2010 IEEE Intelligent Vehicles Symposium
University of California, San Diego, CA, USA
June 21-24, 2010

Stadtpilot: Driving Autonomously on Braunschweig's Inner Ring Road

Jörn Marten Wille, Falko Saust and Markus Maurer

Abstract— **The development of the autonomous vehicle named "Caroline" for the 2007 DARPA Urban Challenge was a great opportunity to demonstrate the abilities of the Technische Universität Braunschweig in the research field of autonomous driving. Among 11 teams out of the initially 89, the CarOLO team mastered the challenges to qualify for the final DARPA Urban Challenge event. Based on this experience, the Technische Universität Braunschweig is currently working on the follow-up project "Stadtpilot" with the objective to drive fully autonomously on Braunschweig's entire ring road, which is known as the arterial road of its inner city traffic.**

This paper introduces the "Stadtpilot"-Project in the context of the Urban Challenge experience and identifies the differences to previous activities in this research context. The scientific claim will be shown in contrast to the Urban Challenge scenario. Completely new concepts are required to master the challenges of realizing autonomous driving in the domain of Braunschweig's inner ring road. An approach for the comprehensive treatment of path-planned sections is shown that realizes complex and precise autonomous driving maneuvers in a real urban environment and is observed as the first major success of the "Stadtpilot"-Project. Curvature optimized trajectories are generated over the whole roadway that are independent from the way driving decisions are found.

I. INTRODUCTION

Since a couple of decades already, researchers are fascinated by driving fully autonomously in real road traffic. Particularly the increasing number of electronic components introduced into mass-production vehicles has enabled a variety of well-known research projects in the field of autonomous vehicles. In the early 1990s the VITA-Project in Germany [1], the CMU-Navlab-Project in the USA [2] and the PVS-Project in Japan [3] gained a lot of interest. As part of the European funded Prometheus-Project, researchers from the Universität der Bundeswehr München proved the capabilities of their autonomous vehicle VaMP to drive on public highways in real traffic. In a long-distance test run from South Germany to Denmark in 1995, more than 95% of the driven path could be completed autonomously [4]-[5].

With the announcement of the DARPA Grand Challenge across the Mojave Desert of Nevada in 2004, autonomous driving reached a new height. A prize of one million dollars was to be awarded to the vehicle completing the 150 mile race first. Even though more than 100 teams applied, the result was a disappointment since the most successful vehicle traveled just 7.4 miles [6]. Based on this experience, the DARPA announced the second Grand Challenge in 2005 with an enhanced qualification process. Altogether five teams completed successfully the track and the Stanford Racing Team won the contest with their vehicle "Stanley" [7].

Having thus proved that crossing the Mojave Desert with autonomous vehicles was possible, the DARPA increased the degree of difficulty with the announcement of the Urban Challenge. The environment of the former George Air Force Base close to Victorville, CA, provided the basis for the scenarios of the third DARPA Challenge. In contrast to earlier scenarios on highways or the first two Grand Challenges, this venture required fully autonomous vehicle guidance in an urban-like environment. Besides the compliance with complex traffic rules, interaction with other robots was also part of the Urban Challenge final; thus, driving decisions had to be found in real-time based on other vehicles' behavior.

The third part of the Grand Challenge series took place on November 3, 2007. Prizes of 3.5 million dollars were offered to the first three vehicles to complete a 60 miles track in less than six hours and with as little violations of rules as possible. The Team Tartan Racing (Carnegie Mellon University) won the competition, followed by the Stanford Racing Team (Stanford University) and the Team VictorTango (Virginia Tech). Also, the Technische Universität Braunschweig took part in this contest and equipped a 2006 Volkswagen Passat station wagon named "Caroline" and competed among eleven other teams in the final of the DARPA Urban Challenge [8].

II. "STADTPILOT"-PROJECT

With its participation in the DARPA Urban Challenge the Technische Universität Braunschweig proved that it was capable of building up a state-of-the-art fully autonomous vehicle. Based on this experience the Technische Universität Braunschweig has continued the effort in autonomous driving in urban environments with the follow-up project called "Stadtpilot". A team consisting of different faculties formulated as the goal of the project to create a vehicle able to drive autonomously through the entire ring road around the inner city of Braunschweig (Fig. 1).

While the Urban Challenge had been an artificial, strongly simplified urban environment, the objective of "Stadtpilot" is to drive fully autonomously in real urban traffic. Autonomous driving on 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 moving traffic.

