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Realizing Complex Autonomous Driving Maneuvers The Approach Taken by Team CarOLO at the DARPA Urban Challenge

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Abstract— **The 2007 DARPA Urban Challenge has been a great opportunity to demonstrate the abilities of the Technische Universität Braunschweig to develop an autonomous vehicle named Caroline and to show its capabilities in urban-like environments. Team CarOLO was among 11 of 89 teams who qualified for the final DARPA Urban Challenge early in the competition.**

This paper describes the approaches taken by team CarOLO for the realization of complex autonomous driving maneuvers. Compared to previous activities in autonomous driving this is the first venture to require fully autonomous vehicle guidance in an urban environment: all previous projects have focused on navigating deserts and highways. Completely new concepts are required to make vehicle guidance in urban environments possible. An efficient and flexible interface as well as the control structure of Caroline's system is shown that was applied in the DARPA Urban Challenge.

I. INTRODUCTION

During recent decades automated vehicle operation has been of great interest. In the early nineties autonomous driving gained a lot of importance due to the VITA project in Germany [1], the CMU-Navlab-Project in the USA [2] and the PVS-Project in Japan [3]. Based on these pioneer projects further autonomous vehicles were developed all over the world.

When the DAPRA introduced the first Grand Challenge in March 2004 across the Mojave Desert of Nevada, autonomous driving reached a new height. The vehicle that could complete the 150 mile race first would have won the price of one million dollars. Even though more than 100 teams applied, the farthest distance travelled was 7.4 miles [4].

The second Grand Challenge took place in the Mojave Desert in October 2005. Due to the experience of the first Grand Challenge DAPRA progam managers changed the qualification process entirely. To enhance the barriers a step-by-step qualification process including a video of the car as well as a site visit, similar to a quarter-final, has to be completed. Five teams could finally complete the distance of 132.2 miles and the Stanford Racing Team won the DARPA Grand Challenge 2005 with their vehicle named 'Stanley' [5].

To further increase the difficulty of requirements, the DAPRA announced the Urban Challenge 2007, which took place in Victorville, CA. In contrast to the first two challenges, this venture required full autonomous vehicle guidance in an urban environment.

The Technische Universität Braunschweig equipped a 2006 Volkswagen Passat station wagon named Caroline to compete in the DARPA Urban Challenge. After the qualification process had been mastered, Caroline qualified early for the final and competed among eleven other teams in the final of the DARPA Urban Challenge.

Compared to previous activities in autonomous driving, completely new concepts are required to make vehicle guidance in urban environments possible. Traffic at intersections, blocked roads, parking maneuvers and u-turns have to be handled. New concepts have to be developed to break down high level decisions into driving commands. In the following, a new concept is presented to realize precise driving maneuvers required in urban environments.

II. THE HARDWARE

A 2006 Volkswagen Passat station wagon named Caroline served as the vehicle platform for Technische Universität Braunschweig's DARPA Urban Challenge entry. Equipped with a variety of actuators, sensors and computers, Caroline fullfills the requirements of an autonomous vehicle. To generate an object based model of the environment, laser, lidar and radar are used. Combining the advantages of each sensor modality leads to a redundant environment model. Stereo vision system as well as laser scanners mounted on the roof provide information about the driveability of the terrain. Different cameras track lane markings. Fig. 1 gives an overview of the sensors and their mounting points.

An array of automotive PCs mounted in the trunk of Caroline as shown in Fig. 2 serves as the computational core for different modules. They are connected through Ethernet communication to afford distributed system architecture. A CAN (Controller Area Network) interface opens the opportunity to access Carolines by-wire steering, electronic brake and throttle system. The modular processing systems of Caroline allowed systems to be developed in parallel.

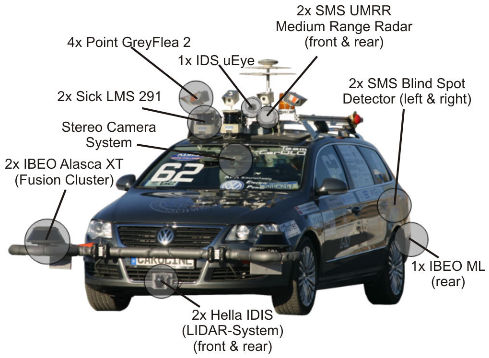

Fig. 1. Sensor cluster of the autonomous Passat Caroline.

