White Paper

Team Autonomous Racing Graz

We make autonomous racing happening.

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https://autonomousracing.ai

1 Introduction

Autonomous driving has gained increasing interest in both academic research and industrial development over the past two decades. Autonomous vehicles are revolutionizing the car industry. The aim is to design a vehicle having the same (or even better) driving skills compared to a human driver in terms of safety, performance, comfort, and efficiency. Being able to produce cars that can drive on their own in a safe manner is going to be very important for car manufacturers in the future.

Autonomous racing is a part of highly and fully automated driving competitions, with the objective to compete with other automated vehicles or human drivers on a racetrack in different driving challenges. It is well known that since the early days of automated driving, such as the DARPA Grand Challenge and the DARPA Urban Challenge have strongly contributed to the development of autonomous cars and constantly pushed the limits of the state-of-the-art. In contrast to these special scientific events in the past, autonomous racing nowadays evolves into a new type of sports event, dealing with a rapidly advancing technology.

The Autonomous Racing Graz (ARG) team was founded to be part of this adventure and to help enhancing already existing functionalities in the field of autonomous racing. We are a team of students and postdocs highly interested and experienced in automotive sensors, software, and control with the spirit to make autonomous racing happening. Our vision: "*We would like to prove and demonstrate autonomous driving at the edge (high speeds, high lateral dynamics, adverse weather conditions) to build trust and acceptance in such systems" and "serious research and fun can go together*". Our goal is to improve the software stack we are currently using in different tests. Since 2019, we have been one out of several teams of the ROBORACE competition (Season Alpha in 2019, Season Beta in 2020/21), working on three main challenges in autonomous racing: performance, precision and wheel-to-wheel racing. Since 2020, we are also one out of 31 teams competing in the Indy Autonomous Challenge.

2 About the Team

The team members have previously participated in ROBORACE [1] Season Alpha performance and precision racing competitions. In 2020, we are part of the ROBORACE Season Beta and the Indy Autonomous Challenge. Our current team members are:

- Prof. Daniel Watzenig received his PhD from Graz University of Technology in Electrical Engineering in 2006 and his habilitation (venia docendi, associate professorship) in Electrical Measurement and Signal Processing in 2009, respectively. He is the Head of the Automotive Electronics Department at the Virtual Vehicle Research Graz [2]. In 2017, he has been appointed as full professor at the Institute of Automation and Control [3] at Graz University of Technology. He has long experience in supervising PhD and Master students in the fields of control engineering, signal processing, automotive electronics, and automated driving. Since 2019, he has been a lecturer at Stanford University, USA, teaching multi-sensor data fusion and autonomous software. He is Editor-in-Chief of the SAE Int. Journal on Connected and Automated Vehicles. His main fields of expertise are automated driving, fusion techniques, sensor modeling, embedded automotive systems, control and robust optimization methods, inverse problems, and statistical signal processing.
- Michael Stolz is part of the automated driving research team at the Institute of Automation and Control [3] of Graz University of Technology as a post-doctoral project assistant and was responsible for the lecture *Selected Topics of Control & Dynamic Systems* in winter semester 2019/20, dealing with motion planning and control in the context of automated driving. He is also part of the control-systems group at Virtual Vehicle Research [2] as a key researcher, responsible for project management and technical guidance of funded projects in the field of automated driving. Michael Stolz finished his Master studies in Mechanical Engineering and received his PhD on Control Engineering from Graz University of Technology. He has worked in the automotive industry as a development engineer for 10 years (one year as skill team leader in the field of automated driving). Main fields of interest and expertise are: Automated driving; automotive control systems; embedded control; control-system-architecture; algorithms for path-planning and control; simulation, synchronization, optimization in control; validation of automated driving.
- Markus Schratter is a researcher for advanced driver assistance systems and automated driving functions. He studied Information and Computer Engineering at Graz University of Technology. In 2011, he joined the Virtual Vehicle Research and was involved in different research projects. His main task is the development of active safety systems and the integration of concepts in test vehicles. Currently, he is writing his PhD thesis together with the BMW Group with the subject: How technology from highly automated driving can be used to improve active safety systems, such as [4]. His research interests are related to automated driving, active safety systems, robotics, sensors, and the integration of distributed systems. In the ROBORACE competition, he is in charge of system design and integrating the software stack, which is running on the race car. More details about the structure and general pipeline can be found in [5].

