Development of the Kinematic Crane-Track-Surveying-System „RailControl“ – Reducing Operational Interruption of Crane Tracks

Entwicklung des kinematischen Kranbahnvermessungssystems „RailControl“ – Reduzierung von Stillstandszeiten bei Kranbahnen

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Repair work of crane tracks leads to expensive operational interruption for the operating company. The decision, if or when the repair work is necessary, is among others based on geodetic measurements, which make a set-actual comparison of the crane rail geometry essential. In this contribution, the development of the automatic Crane-Track-Surveying-System (CTSS) „RailControl“ is presented. In order to reduce the non-operation periods of cranes during the monitoring process a kinematic measurement method was developed. Furthermore, the CTSS allows the identification of the deformations of the track rails during crane movements (without and under additional load). The contribution shows the system architecture, and the general data processing steps. It will be shown, that the measurement configuration in combination with a refined adjustment concept provides the required geometrical information very accurately and detailed with minimum rest periods for the operating cranes.

Keywords: **Crane track surveying, rail surveying, kinematic measurement methods, quality**

Die Reparatur von Kranbahnen führt zu kostenintensiven Produktionsunterbrechungen für den Betreiber. Die Entscheidung, ob eine Reparatur notwendig ist, basiert unter anderem auf geodätischen Messungen, die einen Soll-Ist-Vergleich der Kranbahnschienengeometrie ermöglichen. In diesem Beitrag wird die Entwicklung des automatischen Kranbahnvermessungssystems „RailControl“ geschildert. Für eine Reduktion der Stillstandzeiten von Kranen wurde ein kinematischer Messprozess für die Überwachung von Kranbahnen entwickelt. Des Weiteren ermöglicht das Kranbahnvermessungssystem eine Identifikation der Kranbahnschienengeometrie während der Kranfahrten (ohne und mit zusätzlicher Last). Dieser Beitrag erläutert die Systemkonstruktion und die generellen Schritte der Datenanalyse. Es wird gezeigt, dass die gewählte Messkonfiguration im Zusammenspiel mit einem durchdachten Ausgleichungskonzept die benötigten geometrischen Informationen sehr genau und detailliert zur Verfügung stellt und zugleich die Stillstandzeiten für Krane minimiert.

Schlüsselbegriffe: **Kranbahnvermessung, Gleisvermessung, kinematische Messverfahren, Qualität**

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1 Introduction: Set-actual comparison of crane track rails

According to the German VDI-Guideline 3576, comparable to ISO 12488-1, „…the proper installation of the rails is a prerequisite for a trouble-free operation. Repairs on rails cause high costs and prolonged rest periods“ [VDI 3576]. The ThyssenKrupp GfT Gleistechnik GmbH in Bochum, an international contractor of crane rails, crane tracks, crane rail fastening systems and other track systems has developed a new crane runway girder in close collaboration with the Hamburger Hafen und Logistik GmbH (HHLA) CT Bautechnik. The new crane track consists of pre-fabricated segments of concrete. Their height with respect to the underground can be modified over time, e. g., due to deformations caused by an unstable underground. Together with the Engineering office „Hanack und Partner“ from Hamburg, an automatic monitoring concept for the new crane track, which can be applied to any type of rail, has been developed. It comprises the automatic Crane-Track-Surveying- System (CTSS) *„RailControl“*, which is described in the following. ThyssenKrupp GfT Gleistechnik applied for a patent of this invention.

The Geodetic Institute (GIH) of the Leibniz University of Hanover and the Geodetic Laboratory of the University FAF Munich significantly contributed to the development of the CTSS. *„RailControl“* allows the verification if the actual geometrical conditions comply with the requirements of the crane track with respect to defined tolerances, e. g., in VDI 3576. The aim of the system is the reduction of non-operation periods of the cranes during the survey. Additionally, an automatic data flow shall assure the actuality of the sampled data and make an in situ validation of, e. g., repair work possible. In order to compare periodical measurements, the geometrical information of the rails has to be connected to a subordinate coordinate system. This also allows analyzing adjacent rails of crane tracks, e. g., in order to obtain the track centre distance. The detailed requirements of the analysis concept have to be conform with VDI 3576, DIN 4132, ISO 12488-1 and ISO 8306. Some comparable informations and guidelines for North America can be found in [STRUCTURAL ENGINEERING, 2011].