III. TRANSFERRING AUTONOMOUS DRIVING INTO A REAL URBAN ENVIRONMENT

The ring road environment differs significantly from the Urban Challenge scenario. In the following, the differences

All authors are with the Institute of Control Engineering, Technische Universität Braunschweig, 38106 Braunschweig, Germany. {wille,saust,maurer}@ifr.ing.tu-bs.de

Fig. 1. Proposed track for autonomous driving around Braunschweig with an overall length of 12 km (marked in red).

between "Stadtpilot" and Urban Challenge are discussed in detail confirming the increased scientific requirements.

1) New basic conditions: As is typical for a race contest, the teams in the DARPA Urban Challenge participated with the objective of winning the challenge or at least reaching a top ranking. Most of the vehicles were developed to attain this goal, resulting in shortcuts when running out of time. In contrast to such a singular event, the "Stadtpilot"-Project is set up as a long-term project with the goal of achieving a high research sustainability. However, this may lead to a delayed operating schedule to assure lasting research output.

While traffic in the Challenge had been simulated by trained stunt drivers and was therefore controlled by the DARPA, all road users in the "Stadtpilot"-Project belong to real traffic scenarios. Vehicles do not behave according to DARPA regulations anymore, but to normal road traffic regulations for human drivers.

According to Article 8 of the Vienna Convention on Road Traffic [9], full autonomous driving on public roads is not intended. The guidelines related to the project are in detail:

"(1) Every moving vehicle or combination of vehicles shall have a driver."

...

"(5) Every driver shall at all times be able to control his vehicle or to guide his animals."

However, for research and development purposes automated driving maneuvers on public roads might be possible based on a safety concept according to which a trained surveillance driver can always gain control of the car.

2) More complex infrastructure: The infrastructure of the disused military area in Victorville, is substituted by the densely populated surroundings of Braunschweig's inner ring road and is much more complex due to its real urban structural conditions (Fig. 2). While difficulties of unpaved roads known from the Challenge are omitted, the densely built-up area imposes extremely high demands on a precise positioning system. A differential global positioning system (DGPS) coupled with inertial measurement data was sufficient to position a vehicle in the Urban Challenge accurately.

However in the "Stadtpilot" scenarios, shadowing effects due to tall houses or trees can interfere with the reception of the GPS signals [10]. Even with enhanced information

Fig. 2. Infrastructure in Urban Challenge (left) and on the ring road (right).

using an accurate DGPS, the precise vehicle positioning on the narrow urban ring road lanes is not always granted. Fig. 3 shows the number of seen satellites during a test run on the outer lane of the ring road. In the current example it cannot be guaranteed anymore that the vehicle is still in the right lane. As a result, due to this insufficient satellite visibility, "Leonie's" positioning system needs to be extended by a supplementary lane detection system.

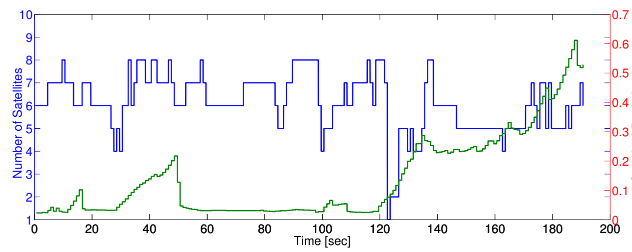


Fig. 3. Typical satellite visibility while driving on the ring road.

At most of the road intersections focused in the "Stadtpilot"-Project, the traffic flow is controlled by traffic lights. Its states are of key importance for the decision finding and necessarily influence the vehicle's behavior. In contrast, in the Urban Challenge every vehicle had to follow California's driving regulations; thus, all road intersections were designed as three- or four-way stops. The signs' locations used to define the right-of-way were stored in a digital map so no on-board detection was needed.

3) More complex environment: Not only the infrastructure but also the environment around the ring road is much more complex (Fig. 4). The environment in the Challenge was completely controlled by the DARPA: surroundings were only composed of vehicles and static obstacles and the manipulated traffic was mainly characterized by a defensive stunt driver behavior. The result was a totally self dependent speed selection of the robots. Although approximately 48 km/h (30 mph) were allowed, even the fastest robots reached this top speed rarely and ended up with an average speed of around 22.5 km/h.

Fig. 4. Environment in Urban Challenge (left) and on the ring road (right).

