Separation of Control Quality and Measurement Accuracy for Guiding Control Tasks of an Indoor Construction Machine Simulator

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Abstract— **An indoor construction machine simulator has been developed at the Institute of Engineering Geodesy (IIGS) to carry out investigations of tachymeters, additional sensors and Kalman filters during the operation in control-loops for guiding tasks of construction machines. In this simulator remote-controlled model vehicles are used in a scale of 1:14 which project the kinematic behaviour of construction machines close to reality. In combination with a control computer, a remote control, and a robot tachymeter as position sensor, it is possible to guide the model vehicles on a given trajectory autonomously. The control aim is to guide the vehicles as well as possible on the given trajectory.**

To describe the achieved control quality, a Root Mean Square (*RMS*) is computed with lateral deviations between the given trajectory and vehicle positions during a test drive. Due to the achieved position accuracy of the tachymeters (3-10 mm), the *RMS* represents not only the control quality. There is also a random part included which falsifies the result of control quality.

In this paper a measurement setup will be shown which makes it possible to use a tachymeter as position sensor for the control task and a laser tracker (accuracy less than 1 mm) as reference sensor for the vehicle trajectory simultaneously. By using the results of this measurement setup it will be possible to separate control quality and position accuracy of the tachymeter.

During the test drives a measurement accuracy of the tachymeters of around 1-3 mm could be reached. Thereby, the control quality achieved was 2-4 mm by using a PID controller at a velocity of 10 cm/s (average speed of an asphalt paver). Furthermore, it is possible to show the influence of systematic effects during the test drives e.g. due to the use of 360° prisms.

Keywords-component; Laser Tracker, Robot Tachymeter, Control Quality, Construction Machine Control and Guidance, Simulation

I. INTRODUCTION

In recent years, great progress has been made in measurement techniques and data processing in the field of engineering geodesy [1]. Meanwhile, these enhancements are also widely used for automated road construction, for example on large highway construction sites [2]. The design of such automated systems is usually developed individually for each machine. Previous simulations for the implementation of the software on the machine computer are usually realized based on software. An intermediate step is missing in which sensor components or filter algorithms can be tested individually in the laboratory without being affected by outside influences such as of the ground or other environmental influences.

For this reason an indoor hardware-in-the-loop simulator ([3], [4], [5]) has been developed at the Institute of Engineering Geodesy (IIGS) which is able to contribute a part to solve this problem. With this simulator it is possible to achieve a level during the development of a guiding system, where many problems can already be solved before starting the implementation at the real machine. The main task of this simulator focuses on high precision 2D guiding. For example, the required position and height accuracy of an asphalt paver are 5 mm [2]. Tachymeters of the latest generation are implemented in the simulator system to reach this standard. Within the simulator it is possible to combine these tachymeters with different filter and control algorithms to investigate the guiding abilities with remote controlled model vehicles on reference trajectories. Up to now the *RMS* of measured lateral deviations has been used as a quality parameter to give a statement on the investigation of the controllers. Here the *RMS* is influenced by the accuracy of the tachymeter. This means the *RMS* has a random part which falsifies this *RMS*.

In this paper a measurement setup will be shown which allows the individual examination of the accuracy of the controller and the accuracy of the position sensor. The following chapters give an insight into the simulator system, the theoretical foundations, the measurement setup and present first results.

II. PRESENTATION OF THE INDOOR-SIMULATOR

A. Hardware and Software of the Simulator System

The simulator system which has been developed at the IIGS (cf. [3], [4] and [5]), consists of different hardware components, software modules, sensors and remote-controlled vehicles. In combination, all these different parts result in a hardware-in-the-loop simulator which allows the evaluation of different controllers, position sensors and filter algorithms. A sensor which measures the position of a moving vehicle is connected over a RS232 interface with a control PC. The whole software of the simulator system is implemented in this

control PC which will be explained later on. The software on the control PC computes the steering signals for the remote-controlled vehicles. A digital-analogue converter is connected with the control PC and the potentiometers of the remote control. It transforms the computed steering signals into a voltage and the remote control sends the converted steering signals to the model vehicles. The control aim is to guide the vehicle as accurately as possible on a given trajectory (cf. Fig. 1).
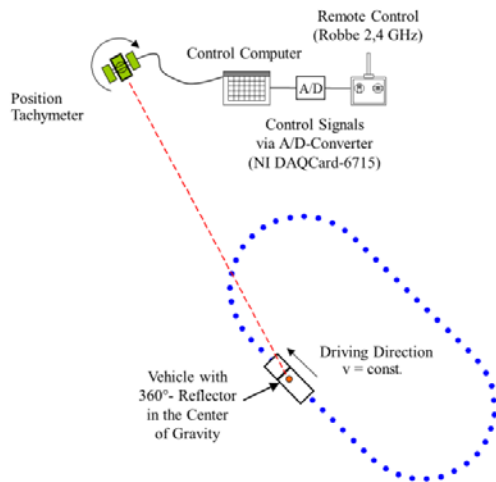

Figure 1.   Hardware Components of the Simulator System [3]

To achieve the control aim the software has four main modules which are realized in the graphical programming language LabView© from National Instruments. The four modules are:

- Trajectory Generator Module (TGM),
- Automated Steering Calibration Module (ASCM),
- Enhanced Guiding Module (EGM),
- Software Simulator Module (SSM).