- Konstantin Mautner-Lassnig is a researcher in robotics, autonomous driving and artificial intelligence. He specialized in AI and robotics during his studies at Graz University of Technology and competed in several international competitions with great success. Moreover, he participated in a research project about an autonomous parcel delivery robot in inner-city areas [6]. As a member of the ROBORACE team ARG, he is responsible for the system integration and provides support in algorithm designs and concepts.
- Jasmina Zubača is a researcher and project assistant at the Institute of Automation and Control at Graz University of Technology. Her main research topic is related to the field of automated driving. She focuses on different vehicle motion models and state estimation techniques which are used for ego vehicle tracking, e.g. [7], [8]. For the ROBORACE competition, she developed an approach of reference line generation used as an input for the racing line optimization. The described data processing is based on track geometry defined by borders only and can be found in [9].
- Tobias Renzler is a researcher and project assistant at the Institute of Automation and Control at Graz University of Technology. He researches in the field of automated driving, focusing on platooning. There he deals with the complexity of platoon management and the challenges that come along with V2X communication [10]. For the ROBORACE competition, he developed a distortion correction for LiDAR point clouds, especially needed while high speed driving [11].
- Stefan Loigge is a researcher for robotics. During his studies, he was part of the RoboCup team of Graz University of Technology and was able to successfully participate in international competitions. In 2017, he worked as a researcher at Graz University of Technology on an autonomous parcel delivery vehicle for cities [6]. In 2018, he joined the Vehicle Research and since then has been working on several projects that focus on robotics and autonomous driving. In the ROBORACE competition, he is responsible for the automatic monitoring of the software stack and for data recording and post processing [12].
- Martin Kirchengast is a post-doctoral project assistant at the Institute of Automation and Control of Graz University of Technology. He received his PhD in Control Engineering and his Master's degree in Information and Computer Engineering from Graz University of Technology. During the last years he has been involved in many projects together with automotive industry partners (all-wheel powertrain modeling, actuator modeling and control, trajectory planning of parking assistance systems, perception sensor modeling for virtual testing of automated driving functions) as well as pharmaceutical industry (model predictive control for pharmaceutical manufacturing plants). His main research interests are automated driving, automotive control, control allocation, sensor modeling, model predictive control and optimization algorithms.
- Rudolf Reiter is a researcher for nonlinear optimization-based planning and control approaches for automotive applications. He graduated from Graz University of Technology in 2016 at the Faculty of Electrical Engineering in the Department of Control Systems and has several years of experience with the application of control and estimation systems. Currently he is enrolled as a PhD student at the Albert-Ludwigs-University Freiburg at the Technical Faculty and in the Systems Control and Optimization Laboratory group under the supervision of Prof. Moritz Diehl. He investigates real time optimization approaches. His research interests include optimal robust planning and control, planning with

uncertainties, numerical optimization, reinforcement learning and deep learning in optimal control, state estimation, autonomous systems, and robotics. Regarding the ROBORACE competition, he is focusing on time-optimal algorithms.

3 Autonomous Racing Highlights

Our team – Autonomous Racing Graz (ARG) – was founded in the beginning of the year 2019 with the goal to compete in ROBORACE's Season Alpha [1]. The team consists of researchers from two different entities – the Institute of Automation and Control at Graz University of Technology[1] and the Virtual Vehicle Research[2] (both located in Graz, Austria). The latter one is an applied automotive research center with different shareholders from academia and industry (Graz University of Technology, Joanneum Research, Infineon Technologies, Magna Steyr, AVL List, Siemens, and Voest Alpine).