The ring road environment differs markedly from the

TABLE I

RING ROAD COURSE DATA SEPARATED IN FOUR SECTORS.

Category	Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sum
Length in km	2	2.8	3	4.2	12
Duration in min	6.2	4.3	6.9	5.1	22.5
Average Speed in km/h	19.4	39.1	26.1	49.4	33.5
Required Lane Changes	1.1	0.2	2.1	0.5	3.9
Traffic Light Stops	2.7	1.7	3.7	3	11.1

Urban Challenge conditions: the unaffected traffic is characterized by a variety of different road users with manifold driving styles in a real volume of traffic. The vehicle's speed has mainly to be chosen based on the traffic conditions to prevent the robot of slowing down the traffic flow.

Tab. I shows averaged measurements taken in the ring road environment. The data are collected in ten different manual test runs, which were scheduled at different weekdays and varied times of day. A separation into four different sectors underlines the variety of the environment. The overall average speed in this example is 33.5 km/h with an overall top speed of almost 58 km/h, what differs enormously from the Urban Challenge.

It has been a unique situation in the final event of the DARPA challenge that all robots were driving simultaneously to fulfill their desired missions. Thus, robots had to interact with each other. While the stunt drivers were instructed to drive defensively, autonomous vehicles were programmed to consider rule violation in unforeseen situations to prevent themselves from getting stuck. However, such tiny breaches of rule are very common in usual urban traffic. Evasive movements in the adjacent lane, a forgotten turn signal or a jaywalking pedestrian are normal situations human drivers have to deal with; thus, this behavior needs to be suitably represented in "Leonie's" decision unit.

4) Increased vehicle requirements: According to the DARPA regulations almost any modifications of the vehicles were allowed. Fig. 5 exemplifies the free design of prototypes with "Caroline's" special mounted lidar system. Road traffic regulations constrain the modifications of the "Stadtpilot" vehicles; as a result, the robot's sensor system is not allowed to enlarge the car's silhouette.

Fig. 5. Urban Challenge vehicle "Caroline" and its special mounted lidar system (left) in comparison to the "Stadtpilot" vehicle "Leonie" (right).

A participation in the Urban Challenge necessitated to install a remote-controlled emergency stop into the vehicles to convert them in case of a failure into a safe stop. Such an interception system will not be required in the "Stadtpilot"-vehicles, since a surveillance driver will be on board, trained to take control of the system if necessary. Accessing the steering wheel, pressing the brake or gas pedal results in an immediate abandonment of the autonomous functionality. Emergency buttons offer another option to intervene. In addition, an extensive monitoring informs the surveillance driver about the current state of the system to advert to potential malfunctions.

IV. SYSTEM ARCHITECTURE

A 2007 Volkswagen Passat station wagon named "Leonie" (Fig. 5) serves as the first vehicle platform in the "Stadtpilot"-Project and has been equipped with a variety of actuators, sensors and computers. In addition, "Leonie's" brother "Henry" is currently built up to enable parallel research activities in the field of grid-based and object-based environmental perception, overall vehicle guidance systems, reliable positioning and safety concepts.

To generate an object-based model of the environment, lidar and radar sensors are used. The combination of the advantages of each sensor modality leads to a redundant environment model. Laser scanners mounted on both sides of the vehicle provide information about the lane marking to improve the vehicle's self-positioning. A server rack mounted in the trunk of "Leonie" serves as the computational core. While these modules are connected through Ethernet communication, a CAN (Controller Area Network) interface opens the opportunity to access "Leonie's" steering, electronic brake and throttle system.

Different software modules for sensorfusion, decision instance, trajectory planning and low level control provide the system functionality. Fig. 6 shows a simplified version of the overall system architecture arranged in four different layers. The raw sensor and localization data are provided by a central data acquisition module that prepares the input for an object- and grid-based sensorfusion. The object and grid sensor data are correlated with the a-priori knowledge (digital map, speed limits, etc.) by a central module that allows to assess the current driving situation. The decision unit calculates the desired path for the vehicle; thus, a trajectory planner determines an optimized trajectory that can be realized by low level controllers.

The demanding terms of the surroundings require an extremely high precision of all modules describing the overall system functionality. The remaining of the paper will introduce a new approach for trajectory planning having the comprehensive treatment of path-planned sections as its distinctive feature. The approach has already successfully implemented and tested and can be considered as the first success of the "Stadtpilot"-Project. The potential of the algorithm is shown on the basis of a typical driving maneuver on the ring road.

