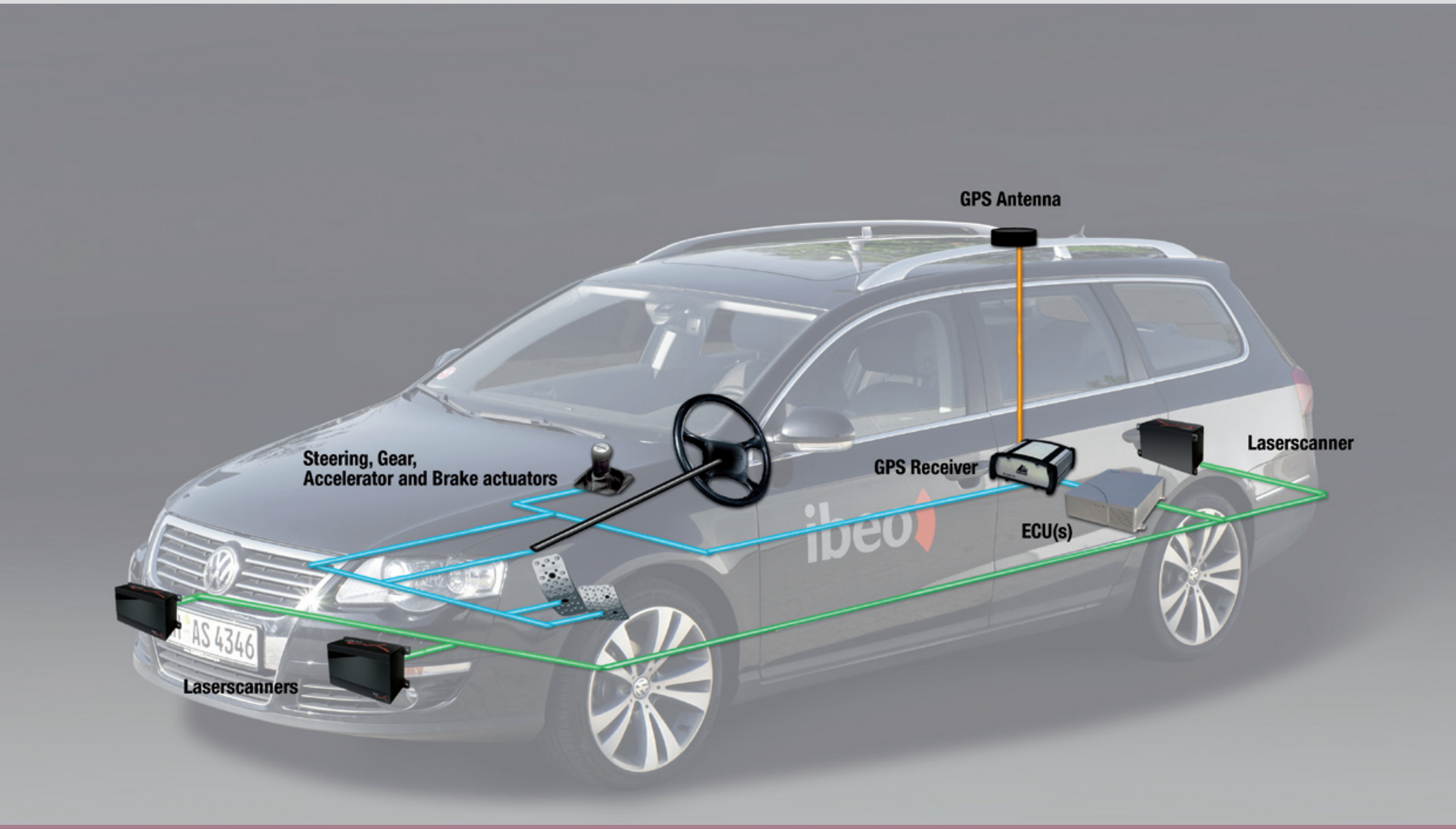

Autonomous Driving
Object Tracking and Path Planning for the Team-Lux Robot Vehicle

The Team-Lux, a company co-operation between Ibeo and Sick, took part at the competition race "Darpa Urban Challenge 2007" for the first time. It is an interesting way of integrating both sensors and software into the driver assistance system for autonomous driving. The solution for the competition is the robot vehicle Lux.

1 Introduction

In the "Darpa Urban Challenge", which is being held for the third time since 2004, eleven teams took up with completely driverless vehicles in the final of November 3, 2007. The Team-Lux, Woodstock, Maryland (USA), made it into the semi-final. What makes this race so special is that all of the competing vehicles must master a 60-mile course entirely autonomously in less than six hours, with neither a driver nor remote control.

For the first time, the 2007 race was held in a US city, under real traffic conditions. The "Darpa Urban Challenge" is a prize competition for driverless cars, sponsored by the Defense Advanced Research Projects Agency (Darpa), the central research organization of the United States Department of Defense.