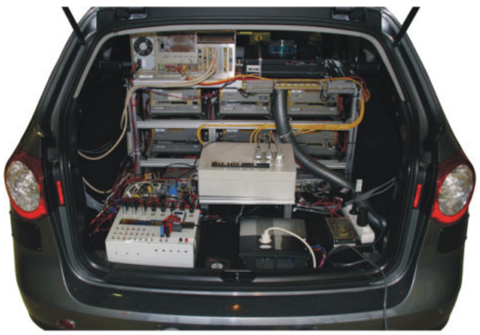

Fig. 2. Computation unit.

A good vehicle guidance system is needed to control the precise driving maneuvers required in an urban environment. The guidance system inside Caroline is separated into a decision unit, an optimized path planning unit and a vehicle control unit. The goal is not only to realize autonomous driving in general, but also to convert abstract decisions into a smooth driving experience.

The remainder of this paper will focus on Caroline's overall vehicle guidance system including path planning and the control module. A detailed implementation of Caroline's decision unit can be found in [6], including a discussion of the Distributed Architecture for Mobile Navigation (DAMN).

III. FLEXIBLE INTERFACE FOR HIGH LEVEL DECISIONS

To decouple the decision unit from the final path planning and control systems, an innovative and extensible interface was created by developing a compact decision data structure. The interface established as much freedom as possible for the path planning module, enabling it to make precise driving maneuvers. The modular interface allowed different control approaches to be easily tested. Thus far, two different strategies have been implemented, resulting in Caroline's navigational flexibility.

The most commonly used driving mode is named 'follow trajectory'. Based on environmental conditions, the decision unit determines a drivable area bounded through so-called pearls (Fig. 3). To plan a dynamic optimized trajectory, a representation of the road edge can be achieved by connecting those pearls on each side. Distance and width of pearls can be adjusted to current conditions resulting in a flexible data structure.

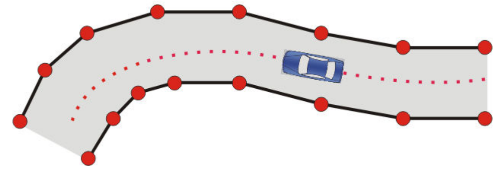

Fig. 3. Interface between decision unit and path planning.

A multistage process determines the drivable area and optimal path of the vehicle. An optimization algorithm based on elastic band theory [7] places the nodes for the trajectory at the optimal position in terms of overall curvature and trajectory length. Connecting those nodes with b-splines, results in temporary trajectory inside the drivable area. Since the curvature characteristics are not optimized to the holonomic constraints of a vehicle, smoothing splines are applied to flatten the curvature gradient. Finally, the smoothed curvature serves for the calculation of the final trajectory. The described process results in lower lateral forces at the tires and a smoother autonomous driving. Fig. 4 visualizes the different steps of the optimization routine, Fig. 5 shows an example of an optimized trajectory. A detailed explanation of the path planning process will be described in a future publication.

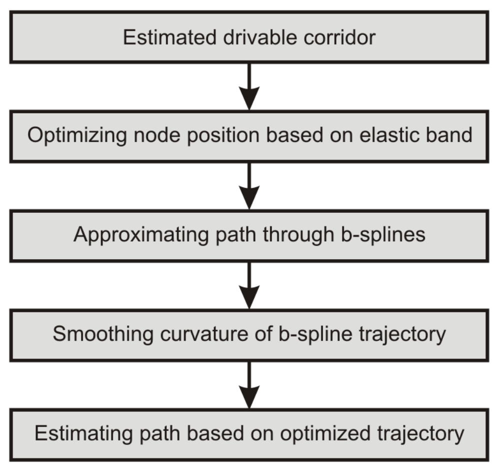

Fig. 4. Multistage optimisation of trajectory.

