In: Stilla U et al (Eds) PIA07. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36 (3/W49B)

NOVEL PLATFORM FOR TERRESTRIAL 3D MAPPING FROM FAST VEHICLES

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KEY WORDS: Mobile, Mapping, Fusion, Laser scanning, Terrestrial, Close Range, City, Model

ABSTRACT:

We present the novel THelix 3D mapping system running on the LIMEZ III measurement train which is able to record clearance data and visual information about the surroundings of railway lines at velocities up to 100km/h. Due to a unique integration of complementary optical sensors and a sophisticated data management, the system provides comprehensive geometrical information about all trackside objects in both, global and local co-ordinates. A new and extremely fast close range laser scanning arrangement, stereo photogrammetry images, light sheet technology, GPS/INS and forward view laser scanning are combined to overcome the typical disadvantages of each single method. All geometric results are registered automatically to track centre, enabling the calculation of the closest profile within 0.1m in real time. Stereo photogrammetry complements the laser scanner point cloud for missed objects. The result is geometrical and texture information acquired from different perspectives.
The presented system is quite a universal close range 3D measurement system suitable for many mobile mapping applications. A similar system mounted on a car might be used for large area 3D mapping in roads without obstructing normal traffic. The results can be used to complement aerial city models (LoD 2) with realistic façade information in order to build large area LoD 3 models.

1. INTRODUCTION

1.1 Clearance Gauge Measurements

Clearance gauge measurement of railway lines is crucial for safe operation with regular trains and even more for oversized loadings. Even small objects extending into the allowed clearance and small displacements of the track may cause considerable damage. In any case disturbance of the regular service due to data recording should be avoided if possible. This can only be achieved if the measurement trains are able to speed up to at least 100 km/h so that they are allowed to enter even high speed lines. This application therefore requires gapless 3D measurement, documentation and visualization of the track ambience at high acquisition speed.

The THelix measurement system (THelix stands for travelling helix, describing the movements of the laser spots) was designed by Metronom Automation Gmbh, Mainz, FTI Engineering Network GmbH, Dahlewitz, and Fraunhofer Institute for Physical Measurement Techniques for the Deutsche Bahn AG in order to generate a 3D and visual documentation of the complete German railway network of about 40,000km once a year. Measurement quantities are the clearance profile with reference towards track centre of all objects within a distance of ±3m along the track (including signs) with an accuracy of ±20mm (3σ). 3D data is recorded within ±8m, including distance, height, gauge and cant of the adjacent track. Additionally, gauge and cant of the track under test and vehicle position in global co-ordinates are acquired.

Several approaches for clearance measurement were published in the past (Blondeau, 1999; Meixner 2002; Cybernetix 2003; Blug 2004). All of them apply optical measurement principles, and optics still meets the users' demands best. However, none of the known and applicable measurement principles satisfies all the requirements of modern railway lines.

