Laser Scanner-Based Navigation and Motion Planning for Truck-Trailer Combinations

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Abstract—This paper presents a navigation system for truck-trailer combinations that enables accurate maneuvering to a target position, either assisted or automated. Functional and collision-free motion is achieved by a combination of laser scanner-based navigation and multimodal motion planning. The navigation system uses laser range data to recognize target objects and calculates corresponding target positions. The grid-based multi-dimensional path planner generates a collision-free minimum-cost trajectory for truck-trailer combinations with up to five degrees of freedom. The multimodal planner decides whether the approach is planned as a single backward motion, as a maneuvering path with reversal points or as a long distance approach using free navigation and virtual tracks. Optimized planning algorithms are used for each case. The complete system has been successfully tested using a combination of a Mercedes-Benz truck and a full trailer under varying environmental conditions. The test application was an assistance system for backward driving under a swap body—a very challenging application due to its strict accuracy requirements. The results promise high benefits for this and further applications.

I. INTRODUCTION

Professional drivers of truck-trailer vehicles usually have to perform additional tasks such as loading and unloading. Routine tasks on customer yards and public roads include docking at ramps, interchanging swap bodies and approaching specific parking positions precisely. Such procedures often require maneuvering truck and trailer jointly. This also applies to upcoming European road trains, called Gigaliner or EuroCombi, as combination of a semi-truck together with a full trailer or a single truck together with a semi-trailer on a dolly.

Approaching a target position accurately demands intensive training and experience—especially during reversing. Only experienced drivers master positioning a full trailer exactly at a specific spot. Therefore, our current research is aimed towards developing assistance systems, that support drivers and relieve them of stress during maneuvering tasks with truck-trailer combinations. In this way, the number of accidents with damage to the vehicle and other objects shall be reduced significantly. In addition, even non-expert drivers shall be enabled to accomplish such complex driving tasks.

Assistance systems for maneuvering are designed as semi-automated systems preferably, in order to allow the driver to concentrate on supervising the approach. We have built an assistance system for picking up swap bodies, with either a single truck or a truck-trailer combination, as our prototype application of laser scanner-based navigation to commercial vehicles. Details of the navigation algorithms of this system will be described in a separate paper [1]. The current paper presents our solution to the motion planning task regarding maneuvering truck-trailer combinations.

Planning collision-free, minimum-cost trajectories for the respective vehicle combinations is vital for precise and reliable navigation. Motion planning of nonholonomic systems has been part of robotic research for many years. The principles of motion planning can be found in [2] and [3]. Specific problems of vehicles like nonholonomic systems are summarized in [4]. A well known approach to nonholonomic planning is to initially determine a path for a holonomic vehicle and adjust it to fulfill nonholonomic constraints afterwards [5]. The algorithms presented in this paper aim at motion planning in a single step, including consideration of any motion constraints and collision checking. In literature truck-trailer combinations are treated as $n$-trailer problem. However, often the off-axle connection of real trailers is disregarded. [6] presents an approach to the $n$-trailer problem including off-axle connections. A completely different approach to handle truck-trailer combinations is discussed in [7] and [8]. Instead of complex motion planning, the motion controller is extended to track composed simplified paths. This does not guarantee precise positioning of both truck and trailer at a specific target position, though.

![Fig. 1. Combination of Mercedes-Benz Actros 2540 truck and trailer at the target position for picking up an European Norm swap body.](image)

This paper describes our technical approach to a flexible assistance system for maneuvering truck-trailer combinations. This includes methods for multimodal motion planning...
and laser scanner-based navigation. Section II contains an introduction to laser scanner-based navigation and provides an overview of the system’s architecture. The main focus of the paper, motion planning, is discussed in section III and section IV. They present the algorithms and their application, respectively. Section V summarizes the results of our system evaluation.

II. LASER SCANNER-BASED NAVIGATION

Laser scanner-based navigation is our approach for safe and precise localization and for control of vehicles relative to one or more objects within the surrounding area [1]. This is done by processing range data of a scanning laser sensor and computing control instructions for the vehicle accordingly. The nominal procedure for navigation towards a target object comprises the following steps:

1. Positioning of the vehicle in such a way that the target object lies within the viewing range of the laser sensor
2. Scene analysis identifying potential target objects
3. Manual or automatic selection of the desired object
4. Motion planning from the current to the target position
5. Target approach using laser scanner-based navigation

