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From a Competition for Self-Driving Miniature Cars to a Standardized Experimental Platform: Concept, Models, Architecture, and Evaluation

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Abstract—*Context:* Competitions for self-driving cars facilitated the development and research in the domain of autonomous vehicles towards potential solutions for the future mobility. *Objective:* Miniature vehicles can bridge the gap between simulation-based evaluations of algorithms relying on simplified models, and those time-consuming vehicle test on real-scale proving grounds. *Method:* This article combines findings from a systematic literature review, an in-depth analysis of results and technical concepts from contestants in a competition for self-driving miniature cars, and experiences of participating in the 2013 competition for self-driving cars. *Results:* A simulation-based development platform for real-scale vehicles has been adapted to support the development of a self-driving miniature car. Furthermore, a standardized platform was designed and realized to enable research and experiments in the context of future mobility solutions. *Conclusion:* A clear separation between algorithm conceptualization and validation in a model-based simulation environment enabled efficient and riskless experiments and validation. The design of a reusable, low-cost, and energy-efficient hardware architecture utilizing a standardized software/hardware interface enables experiments, which would otherwise require resources like a large real-scale test track.

Index Terms—Wheeled Robots, Programming Environment, Computer Vision, Recognition, Micro/Nano Robots.

1 Introduction

Self-driving vehicle technology as fostered by international competitions like the DARPA Urban Challenge [1], [2] or the Grand Cooperative Driving Challenge in 2011 is reported to be available for customers by the end of this decade [3]. On the one hand, this technology shall replace driving tasks where the human driver is "under-challenged", for example long distance travels on highways. Thus, the driver can focus on other tasks during such periods like doing business or relaxing. On the other hand, such technology is said to be infallible from human failure because computer programs never get tired. Thus, they can manage complex and critical traffic situations where the human driver might be "over-challenged" – for example unexpectedly crossing pedestrians between vehicles parked on a sideways parking strip where emergency braking is required [4]. In such situations, a pattern-based algorithm, which is classifying the criticality of the current situation perceived from the surroundings, does not suffer from the "reaction time" in contrast to the human driver. Therefore, vehicles that intelligently monitor the surroundings are supposed to reduce the number of severely or fatally injured traffic participants.

1.1 Motivation

The aforementioned scenarios assume that the technology, which is used to realize comfort assistant and safety systems for critical traffic situations, is fault-tolerant and robust itself. Thus, the driver – especially when he/she is "out of the driving loop" and hence, not mentally involved in the traffic situation – relies and depends on the technology, which needs to handle all traffic situations that could happen regularly during a vehicle's life-time in a safe and reliable manner. Therefore, the system of a self-driving and potentially interconnected vehicle needs to be as good and robust as the ordinarily experienced driver.

However, the question arises how to determine and model the "average experience" in such a way that a self-driving system can make sense out of it. Furthermore, this experience model

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depends at least on different countries, the capability to reliably predict the traffic participants' future behavior, and in some cases even on the "eye contact" – a level of communication that is hardly realizable for self-driving cars.

Thus, further research and experiments are required to develop algorithms, evaluation methodologies, and protocols for information interchange to understand dependencies between traffic maneuvers and to increase the future reliability of these systems [5]. However, the more complex the traffic scenarios become like autonomous overtaking maneuvers on highways or turning assistants at intersections, the more space and further actors are needed to conduct experiments and validations in a repeatable manner on proving grounds.

Therefore, simulations are used to investigate interactively such traffic scenarios or to run extensive simulations in an automated manner to ensure the quality of a software system implementation [6]. Nevertheless, these simulations rely on models of reality, which in turn base on simplifications and assumptions. However, transferring results from simulations to real scale vehicles on a proving ground might bear the risk that technical challenges like syntactical or semantic incompatibilities on the software/software or software/hardware level delay the actual experiments. Furthermore, real scale experiments require enough space to run a test and means to ensure repeatability. Here, an intermediate step between purely digital simulations and real scale experiments can help to transfer results from the simulation and to evaluate real world effects in a safe and yet manageable manner [7].

1.2 Research Questions

In consequence, this article aims to investigate the following research questions mainly on the example of the international competition "CaroloCup" in Germany[1] for self-driving miniature vehicles:

RQ-1: Which design decisions for self-driving miniature vehicles with respect to sensors and algorithms to fulfill the tasks (a) lane-following, (b) overtaking obstacles, (c) intersection handling, and (d) sideways parking have to be considered?

RQ-2: Which design decisions in the software and hardware architecture towards a reusable and standardized experimental platform need to be regarded?

RQ-3: How can a development and evaluation environment of a real scale self-driving vehicle be adapted and reused during the design, development, and evaluation of a self-driving miniature vehicle?

RQ-4: Which design considerations for a reusable and extendable algorithm for autonomous lane-following with overtaking obstacles are of interest?

RQ-5: Which design considerations for a reusable and extendable algorithm for autonomous parking on a sideways parking strip need to be considered?

1. www.carolocup.de

1.3 Contributions of the Article

The contributions of this article are (a) results from a systematic literature review for relevant work, (b) an analysis of the results of the last five years from participants in a competition for self-driving miniature vehicles; (c) the systematic investigation of design decisions from nine participating teams in the 2013 competition with respect to sensors and algorithms for supporting the perception and feature handling in the aforementioned use cases; and (d) derived considerations and design drivers towards a standardized experimental platform with respect to the hardware/software interface as well as concepts and evaluations for the fundamental algorithms for lane-following with overtaking obstacles and parking on a sideways parking strip.

1.4 Structure of the Article

In Sec. 2, a structured approach to find similar work with respect to the design criteria for a standardized automotive-like experimental platform was carried out. Furthermore, a systematic investigation of the results from the last years' attendees in the competition as well as an analysis of their respective approaches is conducted. Sec. 3 uses the results from analyzing this state-of-the-art to discuss and outline considerations about the design for the software and hardware architecture for a self-driving miniature vehicle experimental platform; a specific focus is given to experimenting and evaluating algorithms in a virtual test environment that was already successfully applied to the development of a real scale self-driving vehicle. In Sec. 4 and 5, two reusable and extendable algorithms to realize the fundamental behavior of a self-driving vehicle are described and evaluated. Sec. 6 summarizes important design criteria for the software and hardware architecture of an experimental platform and gives an overview of the software development and evaluation process, which was applied during the development of the self-driving miniature car "Meili" that participated successfully in the "Junior Edition" of the 2013 CaroloCup competition. In Sec. 7, the article concludes and gives an outlook about future work.

2 Related Work

This section investigates the current state-of-the-art related to this work. Additionally, the results from the international competition for self-driving miniature cars between 2009 and 2013 are described alongside with an analysis of the concepts of the competitors from the 2013 edition.

2.1 Systematic Literature Review

A systematic literature review (SLR) according to the guidelines of Kitchenham and Charters [8] to address *RQ-2* was conducted.

Library	#	E_1	E_2	E_3	E_4	⟳	√
ACM DL	46	7	31	-	8	-	-
Google Scholar	62	11	-	-	40	7	4
IEEE Xplore	17	3	-	6	7	-	1
ScienceDirect	5	1	-	-	3	1	-
SpringerLink	401	102	203	-	78	15	3
Total	531	124	234	6	136	23	8
Total (unique)	156					22	6

TABLE 1
Results from searching for related work during the different stages of the SLR.

Ref.	Design	SW-A	HW-A	Reuse	Sim	MSV
[17]	X	X	-	X	X	-
[18]	X	-	X	X	-	-
[19]	X	X	X	X	X	-
[20]	X	X	X	X	-	X
[21]	X	X	X	X	-	-
[22]	X	-	-	-	X	-
[23]	X	X	-	X	X	-
[24]	X	X	-	-	-	-
[25]	X	X	-	X	-	-
[26]	X	X	-	X	X	-
[27]	X	X	X	X	-	-
[28]	X	X	-	-	-	-
[29]	X	X	-	-	-	
[30]	X	X	X	-	X	-
[31]	X	X	-	X	X	-
[32]	X	-	X	X	-	-

TABLE 2
Classifying important aspects from related work.

2.1.1 Data Sources and Search Strategy

For the SLR, the following digital libraries were used as data sources: ACM Digital Library (ACM DL), IEEE Xplore Digital Library (IEEE Xplore), ScienceDirect, and SpringerLink. As an additional resource, Google Scholar was used as a meta-search to complement the results of the digital libraries. Within these databases, the following search strategy was applied:

Publication date: "2004 or newer" because the related work of interest should be influenced by the DARPA Grand Challenges and beyond.

Search phrase: "design" AND ("driver" OR "decision") AND "software architecture" AND "hardware architecture" AND ("reusable" OR "reusability") AND ("miniature" OR "small-scale") AND ("vehicle" OR "vehicular" OR "mobile") AND "platform"

The search phrase could be directly applied at IEEE Xplore, ScienceDirect, and Google Scholar. For ACM DL and SpringerLink, the search phrase was unrolled to 24 individual searches, whose results were merged afterwards.

