A Multisensor Platform for Kinematic Track Surveying

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Abstract. The increasing use of modern high-speed trains requires increasing safety standards and, consequently, accurate railway tracks. Traditional methods for track surveying do not any longer satisfy economic aspects. For these reasons, HTA Burgdorf developed a track surveying platform in co-operation with terra vermessungen AG, Switzerland. The project is financed by KTI (Commission for Technology and Innovation by the Federal Office for Professional Education and Technology).

The system features the modular structure and the capability of kinematic surveying. For various surveying tasks (track surveys, deformation measurements, staking out of railway lines, tunnel profile measurements) the platform can be flexibly adapted. The platform is designed as a lightweight construction (operation weight: 45 kg) and can be easily handled by two operators. It contains sensors such as two inclinometers (super-elevation and gradient), a track gauge meter and two odometers. For the trajectory survey, a GPS-RTK or an autotracking tacheometer can be used, alternatively. With a post processing software, track geometry parameters such as inclination (super-elevation and gradient), height differences, twist, track gauge and the trajectory (horizontal / vertical) can be computed.

The Institute of Geodesy and Photogrammetry together with Grunder Ingenieure AG carried out first tests using the platform combined with GPS-RTK. An 18 km long railway line was surveyed. The forth and back track allowed a comparison of the observed trajectories. In sections without GPS obstructions, an accuracy of 1.5 cm was obtained for the horizontal component. The vertical component was worse by a factor of 1.5.

A system is being developed for staking out slab tracks. A remote-controlled tacheometer tracks the survey platform where the super-elevation and the track gauge are monitored. Corrections to the nominal track layout are displayed and can be used for staking out.

Key words: Kinematic surveying, track surveying , staking out of slab tracks

1 Introduction

For surveying tasks in the context of rail construction, many different systems exist. Apart of still used conventional static methods, kinematic measuring systems become more important. Several railway companies own expensive positioning systems acquiring track data on a large area [e.g. Presle, 1995]. These systems are used in order to study the behaviour of the rails under dynamic stress for different velocities. In the context of track renewal, project engineers need a measuring system yielding the required absolute accuracy. Moreover, the system should be applied cost-effectively even on short track sections. An example of such a kinematic measuring system represents the track surveying vehicle developed by HTA Burgdorf in collaboration with terra vermessungen AG. The track surveying vehicle features a modular design and can be equipped with different sensors. The project was supervised and financially supported by the Commission for Technology and Innovation by the Federal Office for Professional Education and Technology. In a follow-up project, the data acquired by the track surveying vehicle should be optimised for different applications. The Institute of Geodesy and Photogrammetry of the Swiss Federal Institute of Technology as well as the company Grunder Ingenieure AG will collaborate as further project partners. This paper gives a system overview of the track surveying vehicle and presents first results of two pilot projects which point out the possible fields of applications.

2 Concept of the Multisensor Platform

2.1 System Design

The modular design permits the adaptation for different surveying tasks. It can be divided into a basic configuration *B* and the arbitrarily extendable configurations *P* (positioning) und *S* (scanning). By means of the basic configuration, super-elevation, gradient, chainage, track gauge and temperature can be acquired. Based on these data, longitudinal profiles for vertical deformation measurements and first track quality checks can be carried out. Using the option *P*, the track geometry can be obtained by means of RTK-GPS or tracking tacheometers. Applying the option *S*, terrain profiles can be surveyed by fast tracking laser scanners (LMS1, LMS2). Possible fields of applications are the surveying of objects close to the track bed (embankment, catenary posts), the surveying of catenaries and the scanning of tunnel profiles. The data acquisition is laid out for kinematic surveying. All data are acquired synchronically to the PPS pulse of the GPS. The latency of the sensor data (inclinations, track gauge and chainage) with regard to the PPS pulse does not exceed 5 ms. The synchronicity within these data is better than 0.5 ms. If no GPS signal is available (e.g. working with tracking tacheometers), the quality of the synchronicity is worse (depending on the manufacturer’s specification). Fig. 1 gives an overview of the system design. The software „TrackDAQ“ carries out the data acquisition and a preprocessing for the configurations *B* and *P*. The applications “ScanFilter” and “ScanLog” filter and record data of laser scanner profiles.