V. TRAJECTORY PLANNING

The course of the ring road has developed over time and is usually not subject to the clothoid model based road

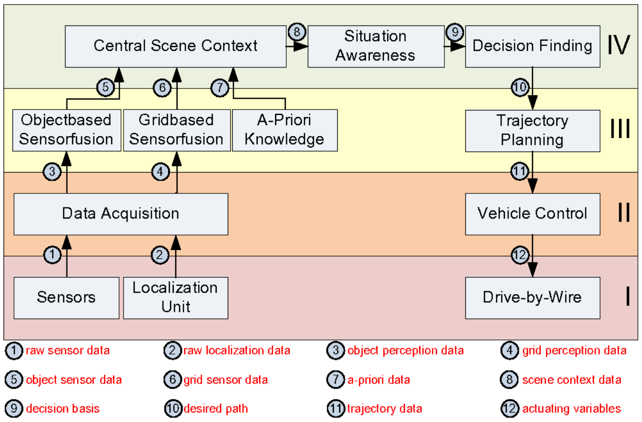


Fig. 6. Overall system architecture.

construction as is typical for highways. Road characteristics are manifold and vary significantly in width of roadway and have both narrow curves and straight roads. Compared to highly structured surroundings like highway scenarios, driving autonomously in such urban environments is too complex to fulfill all requirements with a single maneuver based approach. Therefore, it is part of the project to evaluate different approaches for decision finding. An approach is required that combines both, the advantages of maneuver based and behavior based autonomous driving. This enables the vehicle to handle typical situations such as lane changes reliably with a maneuver representation while less structured situations can be treated with a behavior based approach.

These conditions have a demanding impact on the realization module since it needs to be independent from how driving decisions are found. Also, a more suitable driving behavior can be realized if the driving maneuvers are treated as one combined sequence in the trajectory planning. Limited lateral actuator dynamics and the requirement of smooth driving can be met by a new approach for trajectory planning having the comprehensive treatment of path-planned sections as its distinctive feature. The overall vehicle guidance system can thus be structured in two parts. On the one hand, situation awareness and decision finding lead to a path for the vehicle to follow that is affected by environmental constraints and basic driving kinematics only. This results in a path and a rough speed profile guiding the vehicle collision free through the current situation according to traffic rules. On the other hand, the realization of the driving decisions is based on a trajectory planning approach in Layer III of Fig. 6 that results in smooth trajectories taking driving dynamics into account.

The need for a decision unit independent way of realizing driving decisions leads to an innovative interface that decouples decision finding from the final trajectory planning and low level control. Software modules can easily be replaced and different approaches for decision finding tested by introducing such a decision data structure. Thus, dynamically optimized trajectories can be determined.

Starting at interface number 7 in Fig. 6, a decision data structure is used that is compact, yet does not distort information content and establishes as much freedom as possible for the trajectory planning module. Based on data from an a-priori digital map, a grid- and object-based representation of the surroundings, a drivable area in front of “Leonie” is determined in Layer IV of the shown architecture. Pearls on each side bound this area, representing the configuration space for the trajectory planning; thus, connecting these pearls results in a representation of the road edge (Fig. 7). The distance of the pearls and the width of the path can be adjusted to current conditions.

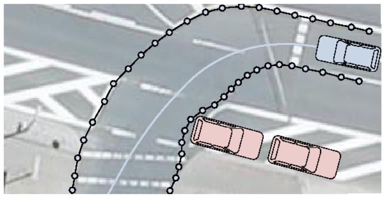


Fig. 7. Representation of driving decisions.

All necessary information can be represented in this data structure: position of traffic lights, areas with banned lane changes, number of lanes, and so on. Also the desired vehicle speed at each pearl position is stored in the same data structure and serves a velocity planner to determine a dynamically optimized speed profile. Low level controllers are in charge of generating the required command to meet the desired speed. If necessary, it is feasible to extend the data structure by comfort levels to give the decision unit the capability to influence the driving comfort of the car. Comfort levels are represented by a set of parameters that influence the maximal and minimal accelerations.

