Proceedings of the
2007 IEEE Intelligent Vehicles Symposium
Istanbul, Turkey, June 13-15, 2007

Laser Scanner-Based Navigation for Commercial Vehicles

Roland Stahn[1,2], Gerd Heiserich[1] and Andreas Stopp[1]

[1] DaimlerChrysler AG, Group Research, Assistance and Safety Systems, Berlin, Germany
[2] Technical University of Berlin, Computer Vision and Remote Sensing Group

Abstract— **In this paper a novel navigation system for commercial vehicles using laser range sensors is presented, which in particular supports backward driving of trucks and truck-trailer combinations in order to approach target objects or target positions precisely and collision-free. The system can be used in an autonomous or a semi-autonomous manner and is aimed to relieve drivers of the stress of maneuvering tasks and to help them avoid damages. A laser range scanner mounted at the rear of the vehicle measures the pose of all objects in the scene. After target selection the system generates a navigable path from the current position to the final target position. During the approach the system tracks the target object using a hierarchical, multi-phase object model and continuously computes the current vehicle pose. It controls the vehicle along the planned path by generating commands for autonomous steering and speed limitation as well as for braking at the final target position and for collision avoidance. The driver only supervises the approach and confirms vehicle motion by using the throttle pedal. For system evaluation a very challenging application example has been implemented which is backward driving under a swap body for picking it up and interchanging it. The prototypical application has been successfully tested with a truck and a truck-trailer combination under varying environmental conditions. The results prove the system's suitability for further applications.**

I. Introduction

Besides the usual driving task, drivers of commercial vehicles frequently have to perform time-consuming and stressful additional tasks, e.g. maneuvering tasks for loading and unloading trucks and trailers on small customer yards, docking at ramps, coupling trailers, driving backward into small parking lots, interchanging swap bodies, trailers, or semi-trailers on public roads or parking spaces. Our current research is aimed towards developing assistance systems for drivers of commercial vehicles which simplify maneuvering trucks and truck-trailer combinations so that even unexperienced drivers or newcomers are able to accomplish complex tasks precisely and safely without any damage.

Navigation for autonomous vehicles using vision already received wide attention [1]. Approaching objects is usually done by visual servoing using cameras. Laser scanners are used for driver assistance systems (e.g. adaptive cruise control) [2], safety applications (e.g. collision avoidance) [2], [3] and map building [4]. *Mercedes-Benz* trucks are equipped with a growing set of comfortable assistance functions supporting drivers and are even used as automated vehicles for driverless transport on factory yards guided by transponders within the ground.

In the past we successfully did research in the field of autonomous navigation using laser range sensors especially for autonomous systems [5], e.g. mobile robots and AGVs and for assistance systems for vehicles, e.g. autonomous parking for passenger cars [6]. During the last years we have focussed our research on assistance systems for commercial vehicles. In this paper we describe our approach to laser scanner-based recognition methods for target-oriented guidance and collision avoidance and we describe a challenging application example - swap body changing using a truck or a truck-trailer-combination. This task is quite ambitious since we need to position the vehicle exactly below the swap body in order to pick it up (max. tolerance is ± 3 cm for x/y position and 0.3° for alignment to the object). Target object recognition has to work for at least 20 m range.

In Section II the system architecture and the general navigation procedure are outlined. In Sections III, IV and V object recognition, object tracking and motion control are described. In Section VI the individual model adaptation for precise approach and in Section VII the application to truck-trailer combinations is briefly presented. Finally, in Section VIII the results are discussed and summarised.

Fig. 1. Test vehicle during semi-autonomous navigation into a swap body.

II. System Architecture

The vehicle used for development and testing of the described system is an off-the-shelf *Mercedes-Benz Actros 2540* (Fig. 1) with chassis frame for swap body transport. In addition, the vehicle has been equipped by *DaimlerChrysler Truck-Product-Engineering* with a steering actuator for lateral control, and with access to the longitudinal control (speed control, acceleration and braking) via a CAN-Bus interface. At the rear end of the vehicle we have mounted a laser range sensor *SICK LMS 200* (Fig. 2), so that we are able to scan a 180° field of view with an angular resolution of 0.25° behind the vehicle. The maximum range is 80 m.