The geometrical conditions of the rails are of high importance for the total service life of a crane track system. Deformations of the rail lead to wear of the rail and stress of the crane. This concerns, if existing, the flanges of the wheels of the crane, the entire crane construction, the rail fastening material and the track itself (e. g., steel supports, reinforced concrete foundations, etc.). The crane can also be switched off when tolerances are not satisfied; either manually or automatically. If worst comes to worst, a rail or wheel breakage may happen and the crane derails or tilts over. Knowledge about the geometric situation of the rail makes the analysis of the causes of the increased abrasion easier. It should be noted that, of course for the optimum combination of wheel and rail, the position of the wheel sets has to be reviewed. The accuracy requirements for this are defined in ISO 12488-1 as well. The mentioned guidelines are not obligatory by law. The guideline for each survey has to be jointly agreed between the operating company, and the manufacturer of the crane and the track. Whereas the VDI 3576 is mostly used in Germany, in the other countries of Europe, the ISO 12488-1 is prevalent. In case of a long experience with the technical underlying data of a crane track and for exceptional cases, the tolerances can also be specified between the operating company and the manufacturer without using guidelines. In case of automatic and economic positioning of goods, e. g., for high bay warehouses or automatic container terminals an accurate condition of the crane track rails is mandatory. During the total service life of a crane the VDI 3576 distinguishes between production tolerances and operational tolerances. Operational tolerances can be twice of the production tolerances and should be jointly agreed between the manufacturer and the operating company of the cranes.

2 State of the art and potentials in crane rail surveying

Since the last decade, the development of the (geodetic) instrumentation and measurement methods is rapidly proceeding. Especially, the kinematic measurement methods open up new economic and accurate possibilities for the determination of geometric object informations. In this contribution, a kinematic measurement method means a moving target or object that is continuously observed over time by a geodetic instrument. The instrument itself is placed on a fix standpoint. The 3D-coordinates of the observed object are determined over time by angle and distance measurements of the instrument (tacheometer). The z-coordinate is defined in plumb line direction. In the following, the key word „horizontal“ means that values are on a surface, which is perpendicular to the plumb line.

The state of the art of rail surveying varies largely. Whereas the systems in railroad surveying [GLAUS, 2006 and HEISTER et al., 2007] can work fully automatically, crane track surveying is highly staff- and time-consuming [Baumann, 2004]. Therefore, the automatic CTSS *„RailControl“* is developed. It allows in comparison to the above mentioned systems the monitoring of a single rail, which is essential for crane tracks (see Figure 1). Railroad surveying is not concerned in this paper, the reader is referred, e. g., to [GLAUS, 2006] for an overview and for further details.

Geodetic measurement techniques (Engineering Geodesy) play a key role in the quality management of crane tracks, especially for the rails of crane tracks [KLEIN and SCHULZ, 2001]. Up to now, many or even most of the crane rail surveys were carried out manually. One of the first automatic CTSS was developed by DEMAG Cranes & Components. The System consists of a radio controlled, self-propelled gauge trolley which is observed by a self leveling alignment laser. According to [DEMAG-CRANES, 2010], the principle is based on the determination of the laser point on a position sensitive device carried by the gauge trolley. The hold system is controlled by a radio modem and a notebook. Since 2010, the Finnish company Konecranes offers a solution for crane rail surveys called RailQ that is similar to the solution of *„RailControl“*. RailQ is „…a laser survey technique that typically utilizes a proprietary remote controlled robot trolley, Roborail, which runs along the rail collecting and feeding information to a total station laser tachymeter“ [KONE-CRANES, 2010]. The development of the here described CTTS *„RailControl“* began in 2006 and reached the here presented development status in 2009.

The benefit of the described systems is manifold. On the one hand, the distance in-between two measurements of the rail is more detailed than the standard surveying methods. On the other hand, the kinematic measurements al-

Figure 1: The Crane-Track-Surveying-System (CTSS) „RailControl“.

low a very fast acquisition of the required data. If a high accurate determination of the rail geometry is necessary, the above mentioned three CTSSs can be operated in a stop and go mode, whereby the moving trolley stops for each executed measurement. This allows static measurements which are more accurate than the kinematic ones. Some relevant characteristics and specifications of the above mentioned CTSSs are shown in Table 1. All values shall give an order of magnitude to the reader and depend in detail on the respective application. Furthermore, detailed informations of the systems are hardly accessible. The main difference is in the measurement method. Whereas the DEMAG-System can only operate in a stop and go modus, the two other systems can also be operated in a kinematic mode. In addition, the CTSS RailControl allows the measurements when the crane pulls or pushes the vehicle (see Section 4 for details).