After the first months of research and development, the team has gained experience with the ROBORACE DevBot 2.0 on the test track in England. The first competition took place in the Zala Zone [15] proving ground in Hungary. In the so-called precision and localization challenge, a circuit had to be driven as fast and as accurate as possible using LiDAR based localization. The track consisted of narrow gates, represented by cones that had to be passed collision-free in order to avoid time penalties. The team finished second.

Subsequent to the promising start into Season Alpha, in November 2019 our team was able to win the performance challenge at the Circuit de Croix-en-Ternois [13] in France, during the final Season Alpha event. There, over 6 laps of high-speed sections were paired with tight gates. Our team successfully completed the final competition, finishing 1st. The fastest lap time for the first session was 1 [min] 37.440 [sec] and 1 [min] 17.830 [sec] for the second session

Figure 1: The Autonomous Racing Graz Team

[1] https://www.tugraz.at/institute/irt/home/
[2] https://www.v2c2.at/

The time difference between the first and second session is nearly 20 seconds, which represents a remarkable improvement that was achieved by pushing the vehicle dynamics limits.

Figure 2: The fully electric ROBORACE DevBot 2.0 passes a gate on the Circuit de Croix-en-Ternois in France [13]. The Ouster OS1-16 LiDAR [14] for localization is placed on the top of the race car.

Currently, team ARG prepares for ROBORACE's Season Beta, consisting of 12 competitions (6 doubleheader events) starting in March 2020.

4 Technical Background and Experience

Over the last 5 years, we have built three different vehicle demonstrators, our Automated Driving Demonstrators (ADD), owned by the Virtual Vehicle Research. The ADDs are running the Autoware software stack, an open-source stack developed for self-driving vehicles. The Autoware algorithms are stepwise replaced byself-developed functions (localization, fusion, path matching, path planning, longitudinal and lateral control etc.).

4.1 Automated Driving Demonstrator

The AD-Demonstrators used for testing different automated driving functionalities are depicted in Figure 3. One of the cars is Ford Fusion Hybrid. It is equipped with the latest "steer-by-wire" and "brake-by-wire" systems as well as simple driver assistance functions. Based on this vehicle, a unique research platform has been developed in three phases:

- In the first step, our researchers ensured that the electronics had full access to the vehicle. The aim was to create an "artificial intelligence on wheels" that enables acceleration, braking and steering by a computer alone.

- The latest sensors (e.g. LiDAR, radar, cameras, GPS or Car-2-X systems) have been installed to enable a 360° field view (see Figure 4). At this stage, high-performance multicore computer platforms (such as Nvidia, Infineon AURIX, TTTech Razormotion and dSPACE) have also been integrated for data analysis and data integration in order to prepare the third phase as well as possible.

Figure 3: Virtual Vehicle AD-Demonstrators: Ford Mondeo (left), Ford Fusion (middle), Mercedes Vito (right)

- Autonomous driving functions have been implemented in the third stage. In this context localization, object detection, object prediction, path planning and trajectory tracking are integrated in the research vehicle. The majority of software components used in the research vehicle come from the Autoware stack.

4.2 Autoware

In the field of autonomous driving, only few open-source stacks exist that address the entire problem of self-driving vehicles, and Autoware [16] is one of them. Autoware is a popular open-source software that provides a complete set of self-driving modules, including localization, detection, prediction, planning, and control. It is based on Robot Operating System (ROS) [17] and other well-established open-source software libraries. It unites individual software components and provides interfaces and tools for fast and easy setup routines. Figure 5 shows the software components for the LiDAR based object detection and the path planning integrated in the research vehicle. Autoware is intended for urban areas, but also other regions like highways and freeways can be partly covered. Prof. Daniel Watzenig *et al.* is organizing the second Autoware Workshop during the IEEE Intelligent Vehicles Symposium 2020 in Las Vegas, USA[3].