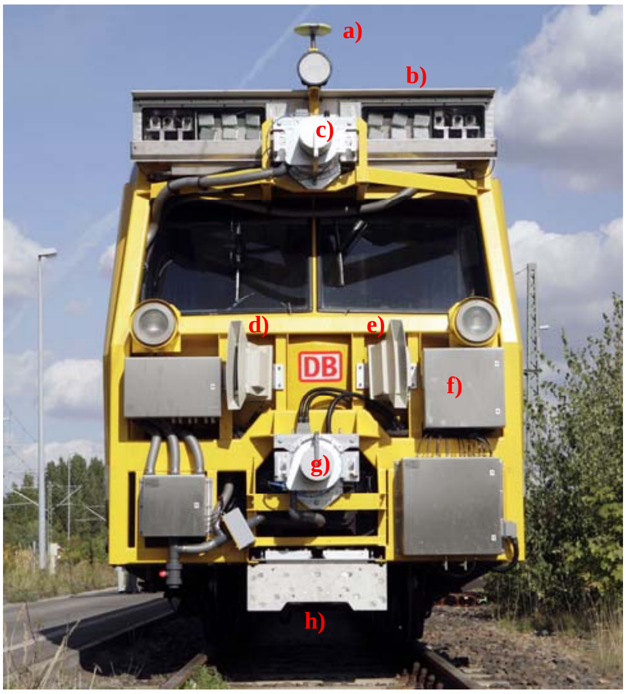

Fig. 1: 3D mapping system on the measurement train. Components: GPS/INS system (a, f), video and stereo photogrammetry system (b), twin head laser scanners (c, g), forward looking scanners (d, e), track reference (h).

1.2 Other Applications

Regarding its components, the system is very similar to other mobile mapping systems used on the road (Gräfe 2003; Haring 2005). It delivers globally and locally referenced geometric and texture information needed for applications such as city modelling, terrestrial navigation or disaster engineering, e.g. virtual fire fighting. For many applications, a vehicle velocity up to 100 km/h during acquisition is highly advantageous, because it allows for cost-effective data acquisition without obstruction of the traffic flow. Differences lie in the measurement range and in the reference to the road instead to the rails and in the evaluation of the data.

2. SYSTEM DESIGN

Fig. 1 shows the system in front of the measurement train. All components are mounted on a single measurement frame making it easy to migrate this system, e.g. onto the rear side of a car. To meet the clearance profile requirements, state of the art stereo photogrammetry was combined with two extremely fast laser scanners based on the twin head geometry. Additionally, it comprises a GPS/INS system for global localization and a sheet of light rail reference system. The manual evaluation of the photogrammetric data is supported by two forward looking scanners. Some more details can be found in Höfler, 2006.

2.1 Track reference system

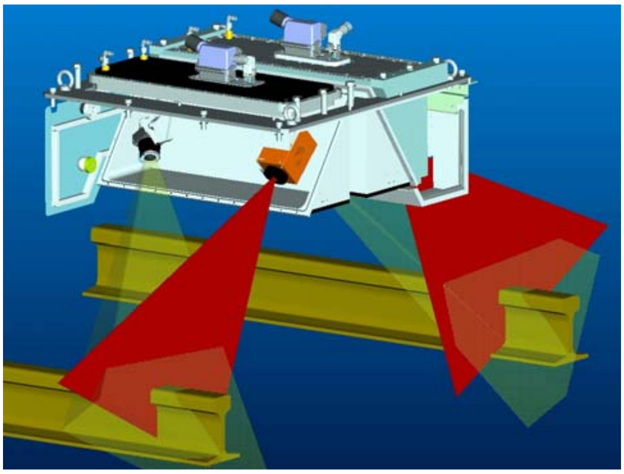

Fig. 2: Sheet-of-light track reference system

The track reference system (Fig. 2) consists of two sheet-of-light triangulation systems which are tilted 45° to measure horizontal and vertical position of both rails. The horizontal field of view is 0.56 m on each side. It measures rail position with a frequency of 50 Hz and an uncertainty of ±1 mm for horizontal and vertical position. Therefore this system enhances the overall measurement uncertainty towards track centre of the laser scanners and the stereo photogrammetry system.

2.2 Twin Head Laser Scanners

Fig. 3 is a CAD drawing of a twin head laser scanner (Blug, 2004; Blug, 2005; Wölfelschneider 2005). Each scanner contains two fibre coupled measurement modules with sampling rates of 1 MHz for distance and 4 MHz for intensity. The distance is measured using the phase shifting technique (Wölfelschneider 2005) with two modulation frequencies resulting in unambiguous measurement ranges of about 1.2 and 20 meters. The laser beams of the two modules are directed on both surfaces of a double sided mirror and therefore propagating in opposite directions. The angle of the second scanner is fixed to 90° towards the first one. Each mirror rotates with 278 Hz. Therefore both scanners together acquire 1112 profiles per second with 3600 distance values and 14400 intensity values. These specifications allow for a minimum object size of less than 30 mm in driving direction at a speed of 100 km/h.

