajectory of the leading vehicle is calculated, an optimal trajectory is generated for the host vehicle. In order to avoid collision with the leading vehicle, constraints on the distance between the generated trajectory and the predicted occupancy of the leading vehicle obji are taken into account. This involves ensuring that the minimum Euclidean distance d_i between the rectangle r_i, which surrounds the host vehicle, and the predicted polygon obj_i is greater than or equal to a parameter λ: $d_i \geq \lambda$. The chosen cost function minimizes the variation of the speed and the variation of the steering rate:

$$J_1 = \int_t^{t+T_{h_1}} \Big[\gamma_1 u_1^2 + \gamma_2 u_2^2 + \gamma_3(\theta - \theta_r)^2 + \gamma_4 \delta^2 + \gamma_5 d_r^2\Big] d\tau,$$

with γ_i, $i \in \{1, \dots, 5\}$ the weighting parameters and θ_r the orientation of the reference trajectory. As mentioned earlier, the reference trajectory of the host vehicle is the centerline of the current lane, so if no feasible trajectory is found using this line as a reference, then the centerline of the adjacent lanes is considered the new reference trajectory. The generated trajectory thus corresponds to a lane change maneuver.

3.2 Emergency trajectory

As mentioned earlier, the leading vehicle can perform an infinite number of unpredictable maneuvers, which are not taken into account when generating an optimal trajectory H. Therefore, an emergency plan taking into account all these possible maneuvers in a given time horizon Th_2 must be maintained. For this purpose, the constraints derived from the traffic rules listed in the Vienna Convention on Road Traffic [31] and the physical constraints are taken into account, and then the sets reachable by the leading vehicle are calculated. Among the physical constraints imposed are the following:

- reversing and leaving the road is prohibited ;
- the maximum absolute acceleration is limited by amax ;
- the longitudinal acceleration is zero when a parameterized vmax is reached and is inversely proportional to the speed whose value is greater than a parameter vs, which models a maximum engine power.

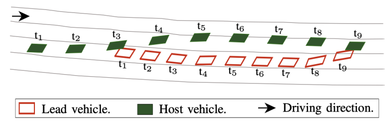
This approach has two main advantages: First, it ensures that all possible trajectories are included in the approximate occupancy set. Second, the computation time is low which makes it suitable for real-time computation. Once the occupancy set of the leading vehicle is calculated, a collision-free trajectory is generated for the host vehicle. The cost function is similar to the one used for generating the optimal trajectory. The difference is that we are no longer trying to drive along a reference trajectory, but rather to minimize the speed v :

$$J_2 = \int_t^{t+T_{h_1}} \Big[\gamma_1 u_1^2 + \gamma_2 u_2^2 + \gamma_3(\theta - \theta_r)^2 + \gamma_4 \delta^2 + \gamma_5 v^2\Big] d\tau$$

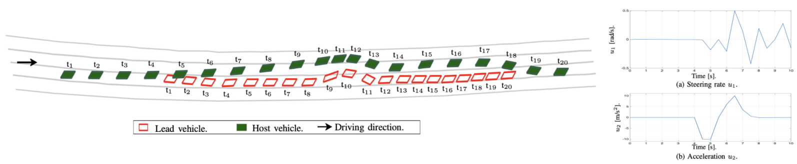
4 Numerical Experiments

To assess the proposed framework, real traffic data are used: for each vehicle considered, the position, velocity and acceleration at every $0.1s$ are available. Three scenarios are then considered:

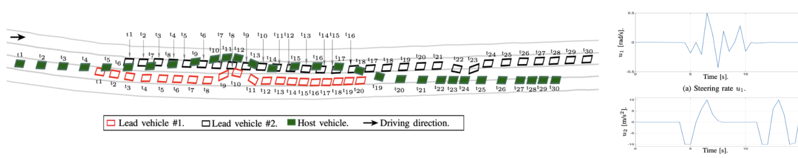
Scenario 1: We first consider that the motion planner does not support fail-safe maneuvers. Initially, the host and leading vehicles are driving about $40m$ apart on the same lane at speeds of $20m/s$ and $14m/s$. At a time $t_9 = 4.5s$, the leading vehicle performs an unexpected maneuver and moves to the left lane. Since no safety maneuver is considered, this last maneuver causes an accident.



Scenario 2: This second scenario assumes fail-safe maneuvers. As in the first scenario, the leading vehicle moves to the left at time $t_9 = 4.5s$. This unexpected behavior of the leading vehicle triggers an emergency maneuver by the host vehicle in order to avoid the collision.



Scenario 3: In this last scenario, two leading vehicles are considered. The initial distances between the host vehicle and the other vehicles are about $40m$ and $50m$, and the initial speeds of the leading vehicles are about $14m/s$. The first leading vehicle makes an unexpected maneuver at time t_9 to the left lane, where the host vehicle is driving. The host vehicle successfully avoids the collision by applying the available emergency maneuver. Later, at time t_{22}, the second leading vehicle also performs an unexpected maneuver but returns to its lane at the very next time step. The host vehicle's lane change maneuver is therefore cancelled and it continues to drive on the planned trajectory. Finally, the host vehicle has managed to avoid any collisions with the two leading vehicles.



Conclusion

In this report we presented the fail-safe motion planning approach proposed by Silvia Magdici and Matthias Althoff. This approach is based on the prediction of the most likely trajectory of the leading vehicle as well as on the availability of an emergency maneuver for the host vehicle. To assess the availability of this maneuver, the approach takes into account all possible trajectories of the leading vehicle. This ensures that the host vehicle is able to stop safely regardless of the actual maneuver performed by the leading vehicle. Finally, the tests conducted on real traffic data proved the effectiveness of this approach.

References

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