Autonomously driving trains on open tracks—concepts, system architecture and implementation aspects

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Abstract

This paper describes a cyber-physical system that we called autoBAHN[1] as well as some economic and legal aspects for the realization of the vision of a driverless train operating on openly accessible existing railroads, particularly regional branch lines. Existing autonomous trains, for example in use on airports, do not need obstacle recognition because they operate on closed tracks that cannot be accessed by humans and have no intersections with roads. The vision is to economically offer a train frequency of ca. 10 minutes on regional branch lines. This requires more, but smaller trains. As it would not be economically feasible to operate them with human drivers, they need to be autonomous. As it would again not be economically feasible to change the infrastructure (from open to closed tracks), the autonomous trains need to recognize potential obstacles on or near tracks analogous to autonomous cars.

First we describe how train intervals of ca. 10 minutes—comparable to urban public transport systems—can be achieved on single-track railroads. This implies a significantly improved comfort for passengers by dissolving the traditional schedule concept of trains. What kind and degree of changes in infrastructural equipment is necessary was validated with the help of a discrete event simulation. The focus of the paper is on the overall system architecture of the prototypical autonomous train that we have implemented and in particular on obstacle recognition based on a lean yet powerful algorithm for sensor fusion. Finally, the current legislation in German speaking countries is surveyed for the assessment of whether an autonomously operating railway system can become reality in the future.

1 Motivation and related work

[1] *auto* for autonomous; *BAHN* is the German word for rail(road)

What we have called the autoBAHN system aims at offering a tramway frequency of autonomously driving vehicles on freely accessible and usually single-lane regional railway tracks. The autoBAHN system comprises obstacle recognition and train control by means of sensors, actuators, and radio communication as part of a complex cyber-physical system which has to fulfill the strict quality standards for accreditation of railway systems according to CENELEC.

The autoBAHN system should make regional railways attractive again. The train frequency has a significant influence on the acceptance of public transport. With the visionary autoBAHN system, a train arriving every ca. 10 minutes can be realized and at the same time economic parameters of operating regional railways can even be improved. Increasing the train frequency requires more, but smaller vehicles. The additional costs for drivers would not be economically feasible. Therefore, the autoBAHN system has to be operated autonomously. Existing autonomously operated rail systems such as on airports (so called "people mover") or subways require the physical fencing in of railroads as no obstacle detection is used. This physical fencing would again not be economically viable for regional lines. Thus, the autoBAHN system uses an obstacle recognition to avoid the fencing in of the tracks or similarly effective measures for closing the tracks.

Overview of other autonomous driving systems

The track-guided rail transport system offers important advantages for automation because a train cannot leave the track in regular operation. A road vehicle does not only have freedom of movement within the travel path, but it can leave it with little change in the tracking or due to road damages, inconsistent roadway markings and many other irregularities. In other words, its environment is less homogeneously defined than that of railroads. These features suggest that the automation of railways is more straight-forward compared to road traffic. Since there exist already car driver assistance systems for track and distance control, braking assistence, blind spot monitoring, night vision support, traction control, automatic parking and other tasks, and research prototypes of fully autonomous cars [THRUN2008], efforts to automate the railway traffic are overdue.

There have already been various initiatives aiming at the automation of passenger- and cargo rail traffic. For cargo traffic the following projects are a selection of representative research efforts in Germany in that direction: the „Cargomover" system from Siemens (see [CARGOMOVER1]), a self organizing cargo traffic system suggested by Prof. Frederich (see [FREDERICH1994] [FREDERICH1997]), the „Selbsttätig signalgeführte Triebfahrzeug" (SST) (see [FREDERICH1996]) and the project „Innovativer Güterwagen" (IGW) of the Deutsche Bahn AG (see [EISENB1997]). But none of them got an approval and became a product. One reason might be that these autonomous trains would have operated in a mixed mode along with regular trains. Mixed type traffic is an additional operational, technical and economical barrier. In Australia, the mining company Rio Tinto, plans to introduce driverless trains for transporting iron ore in 2014 [REF: http://www.riotinto.com/media/5157_21665.asp]. We found no description of its socalled AutoHaul™ system. In particular, it is not published whether AutoHaul™ will use obstacle recognition.

For passenger traffic the *RailCab – Neue Bahntechnik Paderborn* (short RailCab) presented a new concept for the automation of railway traffic. In this concept vehicles for 10-12 passengers should travel on a significantly adapted railway network. Due to the envisioned use of obstacle recognition, which was to our knowledge not implented so far, the fencing in of the track would be unnecessary. The required adaptions stem from the propulsion system, which should be a linear motor. It requires the installation of electromagnets into the rail bed with costs of estimated Euro 2-3 Mio. per kilometer rail track. Furthermore RailCab would utilize a passive switch combined with an active vehicle steering in order to handle the planned maximum speed of 160 km/h, which would require the replacement of all switches on existing tracks. There is a test track on the campus of the University of Paderborn. Activities for the certification of the system for public passenger traffic are not known (see [RAILCAB2008]). We regard RailCab as economically infeasible due to the enormous adaptation costs of existing infrastructure.

To avoid the fate of ending as research prototype and never becoming a product, the autoBAHN system vision (a) focuses on regional lines, because those are typically closed systems with only one connecting point to main lines which allows the avoidance of mixed traffic in the system transformation phase, and (b) tries to harness existing infrastructure.

Altogether, the autoBAHN system (subsequently called autoBAHN) differs from traditional train systems in the following aspects:

	autoBAHN	traditional train
car design	20-30 persons capacity 10-15 m length ca. 10 to weight	50-200 persons capacity 25-100 m length 20-100 to weight
train control	purely IT-based with additional radio transmission, driving in "moving block" control concept	several non-automated systems; train signalling with fixed block distance; electronic block; stationary signals

train location	through GPS and other sensor information	by track bound sensors (e.g. axle counters) or by a human supervision
headway time	6-15 min	20 min – 2 h

Table 1-1: Differences between an autoBAHN and traditional train systems

2 Discrete event simulation of an autoBAHN system for validating its feasibility on single-track railways

As stated above, regional lines are ideally suited for a system change towards autoBAHN as regional lines are typically closed systems. On the other hand, the fact that regional lines are operated on single tracks in most cases represents a challenge: the goal of changing the infrastructure as little as necessary conflicts with the fact that an autoBAHN has to run more but smaller train cars in both directions at the same time, and hopefully due to its increased attractiveness transport more passengers as today's systems. Thus, we accomplished detailed simulations of regional lines transformed to an autoBAHN to find out whether this is feasible at all and to find out a reasonable number of train cars and the minimum number of infrastructure adaptations in the form of additional side tracks forming pass-by zones. The passenger data of existing regional lines form the basis for such simulations. A discrete event simulation was developed in Java to assess the following aspects for representative regional railways:

- number and positioning of additional side tracks
- required vehicle capacity, number of vehicles, vehicle frequency
- speed ranges, waiting times, number of waiting passengers

The results should verify the following hypotheses:

1. For passengers the autoBAHN concept allows the reduction of the sum of waiting- and driving times.
2. The operation of an autonomously driving regional train according to the autoBAHN concept improves its economy.