2.1.2 Study Selection

After retrieving results from the databases, the following *exclusion criteria* were applied: (a) The publication was outside the specified time frame (E_1), (b) the publication was a duplicate (E_2), (c) the publication is an ISO standard (E_3), or (d) the title and abstract are referring to a clearly unrelated domain (E_4). Afterwards, the remaining papers were classified as (e) re-evaluation ⟳ or (f) directly related (√). Finally, all results were merged and duplicates among all databases were removed. The results are shown in Tab. 1 reflecting that six publications are directly relevant to this work.

2.1.3 Study Quality Assessment

Before the relevant data was extracted from the identified papers, publications from group "⟳" were re-evaluated. Four papers turned out to be thematically clearly unrelated to the work, one was a thorough description of experiences from applying control theory in practice (cf. [9]), and two were dealing with sensor networks (cf. [10], [11]). Another five papers from that group were evaluating robotic software frameworks and agent systems or describing research roadmaps thereof (cf. [12], [13], [14], [15], [16]). When summarizing these findings after removing duplicates, 132 papers were thematically not relevant based on the applied search phrase and 16 papers are related to the work outlined in this article.

2.1.4 Data Extraction and Synthesis

These remaining 16 papers were further analyzed with respect to (a) clearly describing *design drivers/decisions* for their presented work (Design), (b) description of a proposed *software architecture* (SW-A), (c) description of a proposed *hardware architecture* (HW-A), (d) addressing *reusability* (Reuse), (e) incorporating *simulative* aspects (Sim), and targeting the domain of *miniature or small-scale vehicles* (MSV). These aspects are shown in Tab. 2, where the rows 1-6 show the results from papers of group "√", the rows 7-13 list relevant publications of group "⟳" after re-evaluation, and the last three rows show papers targeting *unmanned aerial vehicles* (UAS).

The synthesized results in Tab. 2 show that the addressed topics of developing and maintaining an appropriate architecture enabling reusability is an important design consideration for the software and hardware. A clear incorporation of a simulative approach in the development process is only reported by approx. 38% from the first and second group of papers; however, it clearly plays an important role during the development of algorithms and systems for UAS.

2.2 Systematic Competition Analysis

To address *RQ-1*, both the results from the last five years of the international competition for miniature self-driving cars described in Sec. 2.2.1–2.2.4 and individual technical concepts of the 2013 contestants were investigated. Therefore, the concept presentations of the teams published after the competition on the competition's website were analyzed and classified as reported in the concept classification matrix in Sec. 2.2.5.

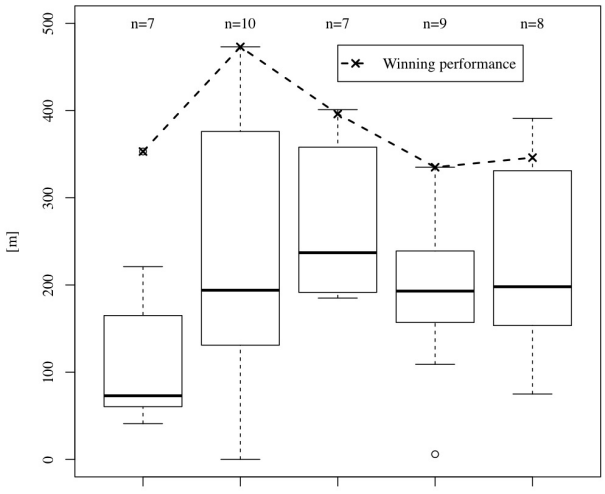


Fig. 1. Distribution of driven distances on the track without obstacles and without penalty meters of the last five competitions.

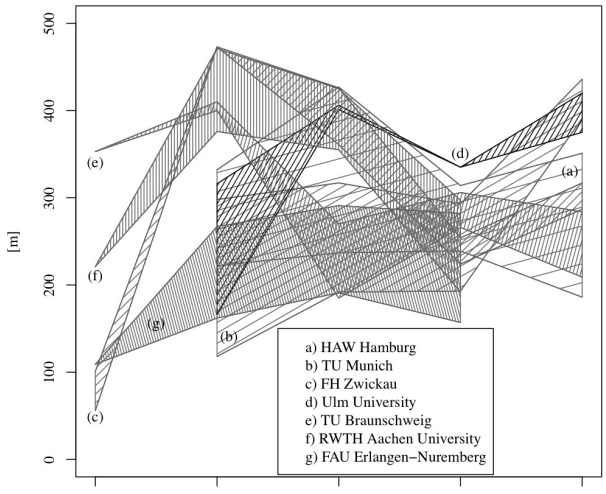


Fig. 2. Visualization of driven distances including penalty meters of participants, who participated at least four times in the last five years.

2.2.1 *Competition "CaroloCup"*

The international competition "CaroloCup" is an annual competition for self-driving miniature vehicles founded in 2008 after the DARPA Urban Challenge and carried out at TU Braunschweig in Germany. The goal is to facilitate education and research related to self-driving vehicular technology with a focus on urban environments. Participants have to develop a 1/10 scale autonomously driving vehicle consisting of hardware and software that is able to (a) follow a track made out of lane markings, (b) behave correctly at intersections and overtake stationary and dynamic obstacles, and (c) park autonomously on a sideways parking strip according to the official rules and regulations document [33].

Using this approach with a competitive character, participants get in contact with algorithmic challenges of this technology, which is supposed to be part of the future intelligent cars as described in Sec. 1. Especially the aspects of developing, testing, integrating, and mastering a complex distributed and embedded system that has to reliably process volatile data perceived from the surroundings by various sensors is similar to today's approaches for self-driving cars [34].

The aforementioned use cases to be covered by contestants need to be realized with a certain level of quality in terms of adherence to these requirements to avoid

1) Penalties when using the remote control system due to vehicle malfunction.
2) Penalties when leaving the regular track.
3) Penalties when colliding with obstacles.
4) Penalties when not positioning the vehicle correctly in the parking gap.
5) Penalties when not obeying traffic rules like yielding right-of-way or misuse of direction and braking lights.

2.2.2 *Task: "Lane-Following"*

The first task for participants is to drive as many rounds as possible within 3min on a previously unknown track consisting of black ground and white lane markings. Fig. 1 shows the distribution of the driven distances on the track without obstacles and without penalty meters according to the aforementioned list. Obviously, the distance of driven meters on average has increased from 2009 to 2011 significantly. In the last two editions, it was around 200m while the interquartile range was the smallest in 2012.

However, Fig. 1 does not take the penalty meter distribution over the last years into account. Thus, Fig. 2 shows the individually driven distances including the received penalty meters from those teams who participated at least four times in the last five years. The polygons per team over time show on the top edge the totally driven distance and on the bottom edge the distance reduced by penalty meters. Thus, the less both edges are apart from each other, the more reliable is the developed system from a team. This can be seen for the teams from FH Zwickau, Ulm University, and TU Braunschweig for example. Furthermore, it is obvious that the team from Ulm University constantly improved the quality of their vehicle because the amount of penalty meters is shrinking from 2010 until 2012. Additionally, they improved not only the overall quality in this driving task but they also increased the amount of the driven distance to win this discipline in 2012. The median velocity for these teams was $1.59\frac{m}{s}$ and for the top team $2.17\frac{m}{s}$ in 2013. Furthermore, this chart also indicates that several contestants accepted a more risky driving behavior in the 2010 competition, which resulted in a much higher best performance compared to the other competitions.

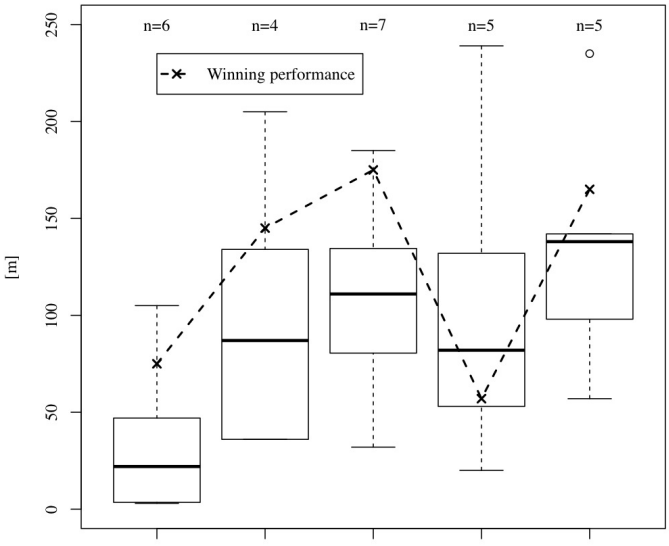


Fig. 3. Distribution of driven distances on the track without penalty meters for the task “overtaking obstacles”.