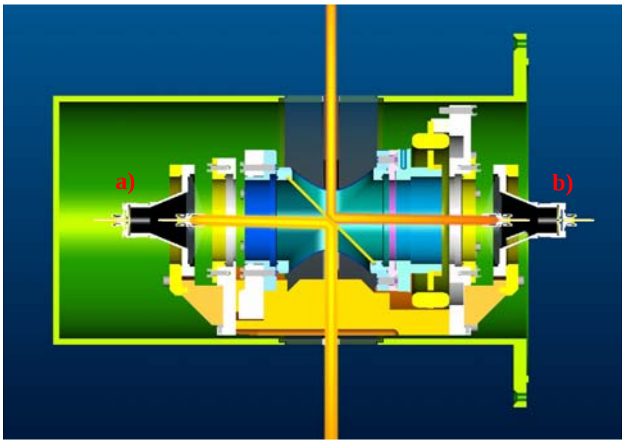

Fig. 3: Twin head laser scanner with two fibre coupled distance measurement modules (a, b) on a double sided mirror.

A very critical issue, especially for fast laser scanners, is the accuracy of measurement points near edges. There are three major limiting quantities: the spot size (which is 5 to 10 mm here, depending on distance), the dynamical response of the detector on changes in intensity and the response time - or bandwidth - of the distance measurement electronics. The bandwidth is independent from the sampling rate (here: bandwidth is 770 kHz, sampling rate 1 MHz) and a compromise between the noise and the response time of the system. Boehler published a target to assess the spatial resolution – which is similar to the edge quality - of laser scanners working in spherical co-ordinates (Fig. 5 in Boehler, 2003). This target requires an equal point density in scanning direction (here: vertical) and perpendicular to it (here: driving direction) which does no apply to the cylindrical scanning symmetry of our scanner. Therefore we constructed a target which combines changes in colour with spatial structures. It consists of several plates (width 5 cm) with different colours (black, grey, and white) mounted 0.6 meters in front of a black wall, half of the unambiguous measurement range of 1.2 meters. Therefore, it causes the maximum phase shift of 180 degrees for this modulation frequency.

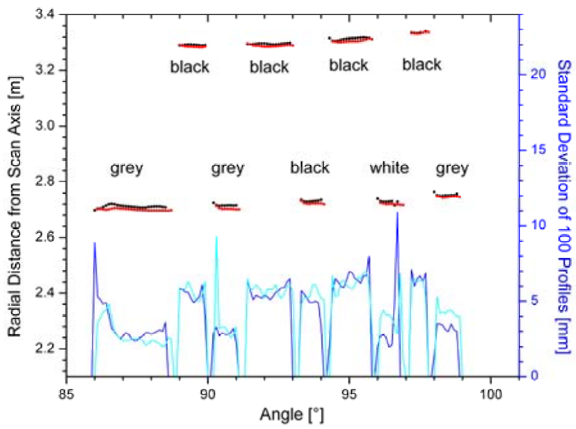

Fig. 4: Measurement accuracy of two distance measurement modules near edges.

Fig. 4 shows the results of the two modules obtained for that target in polar co-ordinates. The radii are averaged over 100 profiles. The standard deviation is given on the right side. A standard deviation of zero means that those points were sorted out as uncertain by the point validation algorithm of the scanners. The graph shows systematic effects in the range of 5 to 10 mm an increased standard deviation near edges. The maximum number of disregarded neighboured points is two. This means, that edges can be measured with an accuracy of about ±1 measurement point.