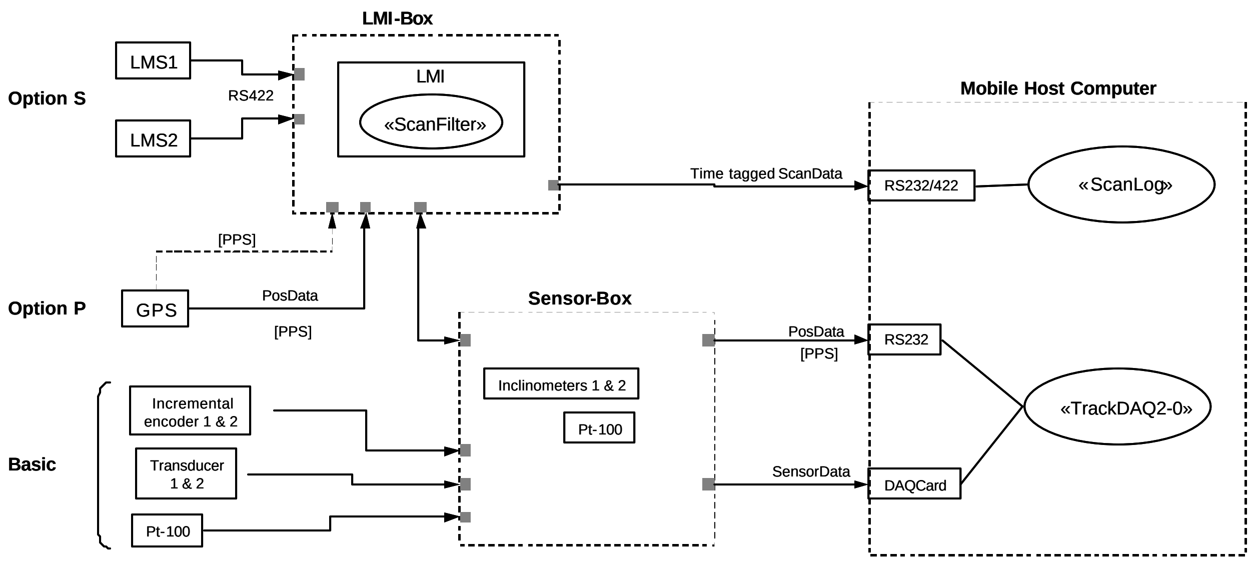

Fig 1: System design of the track surveying vehicle

2.2 Overview of the Sensors

The following table lists the sensor types for the different configurations:

Table 1: Measurement categories and sensors of the track surveying vehicle

	Category	Sensor (Manufacturer)	Range	Resolution
B	Chainage	Incremental encoder (Baumer electric BHL 16.24K2000)	-	0.12 mm
	Super-elevation, gradient	Inclinometer (Midori PMP-S15TA-V1)	± 15°	0.01°
	Track gauge	Angular transducer (Contelec GL 60 / 45°)	1428 - 1480 mm	0.1 mm
	Temperature	PT100	-30°C - 80°C	0.1° C
P	Position	RTK-GPS receiver or tracking tacheometer (*various*)	-	1 mm
S	Terrain profiles	Laser scanner (SICK LMS200-300106)	200° / 8 m 200° / 80 m	0.25° / 1 mm 0.25° / 10 mm