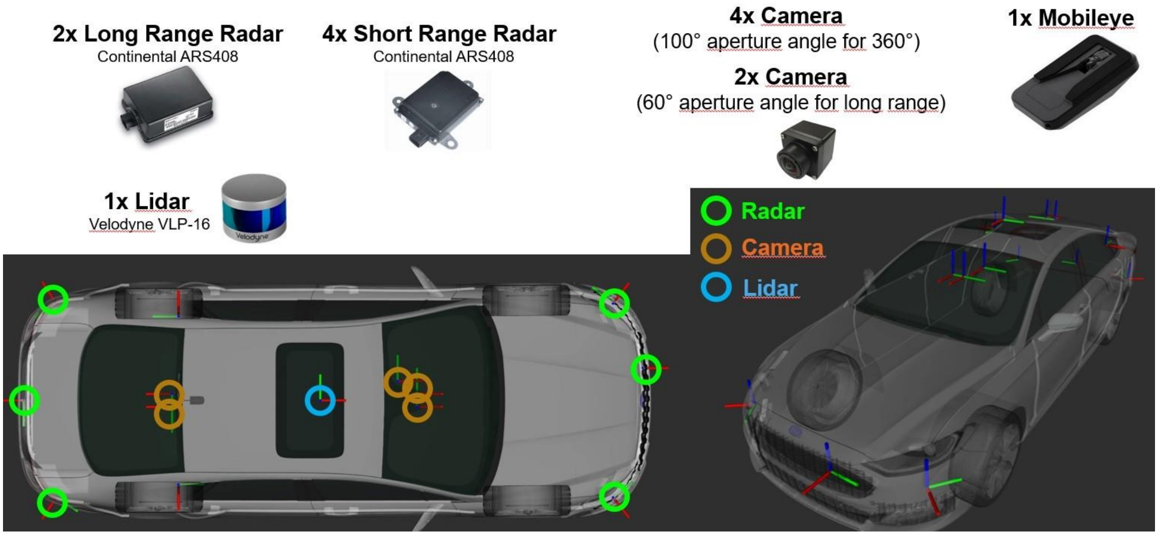

Figure 4: Ford Mondeo: Arrangement of the sensors

[3] https://www.autoware.org/iv2020

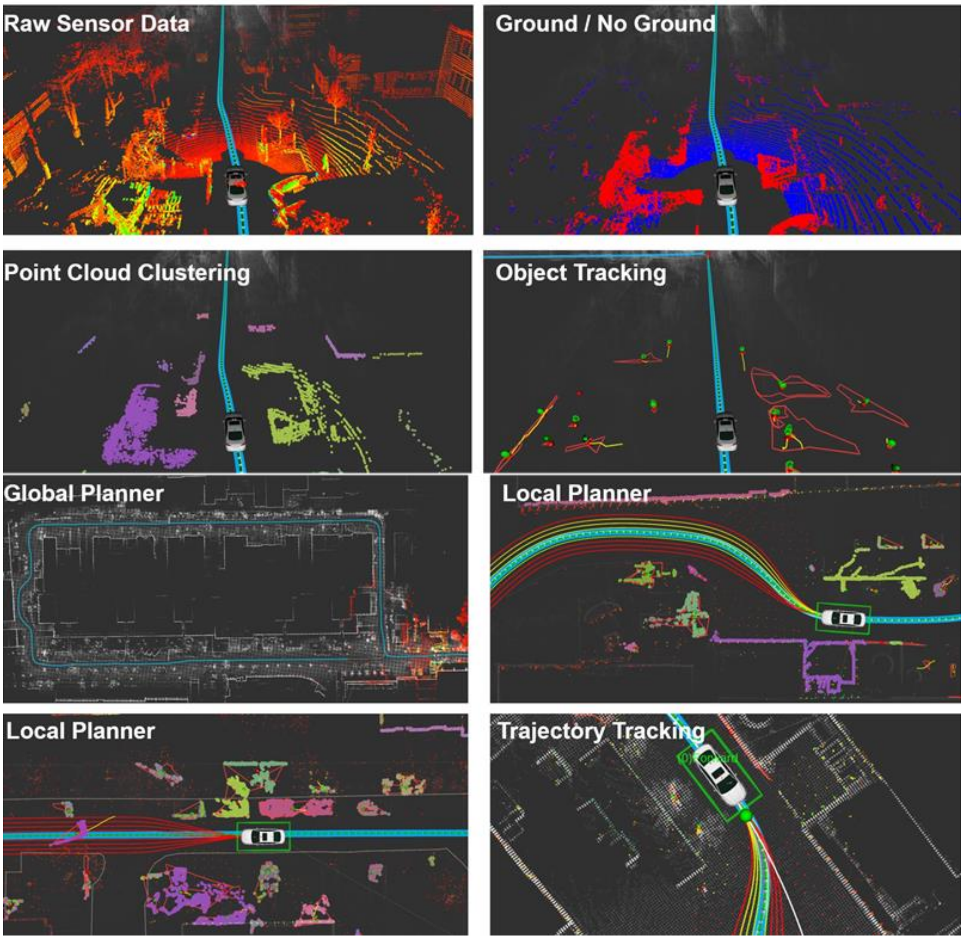

Figure 5: Top four images: LiDAR-based stack for object detection, from the raw data to tracked objects. Bottom four images: Path planning architecture of our Ford Fusion, from global path planning to trajectory tracking.

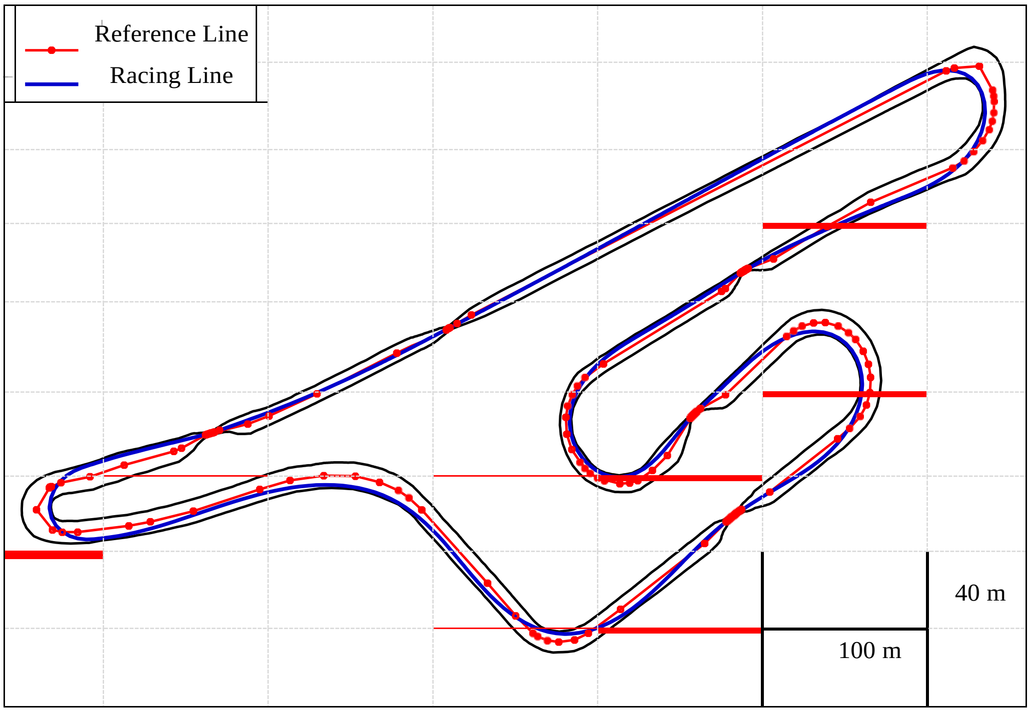

Figure 6: Generated reference line and driven racing line for the Circuit de Croix-en-Ternois racetrack in France.

5 Technical Insights at a glance

Currently, team ARG is able to map a track and to localize itself within this map, using LiDAR only, or also supported by GPS. Using the same map, an optimal racing line can be computed offline. This may be adapted by an online path planner to consider objects or other vehicles, sensed or notified.

