EVALUATION OF THE CONTROL QUALITY FOR TACHYMETRIC CONTROLLED VEHICLES

Otto LERKE, Dipl.-Ing., University of Stuttgart, Institute of Engineering Geodesy, otto.lerke@ingeo.uni-stuttgart.de
Volker SCHWIEGER, Prof.Dr.Ing.habil., University of Stuttgart, Institute of Engineering Geodesy, volker.schwieger@ingeo.uni-stuttgart.de

***Abstract**: This contribution presents the application of a new method for the evaluation of the control quality for vehicles, controlled by robot tachymeters. The method shows in which way a highly accurate measurement system, consisting of a laser tracker and an active target, is used to separate the measurement accuracy from the control quality for a subsequent evaluation. For several years, the Institute of Engineering Geodesy, University of Stuttgart operates a construction machine simulator to evaluate the performance of different sensors as well as filter and control algorithms under laboratory conditions. For this purpose a model truck (scale 1:14) is guided on a predefined reference trajectory as accurately as possible. Thereby the lateral control is realized by a PID controller. The root mean square value (RMS) of the lateral deviation between the driven and reference trajectory is called combined measure and is defined as quality criterion. Under laboratory conditions, the simulator achieves RMS values for combined measures of 2-4 mm. These values contain the measurement accuracy and the control quality. An external measurement system, the API Radian laser tracker, in combination with an active target allows to split up the two quantities. Thus the control quality can be evaluated individually. The investigation has shown that the simulator system reaches a control quality of 3,1 mm and a measurement accuracy of 2,9 mm.*

***Keywords:** Closed-Loop-System, Control Quality, Construction Machine Simulator, Laser Tracker, Active Target, Robot Tachymeter.*

1. Introduction

Automatically controlled construction machines have obtained great importance on construction sites (Mayer 2003). Automation is a modern mean to improve the efficiency and product quality in road construction and maintenance (Kilpeläinen et al. 2011). The developments yield benefits regarding the reduction of expenses and the increase of efficiency (Heikkilä and Jaakkola 2003, Gläser et al. 2008). Partly or fully automated systems can be categorized according to the degree of automation (Stempfhuber and Ingensand 2008). Thereby the quality and precision of work essentially depend on the machine's or more precise on the machine tool's guidance accuracy. Automatization deals with control and regulation of machines or plants. Therefore the guidance accuracy is directly linked to the control quality.

This contribution investigates the control quality of a model truck in the scale 1:14, which is part of the construction machine simulator that has been developed at the Institute of Engineering Geodesy, University of Stuttgart. The simulator system allows to test and evaluate the performance of different sensors or sensor combinations, as well as filter and control algorithms. The simulator in the present configuration is able to perform lateral control on the model truck, that moves automatically along a predefined reference trajectory. A robot tachymeter is the controlling sensor. For the evaluation a new method is introduced. The laser tracker API Radian is used in combination with an active target as an external measurement system. Transferred on real-life construction machines, the lateral control plays a role e.g. in curb- and gutter applications. In the past the separation of the control quality and the measurement accuracy has been conducted and described by Beetz (2012b). However, the technology consisting of laser tracker and active target was not available to the authors at that time.

2. Methodology

2.1 Simulator Design and Current Configuration

The IIGS simulator system comprises a control computer, a robot tachymeter Leica TCRP1201 in combination with a 360° prism GRZ101, an A/D converter, a remote control and the mentioned model truck.