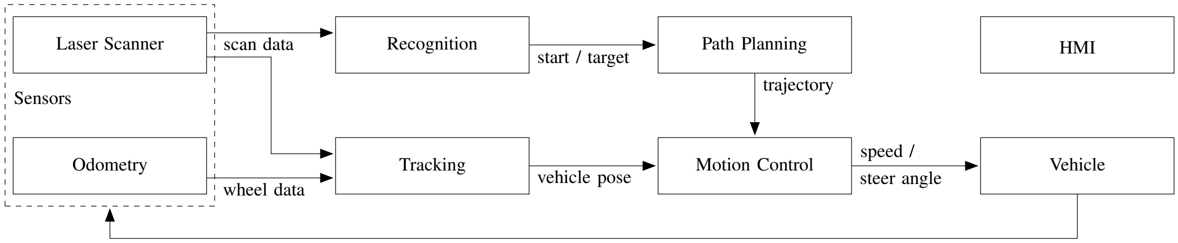

Fig. 3. System architecture

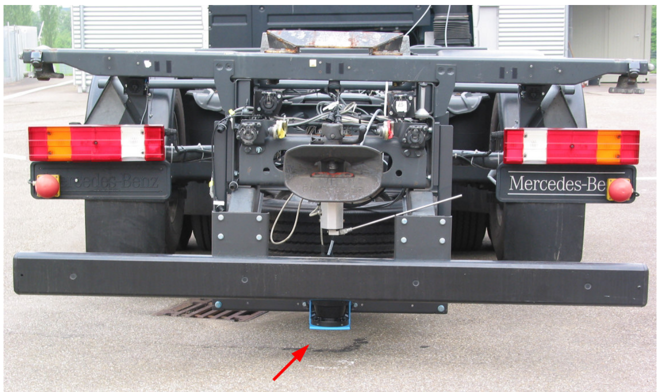

Fig. 2. Location of the laser scanner mounted below the rear bumper of the test vehicle.

The nominal procedure for semi-autonomous vehicle navigation into any target object comprises the following steps:

1) The driver moves the vehicle in front of the target object and starts the navigation system.
2) Scene analysis is performed. The system recognizes all possible target objects within the field of view. The scene, all possible target objects and one highlighted target object preselected by the system are displayed to the driver. Preselection is based on the minimal distance to the vehicle's longitudinal axis.
3) The driver confirms the target selection made by the system or selects another one. The system plans a navigable path to the selected target object, generates the trajectory for the motion controller, and signals readiness for start.
4) The driver starts the navigated motion by pressing the throttle pedal. He/she supervises vehicle motion and confirms the navigated motion by keeping the pedal pressed until the vehicles brakes automatically at the final target position.

The main application mode of the navigation system is the semi-autonomous assistance mode as described above. The driver controls the vehicle's acceleration using throttle and brake pedals while he supervises the whole navigation process continuously. The system controls the steer angle of the truck or tractor and limits the speed by braking if required for path following as well as for collision avoidance and for stopping at the final target position. A further application mode is the full-autonomous mode. Steering and driving are done completely by the navigation system. The driver supervises the motion and can override the system by braking at any time. A future challenging application of the autonomous mode is navigation of commercial vehicles without any driver in non-public areas, e.g. for automated logistic yards. The general idea is to use the navigation system on the one hand as an assistance system supporting the driver for maneuvering in the public space, and on the other hand time-shared as an autonomous navigation system without any driver in the non-public space. This means the driver moves the vehicle through public traffic and leaves the vehicle after arrival at the gate of an automated logistic yard, where the vehicle then moves automatically without driver for loading/unloading.

The modular system architecture of the navigation system is shown in Fig. 3. The architecture contains an inner and an outer control loop. The outer control loop is used during initial phase. The laser scanner delivers the sensor data of the initial scene. The *Recognition* module classifies all possible target objects. After target selection the *Path Planning* module generates a navigable trajectory to the final target position using geometric vehicle models and multi-dimensional grid planning methods. These will be described in detail in a separate paper.

The inner control loop consists of the modules *Laser Scanner*, *Odometry*, *Tracking* and *Motion Control*. It is used for the complete approaching process. Laser scanner and odometry provide the required *sensor* data. The system continuously calculates the current vehicle pose relative to the target object. The motion control module computes the current deviation from the planned values defined by the trajectory and generates new control outputs, steer angle and speed, for the vehicle's actuators.

The *HMI* has been designed for starting and supervising the system. During target selection the display shows a bird view of the scene using laser range data and artificial model data of the recognized objects. Fig. 4 shows an example scene with two different swap bodies (orange). The selected target is marked green. During the approach the planned path and the current vehicle pose are displayed. In addition the HMI generates acoustic signals to the driver if the system decides to brake, in case of emerging obstacles or at the final target position.