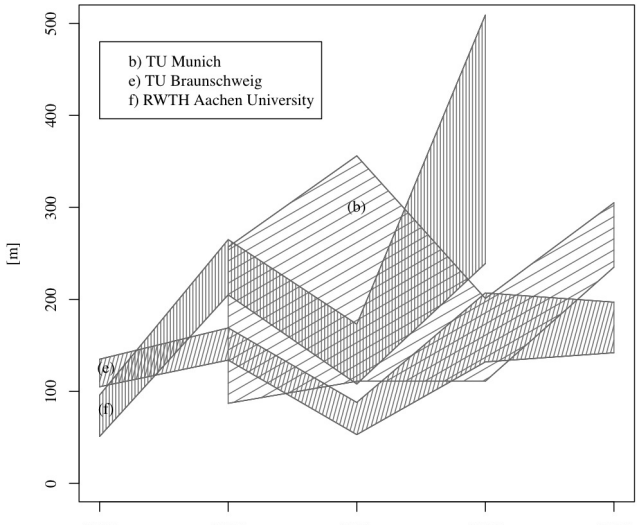


Fig. 4. Visualization of driven distances including penalty meters for the teams, who participated at least four times in the last five years.

2.2.3 Task: “Lane-Following with Obstacle Overtaking”

The second task is to drive as many rounds as possible within 3min on the same track when obstacles made of white paper boxes with predefined minimum dimensions are arbitrarily distributed around the track with a focus on curves. Fig. 3 depicts the distribution of driven distances on the track without penalty meters. Here, a similar pattern with respect to the median values over the years can be seen with an average around 140m in the 2013 edition.

Fig. 4 shows a further analysis of the performance for those teams who participated at least four times in the last five years; in this discipline, fewer teams participated on a regular basis. It is obvious that the difference between totally driven distance and the distance including penalty meters is pretty constant for the team from TU Braunschweig, in the first three editions for the team from RWTH Aachen, and in the last two years for the team from TU Munich. The median velocity for these teams was $0.78\frac{m}{s}$ and for the top team $1.31\frac{m}{s}$ in 2013.

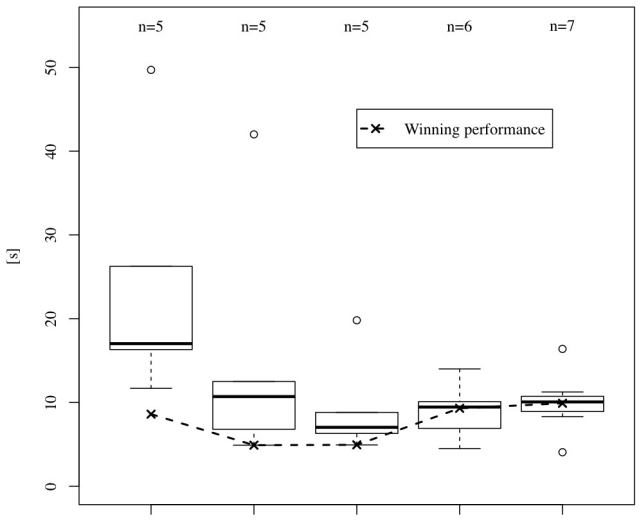


Fig. 5. Distribution of the duration for autonomous parking on a sideways parking strip.

2.2.4 Task: “Sideways Parking”

The third task requires the teams to park as fast as possible on a sideways parking strip alongside a straight road without touching other “parked” obstacles imitated by white paper boxes. Therefore, the vehicle has to find the smallest but yet sufficiently wide parking gap among several possible ones.

Fig. 5 shows the distribution of the duration for the teams from the last five years. It can be seen that the teams have on average converged to a comparable duration for this task in the last four years. For the 2013 edition, the median duration was $10.74s$ and for the top team $4.39s$.

2.2.5 Concept Classification Matrix

After analyzing the results from the last five years of the competition, technical concepts from the contestants in the 2013 “CaroloCup” were further investigated.

Therefore, the individual presentations given by these teams were analyzed regarding the concepts for environment perception. The findings were related to the different aspects of self-driving vehicular functions (alongside the X-axis) and classified according to the different stages for data processing (alongside the Y-axis) as shown in Fig. 6. The following aspects were of interest during the document analysis:

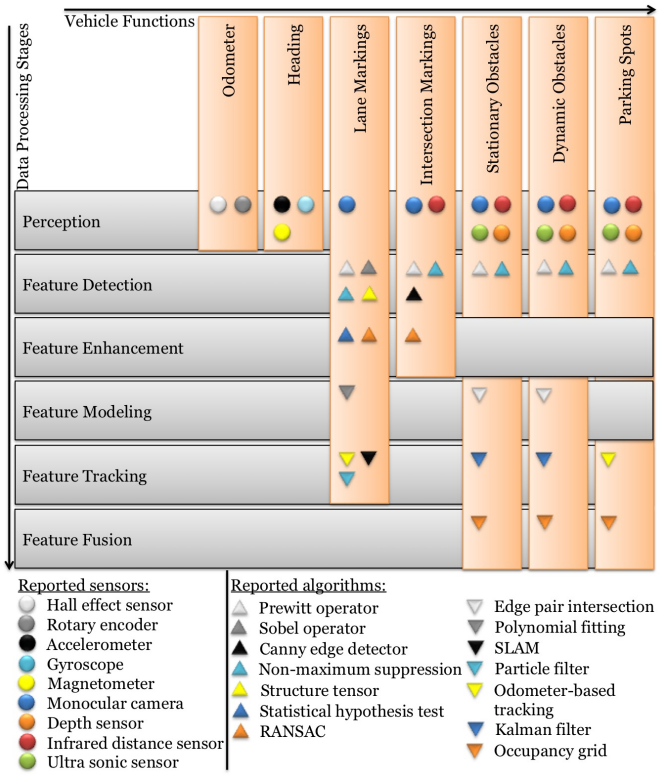


Fig. 6. Sensor types and mapping of algorithms to different data processing stages from 2013 CaroloCup participants.

- The vertical bars describe different technological aspects for sensing environmental data for a self-driving vehicle.
- The horizontal bars describe the different data processing stages.
- The first horizontal bar *Perception* summarizes the different sensors, which are reported to be used as the sensor to perceive data for the given aspect of self-driving vehicular technology. The sensors are denoted by circles.
- The second to last horizontal bars describe different stages in the data processing, which is supported by various algorithms. The different algorithms are denoted by triangles.
- The length of the vertical bars shows up to which data processing stage the specific aspect of the self-driving vehicular technology is supported by algorithms.

After analyzing the classification matrix, it is apparent that no further data processing is applied to handle and improve odometer and heading data. This could be due to the fact that either no specific algorithms have been reported or the data quality is sufficiently precise enough to serve properly the use cases in the competition.

The most effort according to the concepts reported by the teams was spent to realize reliable and robust lane markings and intersection markings detection: Here, ten different algorithms

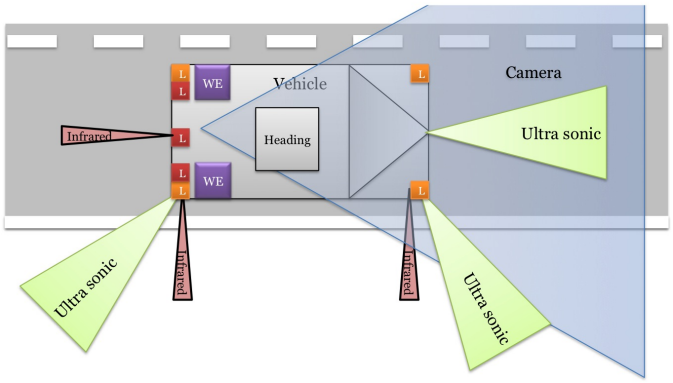


Fig. 7. Sensor layout for the required use cases.

at four subsequent data processing stages are applied. This seems reasonable because having a robust lane-following system, which is able to also handle missing lane marking segments as required from the rules and regulations document, is the basis for the other features of the self-driving car.

Handling obstacles was reported to be supported by six different algorithms and two different sensor types: Vision-based and distance-based sensors. Here, the majority of the teams is using ultrasonic and infrared sensors, while some teams also experiment with depth sensors to retrieve more data from the field of view. Interestingly, no explicit use of specific algorithms was reported to increase the feature quality before further processing the data to react on obstacles in the surroundings. This is in line with the results shown in Fig. 4, where the competition entries from the long-term participants show unreliable behavior resulting in 94.29% additional penalty meters on average when handling obstacles in the years 2010–2012.

3 Concepts and Architecture

In the following, conceptual considerations for a standardized experimental platform for self-driving miniature cars are presented and discussed to address RQ-2 and RQ-3. Firstly, the sensor layout is presented, which is suitable to address the use cases for a self-driving miniature car as required by the competition. Next, design drivers for the hardware architecture are outlined and discussed. Finally, design considerations for the software architecture of the platform are discussed where a specific focus is given to simulation-based evaluation.

The findings that are presented in this section are based on several sources: (a) Results from the SLR presented before, (b) conclusions drawn from the systematic analysis of the results from the last years' competitions, (c) findings from the concept classification matrix, and finally, (d) experiences from the development of the self-driving miniature car "Meili", which won the "Junior Edition" in the 2013 competition.