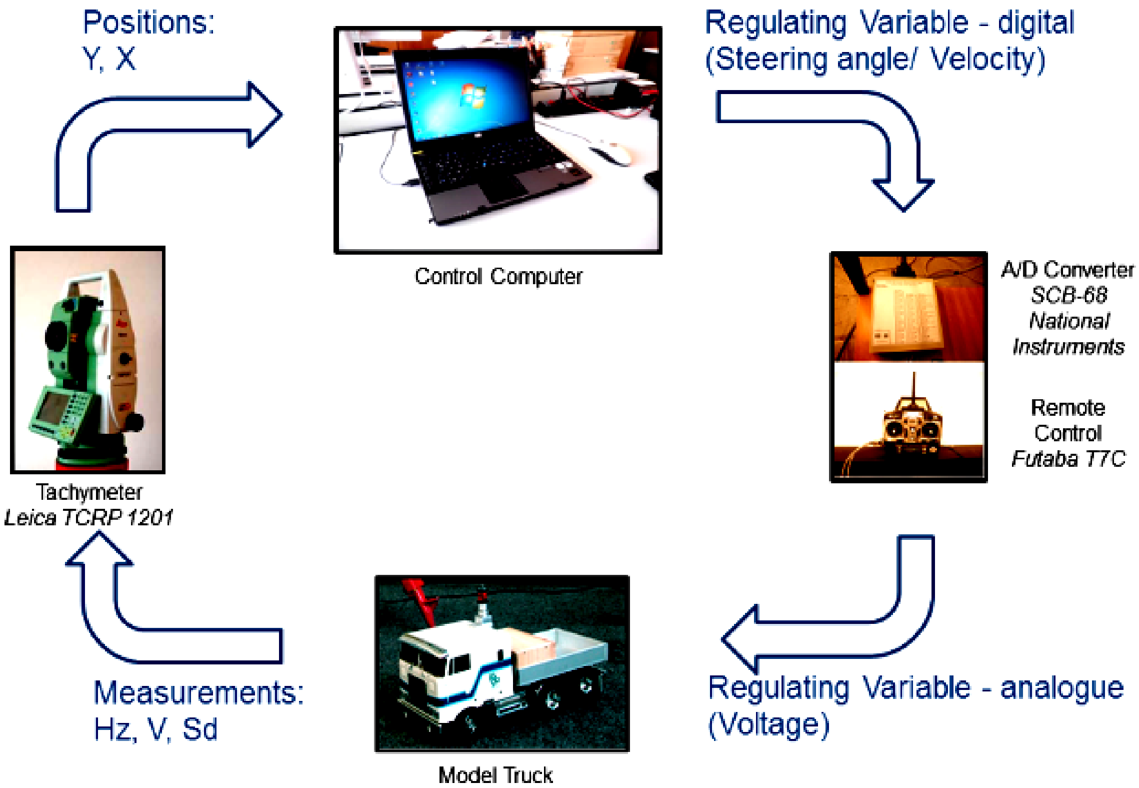


Figure 1: Hardware components of the simulator

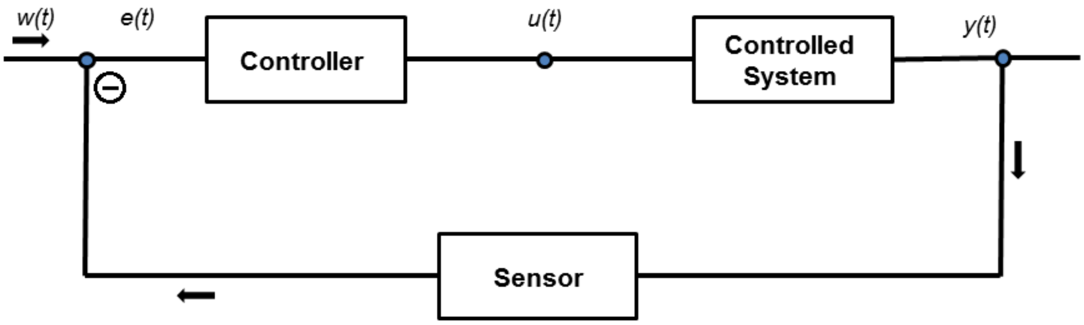


Figure 2: Closed-Loop-System

The control of the model truck is realized by a closed-loop-system. The scheme of the closed-loop-system is depicted in figure 2.