III. Feature-Based Object Recognition

In this section we describe the feature-based object recognition and vehicle self localization using range data obtained

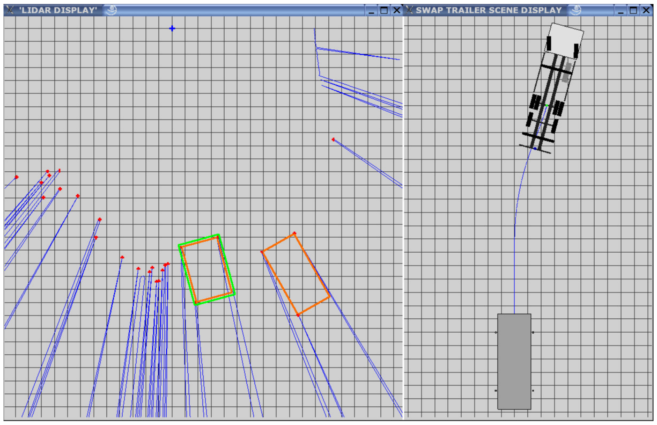

Fig. 4. Details of the HMI. The left window shows raw laser range data (blue), the sensor origin (blue cross), extracted features (red crosses), recognized objects (orange) and the selected target (green). The right window shows the vehicle pose relative to the target and the planned path (blue). The resolution of the drawn grid is 1 m.

by a fix mounted *SICK* 2D-laser scanner. For cost reasons with regard to a final product, we deliberately did not consider 3D object recognition-based on a tilting sensor and chose to focus on 2D recognition only. In this context, 2D means depth information within a single horizontal plane. Object recognition is done using a hierarchical object model. In a first step elementary features (jump edges, line segments) are extracted from the laser scan. In a second step these features are merged into characteristic groups. Finally individual objects are identified. In each step the required free space defined for the respective features is verified.

In case of a standardized swap body, the four fold-out support legs are the characteristic set of features of the target object. A single leg has a quadratic footprint with 10 cm edge length. Due to the divergence of the laser sensor spot, objects of this size are detected reliably for up to 30 m only. Potential legs are identified by the jump edges left and right of the leg within the scan. Depending on the distance to the laser sensor, a single leg receives between 1 and 50+ hits from the laser. Therefore we implemented a multi-level leg model for estimating the position of each leg. For distances of more than 6 m, only the maximum size (30 cm) is checked. Otherwise both a minimum (5 cm) and a maximum (20 cm) size are verified. If a leg receives more than 8 hits, a detailed ICP[1] model is used additionally to improve the position estimation. Thus measurement precision increases during approach of the target swap body.

After identifying all potential legs, these are tested versus a hierarchical object model (see Fig. 5): In a first step we search for valid pairs of support legs out of the set of identified legs. For classification as a valid pair of legs, the distance between the legs of the pair has to be about $a_{st} = 2.8\,\mathrm{m} \pm 0.2\,\mathrm{m}$. The quite large tolerance has to be allowed due to the limited angular resolution of the laser scanner. In a second step the so-called free space below the

[1]The ICP-algorithm (*iterative closest point*) is an iterative method for matching two point clouds [7].

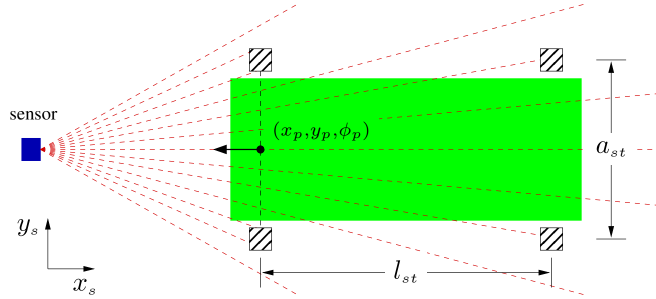

Fig. 5. 2D-model of a swap body with individual object features. The area marked green represents free space.

swap body is checked. Only if a defined rectangular area in-between and behind the pair of support legs is completely clear of any obstacles, the object is identified as approachable swap body (since this space is needed by the vehicle to drive below the swap body). For each identified pair its pose (x_p, y_p, ϕ_p) is calculated. If at least one additional support leg is visible behind the front pair of a swap body, we are able to derive its type[2]from the distance l_{st} between front and rear pair of support legs. Common types are C715 ($l_{st} = 4.35\,\mathrm{m}$) and C745 ($l_{st} = 5.52\,\mathrm{m}$). The type of the target affects the final docking position, where the vehicle will be stopped.