The incremental encoder signals are electronically preprocessed in order to recognize the direction of motion. The rotation counts of the left and right sensor are averaged. Thus, the averaged counts represent the chainage of the track geometry. The inclinometers operate on the basis of fluid-damped pendulums. Additionally, the sensor box temperature and the ambient temperature are recorded. The track gauge is measured by the angle position of two dragging mechanical scanners. The longitudinal dilatation of the vehicle due to temperature variations is considered for the track gauge measurement. For positioning, RTK-GPS receivers or tracking tacheometers can be used, alternatively. If tracking tacheometers are applied, care has to be taken regarding the uncertainty of the synchronisation of direction and distance measurements. Depending on the direction angle and the velocity of the vehicle, large differences can occur due to this uncertainty [Stempfhuber et. al., 2000]. The used laser scanners (LMS) deliver profile data with a high resolution and a scan rate of up to 75 Hz. They can be configured for different ranges, angular resolutions and scan angles. The scan data are processed on a special micro controller device and tagged by the PPS pulse.

2.3 Concept of the Data Processing

The data treatment is divided into three steps. Step I contains the data acquisition and first data checks which are carried out online. The level II processing encloses the reduction of the acquired data into a consistent reference frame. In a third step, it is foreseen to deduce project specific parameters as optimised track geometries.