Since the drivable corridor contains all necessary information about the edge of the path and the speed limits, a trajectory planner can transfer the driving decision in a suitable trajectory for the low level control module according to the holonomic constraints of the vehicle. A trajectory planner with the comprehensive treatment of path-planned sections is based on a unique approach that determines a curvature optimized trajectory inside this corridor and results in less controller activity compared to approaches that treat maneuver sections separately. The goal is not only to realize autonomous driving in general, but also to convert abstract decisions into a smooth driving experience.

Fig. 8 emphasizes, how available environmental data are used in the vehicle guidance system in the “Stadtpilot”-Project. It consists of multiple stages, resulting in a configuration space taking dynamic and static environmental data into account. First, a configuration space is spanned by a digital map limited with a left and a right border according to lane markings. In the absence of any obstacles the vehicle can follow a trajectory that is calculated based on this a-priori data. Static obstacles are considered by adapting the borders of the configuration space according to a grid-based representation of the environment; dynamic object data serve the situation awareness as well as the decision unit to realize an online adaption of the configuration space based on the current driving situation. The realization unit is now in charge to determine trajectories in between these limitations taking the holonomic constraints of the vehicle into account through a partly online adaption of the pre-calculated trajectory.

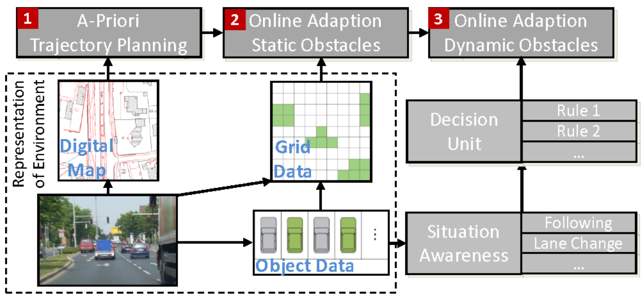


Fig. 8. Vehicle guidance consisting of multiple stages.

VI. REALIZATION OF DRIVING DECISIONS

Most of the so far applied trajectory planners are based on clothoids, sigmoid functions or splines and generate piecewise trajectories ([11], [12], [13]). In the following a new trajectory planning algorithm is stated that is based on elastic band theory and so-called smoothing splines having the comprehensive treatment of path-planned sections as its distinctive feature.

Since the decision unit maps its decisions into a drivable corridor, the trajectory planning module first needs to perform a dynamic placement of nodes inside this area in real time. A unique optimization algorithm including a mechanical model describing the path and application of smoothing splines generates curvature optimized trajectories in the drivable corridor. A three-step algorithm leads to the desired result (Fig. 9).

a) Analysis and typification of route: The overall optimization starts with a typification of the path's interpolation nodes which are initialized centered in the configuration space. It is essential for applying a mechanical model based on elastic band theory to determine the type of each node, which is calculated based on its adjacent nodes and the perpendicular distance d to their connecting line.

$$d = \frac{a}{\sqrt{a^2+b^2}} \cdot x_i + \frac{b}{\sqrt{a^2+b^2}} \cdot y_i + \frac{c}{\sqrt{a^2+b^2}} \quad (1)$$

where a, b, and c are the coefficients of the linear equation given by the points $i-1$ and i

$$a = y_{i-1} - y_i \quad (2)$$

$$b = x_i - x_{i-1} \quad (3)$$

$$c = x_{i-1} \cdot y_i - x_i \cdot y_{i-1} \quad (4)$$

The result is a set of nodes separated into three different classes.

b) A mechanical model reduces maxima of curvature: The application of a modified elastic band algorithm repositions the interpolation nodes and leads to reduced maxima of curvature. The nodes' position is improved by calculating the equilibrium of forces at each node according to elastic band theory. Based on Lagrangian mechanics, the effective force depending on each specific node type is composed of an internal force $\vec{f}_{int}$ and an external force on the left $\vec{f}_{ext,l}$ and right $\vec{f}_{ext,r}$ of the vehicle, where $\vec{q}$ stands for a mechanical potential, $\vec{r}$ for a position vector, k for spring stiffness and l for the length of the non-deflected spring [14].