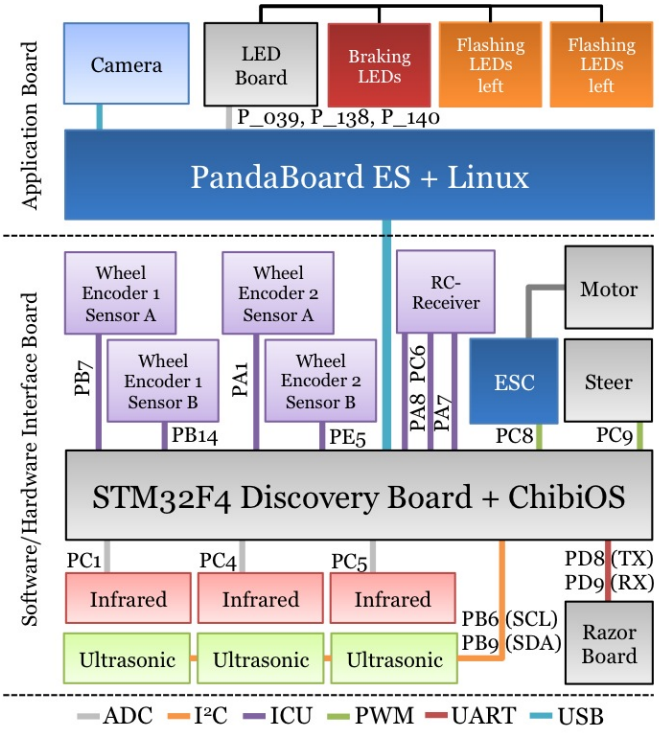


Fig. 8. Hardware architecture and pin connection plan.

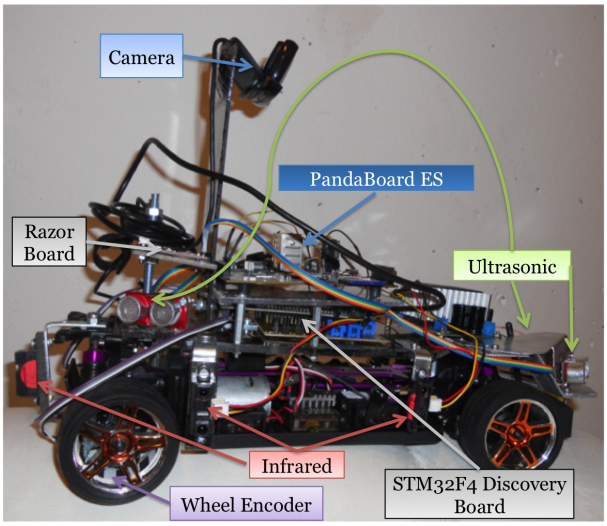


Fig. 9. 1/10 scale vehicle realizing the hardware concept.

3.1 Sensor Layout

As it is evident from Fig. 6, the dominant sensors are distance sensors like ultrasonic and infrared to detect obstacles, which is reported in 50% and respectively 75% of the team presentations, and vision-based sensors to perceive lane markings as reported in all presentations. Furthermore, 75% of the teams reported in their technical presentations the use of incremental sensors to measure the travelled path.

Fig. 7 depicts the resulting sensor layout, which was derived from the required use cases for the competition: Wheel encoders (labelled WE in the figure) are mounted at the rear axle to measure the driven distance and a monocular camera is used to perceive information about the lane markings. The ultrasonic- and infrared-based distance sensors are focusing on the right hand side (a) to serve the parking and (b) to handle overtaking situations. Furthermore, the rules and regulations document states that right-of-way situations will occur where the self-driving vehicle has to yield the right-of-way to another vehicle. Thus, no focus is given to obstacles on the left hand side of the vehicle. Both distance sensors located at the vehicle's rear-end enable dynamic adjustments of the vehicle in the parking spot.

The experience of the development of "Meili" also showed that using ultrasonic- and infrared-based distance sensors is beneficial due to their low power consumption and their low costs in comparison to depth camera sensors or small-scale laser scanners. Furthermore, due to their simple technical interfaces, both types of distance sensors are easy to integrate and to maintain.

The competition takes place indoors and thus, the use of GPS is not recommended. Alternatively, an anchor-based system as suggested by Pahlavan et al. [35] could be used to realize a precise indoor localization. While such a system would not be allowed to be used during the competition, it could serve as a reference system for evaluating algorithms on the experimental platform on the test track.

3.2 Design Drivers for the Hardware Architecture

The software/hardware interface board to perceive data from the sensors or to control the actuators for "Meili" in the 2013 competition was designed and realized as described by Vedder [36]. That design relied on a self-assembled printed circuit board (PCB), which allowed a very compact and resource-efficient realization of the hardware interface. However, the main drawback for that crucial component was the time-consuming and error-prone manufacturing process that could delay the entire integration and testing of all components later. Furthermore, maintaining the software on the PCB required a specific hardware and software flashing environment, which added further complexity to the development and maintenance process.

Based on this experience, important design drivers for the hardware architecture are availability and reusability of components especially when parts are broken while having a strong focus on low effort integration. Therefore and as preliminarily outlined in [37], using commercial-of-the-shelf (COTS) components enabled these requirements especially in terms of quality and costs.

The hardware architecture is separated into two parts: (a) Application board and (b) software/hardware interface board, as shown in Fig. 8. The ARM-based application board runs a

Debian-based Linux with all software components to realize the self-driving vehicle functionality: Image capturing and feature detection, lane-following, overtaking, and sideways parking. The only sensor that is directly connected to this board is the monocular camera due to the required computation power to handle its input data.

Embracing the experiences from the development of "Meili", the software/hardware interface board is realized with the ARM-based STM32F4 Discovery Board[2], which provides enough pins to serve the required sensors and actuators as described by the sensor layout in Fig. 7. This board interfaces with the ultrasonic- and infrared-based distance sensors, the wheel encoders, the inertial measurement unit to determine the vehicle's heading by evaluating accelerometer and gyroscope data, the emergency override for the RC-handset, and the steering servo and acceleration motor. The board itself is connected via a serial-over-USB connection to the application board to enable bi-directional communication.

Furthermore, the STM32F4 Discovery Board allows the extension of the sensor layout as depicted in Fig. 7 by up to five more infrared-based and 13 further ultrasonic-based distance sensors for future use cases and hence, having 24 distance sensors in total. An example of a miniature vehicle realizing the outlined concept is depicted by Fig. 9.

3.3 Design Drivers for the Software Architecture

The design decision for COTS components enabled reusability and flexibility on the hardware architecture; however, this decision also bears the risk that the selected components are not available anymore over time and hence, other boards with different hardware configurations need to be used. Thus, the software architecture needs to compensate for this flexibility in the hardware architecture.

3.3.1 Software/Hardware Interface

This compensation is reflected as reusability of the components from the software architecture, which interface with the sensors, actuators, or rely on system calls of the underlying execution platform. Therefore, a hardware abstraction layer (HAL) is required to reduce these dependencies on the real hardware. For the software/hardware interface board, the open source real-time operating system (OS) ChibiOS/RT[3] was used on the STM32F4 Discovery Board to have a standardized hardware abstraction layer as programming interface. This OS supports several different embedded systems and thus, the low-level software to interface with sensors and actuators can be easily reused in future robotics projects as well. Furthermore, ChibiOS/RT is well documented and the resulting binary exhibits a small memory footprint.

Having a standardized software/hardware interface also enables generative software engineering like model-checking and code generation as outlined in [38]. In this regard, the software components that are interfacing with the sensors and actuators can be adjusted automatically when more sensors are added or the configuration is modified.

2. www.st.com
3. www.chibios.org

3.3.2 Application Environment

The self-driving functionality is composed by software components that realize image processing and lane-following with overtaking, as well as sideways parking. The components are designed according to the *pipes-and-filters* principle [39] running at a constant frequency while reading their input from data sources like a camera, distance sensors, or odometer to compute the required set values as described in Sec. 4 and Sec. 5 to control the vehicle.

To complement the aforementioned embedded real-time OS, which is used as HAL for the software/hardware interface, the portable middleware as described in [40] was used. This middleware written in ANSI C++ provides a component-based execution and data processing environment with real-time capabilities enabled by Linux rt-preempt [41].

The interacting components running on the application board are processing platform-independent data structures, which represent generic distances for the ultrasonic and infrared sensors as well as the information about vehicle heading and travelled path, and generic image data. Thus, the self-driving functionality is standardized in such a way that it is not depending on elements of a concrete hardware environment. Instead, these data structures are mapped to a platform-specific realization by an additional component that realizes the structural design pattern *proxy* [39], which connects the software components from the application environment with the embedded software running on the software/hardware interface board.

This design decision based on experiences from a successful realization of several real-scale self-driving cars [1], [40]. On the one hand, it supports the standardization of the self-driving functionality by reducing dependencies on concrete components of the hardware environment, and on the other hand, it allows seamless reusability of the software components from the application environment in a virtual test environment for evaluating algorithmic concepts before their deployment on the experimental hardware platform.