For a complete review of existing methods for the monitoring of crane tracks one should also mention the possibility to use terrestrial laserscanning (Kremen et al., 2008). The main benefit of terrestrial laserscanning lies in the high point density and the areal based information of the rail geometry. But this will also lead to a problem in extracting the reference edge of the rail from the scanning points, especially in case of wear of the rail. Furthermore, the accuracy and quality of the measurements has to be checked carefully. It depends on the surface of the rail and on the incidence angle of the laser beam on the rail.

3 Hard- und Software of the CTSS

In the next sections, the descriptions focus on the CTSS „RailControl“. It is independent from the electricity network and consists of a remote-controlled vehicle (trolley) with a prism which is observed continuously over time by a tacheometer (see Figure 1 and 2). The tacheometer itself is controlled by a notebook on which also the analysis software for all measurements is installed. The monitoring vehicle has a battery powered motor and a two-axis inclinometer on board (see Figure 3). The measured inclinations are in longitudinal (α) and in cross direction (β) of the rail. Optionally, two ultrasonic distance sensors are adaptable. The two prisms are necessary to measure the rail geometry from both ends of a crane track without turning the monitoring vehicle around. The sampled data of the inclinometer and of the ultrasonic distance sensors is transferred wirelessly to the notebook in order to synchronize it with the tacheometer measurements.

The direct communication between notebook, tacheometer and monitoring vehicle allows an in situ validation of

Table 1: Comparison of the main characteristics of the state of the art CTSSs.

Specification	DEMAG	RailQ	RailControl	Laserscanning
Speed of the robot trolley (measurement method)	stop and go	1 m/s (kinematic) or stop and go	1 m/s (kinematic) or stop and go	No robot trolley
Independence to vibrations of the rail?	NO	YES	YES	YES
Dynamic gauge	YES	YES	YES	—
Accuracy of the vertical and horizontal component (up to max. 50 m)	Not known due to missing references	≥ ca. 1 mm RMS	≥ ca. 1 mm RMS	Not known
Point density	Not known due to missing references	≥ 5 cm (with 1 m/s) depending on the tacheometer and speed of the trolley	≥ 5 cm (with 1 m/s) depending on the tacheometer and speed of the trolley	≤ 5 cm depending on the point density of the laserscanner
Excentric measurements with respect to the rail	NO	YES	YES	YES
Measuring without load	YES	YES	YES	YES
Measuring while operating (with moving crane)	NO	NO (Acceptance due to lack of information)	YES	NO

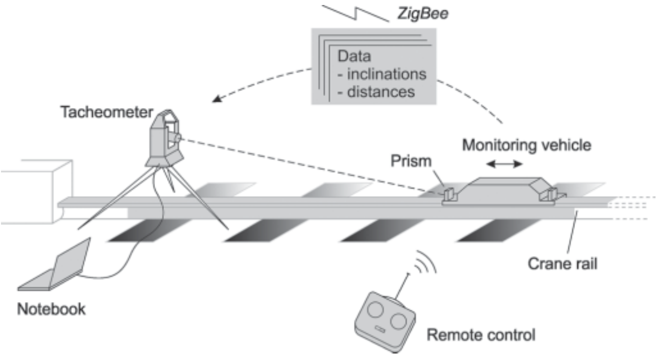


Figure 2: A schematic overview of the components of the CTSS „RailControl“.

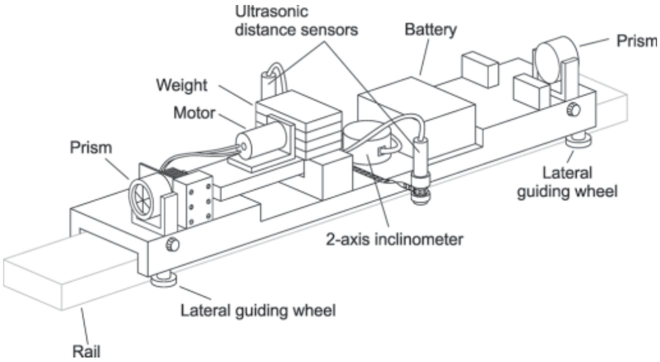


Figure 3: A detailed construction plan of the monitoring vehicle.

the data with respect to the required point density and with respect to mismeasurements and outliers in the data. Then, the analysis software of the system computes the results and checks if the required accuracy of the rail geometry is reached (see Section 5 for details of the analysis process). A graphical interface shows a comparison of the reference values with the actual values of the rail. Additionally, further measurements of the tacheometer can be saved on the notebook, e. g., for the localization of the tacheometer in a subordinate coordinate system (monitoring) or for other interesting geometric information of the crane track.