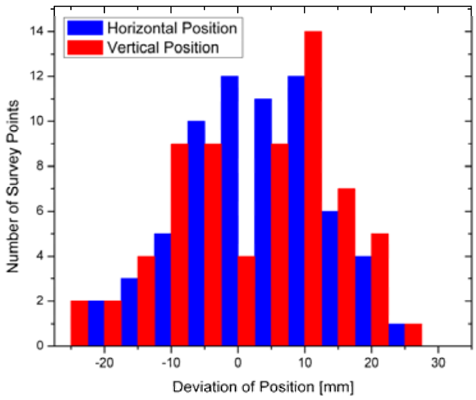

Fig. 5: Measurement deviations on survey points.

In Fig. 5, deviations (3σ) measured from the running train on 66 survey points are listed in the histogram. The survey points were the horizontal and vertical position of the edges of black and white cuboids mounted on masts towards track centre. At those positions the horizontal and the vertical position of the closest point of the track referenced point cloud was compared to tachymeter measurements (Leica TCR 407). Train velocity varied between 83 and 98 km/h and the smallest curve radius was 650 m. The radial measurement distance between survey points and laser scanners varied between 3 and 5 m. Therefore these deviations contain the uncertainties of single measurement points from the laser scanner point cloud, the track reference system and the reference measurements (estimated from control points to ±5 mm, 3σ). As expected for laser scanners, the horizontal positions are slightly better (-18 to 25mm) than the vertical ones (-25 to 23 mm), due to the angular resolution of the scanner of 0.1°.

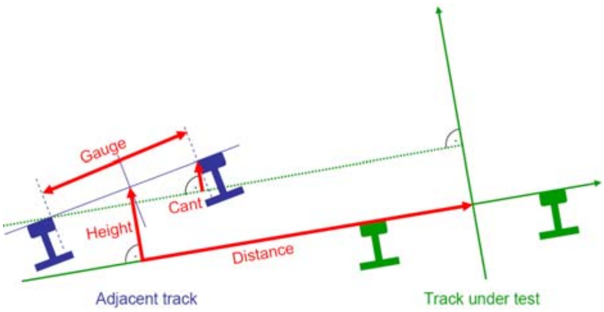

Fig. 6: Definition of adjacent track parameters.

The use of two scanners in a cylindrical symmetry also allows for the exploitation the intensity images for triangulation, which is necessary to achieve an accuracy of ±8 mm (3σ) for the cant of the adjacent track (Fig. 6). For this purpose, the laser scanners are used as cameras with a focal depth defined by the width of the laser spots (Fig. 7).

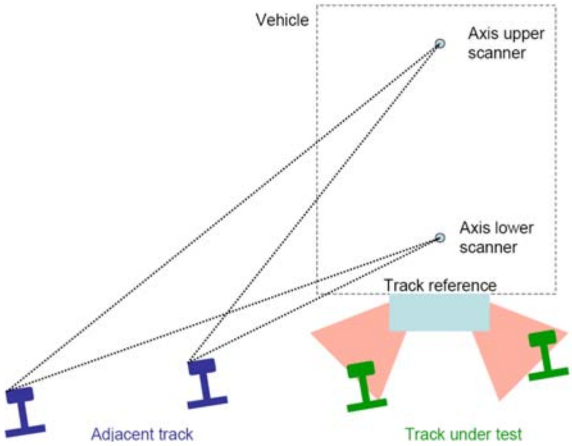

Fig. 7: Determination of the adjacent track parameters by triangulating the intensity information of the two scanners. The dotted lines indicate the angles of the rear rail edges.

For the adjacent track the intensity images of both scanners (Fig. 8) are evaluated for the angles of the rail edges by image processing whereas the underlying 3D data is used to identify the rails within the image. The red lines in Fig. 5 mark the rails identified in the underlying 3D data, the blue ones the rail edges determined in the intensity images with an angular resolution of 0.025°. It therefore improves the angular accuracy of the laser scanners.