5.1 Mapping [5]

A track is mapped accurately enough to localize and race on the basis of this map. The progress of making such a high accuracy map is even today a tedious and not always well-defined procedure: especially, when environmental factors like very few features, fences or hard to detect materials come into play. One has to find the ideal setup between map size and quality due to the amount of data which further affects the processing speed. Nevertheless, a full 3D map of the area can provide major advantages in several disciplines. The localization uses the full extent of the available map information and outputs a more precise and stable position. When having a look at the rich point cloud data in every dimension, it appears obvious that a 3D approach is superior to any other 2D methods. The knowledge about exact borders and passages of the racetrack can increase the robustness and quality in race line computation. Finally, the data and sensor association require adequate height data. This is the case for sensor fusion between GPS measurements and LiDAR predicted positions, otherwise the map and the GPS are not properly aligned.

Recorded LiDAR measurements are used to generate the point cloud map using the normal distributions transform (NDT) algorithm. The created point cloud map is processed in RVIZ to obtain the 3D point cloud. Inner and outer border are defined visually by hand, since the racetracks' boundaries have differed from race to race (cones, boxes, curbs, walls or their combination) and automation does not pay off.

5.2 Racing Line Generation [9]

The gained layout of the racetrack is used to generate a reference line that is used later to optimize the racing line. The reference line generation consists of eight steps: data reading and duplicates' removal (1), linear interpolation (2), distance matrix calculation (3), pair finding (4), reference line calculation (5) and smoothing (6), inclusion of corner points (7) and gate points (8).

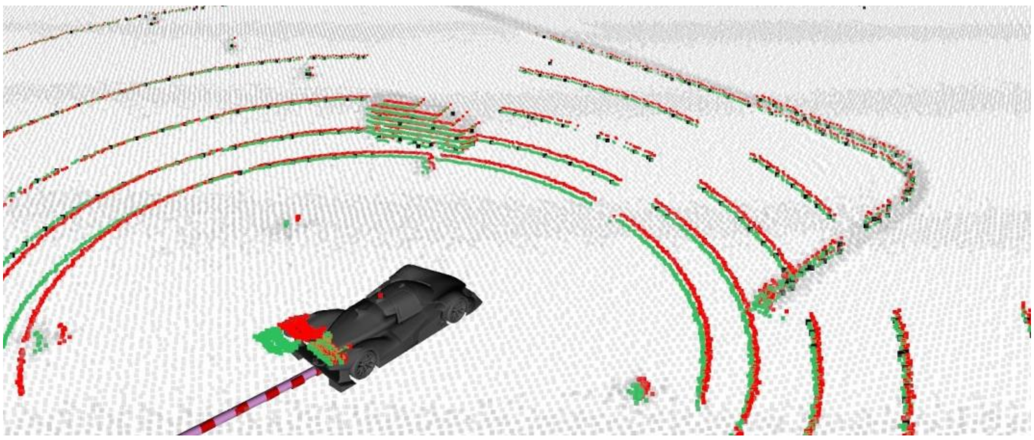

Figure 7: Effect of LiDAR distortion and its correction, containing offline generated map (gray), LiDAR measurement (red), and corrected point cloud (green).

The minimum curvature trajectory planning approach explained in [2] is used for race line optimization. Due to its smooth and limited peak curvature, it is robust in real world application. The minimum curvature path is generated using an iterative quadratic programming (QP) formulation. The smooth reference line is an input of the algorithm that calculates the optimal racing line (see Figure 6).

5.3 LiDAR Distortion Correction [11]

Scanning sensors perform multiple single measurements at different time instances to cover a certain field of view. Usually, LiDAR sensors provide data in one single point cloud, made available at the end of a complete scan. All points stored in this point cloud, refer to the same origin - the sensor's position. Once the sensor is moving during a scan process, single measurements refer to globally different reference locations, leading to errors in distance and direction. These errors, caused by the so-called LiDAR distortion, increase with speed and turn rate. As the performance of localization is highly dependent on the accuracy of the measurement, distortion needs to be corrected. To do so, we use odometry information. The correction presented in [11] can be applied for extrapolating the point cloud to future reference frames. This additionally accounts for a known time delay between point cloud measurement and computations based on it. The corrected data allows accurate localization and object detection. The effect of LiDAR distortion and its correction is illustrated in Figure7.