Table 1: Closed-Loop System Variables

Variable	Meaning within Closed-Loop	Appropriate Simulator Item
w(t)	reference variable	reference trajectory
e(t)	control deviation	lateral deviation between reference trajectory and actual position
u(t)	regulating variable	steering angle
y(t)	controlled variable	position

The loop performs as follows: the tachymeter measures the position of the prism y(t), mounted on the truck and sends it to the control computer. The computer calculates the perpendicular distance/ lateral deviation e(t) between the truck position and the reference trajectory. Based on this information, the algorithm calculates the best steering angle u(t) to get the truck back on the reference trajectory as fast as possible. This sequence is executed 8 to 10 times per second. This rate is mainly depending on the kinematic measurement ability of the used tachymeter. According to the instrument's data sheet the rate is between 8 and 10 Hertz (Leica, 2015b).

2.2 PID-Controller

In the present investigation a PID-controller is used within the closed-loop system. The PID-controller consists of 3 base parts: proportional term, integral term and derivative term. Each term has a specific behaviour as well as specific advantages and disadvantages. Detailed information on controllers and their characteristics can be found in Busch (2012) or Mann et al. (2005). In the following the 3 base terms will be briefly summarized.

The proportional term is described by the following formula (Busch, 2012):

$$x_{outP} = K_p \cdot x_{in}, \qquad (1)$$

K_p – proportional gain,
x_{in} – input signal,
x_{outP} – output signal.

The integral term is defined by the following expression (Busch, 2012):

$$x_{outI} = K_I \cdot x_{in} \cdot \Delta t + x_{out0}, \qquad (2)$$

K_I – integral gain,
Δt – time difference between evaluation point and integration point
x_{out0} – initial value of the output.

The derivative term is expressed by the following equation (Busch, 2012):

$$x_{outD} = K_D \cdot \frac{\Delta x_{in}}{\Delta t}, \qquad (3)$$

K_D – derivative gain.

Furthermore the equation for the PID controller can be defined as a summation of the 3 base terms (Busch, 2012).

$$x_{outPID} = x_{outP} + x_{outI} + x_{outD}. \qquad (4)$$

Using the formulas (1), (2) and (3) and in consideration of formula (4), the following definition of the PID output signal can be established:

$$x_{outPID} = K_P \cdot x_e + K_I \cdot x_e \cdot \Delta t + x_{out0} + K_D \cdot \frac{x_e}{\Delta t}. \qquad (5)$$

The output signal can also be described as a function of hold-back time T_v and the reset time T_n (Busch, 2012). Thus the following equation for the PID output can be established:

$$x_{outPID} = K_P \cdot \left(x_e + \frac{1}{T_n} \cdot x_e \cdot \Delta t + T_v \cdot \frac{\Delta x_e}{\Delta t}\right) + x_{out0} \qquad (6)$$

The PID controller combines the advantages of the individual base terms. Thus it complies with the requirements of high control speed and high accuracy. However, an optimal control performance can only be achieved by an exact tuning of the 3 parameters K_P, K_I ,K_D, respectively K_P, T_n,T_v. This tuning can be realized by different methods, as e.g. approximation methods according to Chien, Hrones and Reswick (CHR). The CHR method is applicable if the parameters of the plant being controlled, are known. In case of unknown plant parameters the method of Ziegler and Nichols, which is based on controller stability limit, is better suited (Mann et al. 2005).

2.3 Definition of Quality Parameters: Control Quality and Measurement Accuracy

The minimization of e(t) within the system is carried out by the previously described PID controller. According to Busch (2012) the control quality mainly depends on the choice of the controller parameters and their alignment. It is defined as the remaining control deviation Δx. Further criteria are the overshooting range x_m,, the rise time T_{an} and the settling time T_{aus}. Hypothetically Δx must reach zero, if using an ideal controller.