IV. Multi-Phase Object Tracking

For scene analysis all potential target objects within a laser scan are recognized. During the approach we need to track the selected target object and estimate the vehicle pose $(x_{tcp}, y_{tcp}, \phi_{tcp})$ relative to the target out of 2D laser range data. This pose is then submitted to the motion control module. Path planning and object tracking are done within a target-object centered coordinate system. This way, inaccuracies during pose estimation lead to (virtual) path deviations of the vehicle only. These deviations are handled by the motion controller.

For tracking we are using the hierarchical object model introduced in the previous section. Due to the variation of the visible features of the target object during the approach, we developed a multi-phase tracking algorithm. It uses different sets of model features depending on the vehicle's distance from the target.

In case of swap bodies, at the beginning of the approach only the front pair of support legs is always visible. The rear pair might be hidden by the front pair or out of sensor range. During the approach both pairs become visible, until the vehicle starts underriding the swap body. Since the laser scanner mounted at the rear end of the vehicle has a limited field of view of 180° directed backwards, first the front pair and later even the rear pair disappear from sensor's sight. To cover the final distance to the target position, the system uses vehicle odometry data only. We call this *blind approach*. Figure 6 shows the four phases used during the approach of a swap body. Phase switching is done depending

[2]The European Norm EN 284 defines types of swap bodies differing in form and size [8].

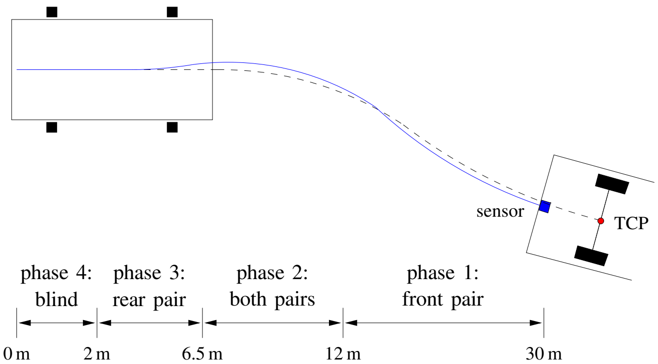

Fig. 6. Phases in object recognition during approach of the target object.

on the distance to the target. In order to avoid oscillations between phases at phase borders a hysteresis behaviour is implemented by choosing different limits for switching in and out of a specific phase. The ability to switch back to an earlier phase is used in case maneuvering back and forth has to be performed due to limited space in front of the target object.

In phase 2 the vehicle pose is calculated from a weighted mean value of both pairs. To prevent discontinuities on entering this phase, we implemented a linear cross fading from the front pair towards the rear pair over the whole phase. During blind approach we use vehicle odometry data for pose calculation. This implies increasing estimation error with covered distance. For improved odometry precision we perform a recognition-based calibration of odometry data within phase 3. Assuming the odometry error is linearly dependent on the covered distance, we calculate a correction factor κ by comparing laser data with odometry data. This factor is applied to the odometry data during blind approach.

Measurement precision of the SICK laser scanner is about ± 1 cm [9]. Therefore the position of a pair of support legs is estimated with ± 1 cm error. The pair's orientation is calculated from the position of both legs, standing 2.5 m apart. Thus the orientation error is about $\pm 0.5\,°$. Hence, calculating the vehicle pose relative to a pair of support legs is more exact in longitudinal direction than in lateral direction, relating to vehicle heading, and estimation errors increase with distance to the target. Practical experiments showed that the lateral position estimation error exceeds the limits for a precise motion control. Adding filtering to pose estimation improved measurement quality significantly.

For filtering we use a Kalman filter that merges laser scanner-based measurements with odometry data. Along with the vehicle pose estimation, the filter provides a covariance matrix describing the uncertainty of its estimation. In case the target object is not found within the current laser scan, tracking is still continued - but the standard deviation σ of the estimation rises. This can be utilized for error detection by validation against an upper limit σ_{max}. If this limit is exceeded, all associated pose estimations of the object tracking module are marked as 'invalid'. Furthermore, standard deviation is used as confidence interval for pose estimation by the motion control module.