Due to the remote controlled monitoring vehicle and the digital and automatic communication, the system can be

Figure 4: „RailControl“ monitoring vehicle.

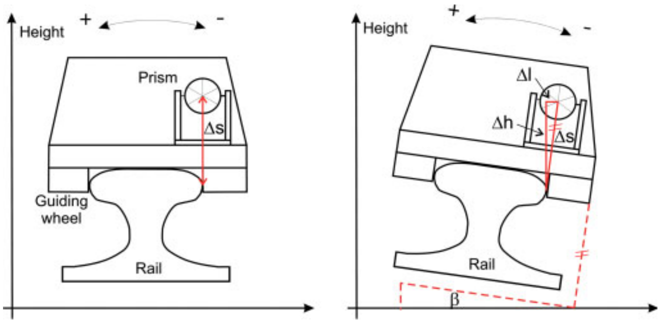


Figure 5: Consequences of a non horizontal monitoring vehicle, after [Schulze, 2009].

operated by only one person. The maximum speed of the vehicle is 1 m/s but it is also operable at lower speeds. With the new generation of tacheometers (e. g., Leica TS30 or Trimble S6/S8) this leads up to 10 values per 1 m rail. The lower the speed of the monitoring vehicle the more detailed and more accurate the rail geometry is. Figure 4 shows a picture of the monitoring vehicle (robot trolley).

In comparison to railroad surveying, an exact guidance of the monitoring vehicle along one edge of the rail is more complex. Additionally, the inclination angle in cross direction (perpendicular to the single rail) varies if the rail is misaligned or has mechanical wear (see Figure 5). This leads to the point, that the prism is misaligned in relation to the reference edge of the rail. The order of magnitude Δl in cross direction depends on the inclination angle β. To overcome these problems, the inclination measurements in cross direction are observed in order to numerically correct these effects. The change in height $(\Delta s - \Delta h)$ can be neglected for angles of $\beta \leq 5\ gon$ to obtain sub-mm accuracy for a basis of $\Delta s \leq 20\ cm$. In a periodic time interval, the mechanical realized position of the prism at the edge of the rail is checked. Therefore, two points of the rail in front and behind of the monitoring vehicle are measured with a track prism adapter. In a horizontal position of the monitoring vehicle, the prism position has to be directly in the straight line of the above mentioned points.

The data acquisition procedure is separated into two parts. Whereas the tacheometer measurements (horizontal direction Hz, vertical angle V, slope distance D) are transferred to the notebook via a cable, the inclinometer measurements require a wireless connection (see Figure 6). The measurement synchronization works in a two step strategy: First, the inclinometer measurements are sampled via a control unit on board of the monitoring vehicle. Second, the measurements from the vehicle are wireless transferred to the notebook, where the synchronization with the tacheometer measurements is realized. For the synchronization, each measurement receives a time stamp onboard of the notebook. Therefore, the measurements of the inclinometer (two axis) and ultrasonic distance sensors are collected packet-wise with the control unit (with a precise internal electronic timer) at a data rate of 10 Hz. The mean duration for the wireless data transfer to the notebook is estimated and corrected. In combination with the applied data transfer technology, the synchronization is better than 0.1–0.2 seconds and therefore acceptable with respect to the moving speed of the monitoring vehicle and the relative slow changes of the observed values. When a connection of the tacheometer measurements to a subordinate coordinate system is required, the analysis software needs the reference coordinates of minimum two points in a data file. The z-coordinate of the tacheometer is usually received trigonometrically. For very high accuracies, a reference point on top of the rail has to be determined by leveling. Furthermore, the reference rail coordinates for the set-actual comparison of the rail are given to the analysis software.