$$\vec{f}_{int}(i) = k_c \left(\frac{\vec{q}_{i+1} - \vec{q}_i}{\|\vec{q}_{i+1} - \vec{q}_i\|} + \frac{\vec{q}_{i-1} - \vec{q}_i}{\|\vec{q}_i - \vec{q}_{i-1}\|} \right) \quad (5)$$

$$\vec{f}_{ext,l}(i) = k_{ext} \cdot (\|\vec{r}_{i,l}\| - l_0) \cdot \frac{\vec{r}_{i,l}}{\|\vec{r}_{i,l}\|} \quad (6)$$

$$\vec{f}_{ext,r}(i) = k_{ext} \cdot (\|\vec{r}_{i,r}\| - l_0) \cdot \frac{\vec{r}_{i,r}}{\|\vec{r}_{i,r}\|} \quad (7)$$

c) Smoothing through optimizing in κ-s-plane: Initially, B-splines are used to approximate the displaced nodes. Since the generated curve in terms of curvature and its derivative do not satisfy defined quality criteria, the curvature is optimized by transforming it into κ-s-plane. Applying so-called Smoothing Splines by Schoenberg and Reimsch [15] and the inverse transformation back into x-y-plane results finally in the trajectory based on comprehensively treated sections. The basic idea of those splines is to minimize a functional J that contents both, a term for approximation and a term for interpolation. The value p is chosen on the interval $[0, 1]$ to control the degree of approximation.

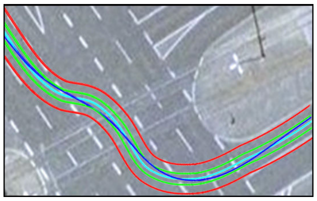
$$J = p \sum_{i=1}^{N} \left(\frac{\kappa_i - f(s_i)}{\delta \kappa_i} \right) + (1-p) \int_{s_0}^{s_N} \left(f''(s) \right)^2 \mathrm{d}s \quad (8)$$

Both, a-priori planning and online adaption are based on the approach described above.

Fig. 9. Optimized trajectory planning with a three-step algorithm.

The introduction of a certain margin inside the configuration space opens the opportunity to directly influence the level of optimization. Initially, this margin is the difference of lane width and vehicle size. Also, it takes for instance any uncertainties in environment recognition or the vehicle's position into consideration. This offers the potential that improvements in those modules can be transformed directly into a smoother driving behavior since a widening of the margin establishes a bigger optimization space for the trajectory planner.

The shown approach gives the decision unit a higher flexibility compared to approaches that treat maneuvers separately. Fig. 10 shows the effect of its application to a maneuver on the ring road of Braunschweig where the vehicle starts in the upper left corner of the path, performs a lane change maneuver to the left, followed by an immediate left turn at an intersection.



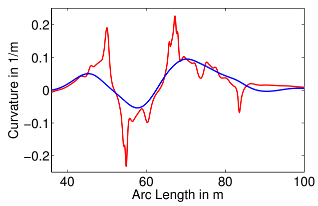


Fig. 10. Result of the comprehensive treatment of trajectory sections.

Fig. 11. Curvature of the optimized (blue) and original trajectory (red).

Fig. 11 shows the associated effect of the optimization approach in terms of the curvature characteristics. The blue curve represents a smooth and flatten curvature in contrast to the non-optimized trajectory shown in red. Without the described comprehensive treatment of path-planned sections, this driving decision could not have been realized. The consecutive execution of lane change and turn maneuver in this particular example would have resulted in an unreachable steering angle due to a too high curvature.

Important for the demonstration of effectiveness of the approach is the impact on the driving behavior and is shown in contrast to the spline approximated trajectory in the center of the road (cyan curve Fig. 10). Applying the same low level control unit, the resulting lateral deviation of the vehicle's position regarding to the trajectory and the actuator activity shows the effectiveness of the optimization (Fig. 12). The mean absolute value of the track deviation could be reduced by 42% from $5.7cm$ to $3.3cm$, the maximum of the track deviation could be decreased by 57.3% from $23.7cm$ to $10.1cm$. The achieved improvement could be mainly attributed to the release of the steering wheel actuator, which cannot realize arbitrary maneuvers: The mean steering angle could be reduced by 29.2% and the maximal steering angle by 40.2%. The steering angle according to the non-optimized curve even reaches several times the actuator limits. A more detailed explanation of the trajectory planning process will be described in a future publication.

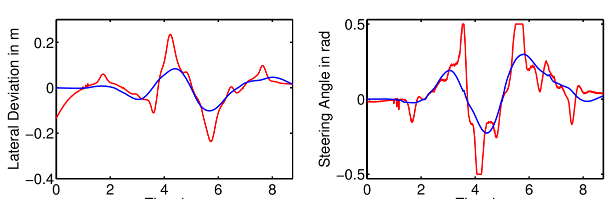


Fig. 12. Lateral deviation and steering angle for the optimized (blue) and original trajectory (red).