Synchronously to object tracking, the motion path is monitored by a collision detection algorithm. Potential obstacles are identified from 2D sensor data. In case of imminent collision, a warning signal is issued and the vehicle is slowed down or even stopped if necessary. This still works while underriding the target swap body. The approach is continued as soon as the obstacle disappears (e.g. moving obstacle).

V. Motion Control

Motion control is implemented through a multimodal controller that models the vehicle as mass point moving on a circular path [10]. It applies a guiding force composed of a lateral part (resulting from path curvature and lateral deviation) and a longitudinal part (correcting orientation deviation). From this force a new set value for the vehicle's steer angle is computed. Path deviation is calculated by comparing the current vehicle pose provided by the object tracking module with the set point pose. The latter is determined on the preplanned approach path, which is composed of circular arcs. The deviation for each coordinate of the current vehicle pose is reduced by its respective confidence interval, in order to avoid oscillations caused by sensor noise.

A new set value for the vehicle's speed is calculated from the current path deviation, the path curvature, an in-path speed limitation and the vehicle's steer angle. It furthermore depends on the kinematic model of the vehicle. For example, the maximum angular velocity of the steering actuator limits the overall speed of movement, since the time needed to actuate a new steer angle leads to path deviation depending on vehicle speed. In semi-autonomous mode the vehicle speed is limited to the calculated maximum value the driver is not able to exceed. In full-autonomous mode the vehicle always drives at maximum feasible speed.

Control performance is affected by several controller parameters, which are varied based on sensor data. For example, path deviation is corrected more slowly if the vehicle is still far away from the target object. On the other hand, maximum precision is enforced near the target. In case the path deviation exceeds path dependent limits, the vehicle is stopped. This way the motion controller dynamically monitors the complete approach. The motion control rate is limited by the data rate of the laser scanner of 18.75 Hz (at 0.25 ° angular resolution). The motion controller was tested at speeds up to 2 m/s.

VI. Individual Model Adaption

Developing an assistance system for practical use means having the system fulfill additional demands. Due to damages or wear out, real swap bodies not necessarily comply with the ideal object model introduced in Section III. Practical experience shows that particularly the positions of the support legs do not always represent the corners of a rectangle (see Fig. 7). Such an irregularity is not properly compensated by the linear cross-fade described in Section IV. Hence the vehicle tends towards the perpendicular bisector of the front pair during phase 1, and in phase 3 towards that of the rear

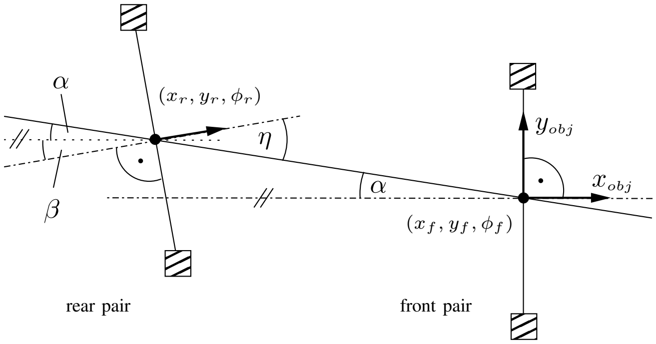

Fig. 7. Calculation model for the offset angle between the front and the rear pair of support legs.

pair. This is not appropriate. The desired behaviour is to drive along the real longitudinal axis of the swap body throughout the whole process. This axis is approximately defined by the respective center of the front and the rear pair of support legs. It is not necessarily perpendicular to the lines connecting the legs of each pair though. The angular offset η of the rear pair is calculated as follows:

$$\eta = \alpha + \beta = \arctan \frac{({}^{obj}y_r)}{-({}^{obj}x_r)} + ({}^{obj}\varphi_r)$$

To achieve the desired behaviour, we adapt the generic object model to the specific target object. This is done by measuring the real stance of both pairs and calculating position and angular offset of the rear pair relating to the front pair. These offsets are included into the estimation of the vehicle pose during the final part of the approach - in particular while only the rear pair is still visible. This model adaption is performed for the respective target object during every individual approach.