The architecture of the modular system performing this procedure is shown in Fig. 2. The modules for processing sensor data, object tracking, collision detection and motion control form an inner control loop: sensor data from the laser scanner and the vehicle’s odometry are used to determine the current pose of both truck and trailer. Subsequently the deviation from the target trajectory is calculated. The motion controller then computes new set values for steer angle and vehicle speed. During the approach the area behind the trailer is monitored for obstacles on the pre-planned trajectory using the laser scanner. In case of previously unknown or moving obstacles the vehicle is slowed down or even stopped. If necessary, re-planning is performed. For autonomous operation additional sensors are required to monitor the area in front and at the sides of the vehicle. Otherwise the driver is liable for surveillance of the vehicle’s surroundings. The modules for scene analysis and target selection, and motion planning are used in the initial procedure of laser scanner-based navigation. During scene analysis all visible objects within the laser scanner’s field of view are classified and their respective position and orientation is determined. Based on the current pose of the vehicle and the pose of the manually or automatically selected target object, a feasible trajectory for the truck-trailer combination is calculated by the motion planner. During planning, data from the world model, which is based on CAD data and gathered laser scanner measurements, are considered. If no path can be found, the system displays a message to the user. The human-machine-interface (HMI) enables the user to activate the system, to select a target object and to pause or abort the approach. In addition, it provides a status display and helps the user to monitor the system by means of visual and acoustic signals.

For development and testing of all system components a Mercedes-Benz Actros 2540 truck together with a full trailer was used (Fig. 1). Both, truck and trailer, feature a chassis frame for swap body transport. The length of the truck is 9.5 m with 5 m wheelbase. The trailer measures 9.3 m (including drawbar) with 5 m wheelbase as well. The truck has been upgraded with a steer actuator for lateral control and with access to longitudinal control by means of a CAN-Bus interface. Additionally, it provides a reversing assistant developed by DaimlerChrysler Truck-Product-Engineering that allows to directly control the steer angle of the trailer. The required steering of the truck is performed autonomously. At the trailer’s rear we have mounted a SICK LMS 200 laser scanner (see Fig. 3) that provides distance measurements for object recognition and obstacle avoidance within an outdoor range of up to 80 m. It scans a 180° field of view with an angular resolution of 0.25°.

III. MULTIMODAL MOTION PLANNING

The motion planner searches for a collision-free, minimum-cost path from a given start configuration of the truck-trailer combination to a final configuration. The desired result is a smooth path with few reversal points. Start and destination are provided by the scene analysis. In case of a docking maneuver into an object, motion planning is done to an object specific approach configuration in front of the target. The resulting path is extended with an object specific docking path. In case of a swap body it consist of a single straight path segment, in order to prevent any orientation changes of the vehicle while underriding the swap body.
The foundation of precise motion planning is the vehicle’s mathematical representation. Fig. 4 shows the model of a truck-trailer combination. In order to describe the pose of both truck and trailer a 5-tuple is needed: \((x, y, \theta_1, \phi_1, \phi_2)\). The tuple \((x, y, \theta_1)\) represents the position and orientation of the towing vehicle, \(\phi_1\) denotes the drawbar angle while \(\phi_2\) labels the steer angle of the trailer. EuroCombi road trains can be described with 5 dimensions, too. For tractor-semi trailer combinations and trucks with a simple trailer 4 dimensions are sufficient. A single truck is described by a 3-tuple. Our planning system allows switching between these vehicle combinations at any time by utilization of different data sets for the vehicle geometry.

![Fig. 3. Laser scanner mounted below the rear bumper of the trailer.](image)

Motion planning for truck-trailer combinations requires a 5D search. Hence we developed a 5D planning algorithm that is based on an A* grid search [2]. This algorithm is target-oriented, i.e. it uses a cost function to select promising adjacent configurations until the target configuration is reached. The cost function is made up of two parts: the calculation of the costs from the start configuration to the current configuration of the truck-trailer combination, and an estimation of the remaining costs to the destination. The current costs are calculated from the sum of the cost for all previous planning steps. The remaining costs are estimated with a weighted sum of Euclidean distance, orientation deviation and deviation of the trailer angles from the target configuration. The cost function significantly affects the quality of the resulting path. For example, if we want a smooth path with few reversal points, we tag straight forward motion with lower costs compared to changes in orientation or even changes in direction.

An important part of 5D motion planning is the calculation of the truck pose and the trailer angles after a single planning step. Based on a given truck-trailer configuration \((x, y, \theta_1, \phi_1, \phi_2)\) the new configuration \((x', y', \theta'_1, \phi'_1, \phi'_2)\) needs to be calculated. For this purpose, at first all feasible adjacent poses \((x', y', \theta'_1)\) of the truck are determined, and afterwards the respective trailer angles \((\phi'_1, \phi'_2)\) are computed. The calculation of the adjacent poses is done with constant step length and \(n\) discrete curve radii in order to reduce the search tree. The step length is automatically chosen in such way, that with each planning step a new grid cell is reached. A configuration file defines the grid resolution and what curve radii are used for forward and backward motion respectively.