Pearls contain information about the edge of the road and the minimum and maximum speeds the vehicle is allowed to travel at that location. The decision unit has the capability to influence the driving comfort of the car by choosing a comfort level that has been introduced into the interface. Comfort levels are represented by a set of parameters that influence the maximal and minimal accelerations. An optimized speed profile is determined based on speed limits and comfort level by the speed planning module. A longitudinal control strategy generates the required commands for the calculated speed profile.

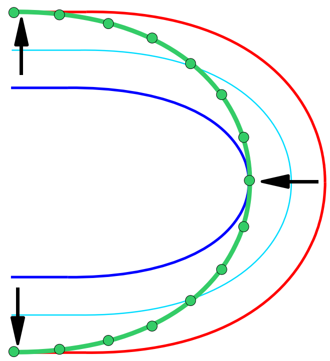

Fig. 5. Reducing curvature by rearranging nodes.

The second driving mode introduced into Caroline so far is the u-turn mode. Instead of a list of pearls, the decision unit determines a bounding box, where the path planning module realizes a u-turn (Fig. 8). Two different maneuvers are shown as an operational example of both interface modes.

A. Automated Parking Maneuvers

Vehicles in the Urban Challenge had to demonstrate the ability to pull forward into, and reverse out of a specified parking spot. According to the rules of the DARPA Urban Challenge, there are at least seven metres available for parking sequences.

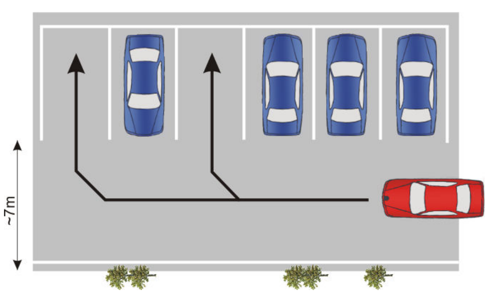

Fig. 6. Parking situation in the Urban Challenge.

A state machine is introduced to realize automated parking procedures based on the 'follow trajectory mode'. In each step, a list of trajectory pearls is generated to communicate the desired behaviour of Caroline to the control unit.

Parking maneuvers consist of three major steps:

1) The vehicle is guided to the parking spot by the decision unit.
2) As soon as the condition for realizing a parking maneuver is met, a parking interrupt is executed.
3) Different steps of a state machine guide the vehicle into the spot.

To enter the final state for guiding the vehicle inside the parking spot, the state machine positions the vehicle either on a line perpendicular or on a straight line into the box (Fig. 6). If the transition condition is met that the state 'enter parkbox' can be performed, a trajectory is aligned to a assistance line that guides the vehicle inside the parking spot. If the box cannot be entered at once, the vehicle is backed up until a successful trajectory is found.

Fig. 7 shows a snapshot from the race, where Caroline successfully entered a parking box.

Fig. 7. Snapshot of a parking maneuver during the race.

B. U-turns Maneuvers

It has been a requirement of the Urban Challenge to recognize blocked roads and dead-end streets, which usually resulted in a multi-stage turn of the vehicle. U-turns are realized through an additional driving mode that uses direct steering commands in order to complete the maneuver faster. If a u-turn should be performed, the decision unit sends a bounding box to the path planning (Fig. 8). Based on street conditions, static and dynamic obstacles as well as lane markings, the bounding box is created that describes the desired u-turn area. If dynamic obstacles rise into the bounding box during the u-turn procedure, the process is adapted to the current situation. A u-turn maneuver can be interrupted by higher level decisions at any time.

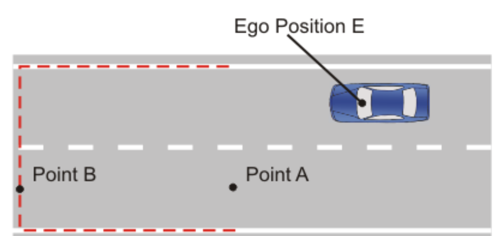

Fig. 8. Bounding box of a u-turn.