VII. Extension to Truck-Trailer Combinations

Backward driving often has to be performed with truck-trailer combinations. Therefore, we extended our system to support trailers as well. In this case a laser range sensor is mounted at the rear end of the trailer. Fig. 8 shows an example of a truck-trailer combination docking into a swap body. Motion planning and motion control now refer to the TCP of the trailer. The motion controller uses an underlying reversing controller developed by *DaimlerChrysler Truck-Product-Engineering* in a former project. It stabilizes the backward motion of the truck-and-trailer combination to the desired current radius set-point by controlling the steer angle of the truck (see Fig. 9). Inputs for the reversing controller are trailer angle and towbar angle. The trailer adds further constraints to the motion control model. The reversing controller allows to directly control the trailer wheel angle - but it is not possible to turn the trailer wheel on the spot, since truck movement is required for any change of the trailer angles. This is considered during motion planning by allowing only slow changes to the trajectory curvature. The motion controller compensates for this behavior by incorporating a delay distance into wheel angle computation.

Fig. 8. Truck-trailer combination. The laser scanner is mounted below the rear bumper of the trailer.

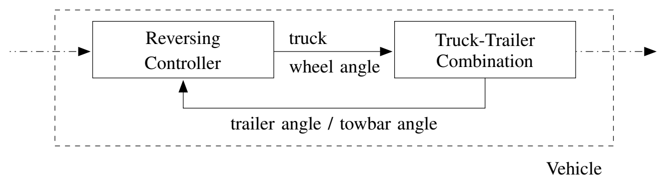

Fig. 9. Vehicle block for truck-trailer combinations showing the integrated backward driving control loop.

For backward driving of truck-trailer combinations our navigation system uses a geometric model comprised of a model of the kinematic chain and geometric outline data of the complete vehicle for planning a navigable trajectory to the target. Configuration data can easily be exchanged for changing vehicle configurations, for maneuvering with or without a trailer or for changing the trailer. We are able to apply the system to various vehicle combinations: truck-trailer, tractor/semi-trailer and so-called GigaLiner (tractor/semi-trailer plus trailer or truck plus trailer/semi-trailer).

VIII. Results

We demonstrated the functional capabilities of our system using a *Mercedes-Benz Actros 2540* truck with and without a trailer in semi-autonomous mode. It operates reliably with different EN 284 swap bodies under various settings.

The proposed multi-phase object tracking delivers accurate pose estimation of vehicle and target object. Increasing precision during approach allows precise motion control of the vehicle accurate to a centimeter in front of the target object. On nearly plain terrain object recognition operates for distances up to 30 m between vehicle tail and target object. Docking into swap bodies was performed with a lateral precision of ± 1 cm, a longitudinal precision of ± 3 cm and an orientation error as low as $\pm 0.2°$ at the target position. These measurements meet the requirements for approaching swap bodies and are achieved with high quality and repeat accuracy. A typical approach of a swap body from a distance of about 20 m requires less than 60 seconds. The average speed along the traveled distance of 30 m is 0.5 m/s. The maximum speed is currently limited to 1 m/s. The sensor's

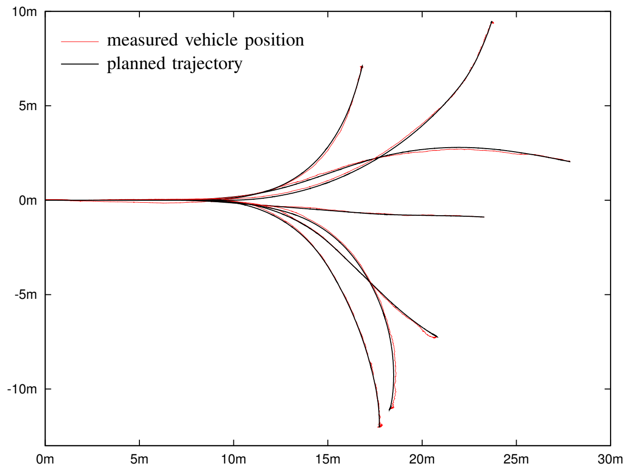

Fig. 10. Logged data from some test approaches to a real swap body with planned trajectories (black) and vehicle poses calculated from laser range data (red). The origin of the coordinate system is in the middle of the front pair of support legs.

$180\,^{\circ}$ field of view allows to start even from rectangular positions of the vehicle in relation to the target. Fig. 10 shows some exemplary approaches.