The TGM can be used for generating reference trajectories by teach-in processes. This means that measured points of driven test drives will be used as reference trajectory for other test drives. The module smoothes the measured points and stores the trajectory as a point list with equidistant distances between the points. Equidistance is needed for the lateral deviation algorithm which will be explained later on.

The ASCM calibrates the linkages of the model vehicles at a scale of 1:14. It computes a calibration function which makes it possible to know the voltage that has to be sent to the remote control to drive the correct radius with the model vehicle.

The test drives will be carried out by means of the EGM. With this module, different controllers and filter algorithms can be tested. All measured data, filtered data, parameter settings and control relevant data will be stored in the module data base.

The SSM is used for testing the control and filter algorithms, prior to their use in the EGM. Several different

vehicles of construction sites and position sensors can be simulated.

The TGM, ASCM and EGM all have the same software interface to connect real time sensors, such as tachymeters, and virtual sensors for further testing sequences within the modules during the development. It is beyond the scope of this paper to explain the whole system in detail. Detailed information on the system and the modules can be found in [3]. Fig. 2 gives an overview of the system's architecture.
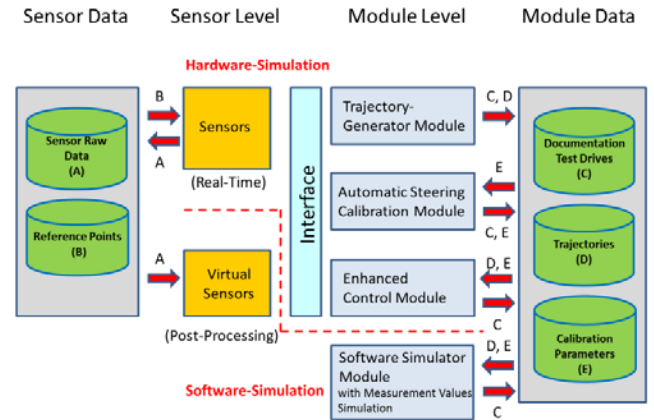

Figure 2.   System Architecture [3]

The model vehicles used within the simulator system are shown in Fig. 3. On the left hand side is a wheeled vehicle with front steering and on the right hand side a tracked vehicle. With these two model vehicles the kinematic driving behavior of many road construction machines can be simulated.

Figure 3.   Model Vehicles used in the Simulator System [3]

For the investigations presented in this paper the "Enhanced Guiding Module" and the wheeled vehicle with front steering are used. The evaluated sensors will be shown in the following chapter.

B. Sensors

1) Tachymeters and Reflectors of the Simulator System

In TABLE I the robot tachymeters of the simulator system are shown. Furthermore, the technical data is listed to compare the different position sensors.

TABLE I. Position Sensors (cf. [3], [8], [9], [10])

	Leica TCRP 1201	Leica TS30	Trimble® SPS930
drive technology	electric motor	Piezo technology	magnet technology
rotational speed	50 gon/sec (45°/sec)	200 gon/sec (180°/sec)	128 gon/sec (115°/sec)
tracking	passive	passive	active/passive
max. sample rate	8 - 10 Hz	8 - 10 Hz	20 Hz
accuracy of angle measurement in tracking mode	1"	0,5"	1"
accuracy of distance measurement in tracking mode	5mm+2ppm	3mm+1ppm	10mm+2ppm
delay time	wire ca. 25 - 40 ms	wire ca. 25 - 40 ms	wire 23 ms modem 40 ms
synchronization error	with MGUIDE not detectable	with MGUIDE not detectable	not detectable

All three tachymeters have different technologies for target tracking and actuators. Therefore, it is very interesting to compare them within the simulator system. For the usage of the tachymeters within the simulator, a special software for each tachymeter was programmed to read out the measurement data and, if necessary, to compute the positions of the tracked moving object.