VII. CONCLUSION

We have introduced our newest project called "Stadtpilot" as the next step of the Technische Universität Braunschweig in the research field of autonomous driving. With our experience in the DARPA Urban Challenge we have described the distinction between the "Stadtpilot"-Project and previous activities. We have shown that transferring autonomous driving to a real urban environment results in increased scientific claims, which need to be solved.

The ring road scenario requires new concepts to guide the vehicle fully autonomously in this special environment. We have presented the architecture and realization concept of driving decisions as they are realized in the autonomous vehicle "Leonie". Decision finding and realization are decoupled through an innovative interface to establish as much freedom as possible for the trajectory planning module. Independent of maneuvers and driving route, trajectories are calculated based on an analytical optimization approach with a comprehensive treatment of path-planned sections. The result is a smooth driving behavior with improved directional stability and less controller activity. With the successful realization of the shown trajectory planner a major requirement of the project has already been mastered.

VIII. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of all team members taking part in the "Stadtpilot"-Project.

REFERENCES

[1] B. Ulmer. "VITA - An Autonomous Road Vehicle(ARV) for Collision Avoidance in Traffic." *IEEE Proceedings of the Intelligent Vehicle Symposium*, Detroit, MI, pp. 36–41, 1992.

[2] C. Thorpe, M. Hebert, T. Kanade, and S. Shafer. "Vision and Navigation for the Carnegie-Mellon Navlab." *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 10, No. 3, pp. 362–373, 1988.

[3] A. Hattori, A. Hosaka, and M. Taniguchi. "Driving Control System for an Autonomous Vehicle Using Multiple Observed Point Information." *IEEE Proceedings of the Intelligent Vehicle Symposium*, Detroit, MI, pp. 207–212, 1992.

[4] E. D. Dickmanns, R. Behringer, D. Dickmanns, T. Hilde-Brandt, M. Maurer, F. Thomanek, and J. Schielen "The seeing passenger car VaMoRs-P." *IEEE Proceedings of the Intelligent Vehicle Symposium*, Paris, France, pp. 68–73, 1994.

[5] M. Maurer, R. Behringer, S. Fürst, F. Thomanek, and E. D. Dickmanns. "A Compact Vision System for Road Vehicle Guidance." *IEEE Proceedings of the 13th International Conference on Pattern Recognition*, Vienna, Austria, pp. 313–317, 1996.

[6] Darpa. "Web Archive of the March 2004 Grand Challenge." *http://www.darpa.mil/grandchallenge04*.

[7] S. Thrun et al. "Winning the DARPA Grand Challenge." *International Journal of Field Robotics Research*, Vol. 23, pp. 661–692, 2006.

[8] J. M. Wille and T. Form "Low Level Control in a Modular System Architecture for Realizing Precise Driving Maneuvers of the Autonomous Vehicle Caroline." *IEEE Proceedings of the International Conference on Intelligent Transportation Systems*, Beijing, China, pp. 705–710, 2008.

[9] Inland Transport Commitee "Convention on Road Traffic." *United Nations Economic Commission For Europe*, 1968.

[10] A. Sasse, T. Nothdurft and P. Hecker "Robust Car Localization for an Autonomous Vehicle in Urban Environments." *Proceedings of the 22nd International Technical Meeting of the Satellite Division of the Institute of Navigation*, Savannah, GA, pp. 1797–1806, 2009.

[11] T. Fraichard and A. Scheuer "From Reeds and Shepp's to Continuous-Curvature Paths" *IEEE Transactions on Robotics*, Vol. 20, No. 6, pp. 1025–1035, 2004.

[12] W. Tölle "Ein Fahrmanöverkonzept für einen maschinellen Kopiloten" *Fortschrittberichte VDI*, Reihe 12, Düsseldorf, 1996.

[13] A. Piazzi and C. Guarino Lo Bianco "Quintic G2-Splines for Trajectory Planning of Autonomous Vehicles" *IEEE Proceedings of the Intelligent Vehicle Symposium*, Dearborn, MI, pp. 198–203, 2000.

[14] S. Quinlan. "Real-Time Modification of Collision-Free Paths." *PhD Thesis*, Stanford University, 1994.

[15] C. de Boor "A Practical Guide to Spline" *Springer-Verlag*, 2001.