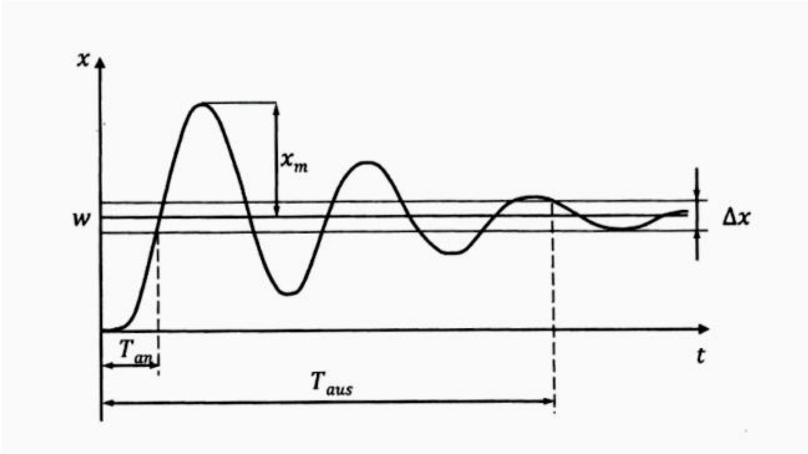


Figure 3: Overshooting range, rise- and settling time (Busch 2012)

Another definition of control quality is the root mean square (RMS) based on the quadratic ruled surface.

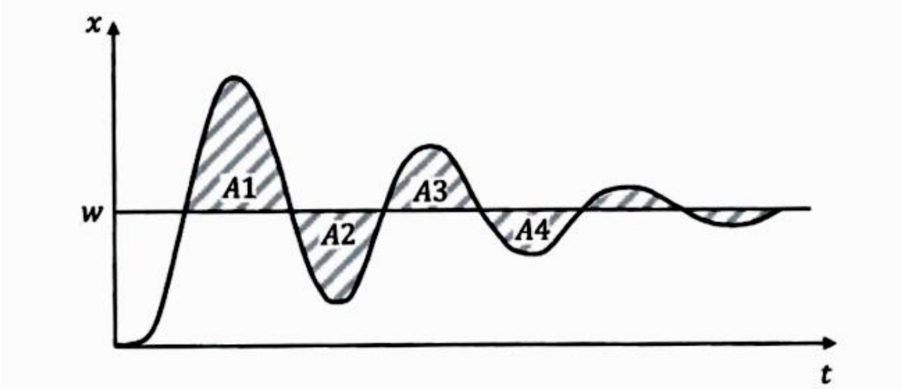


Figure 4: Quadratic ruled surface (Busch 2012)

Referring to figure 4 the following applies:

$$A_{total} = A_1 + A_2 + \cdots + A_n = \int_0^\infty |e| dt, \qquad (7)$$

e – control deviation.

Mann et al. (2005) and Beetz (2012a) describe further steps of integration, discretization and normalization of the quadratic ruled surface to derive and define the quality criterion RMS as follows:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} e_i^{\,2}}{n}}, \qquad (8)$$

n – number of measurements.

Based on (8) the following relation can be stated: small lateral deviation results in small RMS and a high control quality.

According to Beetz (2012b) quality parameters can be derived by the consideration of the differences between the reference trajectory, the recorded tachymeter trajectory and the recorded laser tracker trajectory. Thus, the following specifications for quality parameters can be defined: the RMS between the reference trajectory and the recorded tachymeter trajectory is defined as combined measure, containing the control quality and the measurement accuracy, the RMS between the reference trajectory and the recorded laser tracker trajectory represents the control quality and the RMS between the tachymeter and the laser tracker trajectory represents the measurement accuracy.

2.4 External Measurement System for Evaluation

The introduction of an external measurement system should help to consider the closed-loop-system performance from an independent point of view. Such a system is the laser tracker API Radian in combination with an active target.

The distance measurement accuracy of the laser tracker is orders of magnitude better than that of the used robot tachymeter. The accuracy of the angle measurements is nearly the same. Table 2 gives an overview of the accuracies for both devices.