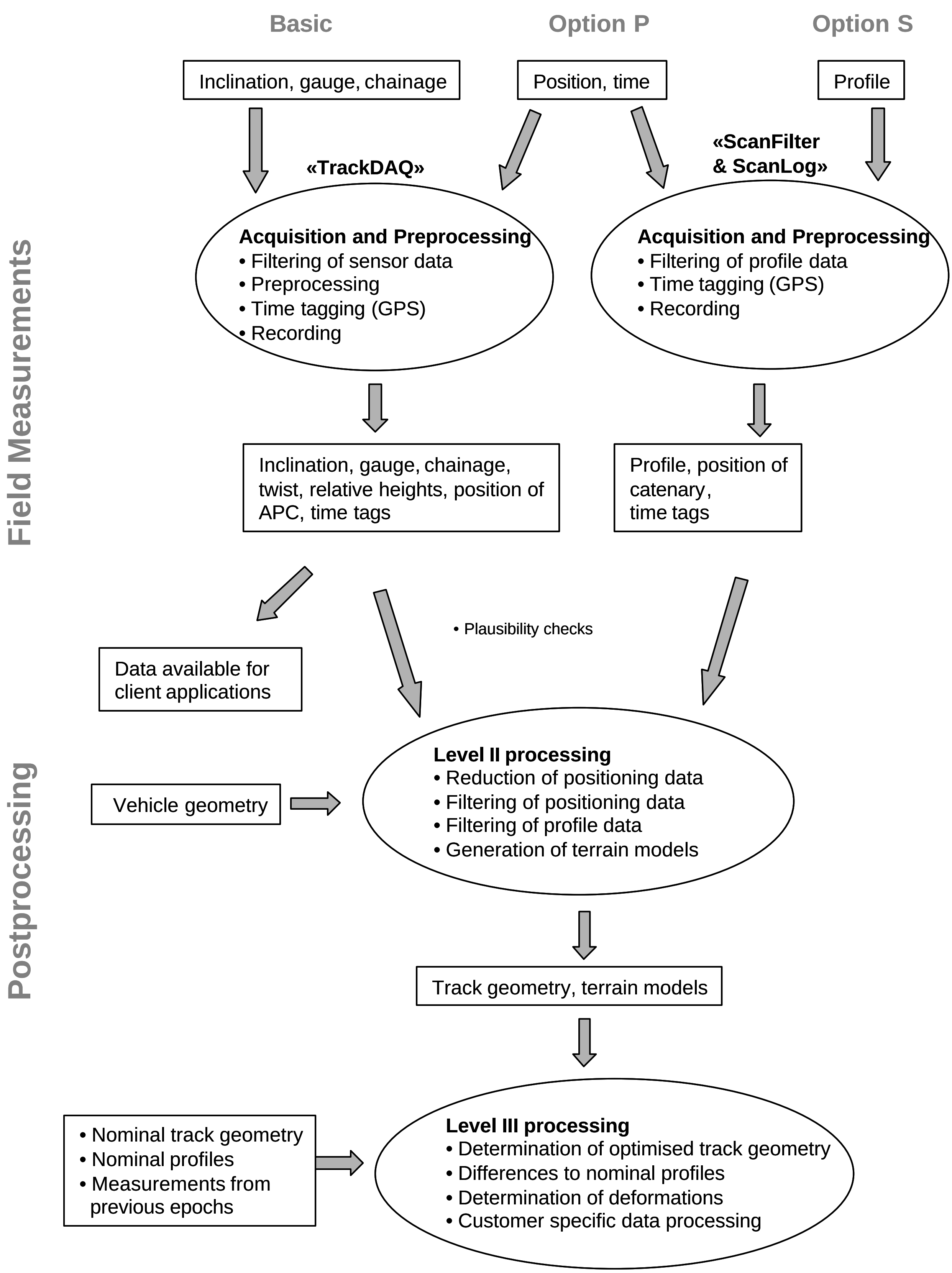

Fig 2: Data processing concept

3 System Performance

3.1 Inclination Measurements

The main error source of the inclination measurements in the static mode is the temperature characteristic of the sensor. For this reason, both sensors are placed in an isolated box. The box temperature is held on a constant temperature of 60°C. Thus, the error due to temperature variety can be minimised and neglected for the inclination measurement.
Other parameters affect the precision applying kinematic surveys. For the super-elevation measurements, the influence of the centripetal acceleration can be neglected. Its contribution is not significant for the reachable velocities. However, for gradient measurements, the translatory acceleration has to be considered. This is realized by means of the odometer recordings. The most significant influence variables for kinematic measurements are the behaviour of the sensor during vibrations and shocks as well as the linearity of the inclinometer dynamics.

Table 2: Specification of inclinometers

	static	**kinematic**
Inclinometer		
Linearity	< 0.5 % [1)]	
Sensitivity	< 0.01° [1)]	
Temperature stability (-20...80°C)	< 1.125° [2)]	
Super-elevation		
Standard deviation	0.003 gon	0.05 gon
Gradient		
Standard deviation	0.003 gon	0.1 gon [3)]

[1)] specification according to manufacturer
[2)] No temperature drift since sensor box is temperature stabilized (60°C ± 1°C).
[3)] Inclination after compensation of odometer measurements

3.2 Track Gauge Measurements

The track gauge is determined as a function of the angular position of two dragging mechanical scanners. For the speed of operation of the vehicle (up to 3 m/s), this method is adequate. Furthermore, compared to contact-free laser sensors, the used sensors are considerably cheaper. Temperature dilation of the aluminium frame is considered by means of the ambient temperature measurement. Applying the dilatation coefficient of aluminium (24 ppm/°C) to the 1.4 m base, differences of up to 1 mm can occur considering ambient temperatures differing significantly from the calibration temperature.

Table 3: Specification of the track gauge measuring system

Angular transducer	
Linearity	0.25 % [1)]
Repeatability	0.1° [1)]
Temperature stability	50 ppm / °C [1)]
Track gauge measurement	
Standard deviation	0.5 mm

[1)] specification according to manufacturer

3.3 Chainage Measurements

Systematic errors are caused by an inappropriate scale factor determined from the wheel diameter. An uncertainty of 0.04 mm for the diameter determination results in a systematic error of 200 ppm. However, slippage and dirt on the wheels have a considerably larger impact on the resulting accuracies. For the field measurements carried out yet, drift values laid around 0.1 %.

Table 4: Specification of odometers

Incremental encoder	
Resolution per rotation	8000 ($\triangleq$ 0.08 mm)
Diameter: approx. 200 mm	
Chainage measurement	
Standard deviation	< 0.2 %

3.4 Laser Scanning

The used laser scanners work according to the principle of the transmission time determination of a modulated pulse. The scan angle, the angular resolution and the range can be configured individually. The beam widening amounts up to 0.25°.