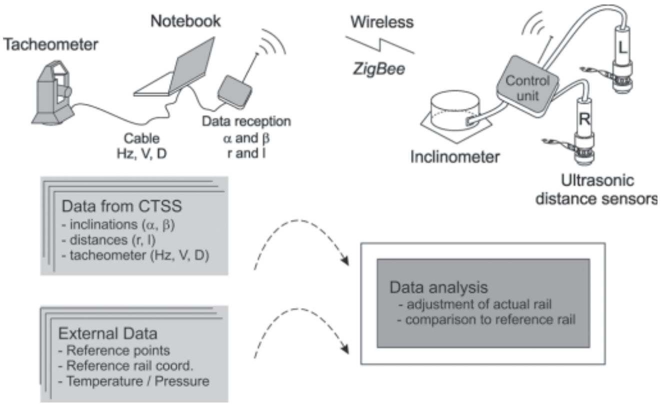


Figure 6: Data acquisition and data flow of the system.

4 Schedule of a kinematic crane track survey

In the first step, the tacheometer is placed at the top end of the rail and the monitoring vehicle is put on the rail. If the rail geometry must be known in a subordinate coordinate system in order to compare periodical measurements, known reference points are observed with the tacheometer (free stationing).

Then, the telescope is pointed on the prism of the monitoring vehicle and the continuous tracking of the prism starts. The tacheometer tracks the prism of the monitoring vehicle fully automatically. The monitoring vehicle is moved from one top end to the other (way there). At the end of the rail, the tacheometer changes to the second face and the prism is continuously observed on its way back to the tacheometer (return way). This specific measurement method eliminates some important instrumental error sources and allows detecting outliers in the measurements.

All measurements are in situ available and the graphical interface of the monitoring software shows a geometrical

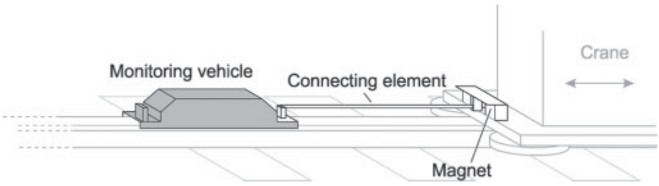


Figure 7: A crane track survey with a moving crane (the crane pulls or pushes the vehicle).

interpretation of all measurement values. The rail can be monitored under three possible conditions:

- Without load (the monitoring vehicle is powered by its own motor, see Figure 1).
- Moving crane (the crane pulls or pushes the monitoring vehicle, see Figure 7).
- Crane under additional load (the crane pulls or pushes the monitoring vehicle and carries additional load)

For the measurements under load, the monitoring vehicle is connected to the crane. The connecting element is spring loaded in order to avoid damage of the vehicle.

5 Data analysis concept

In the first step of the data analysis process, the distance measurements of the tacheometer are corrected due to the actual atmospheric conditions (temperature, air pressure and humidity). Then, the angle and distance measurements to the prism are converted to cartesian coordinates (Hz, V, D → x, y, z).

The main benefit of the data analysis concept lies in the smoothing process of the measurements (see Figure 8). This procedure leads to a very high reliability and accuracy of the rail geometry. In a first step, the measurements of the way there and the return way of the monitoring vehicle are smoothed independently from each other. Then, both ways are averaged in order to eliminate and / or reduce some important instrumental error sources. Additionally, the sensors were calibrated in order to reduce offsets in the measurements. The calibration process of the inclinometer is carried out directly before the practical measurements within two faces (the monitoring vehicle is turned around through 180 °). This procedure is integrated in the analysis software. The relative position of the inclinometer on board of the monitoring vehicle is not necessary due to the reason that the monitoring vehicle is a rigid body.

The ultrasonic distance sensors are used to obtain the height differences of the rail above the crane runway girder (with respect to the concrete surface), e. g., to decide the height modification of the rail due to deformations caused by an unstable underground. The relative position of the ultrasonic distance sensors in longitudinal direction must only be known with cm-accuracy due to the relative slow changes of the rail geometry. They are only operated to detect height differences. Hence, an absolute calibration of the measured distance is not mandatory.

Two strategies for the smoothing process were developed; see, e. g., [Brieden, 2007] and [Schulze, 2009] for details. The first one is a spline based static method, where the rail geometry is modeled with j polynomial approximations to the sampled data. In the transition regions, the j polynomials have to fulfill continuity conditions of zero, first or second order. Zero order means that polynomials have the same functional values in the transition region, first order means that the derivatives are equal (same slope) and the second order stands for the same second derivatives (same curvature). This analysis concept in combination with a robust adjustment is very powerful also in case of a higher number of outliers or mismeasurements during the kinematic measurements. The second strategy is a kinematic analysis with a Kalmanfilter [Schulze, 2009]. The prediction step is based on the actual position with the velocity and the acceleration of the coordinates and the measured two inclination angles. This allows an integrated analysis of the longitudinal inclination and of the z-coordinate in order to obtain a higher accuracy and reliability.