2 Laser Scanner Technology

The Team-Lux vehicle robot, **Figure 1**, is a VW Passat B6 model equipped with a 2-l TDI engine and 103 kW (138 bhp). One of the internal modifications is that three laser scanners are its primary means of environmental perception, **Figure 2**. One of the team's goals is to demonstrate that autonomous driving is possible with laser scanners alone.

In order to detect obstacles as well as lane markings, road boundaries or other vehicles, three high-resolution laser scanners are integrated into the body of the car, giving the car 360° vision, **Figure 3**. Two of them are integrated into the front bumper, which enables a field of vision of up to 220°. For observation of the area behind the vehicle, a third laser scanner is integrated at the rear with a field of vision of about 150°. Additionally, for autonomous control, the car was retrofitted with electronic-steering, electronic-brake and electronic-gearshift actuators. All sensors and actuators are fully integrated into the vehicle, which is a huge safety advantage because no sharp or hard edges of the sensor protrude from the vehicle contours.

Precise ego-localisation is one of the key issues for autonomous driving. The vehicle uses three senses for localisation:

- Laser scanner measurement data: data from the laser scanners are used to determine the local ego-movement of the vehicle. Stationary objects are used to calculate Δx, Δy and $\Delta\Psi$, **Figure 4**.
- GPS data: an RTK GPS system is used for precise global positioning.
- Vehicle data: data received from the vehicle's onboard sensors are processed to determine the local vehicle movement.

For the Darpa Urban Challenge, the Team-Lux has integrated the company's

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Figure 1: Frontal view of the Team-Lux robot vehicle for the Darpa Urban Challenge