Advantages of laser scanners, when compared with other types of sensors, include their high precision and independence of prevailing ambient conditions - indoor and outdoor. This is especially impressive when operating at night, where no additional illumination is needed. In general there are no measurable effects of transition between day and night, shadows or sunshine back-light on the system's performance. Neither was there any malfunction due to surface properties or color of the target objects. A precise approach was always possible - even for dirt covered targets. The only exception are objects with infrared absorbing or reflecting coatings that cannot be detected by a lidar-based sensor. This does not affect suitability for daily use though, as these coatings are unusual or rather easily avoided. Moreover, the system works under changing environmental conditions, e.g. rain and snow. It works fail safe - defects or dirt on the sensor will be recognized. Altogether, this proves the road capability of the laser scanner-based navigation system proposed.

Using a fixed mounted laser scanner meant no restriction for the described application with swap bodies. The sensor plane was aimed at half the height of the support legs of a swap body. This way even variations of the scan plane due to ground unevenness posed no problem. Only with considerable ground unevenness the tracked target may leave the sensor's field of view. This problem can be addressed using a multi-layer laser scanner [11] or an actuated laser sensor. The latter would allow more complex applications of laser scanner-based navigation.

IX. Conclusion

In this paper we have described the prototype of our laser scanner-based navigation for maneuvering commercial vehicles, in particular for backward driving of trucks and truck-trailer combinations to approach target objects and target positions precisely and safely. We have applied the system to pick up swap bodies using a *Mercedes-Benz* truck either with or without trailer. For outdoor object recognition and tracking with a SICK laser range scanner we have implemented a hierarchical object model and a multi-phase tracking algorithm. Variances of real objects are handled by an individual model adaption. A collision avoidance function monitors the whole approach to the target position. We have successfully tested the system in various scenarios and under various environmental conditions. The navigation system works very robustly all-weather, day and night.

By accomplishing the demanding swap body application, we have proven the system's high potential for future applications in the field of safe semi-autonomous and autonomous vehicle navigation using laser range sensors. This includes support for maneuvering tasks i.e. backward driving, moving into parking lots, docking at loading bays/ramps, coupling trailers and semi-trailers, navigation on virtual tracks and further navigational functions. They can be applied to trucks and truck-trailer combinations. Expected benefits for carriers and their customers are cost savings by damage prevention and in particular higher personnel flexibility. Benefits for truckers are mainly collision avoidance, time saving, reduced stress and thereby higher safety in general.

Acknowledgment

This work has been partly supported by *DaimlerChrysler Truck-Product-Engineering*.

References

[1] G. N. DeSouza and A. C. Kak, "Vision for mobile robot navigation: A survey," in *IEEE Transactions on Pattern Analysis and Machine Intelligence*, February 2002, vol. 24, no. 2, pp. 237–267.

[2] K. Fuerstenberg and R. Schulz, "Laserscanner for driver assistance," in *Proceedings of WIT 2006, 3rd International Workshop on Intelligent Transportation, Hamburg*, March 2006.

[3] R. Aufrere, J. Gowdy, C. Mertz, C. Thorpe, C.-C. Wang, and T. Yata, "Perception for collision avoidance and autonomous driving," *Mechatronics*, vol. 13, no. 10, pp. 1149–1161, December 2003.

[4] S. Thrun *et al.*, "Stanley: The robot that won the DARPA Grand Challenge," *Journal of Robotic Systems*, vol. 23, no. 9, pp. 661–692, 2006.

[5] A. Stopp and L. Kuettner, "A unified approach for fast recognition, learning and interpretation of the environment by an autonomous mobile robot," in *Proceedings on "Intelligent Systems and Semiotic - A Learning Perspective"*, Gaithersburg, Maryland, USA, 1997.

[6] A. Schanz, A. Spieker, and K.-D. Kuhnert, "Towards automatic parking," in *Proceedings of International Conference on Robotics, Vision and Parallel Processing 2003*, Penang, Malaysia, January 2003, pp. 789–794.

[7] T. Jost, "Fast geometric matching for shape registration," Ph.D. dissertation, University Neuchâtel, December 2002.

[8] "EN 284 - Swap bodies. Swap bodies of class C. Dimensions and general requirements." European Committee for Standardization (CEN), June 1992.

[9] C. Ye and J. Borenstein, "Characterization of a 2-D laser scanner for mobile robot obstacle negotiation," in *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, Washington DC, USA, May 2002, pp. 2512–2518.

[10] R. Stahn, "Multimodal sensor-based motion controller for mobile robots," Master's thesis, TU Berlin, July 2002, [German].

[11] IBEO Automobile Sensor GmbH. automotive laser scanner ALASCA. [Online]. Available: http://www.alasca.info