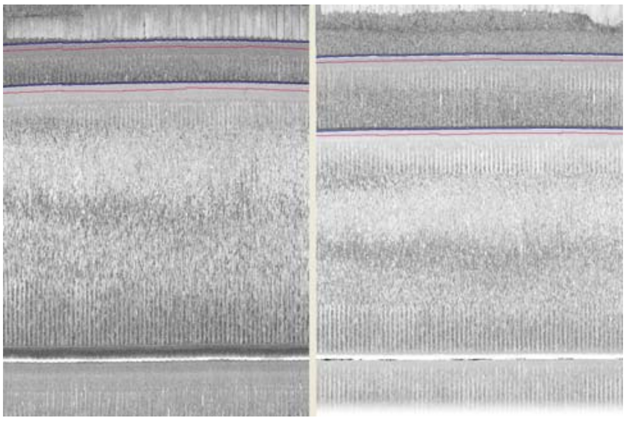
Fig. 8: Intensity images of the adjacent track from the lower scanner (left) and from the upper one (right).

2.3 Video and Stereo Photogrammetry System


Fig. 9: Carbon base and housing of the video photogrammetry system

The video photogrammetry system comprises four 2-megapixel monochrome video cameras, mounted on a stable, warp resistant and temperature inert carbon base in an air-conditioned housing on top of the mounting frame (Fig 9). They group into two pairs of stereo photogrammetry systems covering the left and the right part of the measurement range, respectively.

Fig 10 shows a schematic of the field of view of the different cameras. The measurement range amounts to 8 meters horizontally, 5 meters vertically and 2 meters longitudinally. A set of pulsed infrared LED modules provide illumination of the measurement range and an intelligent brightness sensor, i.e. a fast intelligent CMOS-camera, controls the exposure time of the cameras according to the ambient light.

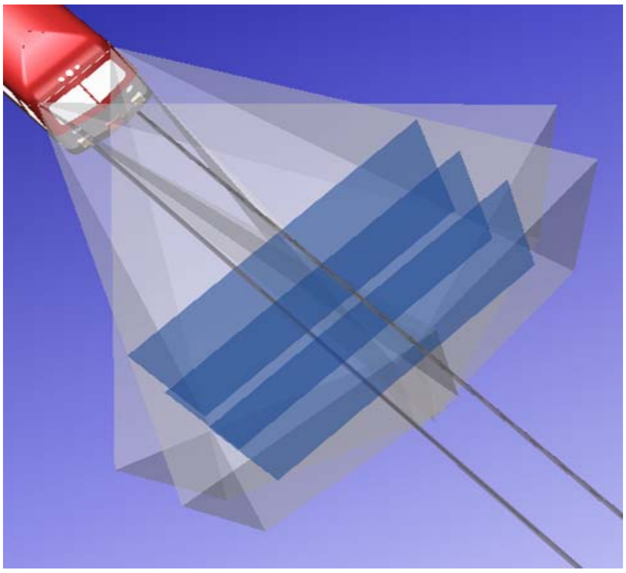

Fig. 10: Schematic diagram of the field of view of the two photogrammetry cameras

Triggered by a position encoder the cameras simultaneously accumulate pictures every 2 meters covering the whole measurement range along the track. At maximum speed this sums up to 14 sets of pictures per second. They are compressed and dumped to disk in real time. The measurement accuracy is currently under evaluation.

2.4 Forward view laser scanners

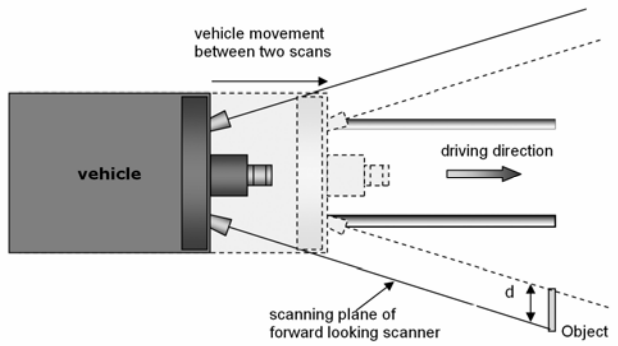

Fig. 11: Top view of the arrangement and the scanning plane of the forward looking scanners.