3.4 Virtual Test Environment

Having a virtual test environment available to conceptualize and evaluate algorithms has been proven a successful approach for real-scale self-driving cars [6]. According to the technical concept classification matrix in Fig. 6, the simulation system, which realizes the virtual test environment, needs to include models to produce images from the virtual surroundings of the vehicle, and models for producing data for distance-based sensors. Furthermore, the simulation needs to include a physical motion model for the vehicle dynamics to enable a closed-loop

experimentation system, where algorithms process data from virtualized sensors to act in response to the surroundings.

There are several simulation environments for robotic platforms available like GAZEBO [42], [43], which was successfully used during the DARPA Robotics Challenge, MORSE [44], or ARGoS [45]. These platforms mainly focus on general experimental robotic platforms and hence, domain-specific modeling support to describe large scale and different automotive scenarios with roads, intersections, and parking lots to be used for validating algorithms for automotive functions is missing.

Furthermore, the aforementioned simulation environments can be integrated with the middleware ROS [46], which allows a convenient realization of communication between distributed processes by encapsulating the low-level and OS-specific implementation details; a similar approach is also realized by the lightweight communications and marshalling (LCM) middleware [47]. While both software environments provide a well structured message interchange, they do not support means to fully control and schedule the communication in case of coordinated simulations.

In contrast, the concepts and middleware used on the self-driving miniature car "Meili" were already successfully used on real-scale self-driving cars [1], [40] while explicitly focusing on seamless integration with a domain-specific simulation environment. While the middleware also realizes a transparent communication based on UDP-multicast, the interacting components can be fully controlled and transparently interrupted when they are embedded in a simulation environment. Thus, synthetic data from virtualized sensors can seamlessly replace real sensor data to validate algorithmic concepts.

The simulation environment that was used for the self-driving miniature car (a) provides a formalized model of the environment by using a domain-specific language (DSL), (b) has virtualized counterparts for the sensors of interest, and (c) provides a model for the vehicle dynamics. To reuse the existing environment, which was used so far for real-scale vehicles, the 1/10 scale environment and its constraints for the miniature vehicles were scaled up.

To create an appropriate model for the environment, the rules and regulations document of the competition was used as a basis because it defines minimum dimensions for roads, lanes, curvatures, and intersections. Furthermore, it provides a potential setup of a track following these constraints in its appendix. The same layout was modeled while considering the aforementioned constraints. Since the minimum radius of the track was defined as 1m measured up to the inner side of the lane marking from the outer lane and considering a lane's width as 0.4m, this radius is scaled up to 12m up to an inner curve's skeleton line. The visualized 2D variant of the resulting model for the exemplary track is shown in Fig. 10.

The technical concept classification matrix in Fig. 6 as well as the analysis of the technical presentations of the teams unveiled monocular cameras as well as distance sensors like

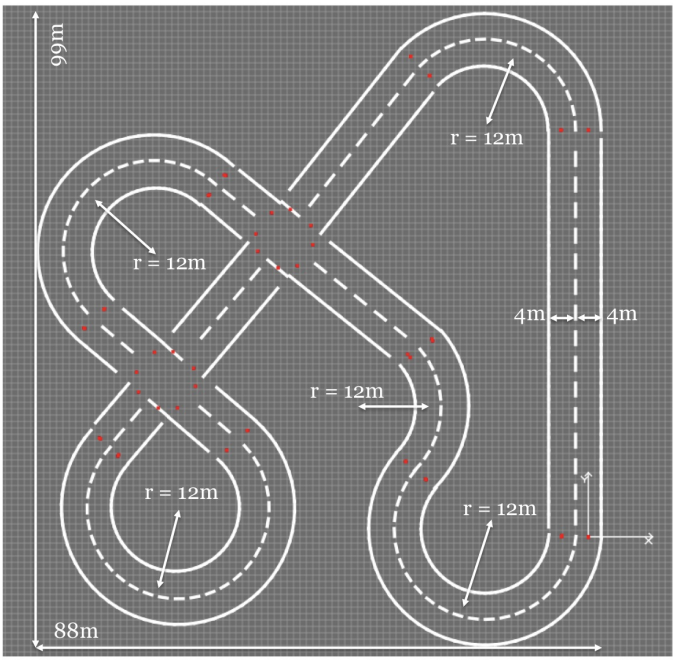


Fig. 10. Model of the environment in the simulation.

ultrasonic- and infrared-based sensors as predominantly chosen sensors. Thus, these sensors needed to be virtualized in the simulation environment as well.

For the former image-providing sensor, a DSL's instance is also transformed to a 3D-OpenGL-representation of the surroundings. This representation is then used to capture perspectively correct virtualized monocular camera images depending on the virtualized mounting position of the camera and the vehicle position. This image sequence can subsequently be used to realize the fundamental vehicle function lane-following. A concept and an evaluation for a lane-following control algorithm based on such image data is described in Sec. 4.

The distance sensors like ultrasonic and infrared sensors were added to the existing simulation environment. Therefore, their virtualized mounting positions were modeled, alongside with their opening angle and up-scaled viewing distance. Depending on the vehicle's current position, a single-layer, ray-based algorithm determines the set I of intersection points per sensor with the modeled surroundings like obstacles or parked vehicles and returns the nearest distance d to a sensor's mounting position.

The vehicle motion model was reused from the existing simulation environment basing on the bicycle-model [40]. Furthermore, the distance between the front and rear axle, and the minimum turning radii to the left and right hand side were determined and scaled up to parametrize the vehicle model from the real-scale environment.

This virtual test environment was used to design, realize,

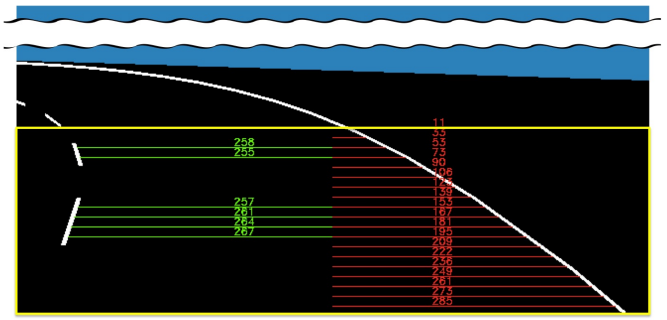


Fig. 11. Image feature detection based on virtualized input images from the simulation environment with shortened horizon and a yellow region-of-interest in the lower-level 40% of the image. The average processing time per frame is $0.719ms$ on a 1.8GHz Intel Core i7 with 4GB RAM.

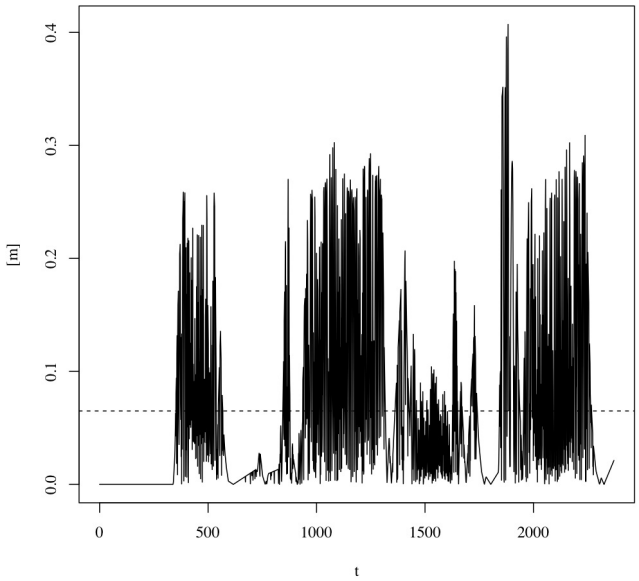


Fig. 12. Deviation from a lane's skeleton line is $\bar{d} = 0.065m$. The highest peak happens during passing an intersection.

and evaluate the algorithmic concepts that are required for the competition: Firstly, an approach for an overtaking algorithm as part of a lane-following control algorithm is described in Sec. 4, and one for a parking algorithm based on distance-sensors is outlined in Sec. 5.

4 Lane-Following with Overtaking

In the following, the general design considerations for a state-machine to realize the fundamental behavior of following lane markings and overtaking obstacles based on image data is described to address *RQ-4*. The focus for this section is to outline the basic ideas behind a lane-following concept and its evaluation in the simulation environment.

4.1 Design Considerations

4.1.1 Lane-Following Algorithm

The idea behind the fundamental lane-following algorithm is based on the calculation of the vehicle's deviation from a lane's skeleton line. This concept does not necessarily result in the shortest or fastest path through a given road network since better trajectories could be found [48]; however, it forms the basis for more advanced algorithms that, e.g., incorporate self-localization and mapping (SLAM) [49], [50], [51] to extend the basic concept presented here.