Table 5: Specification of laser scanners

Laser scanner SICK LMS-200	
Angular resolution	0.25° / 0.5° / 1.0° [1)]
Range	8 m / 80 m (max.)[1)]
Distance resolution	1 mm / 1 cm [1)]
Standard deviation (1..8 m, mm mode)	15 mm [2)]
Standard deviation (1..80 m, cm mode)	40 mm [2)]

[1)] specification according to manufacturer
[2)] Ambient conditions: clear sight, T=23°C, remission: 10%..10000%

4 Applications

4.1 Surveying of Track Geometries

In the context of the update of the database for fixed assets of the Swiss Federal Railways (SBB), the track geometry between Giubiasco and Locarno (Switzerland) had to be surveyed with an accuracy of 5 cm for the horizontal and the vertical component. This assignment was carried out using the track surveying vehicle extended by the option *P*. Track gauges, odometer readings as well as super-elevations and gradients were recorded with a sampling rate of 20 Hz. For positioning, a GPS-RTK receiver Trimble 4700 was used on the vehicle. The GPS base station, equipped with a Trimble 4000SSi receiver, was situated up to 5 km away from the track. The base station provided phase and code data with a sampling rate of 1 Hz. The determination of the phase ambiguities was done “on the fly”. Totally, 18 km of tracks were measured forth and back. In order to guarantee the relative accuracy to the reference network, a benchmark was measured every 500 m by a second rover receiver. 10% of the GPS measurements were affected by obstructions. These sections had to be surveyed in a second phase by means of tacheometry.

In order to fulfil the required accuracy, the data had to be postprocessed. For velocities around 1.5 m/s, it can be assumed that the data are sufficiently synchronized. As mentioned in chapter 2.1, the inclination measurements of the pendulum sensors are superposed by disturbing accelerations. The gradients are particularly affected, which are superposed by frequency contributions caused by pushing the vehicle. This is outlined in fig. 3 showing the amplitude spectrum of the gradients of a section of the track survey. Contributions of 0.9 Hz and 1.8 Hz are found which can be attributed to the vehicle pushing. Thus, the step frequency amounts to 2 Hz. The vehicle perceives after two steps or 1 Hz a similar acceleration.

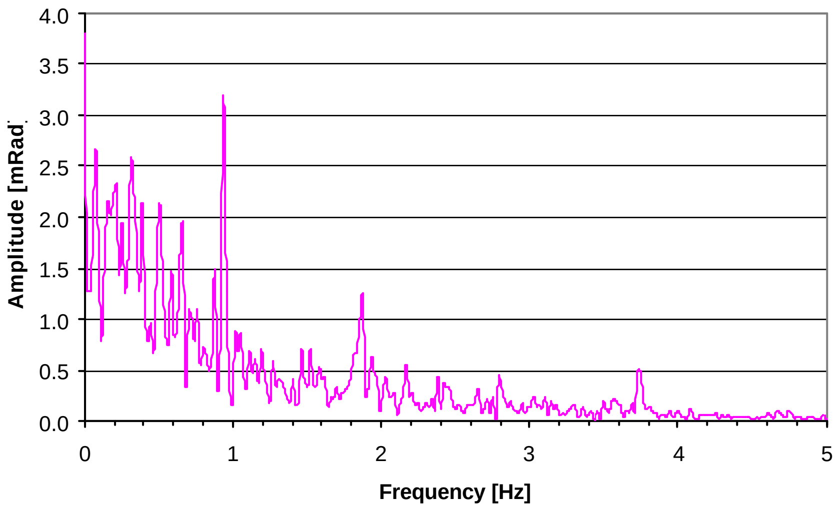

Fig. 3: Amplitude spectrum of the untreated gradient measurements

The inclination measurements can be freed from these accelerations considering the odometer readings. Subsequently, both the gradient and the super-elevation measurements are smoothed by a moving average filter. Figure 4 shows the raw and filtered gradients. The short period contributions could be eliminated.