A state machine inside the path planning module generates commands for the steering wheel to achieve the different states. A u-turn procedure can be described by four different states: 'enter' brings the vehicle inside the bounding box into the correct position and alignment; 'forward left' and 'backward right' are consecutively executed to turn the vehicle until it is recognized that the u-turn can be finished. A condition to initiate the final state is based on the radius r providing a curved exit trajectory:

$$r = \frac{x}{y} \tag{1}$$

$$\begin{aligned} x &= B_x\left(A_y - B_y\right) - B_y\left(A_x - B_x\right) \\ &\quad + E_y\left(A_x - B_x\right) - E_x\left(A_y - B_y\right) \\ y &= \left(cos(\alpha - \frac{\pi}{2}) - cos(\psi - \frac{\pi}{2})\right)\left(A_y - B_y\right) \end{aligned} \tag{2}$$

$$+ (sin(\psi - \frac{\pi}{2}) - sin(\alpha - \frac{\pi}{2}))\,(A_x - B_x) \quad (3)$$

Here ψ is the current orientation of the vehicle, and α the orientation of final u-turn position in global coordinates. If the final steering angle is below maximum possible steering angle, the u-turn can be finished. The final steering angle is calculated based on the wheelbase $l = 2.712m$:

$$\delta_{final} \quad = \quad atan2(\frac{2.712}{r}) \leq \delta_{max} \qquad (4)$$

Fig. 9 gives an overview about the different states of the u-turn procedure.

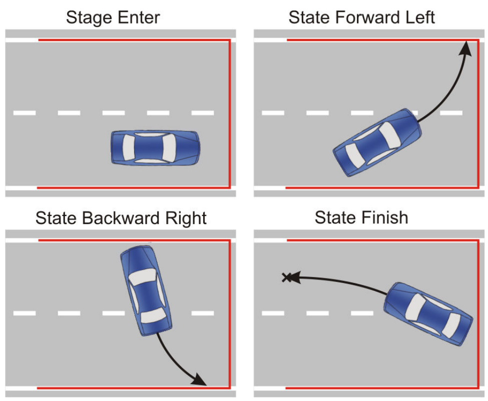

Fig. 9. Different states of the u-turn procedure.

IV. LOW LEVEL CONTROLLERS

Autonomous driving is based on low level control strategies. The goal of the longitudinal control module is to maintain a given speed. Meanwhile, the lateral controller guides the vehicle on a given track. Both concepts as installed in Caroline for the DARPA Urban Challenge are discussed.

A. Longitudinal Control Strategy

The decision unit sets an upper and lower limit for vehicle speed. Path planning prepares a dynamic optimized speed profile in between these limits that takes the comfort level set by the decision unit into account. Finally, the controller calculates braking and accelerator set points in order to maintain a given speed.

1) Cascade Structure Control:: A cascade controller structure with an inner and outer loop is used as shown in Fig. 10. While the outer loop controller determines the required acceleration for a given speed set point, the inner loop controller calculates throttle and brake commands to track the input of the outer loop. An inertial measurement unit measures acceleration to a high resolution for the inner control loop.

Different control parameters of each transfer function $K(s)$ are adjusted for acceleration and deceleration operations. While a PI controller is introduced for the inner loop, a P controller serves for the outer control loop. In addition, an engine map is used for direct feed forward control of the throttle. Predefined logic is used to prevent the throttle and brake from being activated at the same time.

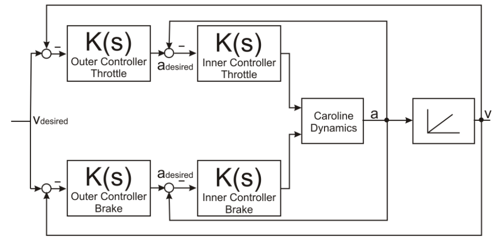

Fig. 10. Block diagram of the longitudinal controller.

2) Performance of the Longitudinal Controller:: Two different speed profiles are used to illustrate the performance of the longitudinal control strategy as shown in Fig. 11. In the first example, the desired velocity is changed in long and large steps. In the second example, shorter and smaller steps are used. The result of the speed planner is not shown in this example.

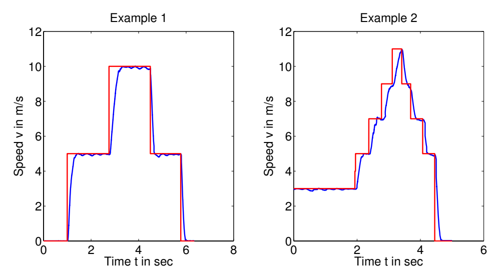

Fig. 11. Performance of the longitudinal controller.