As some of the parameters are interdependent, we had to formulate more detailed questions such as

- How are passenger waiting times and vehicle driving times affected by a vehicle's capacity, the number of side tracks and the number of vehicles used?
- What is the impact of oncoming traffic on the average driving time depending on the positioning of side tracks?
- How many vehicles are required to guarantee at least the same passenger throughput as in the traditional operation?
- What is the expected mileage increase of vehicles?

To answer the above questions we tested the following different operating concepts:

- continuous traffic with different numbers of vehicles and
- traffic on demand, which means the installation of a vehicle calling mechanism similar to elevators in buildings.

Using the detailed statistical data of passenger frequencies and the track data of a representative regional line operated by Stern&Hafferl between Vorchdorf and Gmunden in Upper Austria, which is 13 km long with 14 stations, and currently requires a total travelling time of 25 minutes, the results were as follows:

Number of vehicles on the track	Interval between vehicle arrivals [min]	Average longest waiting time for passengers [min:sec]	Average waiting time for passengers [min:sec]	Average increase of driving time through oncoming traffic
5	9	23:16	6:41	24,5%
5	10	30:23	7:06	29,1%
6	6	72:10	16:36	93,3%
6	7	49:01	9:34	54,4%
6	8	29:17	5:30	32,0%
6	**9**	**14:21**	**5:08**	**31,2%**
7	6	80:54	22:21	124,0%
7	7	56:41	10:12	68,9%
7	8	29:47	4:11	52,7%
8	6	85:26	20:53	146,9%
9	5	86:08	18:27	154,1%
10	5	101:40	26:41	182,1%

Table 2-1: Simulation results for driving time increases depending on the number of vehicles and the frequency, given a minimal number of pass-by-zones

With a passenger capacity of 30 persons the best results were achieved with 6 vehicles, with a frequency (= time interval between the arrival of vehicles) of 9 minutes.

As the positioning of the additional side tracks obviously has a significant influence on the driving time an adequate solution had to be found. If the autoBAHN would be implemented on the particular regional railway mentioned above, the number of side tracks (= pass-by zones) on the track would have to be increased from currently 2 to 5. Taking this infrastructure change into account, the review of the economic consequences of the autoBAHN system and its comparison with the traditional train concept showed an impressive improvement of the costs coverage parameter from currently 24% of revenues to 35%-61%, depending on the assumption of worst and best cases for the increase of passengers.

The originally expected advantage of an on-demand traffic at times of low demand (nights, weekends) could not be confirmed due to occasionally occurring extra long waiting times for a significant number of passengers, which none of the scheduling algorithms that we tried was able to cope with. The alternative of reducing the number of vehicles and offering continuous traffic turned out to be more efficient, avoiding outliers.

3 autoBAHN requirements, system architecture, train control system and risk analysis

Overall requirements: The overall technical requirements of the autoBAHN system are:

- Obstacle detection according to the CENELEC safety requirements
- Fully automated operation with one supervising person for all trains
- Assurance of passenger safety and passenger security

A detailed list of requirements has been writen up (see [GEBAUER2012]) but that must be considered as work in progress while we move from the proof-of-concept project phase towards certification.

System Architecture: In order to demonstrate the technical feasibility of an autoBAHN[2] we implemented a prototype of one autonomous train vehicle whose operation was supervised by a human driver while driving autonomously. It was integrated in the train control system of a regional railway which runs between Gmunden and Vorchdorf in Upper Austria and which is operated by Stern&Hafferl. To avoid the enormous costs of building a new train, we used a ca. 50 years old train (see the picture on the bottom left in Figure 1) which we could easily adapt by mounting sensors on the front.

[2] This project was supported by the Austrian Klima- and Energiefonds (www.klimafonds.gv.at) with ca. Euro 2 Mio. under project number 825624. The project partners were the University Salzburg, the University of Applied Sciences Wels, the railway operator Stern&Hafferl and Siemens-Austria.

Figure 3-1 shows the coarse-grained components of an autoBAHN. The Brake &Engine Control (BEC) component was provided by Siemens as hook-up on the existing train. The BEC programming interface allows other components to set the speed of the train. The BEC itself interfaces with the drive and the brake system of the train. For example, an electric motor is used to change the actuator setting which controls the speed. The Train Control System (TCS) was designed and implemented by the University of Applied Sciences Wels (see [STADLMANN2010]). The TCS checks whether the train sticks to the constraints how far it is allowed to move according to the commands given by a human operator on a central station. For that purpose the Global Navigation Satellite System (GNSS) GPS and a radio system for communication between the central station and the train are used. The obstacle recognition and the behavior components (shown as one yellow box on the right side of the overview) were designed and implemented by the University of Salzburg. The components communicate via a Controller Area Network (CAN) bus and a 1 GBit/sec TCP/IP Ethernet connection.