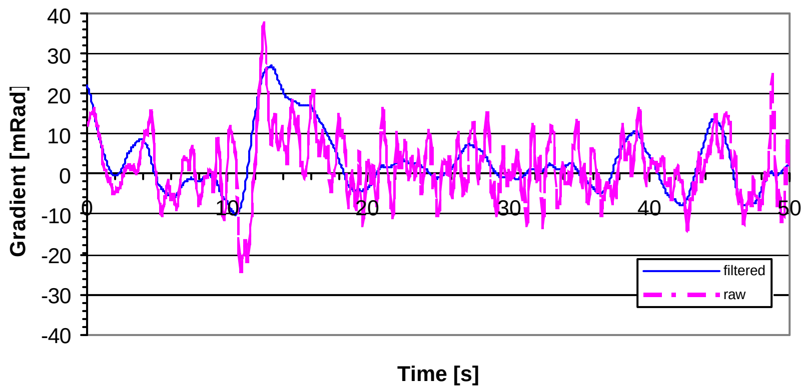

Fig. 4: Raw and filtered gradient measurements of a 75 m track section

A comparison between the odometer readings and the chainage deduced from GPS permitted a determination of drift parameters of the odometers. The drift factors laid between 0.8 m/km and 0.9 m/km for three track surveys.

By means of the odometer readings and the gradients, height differences can be calculated. Generally, these differences reveal a smoother distribution than GPS height differences. However, the inclinometer measurements show temporally varying drift effects. Thus, instead of global drift parameters, the GPS heights were locally adapted by a symmetric smoothing filter applied to the differences between GPS heights and inclinometer heights.

The track survey in forth and back direction permits an independent control on the one hand. On the other hand, the precision can be improved by averaging both trajectories. For averaging, the distances of the forth trajectory to the corresponding chord of the back trajectory were calculated and averaged. This simplification is valid even for small radii. For a chord length of 1.5 m and radii of 300 m, the error is smaller than 1 mm. Table 5 shows the deviations of the forth and back survey from the averaged trajectory. The height deviations refer to the smoothed heights. Smoothing by using the inclinometer measurements improved the height accuracy by a factor of 1.5.

Table 6: Deviations of the track surveys from the averaged trajectories

Track section	D_{Hor} **[m]**	s_{DHor} **[m]**	D_{Ver} **[m]**	s_{DVer} **[m]**
Cadenazzo – Giubiasco (south)	0.004	0.015	-0.008	0.038
Cadenazzo – Giubiasco (north)	0.006	0.015	-0.002	0.020
Cadenazzo – Locarno	0.005	0.016	0.005	0.025

The transformation of the horizontal component of the trajectory into the reference network was done by a Helmert transformation using the measured control points. The vertical component was corrected for the geoid undulation and transformed into the reference system applying a height shift and two tilt parameters. Then, for each trajectory point a correction vector could be linearly interpolated based on the residual field. Residuals of vicinal control points were deweighted by an exponentially decaying covariance function [Carosio, 1980]. This procedure guarantees an optimal neighbouring accuracy with respect to the given distorted reference frame.

4.2 Staking out of the Slab Track

Nowadays, for new high-speed railway lines, slab track technology is frequently used. Contrary to the ballast track with a swimming bed, the connection of the slab track and the underground is rigid. The advantages of this type of construction are the low costs, considering the whole life cycle of tracks, the favourable riding quality at high velocities, the low maintenance and therefore the high track availability. Adaptations to the track geometry after paving over are only possible with additional expenditure. Therefore, the installation of the rails has to be done accurately. Consequently, the accuracy requirements for staking out are very high. Typical tolerance specifications are listed below.

- Horizontal and vertical tolerance: 3 mm
- Tolerance for sagitta of a 5 m chord: 2 mm
- Tolerance for super-elevation: 2 mm
- Tolerance for twist: 0.05 % for a base of 1 m

The main difficulty using a polar measuring system is the completion of the sagitta error. In order to fulfil this tolerance, points have to be staked out with an accuracy (1 sigma) of 0.4 mm.