B. Lateral Control Strategy

In urban environments it is necessary to follow narrow curves and complex trajectories at an acceptable speed and a minimal track error. Vehicle driving maneuvers should also match certain comfort parameters for a smooth driving experience. In the following, a lateral control strategy is discussed that allows straight roads and narrow curves (close to turn radius of the vehicle) to be travelled at high speed.

1) Parallel Structure Control:: According to the well-known bicycle model [8], the vehicle has three degrees of freedom, as there are x and y position as well as the orientation ψ of the car. These neglects for instance rolling and pitch of the vehicle and assumes the center of mass is on street level in between front tires. The controller handles simultaneously all degrees of freedom via the steering angle δ.

Controller deviations (track and track angle error) were described mathematically to introduce them into a state space representation of the system. While track error denotes the distance between center of mass of the vehicle and desired position, track angle is defined as the difference between the desired and actual orientation of the car. Both serve as feedback signals for the controller.

As shown in Fig. 12, the lateral controller consists of two parallel control loops for track error and track angle deviation. In addition, pilot control takes the track curvature into consideration. The map-based pilot control algorithm calculates steering angles that would be needed to follow the desired track based on parameters of the bicycle model. $K(s)$ describes the transfer functions of the different controllers. For both loops, P-controllers are applied with the parameters adapted to vehicle speed and curvature.

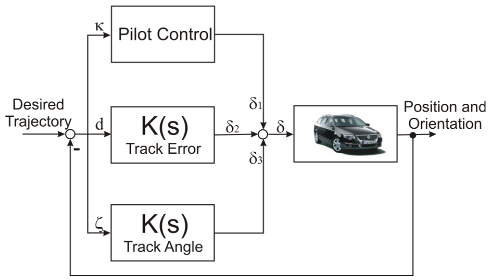

Fig. 12. Lateral control strategy.

2) Performance of the Lateral Controller:: The lateral controller has to perform well on long straight trajectories at higher speeds, yet provide stability and low track error on twisting roads. To show the performance, the vehicle starts on long straight trajectory and enters two sharp curves close to the turn radius of the vehicle. On the first section, the vehicle is accelerated up to a speed of almost $v = 50$ km/h. Both narrow curves are driven at a speed of approximately 20 km/h, which corresponds to a lateral acceleration of up to $6\,\frac{m}{s^2}$. Speed profile, track error and curvature of the trajectory are shown in Fig. 13.

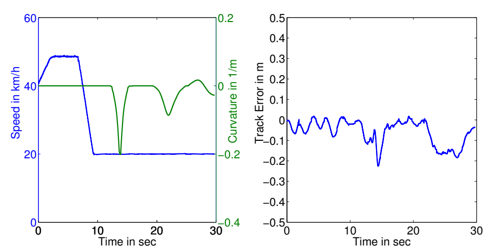

Fig. 13. Speed profile and track error of the trajectory.

During all tests and missions of the DARPA Urban Challenge, the control strategy has always been stable with a low track error, resulting in precise driving maneuvers.

V. CONCLUSION AND OUTLOOK

The DARPA Urban Challenge has been the first venture that required fully autonomous vehicle guidance in an urban environment. Caroline's guidance system was developed with flexibility in mind, allowing complex driving maneuvers to be performed.

Even though autonomous vehicles had to handle many complex driving situations in the DARPA Urban Challenge, automated public transportation systems are still in their infancy. Caroline's driving systems could be extended increasing safety and efficiency. Therefore, the Technische Universität Braunschweig has set up a consecutive project named ‘Der Stadtpilot’ under the leadership of the Institute of Control Engineering to achieve further improvements in autonomous driving. A new prototype named ’Leonie’ is being constructed to drive autonomously through the entire city loop around the city center of Brunswick by 2010. Autonomous driving in this two-lane urban road includes interaction with traffic, behavior at intersections, lane change maneuvers at speeds up to 60 km/h as well as merging into circulating traffic.

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