Figure 4: Laser Tracker API Radian and Active Target (Automated Precision Inc., 2014b)

Table 2: Accuracies; *static mode; **kinematic mode; (Automated Precision Inc., 2014b), (Leica, 2015b)

	Leica TCRP 1201	API Radian Laser Tracker
Angle	≈ 5 µm/m	≈ 3,5 µm/m
Distance	2mm+2ppm* 5mm+2ppm**	10µm or 5ppm* 10µm or 10ppm**

The active target has the ability to permanently align with the tracker's laser beam and thus always keep the line of sight, independently of platform's orientation. The mechanical realization of the alignment is based on two servo actuators for setting the horizontal and vertical directions. Detailed description on the functionality of the active target are not published by the manufacturer. However articles by Horst and von Gösseln (2012) as well as Kyle (2008) give some ideas and presenting different approaches on the alignment functionality. Horst and von Gösseln (2012) designate prerequisites that are necessary for the orientation determination of the prism, namely the knowledge about the prism's position and its orientation relatively to the laser tracker. Methods for generating these information are based on GPS measurements, compass and signal strength measurements by directional antennas. Kyle (2008) describes an optical approach for the determination of the orientation of the active target for indoor scenarios. This method is based on the use of a pinhole reflector and a CCD-array. Thereby a part of the incident laser ray passes the pinhole reflector and hits the CCD-array. The x,y – coordinate of the CCD, which was encountered by the ray, is depending on the direction of the emitted light source. Hereby the position of the reflector, as well as the coordinate system of the laser tracker are known, respectively can be determined or measured directly (Kyle, 2008).

2.5 Measuring Setup and Test Scenarios

The principal measurement setup is depicted in Figure 5. Two different trajectories in the shape of an “oval” and an “eight” were driven. Both trajectories contain route design elements, like clothoides, circle arcs and straights. A PID controller, with empirically determined parameters, has been used. The data acquisition mode of the laser tracker was set to temporal discretization with a rate of 10 Hertz. The tracker was run simultaneously to the closed-loop of the tachymeter and vehicle operations.

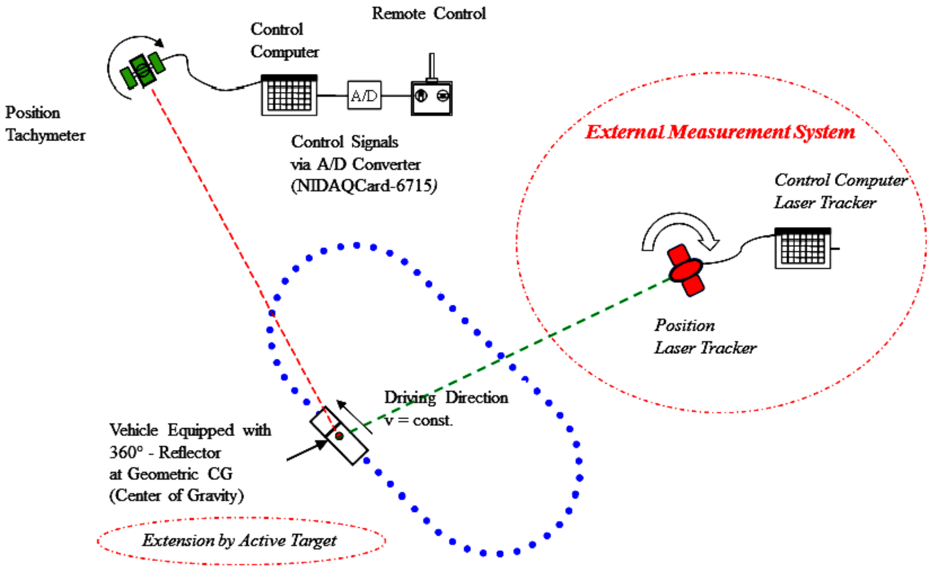


Figure 5: Measurement Setup

In total two laps per scenario were driven. To avoid influences of the initial transient oscillation of the vehicle on the results in the first round, the evaluation only considers the second lap. The two test scenarios are summarized in Figure 6.