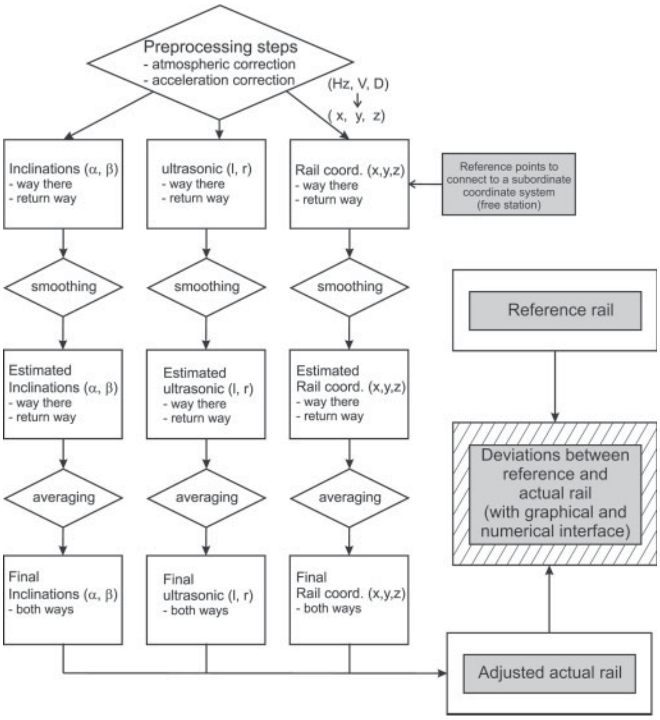
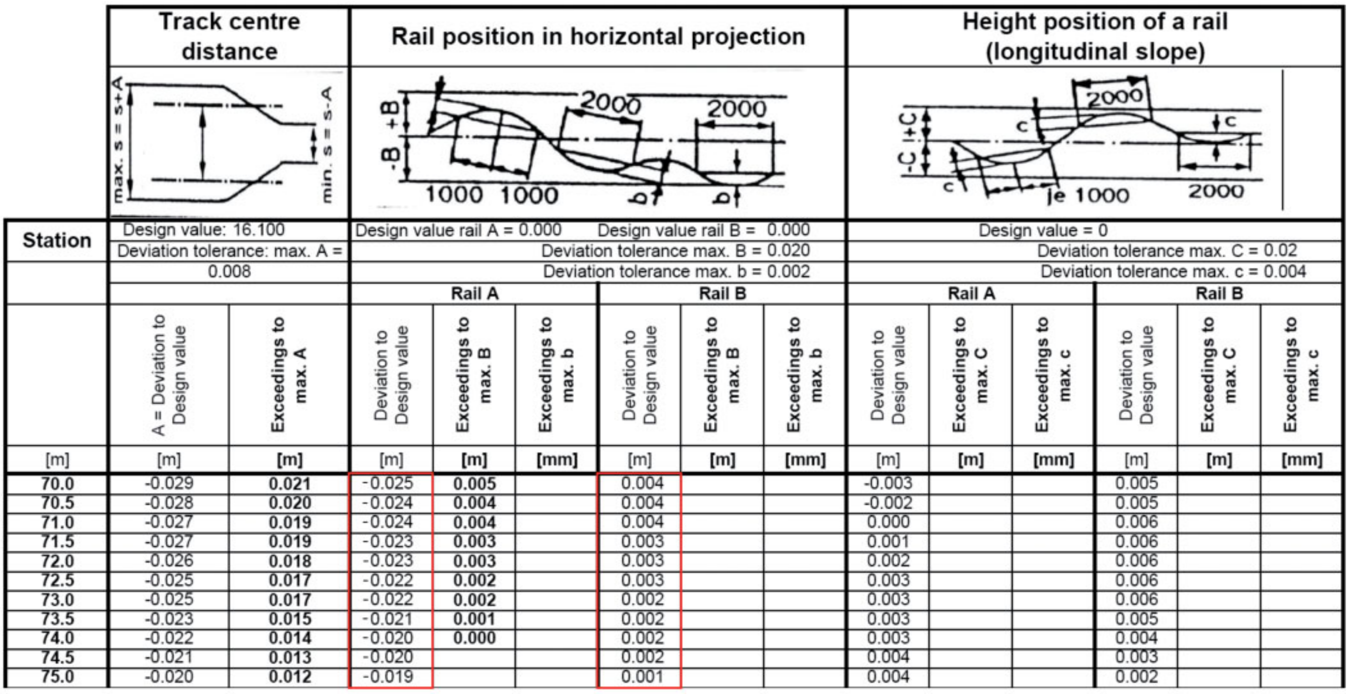


Figure 8: The main steps of the data analysis process.