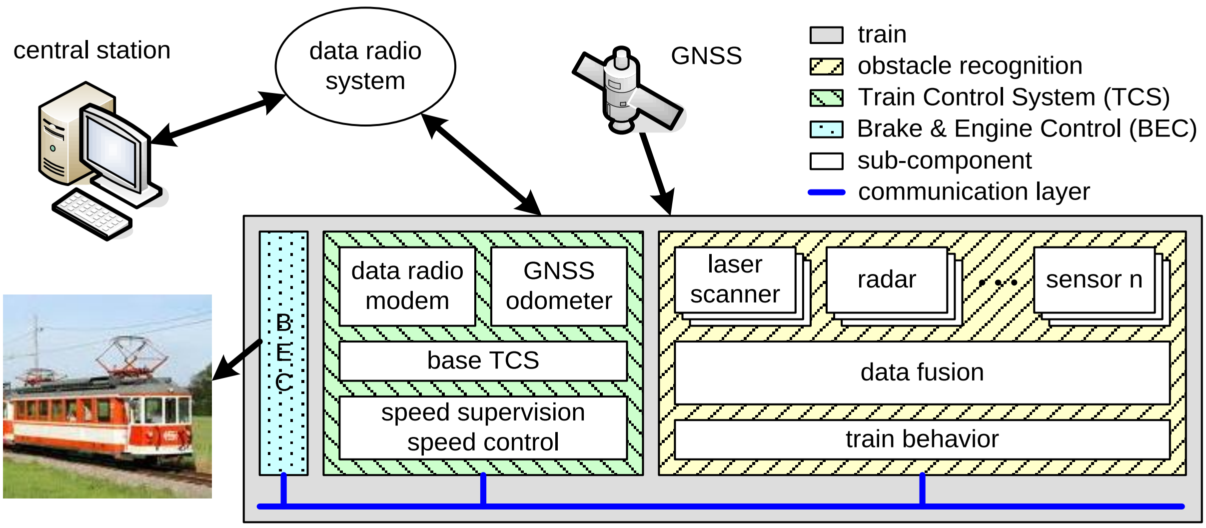

Figure 3-1 Schematic overview of the auto*BAHN* system.

Figure 3-X shows a picture of the hardware rack containing four industry PCs on which the sensor processing tasks, the sensor data fusion component, and the TCS execute. The rack is ca. 1 m x 1m x 40 cm in size and only installed for test rides.

Figure 3-X A fisheye view of the onbooard hardware (except the BEC) for the autoBAHN prototype.

Figure 3-2 shows a more detailed diagram of the autoBAHN system. In particular, it illustrates the plug-in architecture of the obstacle recognition which is explained in detail in the next section. The core design goal of the sensor fusion component is to be extensible to be able to add redundant sensors and to remove sensors dynamically in case of sensor failures.

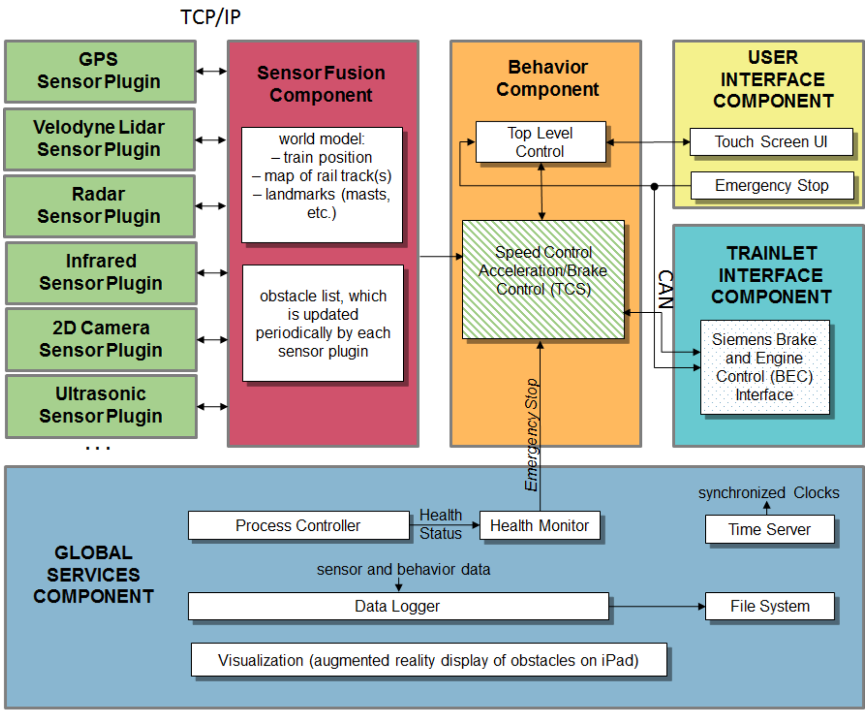

Figure 3-2 Plug-in architecture of auto*BAHN's* obstacle recognition.

The basic idea is that the sensor fusion component keeps a world model based on a detailed map of the track and its landmarks such as masts and sign posts. For mapping the track and its landmarks at a precision of ca. 2-3 centimeters the 3D-laser Riegl VZ-400 [RIEGL2012] was used. If a sensor plug-in reports an obstacle, it needs to be reconfirmed within a certain time interval, ideally by several sensor plug-ins. The behavior component then forwards this obstacle information to the TCS. The TCS calculates the target speed of the train combining the commands from the behavior component, the track line data and the braking curves of the train. The train will then stop in front of the obstacle if possible. As soon as an obstacle is out of the rail clearance the train resumes its regular speed. The long braking distances for rail traffic is a special challenge for both human drivers and the automated version.

Train Control System. The main challenges of the TCS are the timing constraints and the constraints of vehicle behavior in combination with the commands from the behavior component. The safety-relevant communication between the main components is based on a CAN-bus with low reporting cycles and heart beat signals for the supervision of all components. Though the delays of communication and calculation have to be considered for real-time calculations, the most significant timing parameter is the time between the braking command of the TCS and the physical start of braking, that is, the start of deceleration.

The braking curves were calculated according to the definitions of the European Train Control System (ETCS) with an adaption to the needs of a regional branch line including the comparatively low speeds of its operation. The static speed profile is defined in the digital line atlas and the dynamic speed profile is sent via data radio from the central station of the train dispatcher to the autoBAHN train. As the physical conditions of the rails are not known and the worst case delay times have to be considered, the algorithm of the braking curves has to use the most restrictive set of train parameters for safety reasons. On the ca. 50 years old prototype autoBAHN train this leads to a longer travel time and sometimes to unnecessary emergency brakes reducing the convenience of travelling. The algorithm has been implemented as a real-time Ada application. The cycle times of the calculations are approximately 100 ms. The whole functionality has been implemented within an existing train control system which was enhanced to allow autoBAHN test runs in the realm of regular daily operations (see also [GEBAUER2012]). An additional task of the TCS will be the control of level crossings to keep the blocking time as low as possible.

Risk analysis: A basic risk analysis has been accomplished for an autoBAHN. The preliminary results have shown that an autoBAHN on regional lines should be feasible within the given framework for railways. The chosen basic risk acceptance criterion is minimum equal safety. A detailed distribution of tolerable hazard rates and appropriate safety targets to all system components has to be defined as next step.

4 autoBAHN's obstacle recognition plug-in architecture

There are several effective sensors available for the development of an obstacle recognition component. Some sensor types can even exceed human perception: camera tele lenses improve the distance of sight, Radio Detection and Ranging (RADAR) and infrared (IR) cameras can offer advantages at unfavorable weather conditions such as fog, rain or snowfall; and Light Detection and Ranging (LIDAR)- as well as IR-sensors can deliver adequate obstacle recognition results when it is dark.