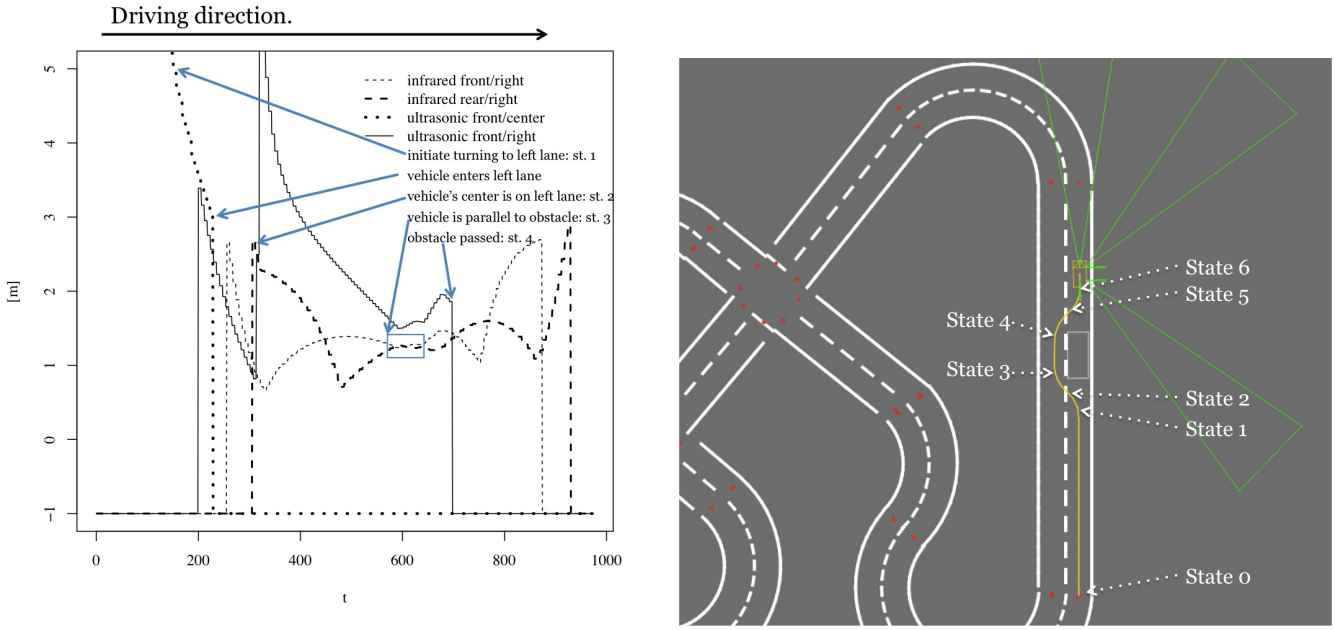
Fig. 11 depicts the basic principle behind the algorithm. Firstly, it is assumed that the vehicle is positioned between two lane markings heading towards the desired driving direction. Secondly, several scan-lines starting from the image's bottom are used to calculate the deviation from the vertical center line in the image to the left and right hand side until a white lane marking is found. To calculate the desired steering angle, the actually measured distance per scan-line from one side is compared either (a) to a previously calibrated desired distance resulting in the desired steering angle to follow this lane marking, or (b) to the distance to the other hand side with the goal to have an equalized distance to the left and right hand side per scan-line, which results in a desired steering angle.

Another possibility utilizes several scan-lines starting from the image's bottom towards the image's center. Hereby, the deviation of the center points per scan-line from the vertical image's center line is calculated resulting in a point sequence, which can be fitted by the best matching arc having its center point on the left or right hand side of the vehicle depending whether it is a left or right curve. This arc in turn represents the curvature that is needed to follow the lane ahead of the vehicle. The advantage of the arc-fitting algorithm is that it can handle missing lane markings more robustly since missing or not plausible center points, which are not following the fitted lane-model, can simply be omitted [52].

Fig. 12 shows an evaluation of the lane-following algorithm using the following PI-controller based on the first approach: $y(t) = 2.5 \cdot e + 8.5 \cdot \int e(\tau)d\tau$, where e is the distance error for the scan-line of interest. On average, the car's deviation from a lane's skeleton is about 6.5cm with peaks up to 30cm in intersection areas, where lane-markings are missing.

4.1.2 Overtaking Algorithm

The concept for the overtaking algorithm using the distance sensors is depicted in Fig. 13. The basic idea behind it is to use the appropriate sensors for the different stages of an overtaking process as annotated in Fig. 13(b) from the simulation: (a) the vehicle approaches an obstacle blocking its own lane. This fact is determined by the data perceived by the ultrasonic front sensor as depicted in Fig. 13(a). Once the values have fallen below a given threshold, the vehicle's trajectory is modified so that it starts moving to the neighboring lane by steering at



(a) Data from several distance sensors over time in the simulation environment.

(b) Overtaking scenario in the simulation environment.

Fig. 13. Concept for the overtaking algorithm.

maximum to the left. This part of the lane changing trajectory is terminated at time point (b) once both infrared-based distance sensors mounted at the right hand side have "seen" the obstacle for the first time. The current state of the vehicle according to Fig. 13(a) and 13(b) is now interpreted as such that the vehicle's center is on the left lane.

Now, the vehicle needs to steer with a maximum to the right to orientate it in parallel to the obstacle. This part of the trajectory is terminated at time point (c) once both infrared-based distance sensors return the same distance to the obstacle. Next, the vehicle continues on the neighboring lane to actually pass the obstacle until the ultrasonic distance sensor mounted at the top/right corner does not "see" the obstacle anymore at time point (d).

Finally, the vehicle returns to its original lane by driving the inverted trajectory from the beginning of the overtaking process. Therefore, the algorithm has tracked the duration during the left and right arc in the initial overtaking phase.

4.2 Lane-Following and Overtaking State-Machine

Fig. 14 depicts the overall state-machine to realize the aforementioned algorithmic concept, which is executed at 10Hz. The main design goal for the state-machine is the separation of the actual overtaking process from the lane-following algorithm. The reason for this design driver is to allow improvements and extensions to the lane-following algorithm while preserving the overtaking capabilities and vice versa.

The architecture of the state-machine is divided into two main parts: (a) observing the front area of the vehicle to determine when to initiate the overtaking process, and (b) the five parts of the overtaking trajectory shown in the upper half of Fig. 14. The first part of the state machine begins with continuing the actual lane-following process, which is realized by the state `moveForward`. The current implementation uses in this case the acceleration and steering set values as determined from the image processing and lane-following algorithm without further manipulation.

Subsequently, it validates measurements from the ultrasonic front sensor. Therefore, only those obstacles are considered, which are either stationary or driving slower in the same direction as the self-driving miniature vehicle as realized by the transition to state `checkObjectPlausible`. Once a plausible object has been found, its distance to the self-driving miniature vehicle is validated to initiate the actual overtaking by changing to state `toLeftLaneLeftTurn`.

The purpose of the states shown in dark blue in Fig. 14 is to steer at maximum to the left until both infrared sensors mounted at the right hand side of the vehicle have "seen" the obstacle. Due to their mounting position, the center of self-driving miniature vehicle has now entered the neighboring lane. During this part of the state-machine, a counter is incremented to record the duration of the left turning part for the lane change and the regular lane-following algorithm is deactivated.

Afterwards, the vehicle steers at maximum to the right until both infrared sensors mounted at the right hand side return the