The influence of the longitudinal accelerations on the longitudinal inclinations is calibrated with a non linear regression analysis with the aid of a known reference rail geometry and a lasertracker to determine the reference values of the vehicle. The more constant the speed of the monitoring vehicle, the more helpful are the longitudinal inclination to determine changes in the z-coordinate. With the speed and the acceleration of the monitoring vehicle in longitudinal direction, the observed inclinations can be used to calculate height differences (changes in the z-coordinate). The inclination angle in cross direction (perpendicular to the single rail) is used to correct the misalignment of the prism in relation to the reference edge of the rail (see Section 3). Due to the complexity of the analysis process, a detailed description of the functional and stochastic model is not part of this contribution. For further details, the reader is referred to [Schulze, 2009].

The final inclinations and coordinates after the smoothing process are corrected due to the effects shown in Figure 5 and explained in Section 3. The interesting deviations between the reference and the actual rail geometry are then displayed to the user with a graphical and numerical user interface of the analysis software. An example for the smoothing process is given in Figure 9 in Section 6.



Station	Track centre distance		Rail position in horizontal projection						Height position of a rail (longitudinal slope)					
	Design value: 16.100 Deviation tolerance: max. A = 0.008		Design value rail A = 0.000			Design value rail B = 0.000 Deviation tolerance max. B = 0.020 Deviation tolerance max. b = 0.002			Design value = 0 Deviation tolerance max. C = 0.02 Deviation tolerance max. c = 0.004					
			Rail A			Rail B			Rail A			Rail B		
	A = Deviation to Design value	**Exceedings to max. A**	Deviation to Design value	**Exceedings to max. B**	**Exceedings to max. b**	Deviation to Design value	**Exceedings to max. B**	**Exceedings to max. b**	Deviation to Design value	**Exceedings to max. C**	**Exceedings to max. c**	Deviation to Design value	**Exceedings to max. C**	**Exceedings to max. c**
[m]	[m]	**[m]**	[m]	**[m]**	**[mm]**	[m]	**[m]**	**[mm]**	[m]	**[m]**	**[mm]**	[m]	**[m]**	**[mm]**
70.0	-0.029	**0.021**	-0.025	**0.005**		0.004			-0.003			0.005		
70.5	-0.028	**0.020**	-0.024	**0.004**		0.004			-0.002			0.005		
71.0	-0.027	**0.019**	-0.024	**0.004**		0.004			0.000			0.006		
71.5	-0.027	**0.019**	-0.023	**0.003**		0.003			0.001			0.006		
72.0	-0.026	**0.018**	-0.023	**0.003**		0.003			0.002			0.006		
72.5	-0.025	**0.017**	-0.022	**0.002**		0.003			0.003			0.006		
73.0	-0.025	**0.017**	-0.022	**0.002**		0.002			0.003			0.006		
73.5	-0.023	**0.015**	-0.021	**0.001**		0.002			0.003			0.005		
74.0	-0.022	**0.014**	-0.020	**0.000**		0.002			0.003			0.004		
74.5	-0.021	**0.013**	-0.020			0.002			0.004			0.003		
75.0	-0.020	**0.012**	-0.019			0.001			0.004			0.002		