Compared to human perception the most significant advantage of sensors is its continuous and consistent availability, which avoids the typical attention deficits and wrong assessments of humans. On the other hand, sensors might degrade, stop providing data due to technical problems, or simply get dirty. Redundancy is one strategy to counter these risks, the placement of sensors, in particular cameras, behind the wind shield, another one.

More challenging than the assurance of sufficient physical performance of sensors is the correct, safe and replicable interpretation of sensor data. The advantage of human perception is that the rate of misinterpretation in optical object detection is close to zero. Thus, it is common to use a combination of different sensors for IT-based obstacle recognition. The sensors are based on different physical principles. The safety of interpretation is increased by the fusion of different sensor data (see [DARMS2007, DARMS2009]).

Compared to the development of an obstacle recognition for road vehicles (see [DARPA CHALLENGE]) there are some differences for autonomous trains:

- The higher investment costs for train vehicles and the larger number of passengers allow more sophisticated and thus more expensive sensors.
- The number of scenario-hypotheses is limited due to the absence of other vehicles on the track except on intersections whose positions are known. Thus, the observation of other vehicles can be omitted.
- Reduced degrees of freedom of the vehicle result from the physical linkage to the track. Diverting or passing scenarios cannot happen.
- There exist position dependent, well known and stable points of interest (railway crossings, station arrivals, ...). Potential dangers can be classified according to the position of the train vehicle on the track.
- A line atlas contains persistent landmarks such as masts, buildings or signal posts.
- The obstacle recognition component's task is reduced to confirm a railway line clear of obstacles. The alternative to also consider the behavior of objects outside the track clearance might increase false positives significantly without improving the reliability of obstacle recognition. This was not evaluated so far.
- The trains never go faster than approximately 70 km/h.

Thus, for an autoBAHN on regional lines we define the following basic requirement for obstacle recognition:

> Detect all relevant obstacles to assure safe operation inside the railway track clearance in a distance of less than 80 meters within direction of movement. Any object larger than 40 x 40 cm is a relevant obstacle.

Note that the reason for the determination of 80 meters visual distance is the top speed of 70 km/h on straight tracks of regional lines. The assumed emergency braking performance is the 2,73 m/s^2 according to the German electric tramway edict [Bostrab1987].

According to §9 of the German railway operation act, the railway clearance is all space being touched by the vehicle during its ride above the rail top edge, as it is schematically visualized with some rectangles in Figure 4-1.

Figure 4-1: Sample rail clearance visualization

In addition to the basic requirement above, we defined the following additional requirements:

- objects with more than 10 centimeters x 10 centimeters in size must be detected within 10 meters
- ground detection with a height deviation of max. 10 cm on a distance of 80 meters
- avoidance of all known uncertainties during operation, which means, for example, the continuous removal of vegetation and snow, and obligatory control drives by personnel ahead of the daily start of operation

4.1 Sensor types

According to the current state of the technology we considered the following sensors Table 4-):

Type of sensor	Range	Characteristics	Costs
Laserscanner (LIDAR)	80 - 200 m	produce a 2D or 3D-point cloud by a rotating laser beam, viewing angle product dependent: horizontal 100-360°, vertical: 3,2 – 28°, Scanrate 5-50 Scans/sec	15 thousand euros (TEUR) for 4-8 levels laser 60 TEUR for 64 levels
Advantage Sensor performance by night is even better than by day due to the wavelength used in laser class 1 (near IR). In foggy conditions it approximates the optical range of the human eye.			
Disadvantage Incorrect measurements are possible through wrong echoes from strong precipitation or snow fall.			
(Stereo)-Video	up to 100 m	image producing method, obstacle recognition by image processing software	<3000 EUR
Advantages Distance information can be gained with high precision by use of a stereo system. Low maintenance requirements, high fail safety, low costs.			
Disadvantages Use is limited to visibility (daylight or illumination), applicability similar to human sight. Continuous calibration of cameras is time consuming.			
Radar	up to 200 m		<3000 EUR
Advantages Insensitive for adverse weather, independent of light conditions, long term reliability in rough conditions at low maintanance requirements			
Disadvantages limited usability at non-metallic reflectors such as humans; no height information of detected objects			
Infrared (IR) camera	up to 200 m	Measurement of temperature differences of objects and bodies	uncooled systems <3000 EUR
Advantage An effective method for the detection of living objects and heat emitting technical objects even at zero visibility conditions			
Disadvantages Time synchronization of stereo IR cameras only supported in expensive systems. Detection performance is strongly reduced in hot environments and in fog. Camera resolution is significantly lower compared to optical cameras.			

Ultrasonic	up to 5 m	good detection of all relevant objects at short range	<3000 EUR
Disadvantage Due to its short range only useful for arrival or departure of train vehicles at very low speeds in danger zones.			

Table 4-1: Sensor characteristics

	Day	Night	Rain	Fog	Snowfall	Heat	Cold	Range
LIDAR	++	++	+	--	0	++	++	<200m
IR camera	<20 ° + >20° --	++	+	++	++	– –	++	<200m
Optical camera	++	–	+	– –	–	+	+	<150m
Radar	–	–	0	+	+	–	–	<200m
Ultrasonic	+	+	+	+	+	+	+	<5 m

Table 4-2: Hypothetical usefulness of sensor types for an autoBAHN

Due to the characteristics of the sensors summarized in Table 4-2 the autoBAHN prototype used 4- and 64-level LIDAR scanners, optical and IR single- and stereo-cameras and ultrasonic sensors. The ++ indicates that a sensor is very well suited, a plus (+) that it is well suited, a minus (–) that it is not well suited and a double minus (– –) that it is not suited at all. Figure 4-2 shows the installation of the various sensors on the prototype autoBAHN vehicle.

Figure 4-2: Sensor installation on the prototype autoBAHN vehicle

A crucial quantitative measure of the quality of obstacle recognition is the number of

- false positives, that is, the classification of not existing or not correctly identified objects as obstacles,
- false negatives, that is, the missing of actual obstacles, and
- correctly detected true positives.

The good news is that true positives have been detected in all situations. But the current autoBAHN prototype still gets ca. 2-3 false positives per kilometer which cause the system to start braking. Though in more than 90% of these cases these false postives cannot be felt, as the characteristic of the braking curves and the delay until the train starts braking allow the correction of false positives by the obstacle recognition and behavior components: as false positives are typically not corroborated for a long time (> 1 second) they are only false positives for a short time frame – 2 to 3 times per kilometer persisting long enough to initiate the start of braking the train. The detection of false positives is then fast enough to avoid a train behavior in which the train randomly accelerates and decelerates. In other words, despite some temporary false positives per driven kilometer on a track without obstacles, humans enjoy a smooth ride in the autoBAHN prototype. In our experience it happens about once per ride between Vorchdorf and Gmunden (ca. 15 kilometers) that a human passenger feels the braking of the autoBAHN train despite no obstacle. Some statistics of how many false positives the particular sensors produce are provided in the following sections.