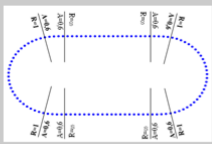
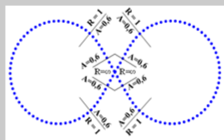
Test Environment	Scenario 1	Scenario 2
Trajectory	*‚Oval‘* 	*‚Eight‘* 
Controller	*PID Controller* $K_P = 25,\ T_n = 0{,}15\ min,\ T_v = 0{,}001\ min$	
Velocity of the Model Truck	$approx.\ 10\frac{cm}{s}$	
Interface between Tachymeter and Simulator	*Leica MGUIDE*	
Laser Tracker Data Acquisition Mode	*ADM, temporal discretization, 10 Hz*	

Figure 6: Test Environment

The measurements have been evaluated in post-processing. The individual steps of the processing are shown in the following flowchart:

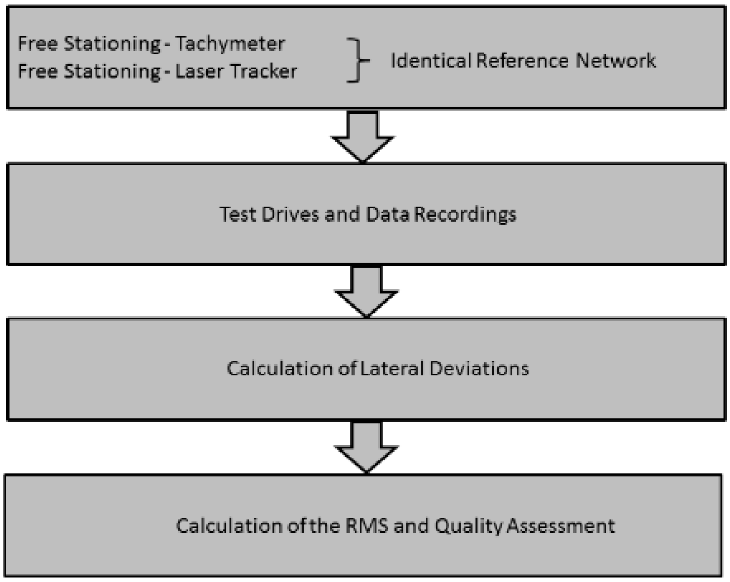


Figure 7: Processing Flowchart

3. Results

Figure 8 exemplarily illustrates the courses of the graphs for the combined measure, the control quality and the measurement accuracy for scenario 1 ('Oval'). The graph for the control quality is distinctly smoother than the other two graphs. This can be explained by a smaller number of measurements, respectively a smaller number of performed comparison operations for the control quality. The number of comparison operations for the combined measure and the measurement accuracy depends on the number of tachymeter measurements, which in turn, depends on the driving velocity. In general, slightly rough courses can be detected for all graphs. This can be related to the remaining control deviation of the PID-controller, which causally lies in the time-dependency of the reference variable.

Table 3: Resulting RMS for the Quality Parameters

	Combined Measure [m]	Control Quality [m]	Measurement Accuracy [m]
"Oval"	0.0029	0.0031	0.0028
"Eight"	0.0028	0.0031	0.0029

Table 3 shows the achieved quality parameters. Reconsidering the definitions from chapter 2.4, where the lateral deviation partly consists of the control quality and the measurement accuracy, one would expect that the quadratic sum of these two RMS values must result in the RMS of the combined measure. Obviously this is not the case. The consequential assumption is that unknown systematic effects play an additional role. These effects couldn't be revealed yet only by observing the combined measure. For the first time this procedure of separating control quality and measurement accuracy allows to detect such effects, which is one of the benefits of the presented, laser tracker based, evaluation system.