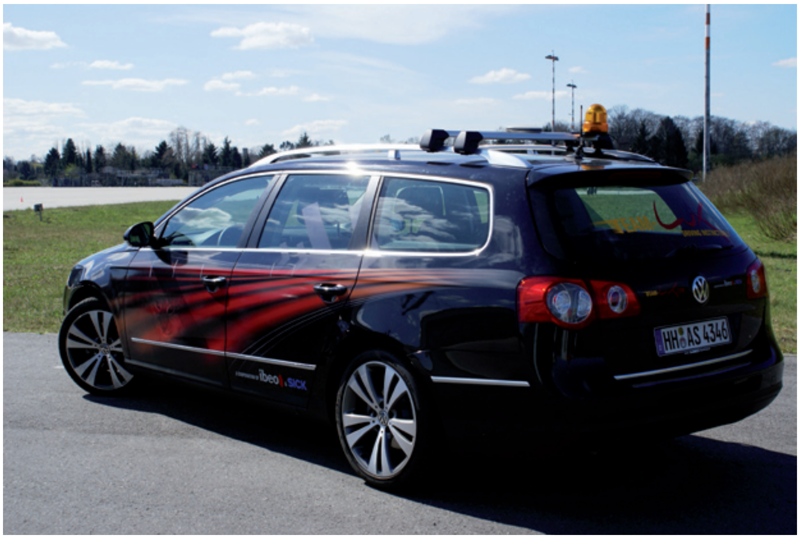

Figure 2: Side view of the Team-Lux robot vehicle

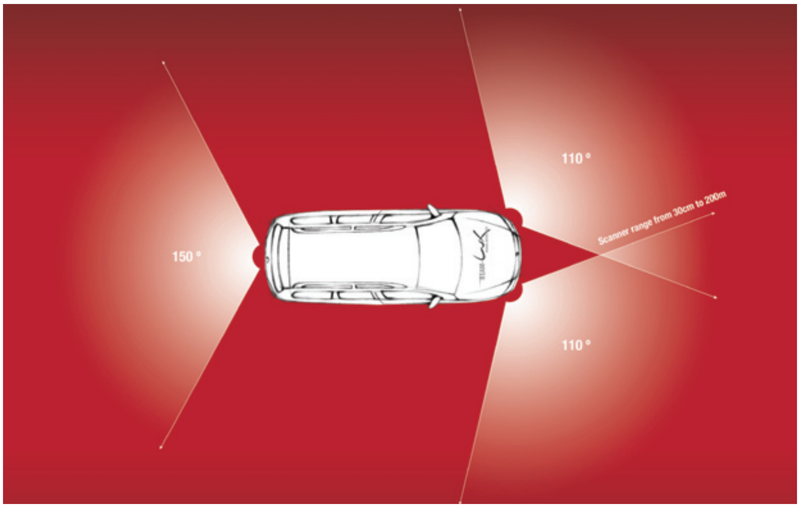

Figure 3: Range and wide horizontal angle of the Ibeo laser scanner

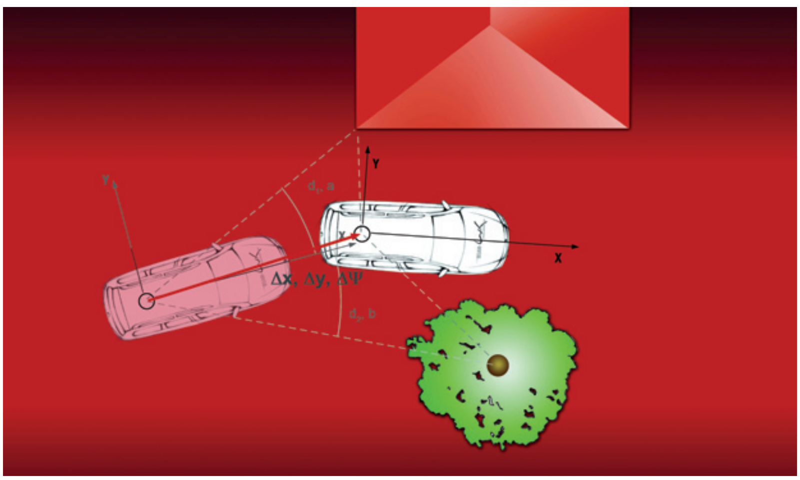

Figure 4: Data from the laser scanners are used to determine the local ego-movement of the vehicle; stationary objects are used to calculate Δx, Δy and ΔΨ

prototype of the latest generation of laser scanners, **Figure 5**, into the car. It is a further development of the current laser scanner and uses the time-of-flight measurement principle with near-infrared light. The reliable measurement range is about 200 m, although vehicles and other well-reflecting objects are typically detected well beyond this distance. In total, a scan may have 15,520 individual distances, so called scan points.

Each laser scanner simultaneously scans in four scan planes, as shown in **Figure 6**. Using the data from all scan planes, both vehicle pitching and road slopes can be compensated for by the processing software without ever losing contact with tracked objects. Each scanner is mounted behind a protective plastic cover, on which dirt, dust or snow may gather during operation. In this case, Multi-Echo technology allows the sensor to work even if the cover is very dirty. The laser scanners measure up to four consecutive distances with every single laser shot. This technology allows the sensor to measure through rain, snow and fog. Every single scan point is analysed by measurement data preprocessing algorithms. As a result, each scan point is marked according to its source. The following types of sources can be classified:

- objects
- lane markings
- ground
- dirt
- rain and snow.

3 Processing the Scan Data

The processing of the scan data is handled by different stages. The signal processing system extracts the scan points of the different sources from the scan before the high-level functions such as object tracking and scanner applications process the data. During signal processing, the scan data is split into three groups: objects, ground (including lane markings) and noise (including rain and snow). The following processing steps then can decide which of the data to use for their task.

Although the car's laser scanner has built-in processing capabilities, all Darpa Urban Challenge application processing is performed in two electronic control units (ECUs) for easier programming. This information must be closely synchronized with the lane and object data generated. After processing, all generated high-level information is sent to the second ECU for further processing. For the Challenge, the ECUs were upgraded with 1.8 GHz processors, but otherwise remained unchanged. In a next processing step, clusters of scan data are isolated and grouped together into so-called segments. Each of these segments belongs to an object, and no segment contains scan data from more than one object. Each segment has basic properties such as size and position. Based on the segment data, movement information is generated in the following step of object tracking.

4 Object Tracking

Object tracking is the heart of the scan data processing. It takes the segments as input signals and generates the simulated objects. Objects are virtual entities that are tracked from scan to scan. Typically, one scan object corresponds to one "real" object, such as cars, pedestrians or signposts. By tracking the objects from scan to scan, dynamic parameters such as velocity and acceleration can be calculated for each object. These parameters become more stable the longer the object is tracked.

By itself, the object tracking can only determine the relative object movement. There are several different processing cores for object tracking, for example centre of gravity tracking, contour tracking or direct tracking, which is a relatively complex algorithm. For the Darpa Urban Challenge 2007, centre of gravity tracking was chosen because it is a robust and reliable source of object data that requires little processing power.

4.1 Classification of the Tracked Object

In order to classify the tracked object, the absolute object velocity is an important criterion. As the scan data has been converted into high-level object information during the object tracking process, object parameters such as position and velocity are now known for further processing. The classification algorithm uses multiple feature extractors and a weighing system to sort all the objects into such categories as cars, bikes, pedestrians, "unknown_small" or "unknown_big".

The two classes "unknown_small" and "unknown_big" collect all of the objects that do not fit into any other class. A classic example of a big unknown object is a wall, while a pole would be a small unknown object. During the competition, all objects are expected to be stationary, except the "cars" class that may be moving or non-moving.

The generated high-level data now have to be processed further to create "system behaviour" (lane detection, route processing and localization). In the competition, it is the control of the vehicle robot that is performing the required missions. The ability to localize the lane and keep the vehicle in its lane is one of the important requirements for the competition. Therefore, the Team-Lux uses a special lane detection algorithm.