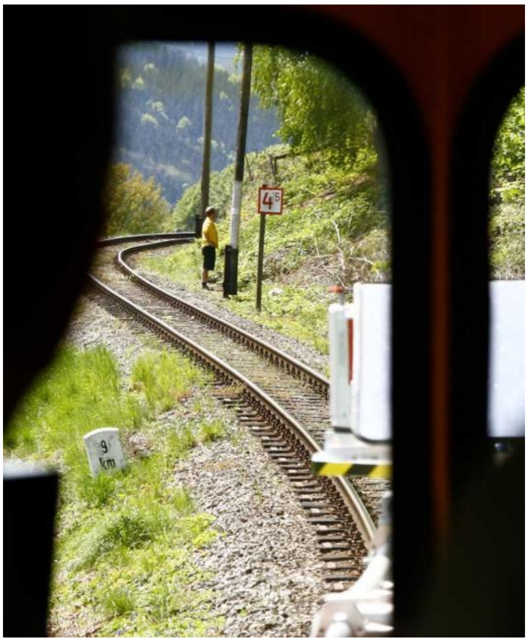

Figure 4-3: Potential false positives at the edge of the track clearance, often caused by too inprecise train positions

A frequent cause for false positives are decision uncertainties if detected objects lie close to the border of the track clearance (see, for example, Figure 4-3). This is sometimes caused by the challenge of continuous correct ground detection and the capacity to differ between ground and objects on the ground. Another reason is that the horizontal alignment of objects on the edge of the track clearance is wrongly detected as lying inside or outside the track clearance.

Another sample scenario leading to false positives are objects which are identified as obstacles by the sensors, though they are irrelevant. Figure 4-4 shows a teared off plastic ribbon waving in the wind. Other examples are snow drifts, vegetation between rails, or newspapers blown away by wind gusts.

Figure 4-4: Ribbon blowing in the wind as example for a potential false positive.

From our experience in the proof-of-concept phase, the following aspects need to be further improved to reduce false positives in the obstacle recognition component:

- the actual vehicle position from < 2 meters to < 1 meter precision
- the continuous calculation of bounding lines of track clearance in a system wide 3D-coordinate system
- the continuous detection of the ground level within the braking range along the track clearance
- the calculation of the spatial position of detected objects relative to the track clearance with a precision of 50 cm in all dimensions within the braking range of 80 m.

4.2 Obstacle recognition with 4-level LIDAR scanners

In addition to the 64-levels LIDAR scanner we used 4-levels LIDAR scanners (see Figure 4-5), which were developed for obstacle recognition on roads, but which are applicable for railroads as well. The advantages compared to more sophisticated systems are a significantly better distance range beyond 200 meters, robustness and low temperature sensibility as well as lower costs. To illustrate obstacle recognition with LIDAR scanners this section focuses on the type with 4-levels.

The LIDAR scanner comes with out-of-the-box software for obstacle detection. Its ground detection characteristics were optimized for roads which represent its original application environment. Thus, it turned out that this kind of detection was quite useless for railways: On railroads the driveway frequently is built as an embankment (see Figure 4-4) with a higher level than the surrounding environment, which can lead to a rail level up to 1 m higher than the rest of the ground. The object detection algorithm of the software is unable to handle these level changes. An additional source of false positives are frequent level changes within the rail bed. Particularly at railway crossings the ground level changes from lower than 15 cm below the top of rail to 0 cm. Switches are another area where the ground level is disrupted temporarily. All these changes are reasons for misinterpretations by the out-of-the-box obstacle detection software.

We therefore developed an alternative detection algorithm to better distinguish between the ground and even small level changes rising out of the rail bed. The algoritm assumes that the LIDAR scanner is installed at a very low height, in case of the autoBAHN prototype on the train in 72 cm above the top of the rail.

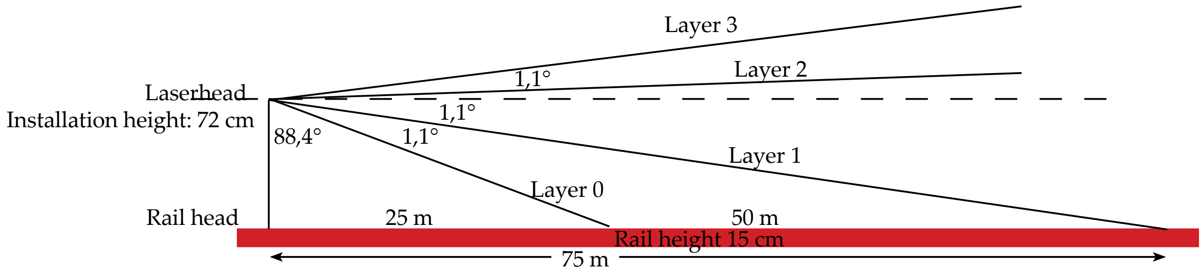

Figure 4-5: Function and adjustments of the 4-level laserscanner

For the effective coverage of the track clearance the angle between the mounting plate and the ground must be known with a high precision. Even smallest changes of the laser beam angle would cause significant changes in the distance measurements by the sensor.

The laser layer 0 is positioned in an angle of 88,4° to the vertical line, which delivers distance measurements at ca. 25 meters on the horizontal line (see Figure 4-5). Layer 1 delivers distance measurements at ca. 50 meters from the train position.

In our configuration the laser layers 2 and 3 already lie parallel or above the horizontal line (see Figure 4-5). At distances beyond 180 m and an angle of 1,6° above the horizontal line a laser echo from layer 3 detects obstacles up to 5,70 m above the top of the rail bed, which assures a full coverage of the track clearance. Figure 4-7 illustrates the measurements as dots in the picture.

To qualify a laser echo as an obstacle it has to lie within the boundaries of the track clearance and must not be a permanent part of the ground. To define the position of an echo relative to the track clearance, the absolute position of the train vehicle in terms of world coordinates is required. The vehicle's position is continuously measured by its navigational sensors and the data fusion component which takes also masts and other landmarks into consideration. The coordinates of laser echoes relative to the vehicle are calculated through the distance measurements and known angles of the laser layers by trigonometry.