![Fig. 5. Kinematic single-track model for a truck-trailer combination.](image)
Equation 1 describes the rate of change of the drawbar angle and equation 2 calculates the rate of change of the trailer steer angle. Eliminating the magnitude time from the equations results in:

\[
\phi_1' = \phi_1 + ds \cdot \Omega_1(\theta_1, \phi_1) \tag{3}
\]

\[
\phi_2' = \phi_2 + ds \cdot \Omega_2(\theta_1, \phi_1, \phi_2) \tag{4}
\]

Within the motion planner the trailer angles \((\phi_1', \phi_2')\) are calculated using a numerical approximation of the equations 3 and 4. They only depend on the current trailer angles \((\phi_1, \phi_2)\), the current steer angle of the truck \(\phi_0\), the vehicle geometry \((L_1, L_2, L_3, M_1)\) and the step length. The derivation of equations for other vehicle combinations (e.g. tractor-semi-trailer) is done analogously.

During planning of a single path, several million configuration calculations have to be performed. For this reason we implemented some optimizations in order to minimize memory requirements and runtime of the algorithms.

Planning is done within a configuration grid, where each grid cell stores the exact configuration of the vehicle and additional data of the search algorithm. Already for small world models, the memory needed for the 5D grid is enormous. For example, a map of 100 m x 100 m size with a grid resolution of 0.5 m for \((x, y)\) and a resolution of 1 ° for \((\theta_1, \phi_1, \phi_2)\) \((\text{with } \phi_1, \phi_2 \in [-50^\circ, +50^\circ])\) contains \(144 \cdot 10^3\) grid cells. Allocating 50 bytes for each grid cell results in an overall memory usage of more than 6 TB. For this reason we developed a dynamic configuration grid that reduces the memory usage by allocating grid cells on demand only. Planning a single path typically covers only a small part of the grid. Therefore, this system already runs on a standard PC with 256 MB main memory.

Not in every case a complete 5D planning is required. Instead, it may be combined with a 4D or 3D search. Exemplary use cases of this type are described in Section IV. During a combined search, at first waypoints and reversal points are determined within a coarse grid. Afterwards partial trajectories are planned in-between using one of the provided planning modes (3D/4D/5D) with a finer grid resolution.

Another optimization is the usage of predefined or learned paths, so called preference trajectories. Fig. 10 shows two preference trajectories (red) that do not necessarily need to be straight lines. The step length of these trajectories is usually much larger than the grid resolution. Thereby less search iterations are necessary to cover longer distances. The trajectories are entered and exited at specific predefined access points. The concept of preference trajectories allows motion planning inside large scale world models within acceptable runtime (see use case in section IV-C).

With grid-based methods the final point of the planned trajectory does not necessarily match the given target location. For 3D searches we developed a compensation algorithm to correct the position grid error. It uses linear orientation-invariant scaling of path sections to distribute the deviation along the path. In case of 4D and 5D planning the grid error is minimized by using a finer grid for the final path section.

Fig. 6 shows the components of the motion planning system. Initially the desired start and target configuration is injected into the configuration pool. Out of this pool successively the current least-cost configuration is selected. Based on this configuration and the kinematic model of the current vehicle combination, the configuration calculation computes valid adjacent configurations. These are checked for collisions within the obstacle grid by the collision verification module. The two-dimensional obstacle grid is initially created out of a polygon-based map provided by the global world model. The cost function determines the costs for all collision-free configurations. These tagged configurations are then stored in the dynamic grid and added to the configuration pool. The algorithm stops, if either the target is reached or the configuration pool runs empty. In the latter case no feasible trajectory could be found. The vehicle geometry is exchangeable in order to allow switching between different vehicle types easily. All modules marked grey in Fig. 6 are multi-dimensional, i.e. for a 3D, 4D and 5D search the respective modules are selected automatically.