5.4 Localization [5]

The algorithm used for mapping and localization is called normal distributions transform (NDT) and is part of the open-source self-driving stack Autoware [16]. The LiDAR serves as the main input source for the algorithm. In principle, a live measurement is compared with previously recorded measurements or a full-scale point cloud map. The created point cloud map is taken as a reference and further broken down to three-dimensional boxes with each having individual probability distributions. During the alignment process, the algorithm searches for similarities. Outliers or changes in the environment alter the matching quality and are a common problem. The applied probability density functions can solve this by enabling a kind of "near match" to the alignment. In Figure 8, both point clouds required for receiving a position are visualized for comparison.

5.5 Objects and other traffic participants

Currently, team ARG is developing an online path planner that allows to avoid and to collectobjects with respect to other vehicles on the track. These objects may be virtual or real: Real world obstacles and other traffic participants such as opponent racing vehicles may be sensed. The latter may be notified additionally over V2X, similar to virtual objects. Virtual objects may represent obstacles or rewards. According to the type of the object, the previously calculated racing line is adapted in order to avoid or to collect the object.

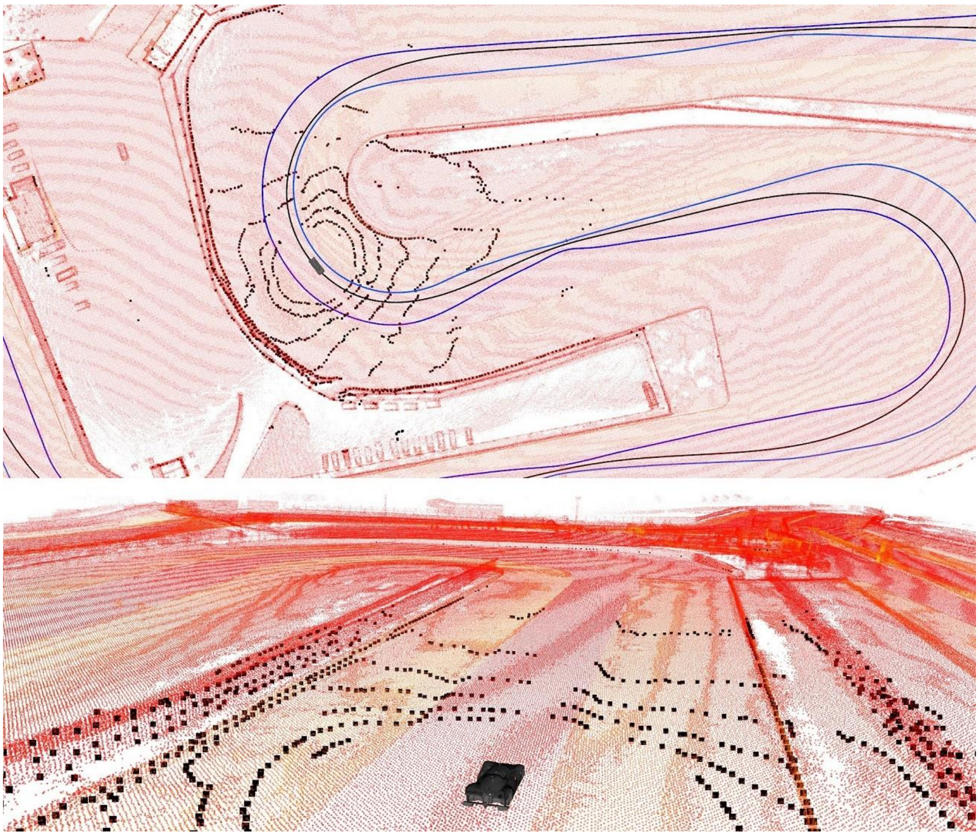

Figure 8: The point cloud map (red) is used to match live measurements (black) that allow to obtain the precise location on the racetrack.