4.2 Lane Detection

Lane detection needs three different information sources:
– lane markings on the ground,
– ground data,
– objects on and beside the road.

In the first step, each of these sources generates identical data in the form of the position of the vehicle in the lane. Then, a fusion algorithm merges this data into the final position information that is used for vehicle control. The lane fusion uses the output of all three lane detection algorithms and combines them into one set of consistent lane boundaries, which gives an estimation of the road curvature ahead. Next, the route processing sub-system handles all mission issues, from reading the Route Network Definition File (RNDF) and Mission Data File (MDF) to creating the driving route. The first step is to read and parse the RNDF. A navigation map is created from the RNDF information and then transformed from the given global latitude/longitude coordinates into a local x/y coordinate system. This map is then extended by analysing the road network. Right-of-way rules are created at intersections and implicit waypoint connections are made.

After RNDF investigation, the MDF is read and parsed. The MDF is split in two sections. The first section creates a mission route by stating the sequence of mission checkpoints that have to be reached. The second section gives speed limits – both upper and lower – for road segments from the RNDF. These speed limits are added to the navigation map. After the mission is known, a mission route for the robot vehicle can be generated. This is done by finding the shortest connections between the required checkpoints, considering both distance and speed limits. As no distance is guaranteed between any two waypoints, subsequent waypoints may be far away from each other. In this case, artificial waypoints are created and inserted between the far-away waypoints, thus closing the gap.

In the case of an impassable connection, the vehicle control sub-system reports that the desired next waypoint is not reachable. The navigation system then marks the section as temporarily unavailable, and re-plans the route. Assuming that a route has been found, the vehicle then proceeds on the new course.

5 Path Planning

All information gathered by the onboard sensors is collected in the map of the surroundings. This map is a list of objects and features that covers the area around the vehicle. Inputs to this map are, for example, objects or lane markings. Unlike the navigation map, the map of the surroundings is saved in the coordinate system of the vehicle. This allows easy path planning.

As soon as the navigation has worked out a mission route for the robot vehicle, it is the job of the path planning to find a local path to the next waypoint. The first step of the path planner is to convert the artificial navigation waypoints into a drivable path. This is done by filling up possible gaps, as RNDF waypoints may be far apart from each other, ensuring that the gap between subsequent waypoints is no more than 5 m. The path

Figure 5: Prototype of the Ibeo laser scanner

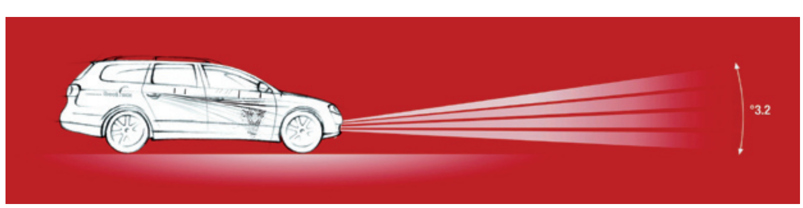

Figure 6: The Ibeo laser scanner scans in four planes

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created now has to be projected onto the real road. To do this, the path planner uses the input from the lane detection as well as the positioning information.

Several situations that require deviant behaviour exist in the race. The most prominent one is a simple standing obstacle. In this case, the path is adapted to make the vehicle pass the obstacle in accordance with the rules of the race, thus keeping safe distances and respecting oncoming traffic in the passing lane. If the obstacle blocks the path completely and no passing manoeuvre is possible, the path planning reports a road block to the navigation system and requests a new mission route. Typically, the vehicle will need to perform a U-turn to continue the mission. Once the path is known, several follow-up modules watch for situations that require changes in the vehicle speed. A typical example is turning at an intersection. Here, the path on the road is unaltered, but the vehicle may or may not be required to stop for oncoming traffic. The same applies to four-way stops and following other traffic.

After the path planning has found the optimum route, the vehicle control module moves the car along the path. The input is a list of "trajectory points". Each of these points contains its position in vehicle coordinates, a set velocity and additional information, for example for indicator activation during turns or delay times. The controller now controls the actuators – steering, brake and accelerator – to optimally move along the path.

6 Summary

The Team-Lux competed in the Darpa Urban Challenge 2007 to demonstrate that laser sensors for autonomous driving will soon be included into safety systems and advanced driver assistance systems of series-production vehicles. One of the team's goals is to demonstrate that autonomous driving in the normal traffic is possible with laser scanners alone.

The featured laser scanner applications, such as automatic emergency braking, pedestrian protection, ACC stop and go, lane departure warning or traffic jam assistant, make driving a car more comfortable and safer at the same time. Ibeo will go into series production with the integrated Ibeo Lux sensor from autumn 2008 on. ■

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