IV. USE CASES

Below we describe three typical use cases of the multi-modal planning system for truck-trailer combinations. They apply for both assistance functions and autonomous operation. Our practical example is the precise approach of target positions with truck-trailer combinations. For this task typically reversing is required for the last part of the way. If necessary, this is preceded by a maneuvering approach or long distance approach.
A. Single backward motion

The starting point for motion planning is the current configuration of truck and trailer. First of all, the planner tries to find a trajectory that allows the vehicle to reach the target position with a single backward motion, that is without the need of reversal points. Instead of a complete 5D search, a modified 4D variant is used for this purpose. This 4D search is based on a 3D pose description of the trailer that is extended by a fourth dimension representing the trailer’s steer angle. This is an adequate simplification, because we utilize the reversing assistant installed in the test vehicle. It allows to directly control the trailer steer angle instead of the truck steer angle. For collision verification of the truck we assume a drawbar angle of 0° and an increased safety distance regarding the vehicle outline.

Fig. 7 depicts the planning result for a backward approach without reversal points. The starting position has a distance of 20 m and an orientation offset of 80°. Additionally the outline of truck and trailer is drawn in grey and the docking path extending the planned path is shown in green.

B. Maneuvering with reversal points

In case the multimodal planner was unable to find a feasible single backward approach, it automatically plans a maneuvering approach. This requires a 5D search in order to be able to determine reversal points and forward motion. The final accurate backward movement is determined using the 4D variant again. Fig. 8 shows a scenario, where maneuvering is necessary. The resulting trajectory has only one reversal point. For more complex tasks trajectories with multiple reversal points are planned, if required.

C. Long distance approach

The planning algorithms presented in this paper are suited for motion planning over long distances, too. This may be utilized for motion planning on an automated factory yard for instance. Fig. 10 shows an example where the vehicle is parked at the yard’s gate in order to drive autonomously underneath a swap body in approximately 100 m distance. The resulting path includes part of a preference trajectory, a single reversal point and a final backward approach.

The laser-based navigation during the approach is divided into two phases. In phase one position estimation is done using landmarks optionally combined with DGPS, until the vehicle is close to the target swap body. In phase two the system switches back to object-oriented navigation.

To provide a world model for motion planning, we scanned our test yard using a vehicle with a vertically mounted laser sensor. Out of this 3D scan data (see Fig. 9) in combination with CAD data all drivable areas (marked green) have been extracted automatically. This data has then been reduced to a 2D world model that can be utilized and updated efficiently.
an orientation error of $\pm 0.2^\circ$, measured manually at the final position. These values meet the requirements of the test application and are achieved with very good repeat accuracy. A typical approach from a distance of 20 m between the rear of the trailer and the target object requires less than 90 s.

Using the multimodal planning system we generated trajectories for backward approaches with orientation offsets of up to $\pm 100^\circ$ within less than 1 s in each case. The planning precision needed for laser scanner-based navigation and vehicle motion control was already achieved by a grid resolution of 0.5 m for $(x,y)$, a resolution of 1° for vehicle orientation and the trailer’s steer angle, and four discrete curve radii (left and right respectively). The remaining grid error was compensated by our correction algorithm. Practical maneuvering trajectories with reversal points were generated within at most 10 s by using a combined search. Planning long distance approaches on our test yard required below 30 s. The coarse grid had a resolution of 2 m for $(x,y)$ and 5° for $(\theta_1, \phi_1, \phi_2)$. The fine grid featured a resolution of 0.5 m for $(x,y)$ and 1° for $(\theta_1, \phi_1, \phi_2)$. For global planning a CAD world model and laser scanner data was used. Furthermore, we successfully planned trajectories for different truck-trailer and truck-semi-trailer combinations.

Position estimation by using natural landmarks (buildings, gates) without direct reference to the target object was tested for distances up to 80 m. The object-oriented navigation used a working range of 30 m in order to guarantee maximum robustness regarding the feature recognition of the target.

VI. CONCLUSION

In this paper we described a navigation system for semi-autonomous and autonomous maneuvering of truck-trailer combinations. This system enables a precise and collision-free approach of target positions accurate to one centimeter. It is suitable for maneuvering, docking and parking of truck-trailer combinations in public and non-public traffic. We used it as an assistance system for backward driving under swap bodies and proved its operability by extensive testing.

The system comprises laser scanner-based scene analysis, multimodal motion planning and laser scanner-based navigation. It supports various use cases like backward approaches, maneuvering with reversal points or long distance approaches and automatically selects the proper variant of the multi-dimensional grid-based planning algorithms. The time needed for planning meets practical requirements. Nevertheless, further optimizations are intended.

It is expected that in near future increasingly more goods are conveyed using truck-trailer combinations or road trains. This will raise the demand for suitable assistance systems. The system presented in this paper offers an appropriate solution. Beyond that, the system is designed for future driverless navigation on customer or factory yards. In order to support multiple heterogeneous vehicle combinations, the system will be extended by cooperative planning methods and a decentralized consistent world model.

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REFERENCES