The video system together with the described side view laser scanners ensure that no trackside object is ignored. However, to identify all objects may be very time consuming if all videos have to be watched by an operator during offline data evaluation. There is still no image processing algorithm available allowing the reliable identification of any imaginable trackside object automatically. That is why two additional forward looking laser scanners are installed. Scanning plane is vertical with an angle of about 10° outwards of the driving direction. As sketched in Fig 11, the minimum detectable object size d is given by the viewing angle, the scanning frequency and the speed of the car. Assuming an angle of 10°, a speed of 100 km/h and a scanning frequency of 50Hz results in d = 100 mm. Therefore, these scanners are able to detect any objects with an extension down to 100 mm perpendicular to the track, independent of their thickness. Together with the side viewing scanner this configuration allows the detection of any trackside object and minimizes the time for the offline evaluation of the video sequences.

2.5 GPS/INS system

The system is equipped with most modern GPS and INS positioning systems using laser gyroscope, accelerometers and differential GPS. The post processing using offline reference data leads to a location precision in the few centimetres range.

3. DATA PROCESSING

3.1 Real Time Data Processing

All laser scanners and the track referencing system are evaluated automatically and in real time in order to minimize post processing time and the amount of stored data. It also enables online visualisation of the recorded data so that the operator is able to judge the measurement quality during the measurement run. The following steps are carried out:

1. All systems with exception of the GPS/INS align their data to a pulse coming every 0.1 meters of travelling distance.
2. The track reference system extracts the position of the rails in vehicle co-ordinates.
3. Both twin head laser scanners calculate the narrowest profile within 0.1 meters.
4. Registration: Transformation of the narrowest profile from both scanners to track co-ordinates.
5. The images of both twin head scanners (Fig. 8) are combined and the adjacent track is extracted. Only adjacent track parameters are stored.
6. The forward looking scanners calculate the narrowest profiles and count infringements into a predefined reference profile.
7. Visualization of the 3D point cloud, track parameters, adjacent track position, and infringements from the forward scanners.

The point density of 0.1 meters in driving direction is sufficient for visualization of the point cloud. The calculation of the narrowest profile in step 3 assures, that the relevant points of smaller objects (down to 30 mm in driving direction) are not lost. At the same time, the amount of data from the twin head scanners is reduced from 70 GB per hour to distance dependant amount between 100 MB per km in tunnels and down to 30 MB per km on free tracks where large parts of the scan profiles do not contain targets within the measurement range. Table 1 lists the amount of data stored for a measurement distance of 500 km which can be acquired within one day.

Measurement system	**Amount of data [GB]**
Twin head laser scanners	50,3
Video documentation	33,6
Stereo photogrammetry	178,9
GPS/INS (time dependant, 10h)	1,1
Total data amount	**263,9**