Figure 4-7: Display of laser echoes within the video picture

The following method is used to differ between echoes from the ground and from obstacles:

- In an obstacle-free calibration ride, the shortest received laser echo of layers 0 and 1 is assigned and stored for each vehicle position. This represents the characteristic curve of the track run, where hills, sinks or bumps as well as switches or level changes at railway crossings are registered.
- After the calibration, the differences of measured distances compared to stored values for the actual position of the vehicle are calculated for layers 0 and 1. Whenever the result exceeds a defined threshold, an object rising above the top of the rails must be the reason.

An advantage of this method is that objects can be easily be detected as even small ones create significant changes in distance measurements. We defined the threshold of length differences between echoes from the rail bed and the obstacle for level 0 at 8,95 m. It turned out that this represents an effective filter.
Nevertheless, the LIDAR sensor reports on average about 25 false positives on the 15 km long railway on which the autoBAHN prototype operates. One reason is the still high variablility of the train position (see section 4.5). Another reason are minor vertical movements of the train caused by speed changes: they change the angles of the levels. The latter needs to be considered in a refined implementation of the obstacle recognition algorithm for this type of LIDAR sensor in the next project phase.

4.3 Obstacle recognition with stereo cameras

Camera pairs can be used as basis for calculating distances to objects. If the distance between the cameras on a vertical line (defined as base line) is known, the angle between the cameras and an object (which is known as parallax) is proportional to the distance from the objects to the cameras. This angle is represented by a displacement of n pixels at which n depends on focal distance, sensor resolution (measured in pixel/inch), the object's distance from the cameras, and additional calibrating factors. At a given image sensor resolution the measure n is called disparity. The precondition for finding disparities is the recognition and correct assignment of identical points on both image sensors. In stereoscopy this is being called the correspondence problem. The results of algorithms for solving that problem are depth maps as exemplified in Figure 4-8, where the distance of objects is denoted in colors: red being close, green being farther away.

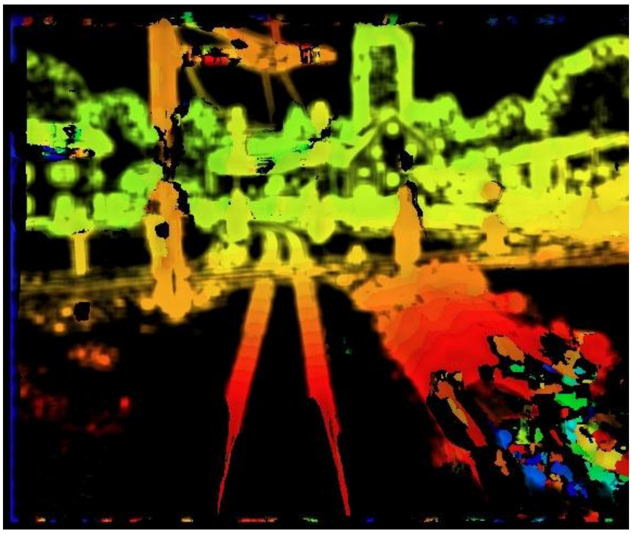

Figure 4-8: Stereoscopic depth map

With the use of stereo and mono cameras as sensors for the autoBAHN prototype a series of practical problems occurred, of which most were tackled by our research partner for that sensor type, the Austrian Institute of Technology (AIT). The exact calibration, which is the measurement and control of camera parameters, is a precondition for getting correct measurements. Of importance are aperture, focal length, angle of aperture, length of base line, image sensor size and resolution, color depth, noise performance, sensitivity and the dynamic range of cameras.

The importance of a high dynamic range demonstrates the following example of a bar lying across the track. Figure 4-9 shows a difficult light scenery due to shadows from trees and laterally inclined light, where light and shadow alternate several times. The bar, lying 45 m ahead of the train vehicle across the rails does not show any recognizable structure or contrasts for the human eye. In Figure 4-9 the color dynamics of the picture is limited to the area of the bar and a quantification has been accomplished, which resulted in additional usable texture. The large bandwidth of calculated distances of 320 – 450 cm shows that only little information is available to retrieve disparities.

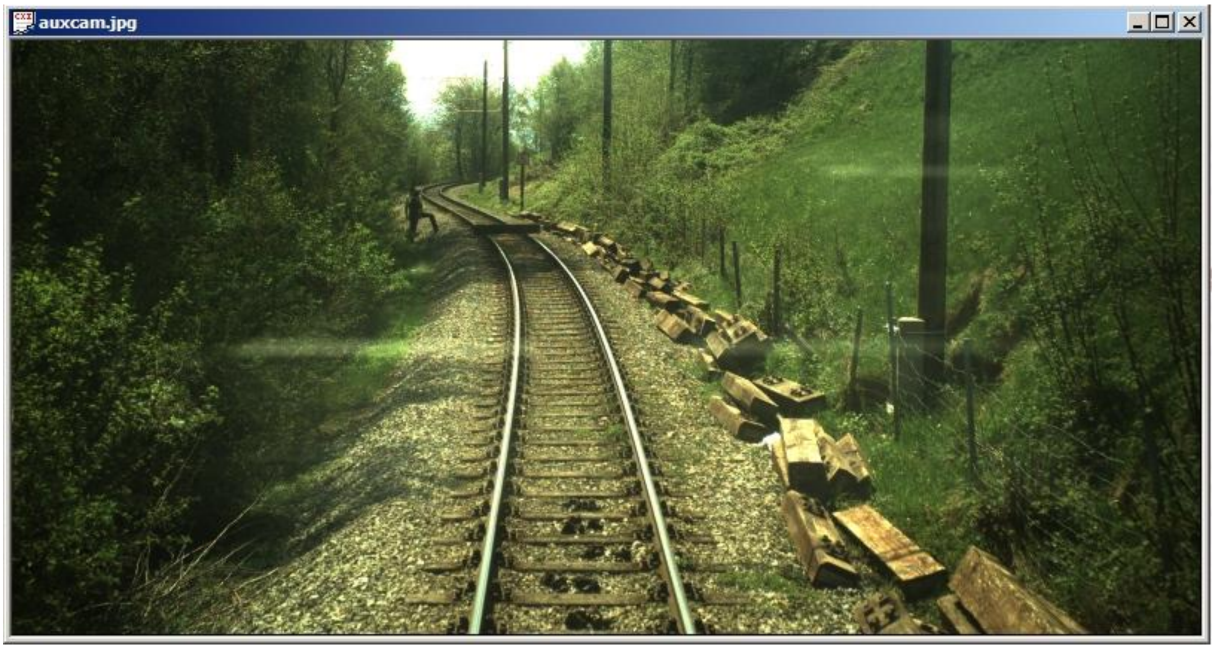

Figure 4-9: Obstacle recognition with a person in a tree shadow. Source: AIT

Besides the technical characteristics of cameras there are optical factors of the installation on the vehicle to be considered for effective image processing:

- The installation must be free of mechanical tensions, because in stereoscopy even smallest physical movements of only 0,05° to each other can cause significant quality losses.
- A stable fixation of lenses reduces vibrations.
- Flaring light, for example through reflections behind glass, needs to be avoided by extra precautions.