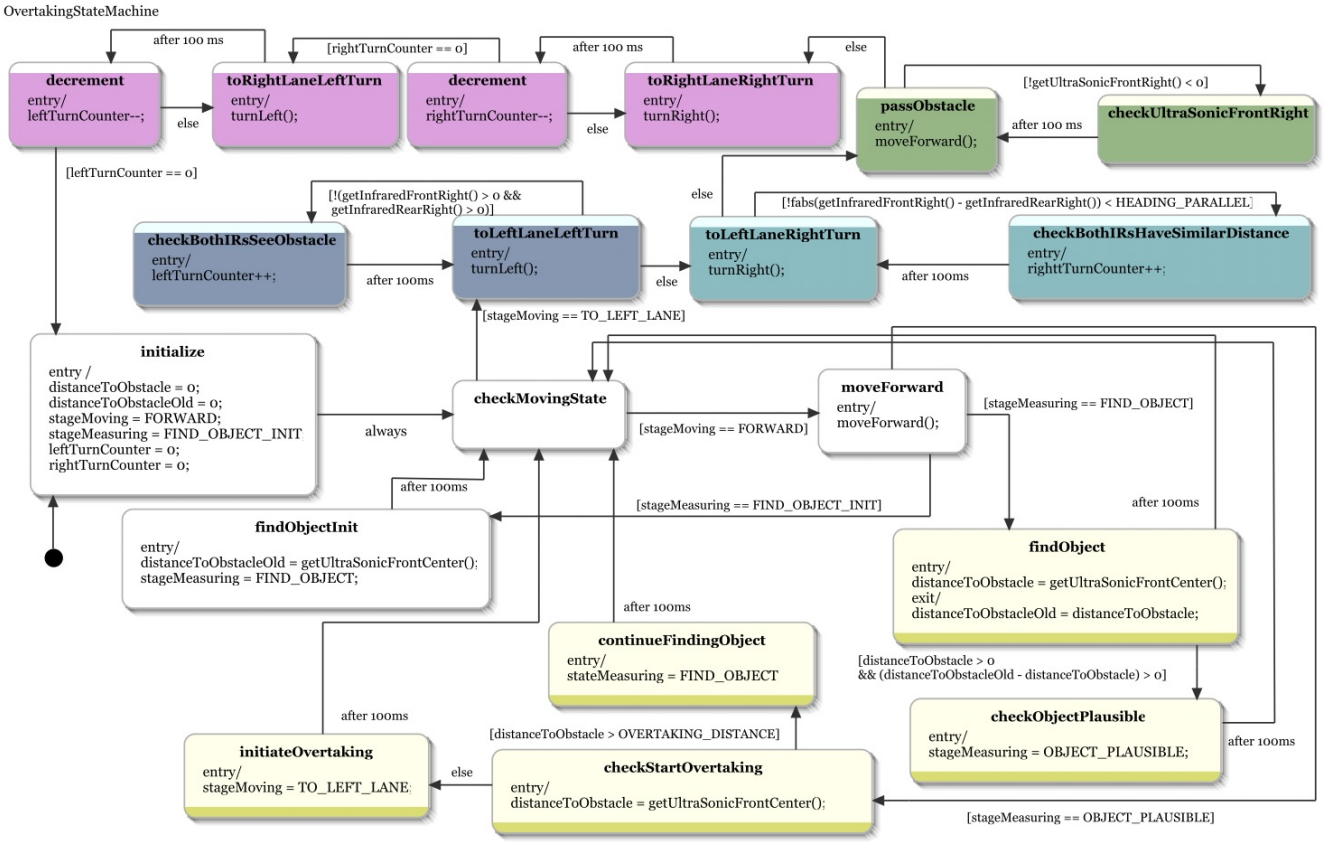


Fig. 14. Overtaking state machine.

same distance with respect to a given threshold. Once these distances are measured, the self-driving miniature vehicle is now oriented in parallel to the obstacle and the right turning part for the lane change can be terminated. A second counter is incremented according to the duration for this part as well.

The third part in the overtaking state-machine consists of the actual obstacle passing. This part is highlighted in green in the top right corner of Fig. 14. Here in state `passObstacle`, the modular lane-following algorithm is activated again and used to follow the lane markings on the neighboring lane until the ultrasonic sensor mounted at the vehicle's front right corner does not "see" the obstacle anymore.

On this event, the last two parts of the overtaking algorithm take place. Their purpose is the return to the original lane. Therefore, the lane-following algorithm is deactivated again and the vehicle steers at maximum to the right until the second counter representing the second part of the lane changing process has reached zero. Afterwards, the vehicle steers to the left again to orient its heading in the correct driving direction again while decrementing the first counter. Finally, the actual lane-following is activated to continue on the original lane again and the state-machine is reset to handle the next obstacle.

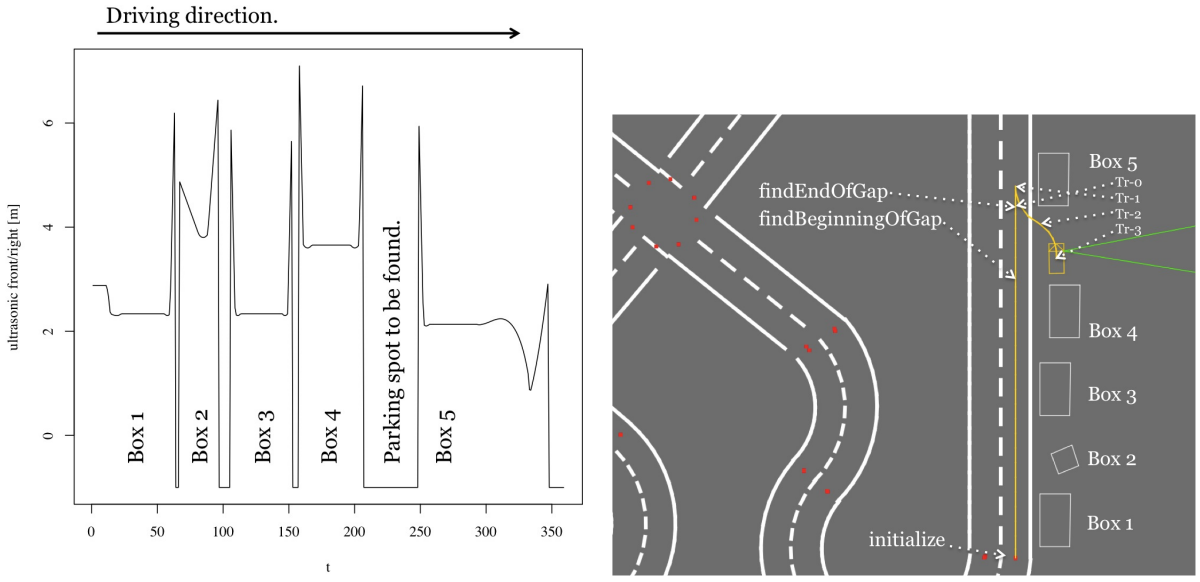
5 Sideways Parking

In this section, the design drivers for a state-machine implementing a sideways parking algorithm is outlined to address *RQ-5*. The focus for this section is to outline the basic ideas behind sideways parking and its evaluation in the simulation environment.

5.1 Design Considerations

The goal for this algorithm is to handle scenarios as depicted by Fig. 15(b), where the self-driving miniature vehicle is placed at the bottom part. After starting the vehicle, it follows the straight lane while measuring the distances to the obstacles placed on its right hand side imitating a sideways parking strip.

Once the vehicle has found a parking spot, which is sufficiently wide enough, it shall stop and move into the parking spot without touching the surrounding obstacles. Furthermore, the vehicle's heading error in comparison to the straight road must be less or equal than 5° and the minimum distance to



(a) Data from ultrasonic front/right distance sensor over time in the simulation environment.

(b) Parking scenario in the simulation environment.

Fig. 15. Concept for the sideways parking algorithm.

the front and rear vehicle must be greater or equal than 1cm. Fig. 15(b) also shows that the obstacles on the parking strip can have different dimensions and can be placed with varying distances to the right lane marking.

The basic idea behind the sideways parking algorithm is shown in Fig. 15. Besides the actual lane-following functionality, the vehicle's odometer to measure the vehicle's travelled distance over time and distance data from the ultrasonic sensor, which is mounted at the vehicle's front/right corner, is used. For the parking scenario shown in Fig. 15(b), the measured distances over time for the ultrasonic sensor front/right are depicted in Fig. 15(a). When the sensor does not measure anything or only obstacles, which are out of the defined viewing distance, $d_U = -1$ is returned. Therefore, the concept for identifying a parking gap, which is sufficiently wide enough, is to observe the following event sequence $d_U > 0 \rightarrow d_U < 0$ followed by $d_U < 0 \rightarrow d_U > 0$ and to measure the driven distance in between. Once the driven distance is greater or equal than a predefined threshold i.e. the vehicle's length extended by an acting margin, the vehicle can terminate the search phase.

After having found the parking gap, there are two possibilities to continue: (a) the conservative approach is to take this first possible parking gap and to park the vehicle; (b) another approach is to continue finding a better parking spot in terms of a more narrow one according to the official rules and regulations to earn more points in the competition. In the latter case, the currently found parking spot needs to be saved if no better spot can be found. Hereby, saving means to record the travelled distance *after* the spot has been found to be able to return to it later. In any of both cases, a termination criterion needs to be defined to abort the search for the first or a better parking gap. This criterion can involve the beginning of a curve since according to the official rules and regulations document, the parking strip is located only on the initial part of the track. As an alternative, the totally travelled distance D_{total} can also be used; however, this D_{total} needs to be determined empirically beforehand.

After a parking spot has been found, the vehicle is stopped to initiate the parking procedure. This can also be realized in two ways: (a) a predefined parking trajectory can be "replayed", which has been determined empirically beforehand, or (b) the steering and acceleration parts for the trajectory are computed online depending on the size of the parking spot. The advantage of the former is that the movements, which are required to compose a complete parking trajectory, can be determined independently from the algorithmic part of finding a proper parking gap. However, the disadvantage is that if the vehicle is not perfectly aligned after stopping once a sufficiently wide enough parking gap has been found, the final position and heading of the vehicle might not be optimal. Therefore, a combination of both where a static trajectory is adapted according to the current parking situation is recommended.