Table 1. Data amount of a 500 km measuring run

3.2 Post Processing

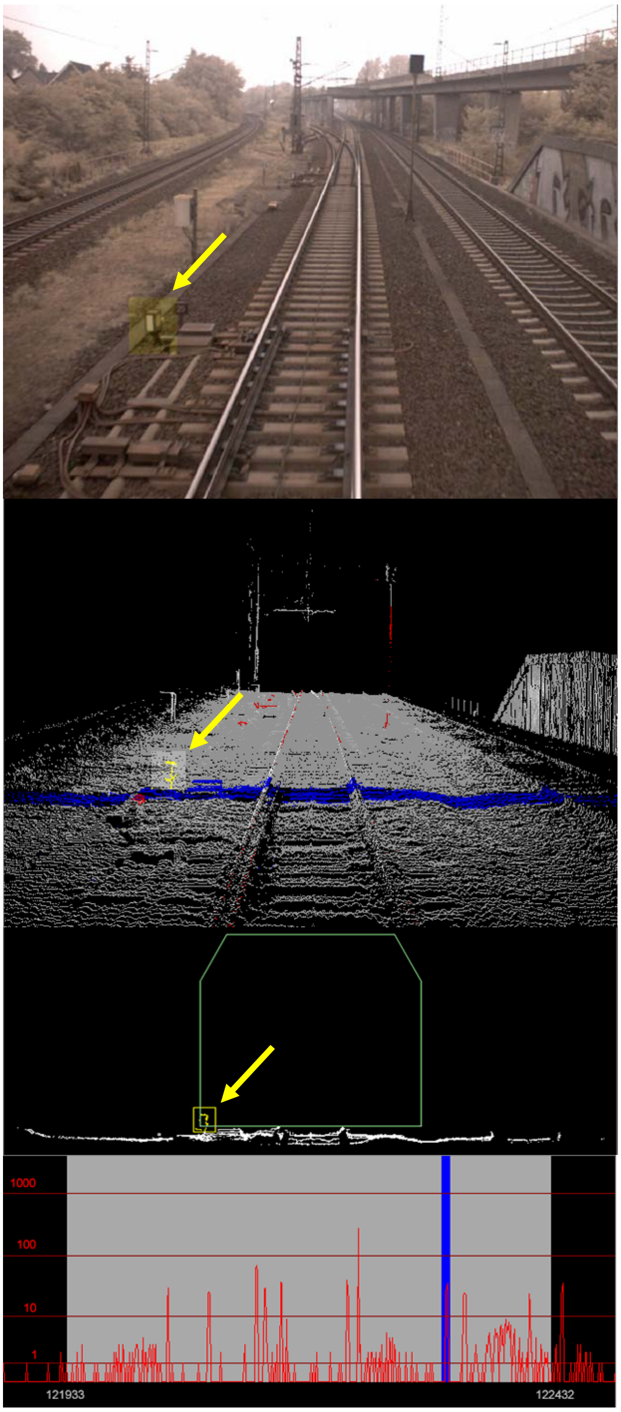

Fig. 12: Video documentation image (top); 3D point cloud from 500 profiles or 50 m (second); 2D view of the blue profiles from the 3D point cloud (third); infringement statistics with the number of points inside of a reference profile (bottom). The red points of the point cloud lie inside the reference profile. The object under test is marked by yellow arrows.

The real time data alignment and registration reduces post processing to two steps:

1. Refinement of the GPS data by differential reference data (ASCOS).
2. Selection and documentation of objects infringing a predefined reference profile.

For the object selection, the 3D point cloud is combined with visual information from the documentation video and with an infringement statistics showing the number of points within a reference profile over track distance (Fig. 11). The object contour is selected in a 2D view. The comparison between video and 3D point cloud visualizes objects missed by the laser scanners, which are typically signs. Their edges are determined by stereo photogrammetry.

4. CONCLUSIONS

The system exploits the complementary properties of stereo photogrammetry and laser scanning. Laser scanning allows for automatic referencing and evaluation of 3D data. The results are verified by the video images and remaining gaps are evaluated manually using stereo photogrammetry. Both together cover almost the complete surroundings at travelling velocities up to 100 km/h and allow for efficient post processing. The total data volume of all systems is about 260 GB for 500 km.

The main purpose of the LIMEZ III train is clearance gauge measurement. Nevertheless, the THelix measurement system provides gapless geometrical and texture information useful for many other applications. In particular, mobile mapping applications profit from the high acquisition speed, because the obstruction of traffic is minimized. Therefore a similar sensor arrangement mounted on a car might be a promising solution to acquire realistic façade information for large area city models on a LoD 3 level. There, the high point density of the laser scanners is advantageous for an automated evaluation like the registration of point clouds and images (Boehm, 2007).

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