The stereo camera system reports on average about 90 false positives on the 15 km long railway on which the autoBAHN prototype operates. One reason common to the LIDAR sensor is the still high variablility of the train position (see section 4.5).

4.4 Sensor data fusion

Sensor data fusion is a real-time task of data analysis, with respect to different characteristics and behavior of all kinds of sensors. Sensor data fusion comprises

- the evaluation, interpretation and integration of signals,
- the reduction of large amounts of data,
- the recognition of relevant obstacles:
  distinguishing between objects lying in-/outside of the track clearance, mobile/immobile, relevant/irrelevant objects
- the establishment of object hypotheses during the movement of the vehicle, and the
- classification of situations as dangerous ones.

Furthermore, the sensor data fusion component accomplishes the continuous navigation and tracking of objects, that is, both obstacles or landmarks. The extensible design of the component allows a plug-and-play of sensors via sensor plug-ins. Thus, redundant sensors can be added. Non-working sensors can be dynamically removed.

The object tracking can be realized for static and dynamic objects. As the tracking of objects does not have the same importance in autonomous railway systems as in autonomous systems for road traffic (see [DARMS2009]), we consider only static objects. In railway systems objects of a certain size inside the track clearance are always obstacles and therefore a reason for an immediate braking action.

Object tracking is the association of new observations to already known objects. Such objects might be either already identified obstacles inside the track clearance or landmarks in the track atlas, that is, known static objects close to the track clearance. Examples are masts, signs, or buildings. In the autoBAHN project masts have turned out to be effective landmarks for improving vehicle navigation (see next section).

All observations of all sensors are merged into a single object list, categorized as obstacles, landmarks or other objects. Together with the vehicle state they define what we call the world model. In the Java implementation of the sensor data fusion component instances of class TrackedObject are subtypes of the class ObservedObject (objects reported by sensors). ObservedObject instances that cannot be associated with existing TrackedObject instances constitute new TrackedObject instances. Tracked objects are eliminated after defined periods of time if their existence cannot be continuously renewed by sensor reports. The calibration of this timing parameter is essential to effectively cancel false positives. We also introduced a probablilistic aspect in the sensor fusion component by logging the duration and number of obstacles reported by the sensor plug-ins.

Overall the performance of obstacle recognition with the chosen sensor fusion strategy were impressive: most false positives were eliminated so that a smooth ride of the autonomous train could be achieved. At the same time actual obstacles could be detected with a 100% reliablity.

The Java implementation of the sensor fusion component comprises about 30 thousand lines of code and thus can be considered as lean component compared to this kind of component in other autonomous robotic vehicles, such as those which participated in DARPA's Urban Challenge [Ref: http://en.wikipedia.org/wiki/DARPA_Grand_Challenge_(2007)]. There typical sensor fusion components comprise several hundred thousand lines of code.

4.5 Determining the train position

The evaluation of the train position is required with a precision of less than 1 m. This rather high precision is necessary because the longitudinal deviation of the train's position along a straight part of the track represents the lateral offset of a detected object in curves (see Figure 4-12). Thus objects can erroneously be observed being inside the track clearance, although lying significantly outside and vice versa.

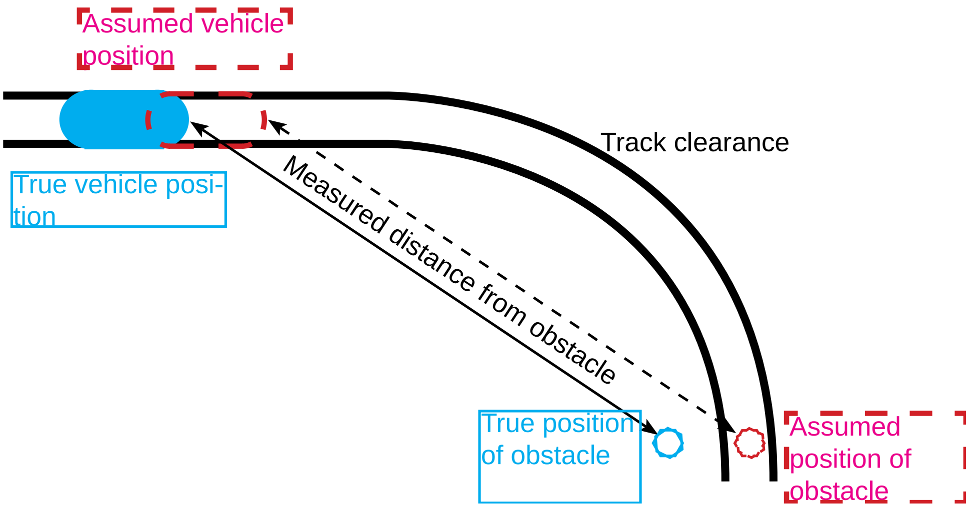

Figure 4-12: Consequences of navigational errors for the obstacle recognition in curves

The exact knowledge of the track routing and its most significant attributes is a precondition for a solid obstacle recognition and the autonomous operation of vehicles. In an autoBAHN masts, signs, stations, railways crossings and others are landmarks in a track atlas. The landmarks were recorded with a differential-GPS at a precision of 2-3 cm. In regular operation of the autoBAHN prototype a combined GPS/INS-system (INS, Inertial Navigation System) is used. It implements a continuous Kalman-filtering of measured data.