Compared to new ballast tracks, where a high degree of automation has been reached thanks to tamping machines, the construction process of slab tracks is associated with a lot of hand-labour. By the use of track surveying vehicles, a contribution to the automation can be given by surveyors. For the construction of the slab track of the high speed line “Cologne –

Frankfurt", a track measuring vehicle with correspondent software was used successfully [Ablinger, 2001, Dünisch et al., 2001]. For the installation of the slab track in the "Zürich – Thalwil" tunnel, it is foreseen to use the Burgdorf track measuring vehicle. Starting from a sufficiently accurate reference network delivered by the orderer, the track geometry is staked out by a tacheometer and the track measuring vehicle. This is made possible by the software "GriPos" based on the data acquisition module "TrackDAQ". The tacheometer is remotely controlled by the vehicle. After a first initialisation measurement, the telescope of the tacheometer can be orientated to the prism mounted on the vehicle any time by the odometer readings and the nominal geometry parameters. By means of the super-elevation and the gauge readings, the reflector coordinates can be reduced to the track axis. A comparison with the nominal geometry provides deviations for the cross component, the heights of the left and right rail and the gauge. Corrections of 1/10 mm can be applied with the rail alignment system. In order to minimise the influence of the distance uncertainty, lines of sight along the track axis have to be observed. Following this constraint, it is sufficient updating distances every five seconds. Hence, using LEICA tacheometers, the standard EDM mode can be applied.

A survey of the track geometry in the submillimetric range requires the knowledge of the relative position of the involved sensors within 1/10 mm. The rail scanners can be controlled by using a calibrated staff. The determination of the staff attached on the vehicle with respect to the prism as well as the determination of the prism with respect to the rail level were done by spatial intersections from totally six theodolite stations. The scale of the survey was given by subtense bar measurements. The industry measuring system Axyz from LEICA was used which allows for an online quality control. The standard deviation of one coordinate laid around 0.15 mm. In addition, the determination of the index error of the inclination sensor is done by measuring the two faces.

First field tests revealed that the fulfilment of the required tolerances is possible. Check points were surveyed on a holding siding by the track surveying vehicle and a LEICA TCRA 1101 tacheometer. The coordinates were compared with the nominal values acquired by the TCRA 1101 and a rail adapter. Eccentricities of the rail adapter could be eliminated by a symmetric measurement layout. For points with lines of sight along the track axis, the required accuracies of 0.4 mm could be fulfilled. However, for a distance dominating track determination, accuracies up to 1 mm were obtained.

5 Conclusions and Outlook

By means of the track surveying vehicle, various tasks can be solved in the context of rail construction. Thus, the used sensors allow for staking out slab tracks in the submillimetric range. This was confirmed in first field tests.

The kinematic positioning of the vehicle by GPS provided accuracies in the range of 1.5 cm for the horizontal component. The accuracy of the vertical component was worse by a factor of 1.5. The vertical component was smoothed applying the height differences achieved from the inclinometer and odometer readings. Better results can be obtained by using optimal smoothing algorithms. [Retscher, 1996] applied for the optimal estimation of track geometries the method of collocation reducing the measurements by trend functions gained by the nominal geometry. The covariance function of the signal was determined on the basis of simulations and verified by real data sets. The signal can be taken by the deviations of the actual from the nominal geometry.

For the determination of track deviations in the subcentimetric range, apart of optimal filters other sensors have to be used. These sensors should be able to bypass sections without GPS reception. An interesting solution represents the tacheometer TRIMBLE ATS600pro. The vehicle equipped by an active prism is kinematically surveyed by the ATS600pro. The deviations evoked by the non-synchronicity of distance and direction measurements is reduced by interpolating the previous and the succeeding direction to the time tag of the distance measurement. Field tests for vehicle velocities up to 1.5 m/s revealed that the deviations laid within 1 cm even for bad configurations.

In the context of the follow-up project, the application of INS will not be contemplated due to financial reasons. Other approaches of measuring yaw rates and the integration along the track are conceivable. The feasibility of these approaches should be studied in the follow-up project.

6 References

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