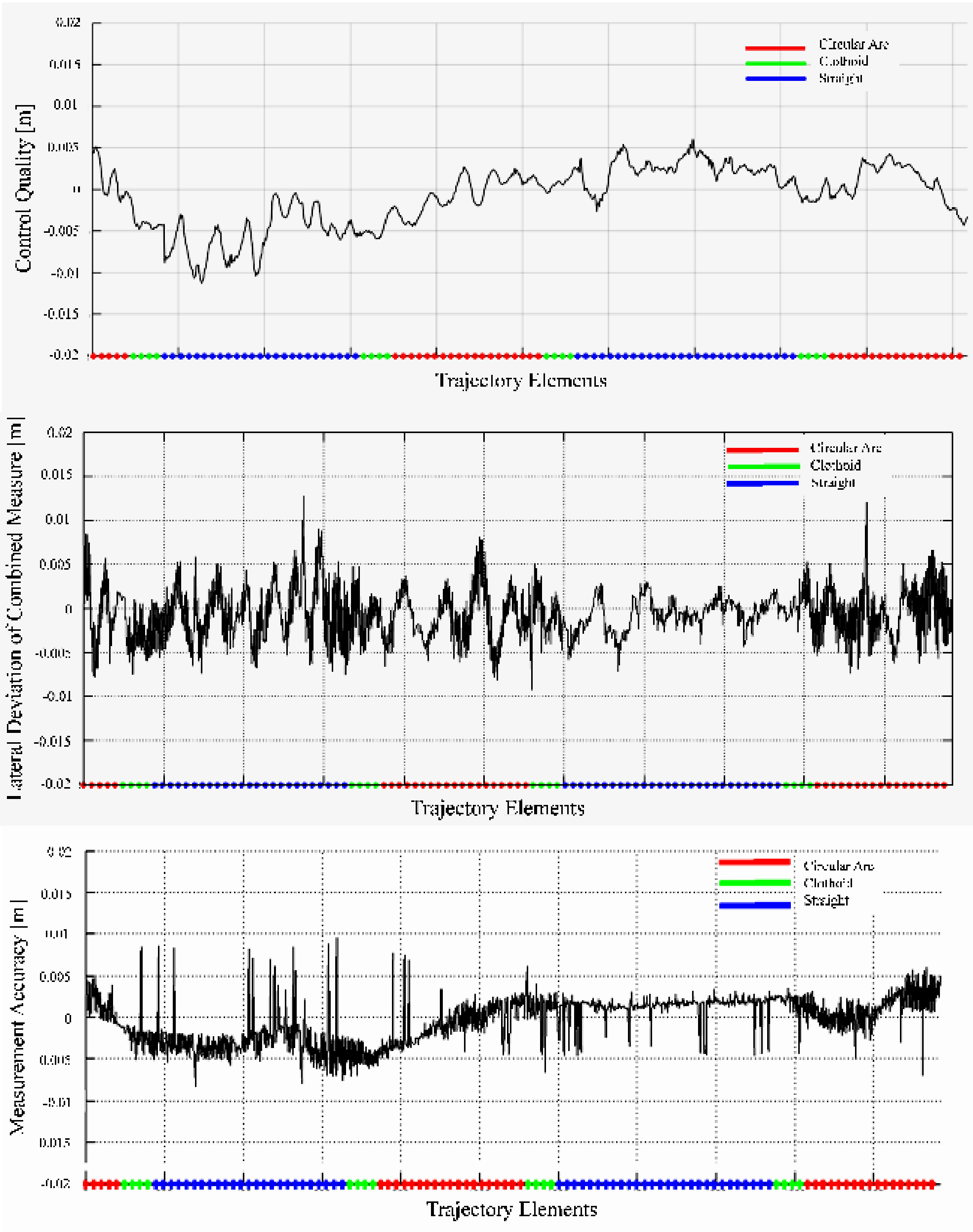


Figure 8: Results for "Oval"

4. Conclusions

A new system to evaluate the control quality of construction machines has been developed. This investigation shows, that the separation of control quality and measurement accuracy, using the laser tracker in combination with an active target, is possible. Moreover, the experiment uncovers, that unknown, systematic effects, which are not explainable so far, are present in the measurement data. The evaluation process results in a control quality of 3.1 mm for the construction machine simulator. The average measurement accuracy of the tachymeter is 2.9 mm, which corresponds to the manufacturer specification. It should be noted, that all present tests were conducted under laboratory conditions and are not representative for real-world outdoor construction sites, where different effects affecting the tachymeter, like refraction or meteorological influences, would decrease the results.

5. Acknowledgments

Essential parts of this paper has been published in German in ZfV – Zeitschrift für Geodäsie, Geoinformation und Landmanagement, Heft 4/2015 – 140. Jahrgang, Pages 211-221, 2015, in German language. Additionally the paper has been presented at MCG 2016 – 5th International Conference on Machine Control & Guidance in Vichy, France in English language.

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