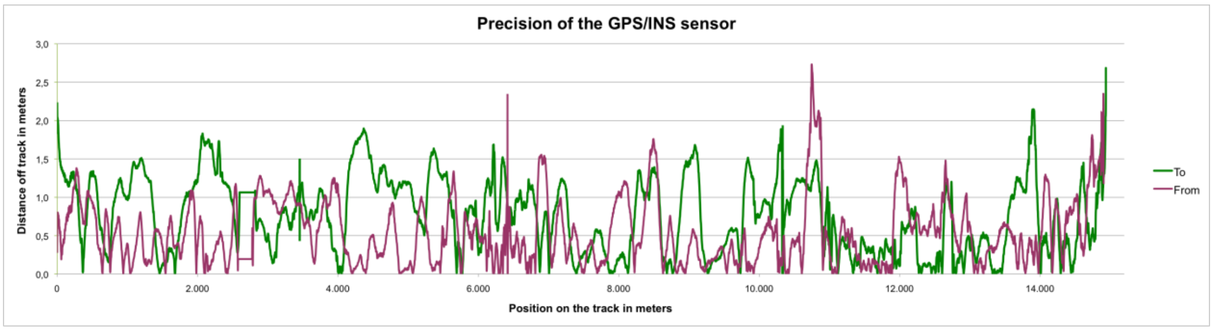

Figure 4-13: Precision of the GPS/INS sensor (distance in meters from track)

To improve the navigational precision of the GPS/INS-Sensors, which is on 97,7% of the track below 2 m (see Figure 4-13), a data fusion with the vehicle's wheel sensor is done. A wheel sensor error cumulates over distance and depends on the rail conditions such as humidity, ice, snow, leaves, the rail's gradient and the vehicle's acceleration. These deviations can add up to several percent of driven distance and therefore the sensor has to be calibrated regularly. One possible but expensive alternative would be the use of electronic beacons as they are implemented in transponder systems. In the autoBAHN system we used the masts along the track, which were surveyed and continuously detected and compared to data from the track atlas. This method allowed us navigational corrections: The accuracy of LIDAR scanning measurements is below 10 cm and the average distance between masts is about 16 meters. Thus, we could consider several masts within the LIDAR scanner's range of around 200 m (see Figure 4-14). We hope that we can further improve the position correction algorithm to achieve a correct position determination with a precision of < 1 meter on 99,5% of the track.

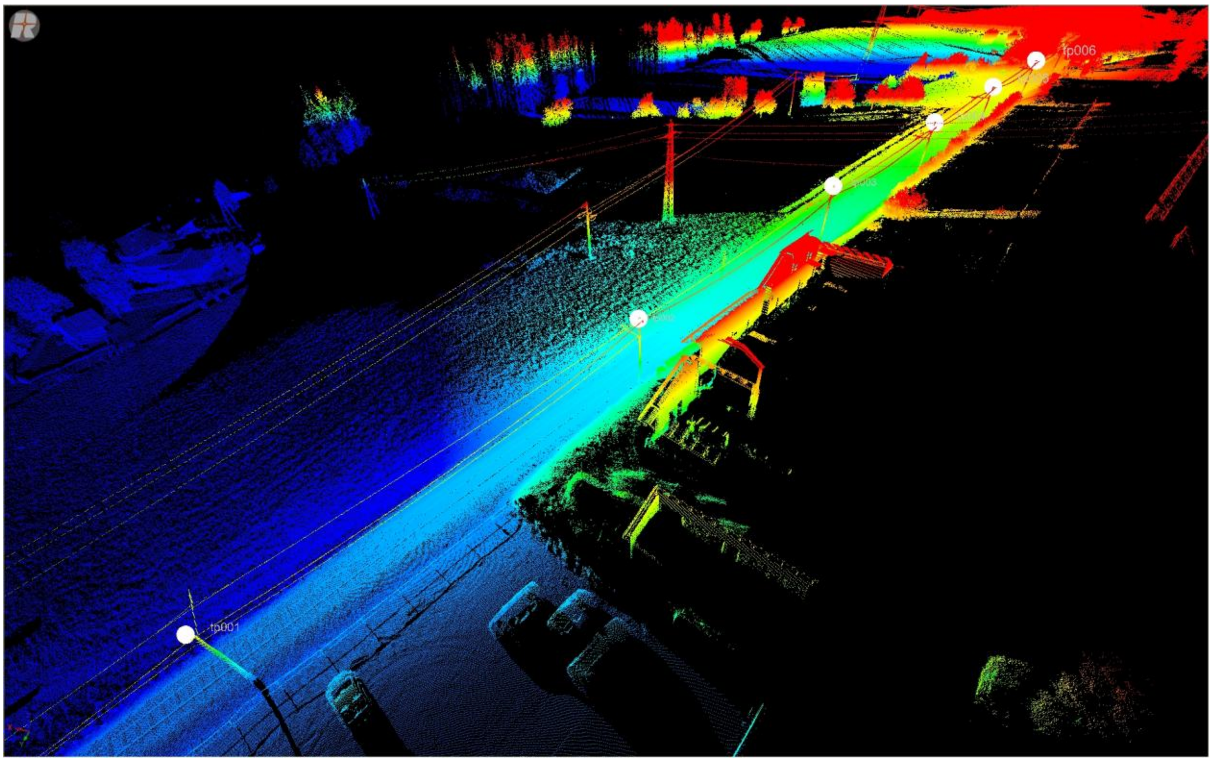

Figure 4-14 Illustration from the GPS/Laser track survey.
Source: RIEGL Laser Measurement Systems GmbH [RIEGL2012]

5 Conclusions and outlook

Despite the fact that the overall autoBAHN prototype is a heterogeneous, complex system, and despite several initial hurdles, it turned out to be straight-forward to implement it. In particular, we harnessed only well-known software construction and engineering concepts. Due to the static environment of railtracks we even did not need to use machine learning. Some effort went into the implementation of a real-time-aware simulation environment so that we could experiment with the processing of the raw sensor data on the desktop instead of on the railroad. This was crucial for the calibration of the sensor plug-ins and the sensor data fusion component. Overall, the autoBAHN system was implemented from scratch (except for the train control component, which existed and which was adapted for the autoBAHN) within 15 months with an effort of ca. 80 person months. We also reused existing software components for the calibration and processing of stereo camera data.

In the next project phase we will need to run autonomous trains supervised by humans on a regular basis. This requires a a further enhanced train control system with a central station for single operator management of this autonomously operated line. In addition the handling of braking curves and train reactions on reported obstacles has to be improved by using more sensor data concerning the physical state of the train-rail-situation to achieve faster and smoother movements, as regular passengers will ride on these trains. In addition the reliability and safety of the proposed system has to be verified according to CENELEC.

So far it is not clear whether some railway laws need to be changed in Europe analogous to Nevada which changed its traffic laws to allow autonomous cars on freeways. The final approval according to the European standards for railway safety and security and according to the railway laws are a significant hurdle towards a product, because of the demanding requirements on the software development and testing process and because of the current legal requirement of having a human driver on a train. Changing the railway laws might require a research effort on its own as basis for a solid political decision.

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