5.2 Sideways Parking State-Machine

Fig. 16 shows the overall state-machine to realize the aforementioned algorithmic concept with a static parking trajectory. The main aspect handled by this state-machine is the determination of the size of an identified parking gap. The outlined state-machine runs with a frequency of 40Hz to calculate the travelled

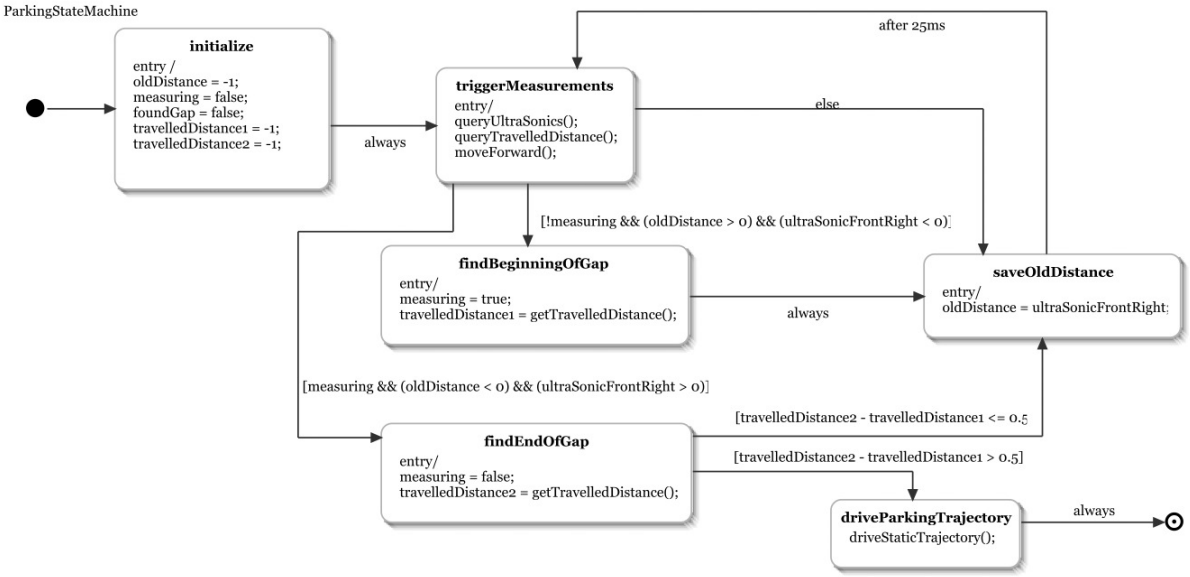


Fig. 16. Parking state machine.

path while the ultrasonic sensor is sampled internally every 70ms.

At the beginning, two variables to record the travelled distance at two consecutive time points are initialized. Afterwards in the state `triggerMeasurements`, the sensor as well as the odometer are queried while the vehicle continuously moves forward. As outlined before, the fundamental lane-following algorithm can be reused to support this task.

Within this state, it is continuously checked for the event $d_U > 0 \rightarrow d_U < 0$, which indicates the end of an object. Once this event occurs, the travelled distance is saved and the boolean measuring flag is set in state `findBeginningOfGap` to observe the subsequent event $d_U < 0 \rightarrow d_U > 0$. Afterwards, the vehicle continues while waiting for the second part of the event sequence to fire the transition to state `findEndOfGap`.

This state now ends the measuring phase by inverting the boolean flag. Additionally, it compares the travelled distance at this time point with the previous one. If the difference is not large enough to fit into the parking gap, the state-machine starts over and continues to find another parking spot. Otherwise, the vehicle is stopped and moved forward for a short distance to optimize the initial position when starting to drive the static parking trajectory (part between `Tr-0` and `Tr-1`). Afterwards, the vehicle initiates the parking process with moving backwards while steering at maximum to the right. Once the vehicle center is half-way in the parking gap (`Tr-2`), the vehicle steers at maximum to the left while already reducing its velocity to come to a full stop at the end (`Tr-3`).

The concrete values for `Tr-0`, `Tr-1`, `Tr-2` and `Tr-3` need to be determined properly. These values can be calculated analytically with simulative data as well, however, the real values to be used on the real vehicle are also influenced by the concrete components for the motor and steering servo and thus, needs to be validated in a real experimental setting afterwards.

6 Best Practices and Lesson's Learnt

This section summarizes the essential findings from the aforementioned sections. In this regard, architectural considerations are recapped followed by a description of the development and evaluation process that was used to develop the self-driving miniature car "Meili".

6.1 Architectural Considerations

Standardized hardware components allow focusing on integrating the required components like sensors and actuators. Using COTS components also reduces the dependency on time-consuming PCB assembly, increases the quality by using professionally assembled boards, and potentially saves costs. The winner of the 2006 DARPA Urban Challenge, Sebastian Thrun, summarizes this strategy by saying "It's all in the algorithms" (cf. [53]).

Standardized hardware abstraction layer compensates the dependency on specific COTS components by encapsulating lower layers. In this regard, a standardized low-level software layer hides implementation details from higher layers and enables the possibility to change hardware components later. Furthermore, reusability for software components on the higher layer is facilitated by providing a standardized software interface. This strategy is also realized with AUTOSAR [54] in real scale automotive platforms.

Standardized software interfaces for the software components that are processing the data on the higher layers enable their reuse in further contexts like a simulation environment. If the components have cleanly designed interfaces as exemplified and discussed in [55] to allow the controlled interruption of

communication and execution, a coordinated execution in a virtual test environment is possible to automatically test the implementation. Furthermore, cleanly defined software interfaces enable code generation to reduce manual implementation tasks and to reuse artifacts in a model-based development process.

Platform-independent data structures

While a standardized hardware abstraction layer reduces the dependency on specific hardware components, the benefits from such layer needs to be preserved by using platform-independent data structures. Instead of propagating sensor properties to the highest layer for example, a generic representation should be chosen to enable a replacement of the content of such data structures by synthetically generated data from simulations. Thus, virtual test environments allow the systematic analysis of an algorithm's behavior and robustness by inject faulty or noise data for example.

6.2 Development and Evaluation Process

The analysis of the team concept presentations in Sec. 2.2.5 did not unveil the use of a specific development process, which was reported to be successful. Therefore, the approach applied during the development of the 2013 competition car "Meili" from Chalmers | University of Gothenburg, Sweden is briefly outlined in the following.

The applied development process relied mainly on the clear separation between the actual algorithm conception, hardware and software design, implementation, evaluation, and the software/hardware integration phase [6]. The motivation for this separation originated from the hardware design and purchasing process, which was on the critical project path, and hence, a time-limiting factor in a sequential development process.

To realize this separation, the simulation environment was used during the conception, design, development, and evaluation phase of the software for the self-driving miniature vehicle [56] with two main purposes: (a) iteratively develop and interactively validate algorithmic concepts, and (b) decouple the hardware manufacturing from the software development. In this regard, the selected development process also addressed some of today's challenges in automotive software engineering [57].

The use of the simulation-based development process was embedded in an agile approach, where the three vehicle functions were divided into smaller work packages with weekly deliverables and aims. Thus, it was possible to track both, the progress and algorithmic robustness over time by comparing the behavior in the simulation from one week to another.

Furthermore, during the integration of the software with the hardware, the algorithms were adjusted as required by real world challenges. The improved components were validated in the simulation environment again to preserve the existing functionality.

7 Conclusion

This article provides concepts, models, and an architecture design for the software and hardware towards a standardized 1/10 scale vehicle experimental platform. Therefore, the article analyzed results from a systematic literature review (SLR), where relevant related work was searched in four digital libraries and in Google Scholar. This review yields that no study exists so far, how an experimental platform for miniature vehicles should be designed covering general design considerations for software and hardware architecture, incorporation of a simulative approach, and fundamental algorithmic concepts.

To extend the results of the literature review, the international competition for self-driving miniature vehicles was systematically reviewed with respect to results for different disciplines over the last five years. Furthermore, technical concepts from the 2013 participants were analyzed and mapped to a technical concept matrix. This mapping unveiled that the most important aspect for a self-driving vehicle is a robust and reliable lane-following capability as the basis for further functionalities like overtaking or finding a parking spot. Furthermore, the competition results showed that having a reliably running car in terms of robustness of algorithmic approaches is more important than focusing solely on speed in the competition.

Based on these results and the own experience from participating with a team in this competition, recommendations for a hardware architecture and a simulation-supported software architecture are described. Furthermore, concepts and state-machines for an image processing-based lane-following algorithm including overtaking capabilities and a sideways parking algorithm are described that comprise the basic features for the self-driving miniature cars in the competition.

Nowadays, vehicular functionalities are getting more and more complex because further information from the vehicle's surroundings is perceived by sensors. Moreover, these systems are getting interconnected to enable safer and efficient vehicle systems in terms of vehicle fleets for example. However, pure digital simulations on the one hand are not considering enough real-world effects and real-scale experiments on the other hand are too costly in terms of time and resources, when experiments with theses systems need to be conducted.

In this regard, further use cases for a miniature vehicular experimental platform as outlined in this article and future work are for example: Performance analysis of algorithms for self-driving vehicles, validations of maneuver protocols between an intelligent vehicle and its stationary surroundings, but also the investigation of advantages and drawbacks of complex maneuver protocols where several dynamically moving actors in a traffic situation are involved.

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