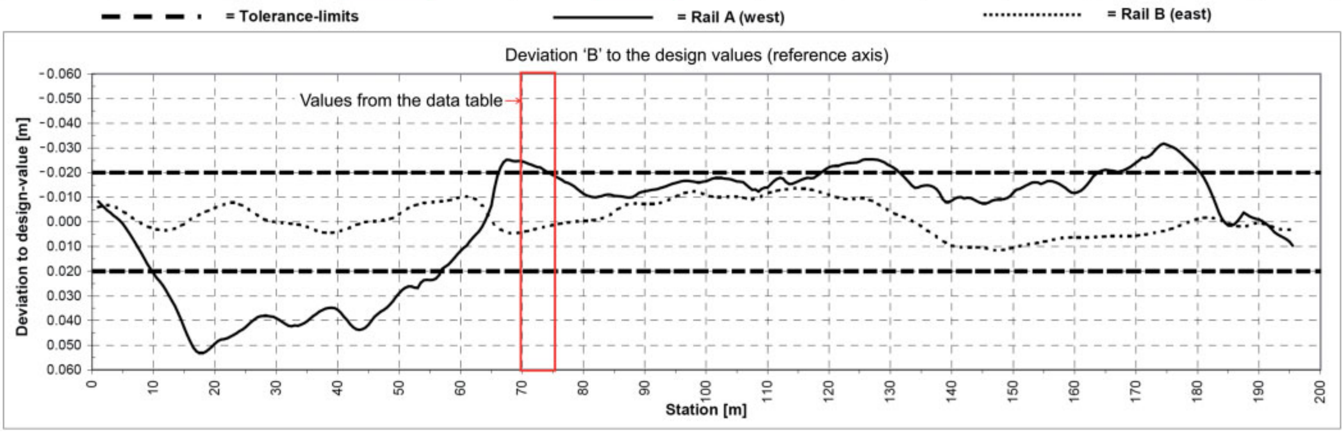


Figure 9: An adjusted rail geometry with a graphical representation of the horizontal projection.

6 Example for a crane track monitoring

The performance of the CTSS *„RailControl“* was extensively tested and validated. It is now used for the monitoring of several crane tracks, e. g., at two container terminals (in Germany), where a VDI 3576 conform survey (class 2) of the crane tracks is requested. In the following, some results of test measurements shall be depicted. The measurements were carried out in a kinematic mode (moving monitoring vehicle). The data was smoothed and averaged from both ways (way there and return way) in order to eliminate some important instrumental errors sources and to have more reliably results. The full documentation includes typically the track centre distance, the horizontal projection, the height position, the height of the opposite rails (transverse slope), the inclination (offset), and the rail tilt. Additionally, a value based table with the deviations of the actual values to the reference values (see Figure 9) is part of the documentation.

The here presented measurements were made under good conditions and with a very accurate tacheometer (Leica TCA 2003). Therefore, the accuracy (as standard deviation) of the coordinates of the rail geometry after the smoothing process is approximately 1 mm for distances up to 150 m and 1,5 mm for the longest distances of max. 200 m. In general, the accuracy of the measured rail geometry depends essentially on the atmospheric refraction, the geometrical measurement configuration, the tacheometer and on the speed of the monitoring vehicle. The lower graphical part in Figure 9 shows the deviations to the nominal position of the rail in the horizontal projection over their full length of 200 m. The solid line represents the rail A and the dashed one the rail B. The results can be delivered in different intervals, as requested by the operating company. Here, the deviations are exemplarily shown in 0.5 m intervals. The red rectangles show the values for the stations from 70–75 m.

7 Final remarks and some characteristics of the CTSS „RailControl“

The maximum measurement range of the CTSS *„RailControl“* is approximately 400 m to obtain mm-accuracy (depending on the atmospheric refraction and on the geometrical measurement configuration). Longer rails are observed from different standpoints of the tacheometer which are connected to the subordinate coordinate system. The main benefits in comparison to existing CTSS can be summarized as follows:

- Very fast kinematic measurements (approximately 1 m/s) with very short operational interruptions of the cranes.
- Simultaneous determination of the rail geometry and inclination of the rail in longitudinal and cross direction
- The rail geometry can be connected to a subordinate coordinate system.
- Graphical and numerical software interface for an in situ check of the measurements, e.g., for outliers and for the obtained accuracy (including a comparison of the reference and actual values of the rail geometry).
- Very high point density of the rail geometry (up to 10 readings/m or even more, depending on the speed of the monitoring vehicle and on the data rate of the tacheometer).
- Applicable in very bad accessible areas, e.g., for overhead travelling cranes.
- Applicable for all common flat-bottom rails, crane rails and rectangle steel profiles
- Outstanding performance in case of adjacent rails (container terminals, high bay warehouses, etc.)

The high quality analysis procedure considers continuity conditions for a better description of the crane rail geometry (see Section 5 and 6 for more details). With the rapid developments in automatic positioning of goods in, e.g., container terminals, the potential applications of kinematic CTSSs will significantly rise in future.

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