6 Collaboration with other Teams and Universities

In general, our team has very good knowledge of LiDAR based mapping and localization up to high velocities and accelerations. For our approaches we use only one LiDAR, which is first used for mapping and afterwards for the localization. Based on the created point cloud of a track, we have a pipeline to create a track layout, which can be used for the calculation of a racing line and to define where a car is allowed to drive. We also have a profound knowledge of the integration of different software components. For many years, we have carried out research in the field of robotics and therefore we are well experienced in ROS and the open-source autonomous driving stackAutoware.

We are also open to share our knowledge and to collaborate with other teams. A specific field where we still lack experience is wheel to wheel racing. Within the ROBORACE competition, we are now entering that field in particular high-level planning strategies, which are required for overtaking or blocking maneuvers. In order to accelerate the development, we are eager to collaborate with other teams. We are convinced that this topic will increase the public interest in autonomous racing, and we believe that we can speed up the realization by bundling forces and resources.

Supported by

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References

[1] Global championship of driverless cars, https://roborace.com/, [Online; accessed 21-January-2020], Roborace, 2016.

[2] VIRTUAL VEHICLE Research GmbH, https://www.v2c2.at/, [Online; accessed 24-February-2020], 2016.

[3] Institute of Automation and Control, https://www.tugraz.at/en/institutes/irt/home/, [Online; accessed 24-February-2020], Graz University of Technology, 2016.

[4] M. Schratter, M. Bouton, M. J. Kochenderfer, and D. Watzenig, "Pedestrian Collision Avoidance System for Scenarios with Occlusions," in 2019 IEEE Intelligent Vehicles Symposium (IV), 2019.

[5] M. Schratter, K. Mautner-Lassnig, J. Zubača, T. Renzler, S. Loigge, M. Kirchnegast, M. Stolz, and D. Watzenig, "Lidar-based Mapping and Localization for Autonomous Racing using Autoware," unpublished, N.D.

[6] A. Buchegger, K. Lassnig, S. Loigge, C. Mühlbacher, and G. Steinbauer, "An autonomous vehicle for parcel delivery in urban areas," in 2018 21st International Conference on Intelligent Transportation Systems (ITSC), 2018.

[7] J. Zubača, M. Stolz, and D. Watzenig, "A Novel Tuning Approach of the H∞ Filter for Longitudinal Tracking of Automated Vehicles," in 2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE), 2019.

[8] A. Rupp, M. Tranninger, R. Wallner, J. Zubača, M. Steinberger, and M. Horn, "Fast and Low-Cost Testing of Advanced Driver Assistance Systems using Small-Scale Vehicles," IFAC-*PapersOnLine*, vol. 52, no. 5, pp. 34–39, 2019.

[9] J. Zubača, M. Stolz, and D. Watzenig, "Smooth Reference Line Generation for a Race Track with Gates based on Defined Borders," unpublished, N.D.

[10] T. Renzler, M. Stolz, and D. Watzenig, "Decentralized dynamic platooning architecture with v2v communication tested in omnet++," in the 8th International Conference on Connected Vehicles and Expo, 2019.

[11] T. Renzler, M. Stolz, and D. Watzenig, "Increased Accuracy for Fast Moving LiDARS: Correction of Distorted Point Clouds," unpublished, N.D.

[12] G. Steinbauer, S. Loigge, and Mühlbacher, "Supervision of hardware, software and behavior of autonomous industrial transport robots," in 2016 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C), 2016.

[13] Circuit de Croix en Ternois, https://www.circuitdecroix.com/, [Online; accessed 24-January-2020], Circuit-de-Croix, 2019.

[14] OS1 Mid-range Lidar sensor, https:// ouster. com/ products/ os1 - lidar - sensor/, [Online; accessed 21- January-2020], Ouster, Inc, 2019.

[15] The Zala Zone test track, https://zalazone.hu/en/, [Online; accessed 24-January-2020], M. Mühely, 2017.

[16] Autoware, https://github.com/autowarefoundation/autoware, [Online; accessed 28-January-2020], The Autoware Foundation, 2019.