To read out the measured data from the Leica tachymeters TCRP1201 and TS30, on the one hand the internal interface of MGUIDE [6] is used. MGUIDE is an optional onboard-software for machine control which is optimized for kinematic measurements. MGUIDE is especially used for applications in the field of machine control and guidance. MGUIDE software enables the user to read out the coordinates of the tracked object directly.

On the other hand the Leica GeoCOM [7] interface was used which enables control of the tachymeters TCRP1201 and TS30 via special commands. This interface was used for former investigations within the simulator. When using the GeoCOM interface, it is necessary to program a software for the positioning of the tachymeter and to compute the real time positions of the moving objects. Here, no optimization of measured data takes place within the tachymeters.

The SPS930 made by Trimble® is a special tachymeter for machine control and guidance. For the usage within the simulator, a software was programmed for the positioning of the tachymeter and the data processing.

Fig. 4 presents the 360°-reflectors used in the simulator. The Leica tachymeters were used with the GRZ 122 and the SPS930 was used with the Trimble® MT1000. A 360°-reflector can be tracked and measured from each position around the reflector. This kind of reflector is mainly used for one-man robotic tachymeters and in machine control and guidance applications. The main difference between the shown reflectors is the fact that Leica uses only passive prisms and Trimble® mainly uses active prisms. Active means, that beside the normal triple-prisms the reflector has diodes which send out a special signal. The tachymeter can recognize the signal and follows only this reflector. The advantage is that the tachymeter can't confuse the used reflector with another reflector due to an individual frequency ID of the emitted signal. For the case of Trimble® MT1000 eight different frequency IDs are selectable. The disadvantage of active reflectors is the need of a power source for the diodes. Further information on the used tachymeters can be found in [3], [8], [9], [10] and of the 360°-reflectors in [11] and [12].

Leica GRZ 122   Trimble® MT1000

Figure 4.   360°-Reflectors [3]

C. Used Reference Trajectory

Beside the possibility to generate a reference trajectory by a teach-in process with the TGM, three computed reference trajectories are available. These reference trajectories are designed in the way of an oval, a kidney and a figure of eight. The trajectories include all elements of a road, like straight lines, circles and clothoids. The trajectories are stored as discrete points in a text file which can be loaded by the enhanced guiding module (EGM) before the test drive. The points have a distance of 0.10 m from one to the other.

For the test drives the design of an eight was chosen since by doing so the whole dynamic range of the model truck is utilised. During the test drives the vehicle is always changing from a long right curve into a long left curve. In Fig. 5 the chosen reference trajectory is presented. It consists of two circles with a radius of R = 1.00 m each, two straight line parts and four clothoids with the parameter A = 0.6.
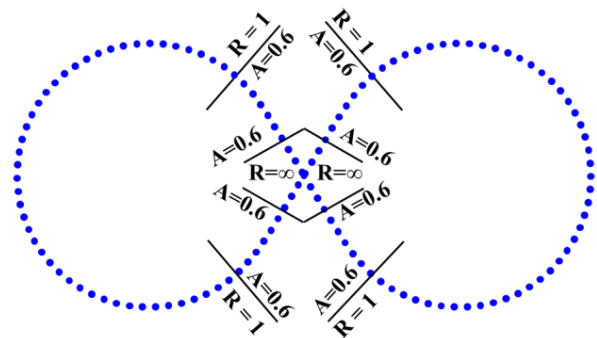

Figure 5.   Reference Trajectory "Figure of Eight" [3]

D. Computation of Lateral Deviation

As mentioned before, the vehicle should be guided on a given trajectory. For the controller explained later on, the main input is the lateral deviation or normal e from the measured position to the reference trajectory. Therefore the procedure to compute the lateral deviation will now be explained briefly. Parts of the procedure were developed in [4] and published in [5].

1. In a first step the point P_T of the reference trajectory will be searched with the closest distance to the current measured position P_V of the vehicle. To do this, all distances from P_V to all points of the reference trajectory are computed. Afterwards an algorithm will compute the shortest distance and identify the respective point number. For a better performance, this is done once. For all other points measured, only a part of the trajectory is taken to identify the nearest point. To achieve this, 5 points before and 5 points after the last identified trajectory point are used.

2. After the identification of point P_T, that part of the trajectory will be determined. This can be a straight line, a clothoid or a circle. For doing so, one point of the reference trajectory before and one point after P_T are selected. According to [13], each 2D point (X, Y) can be represented with a triple (X, Y, r) of its homogenous coordinates. The homogenous coordinates can now be combined in a 3x3 matrix. The decision which element connects the three points is made on the result of the determinant Det of this 3x3 matrix (cf. Fig. 6).

If $Det = 0$, the normal has to be calculated on a straight line.

If $Det \neq 0$, the normal has to be calculated on a circle (here it is not possible to distinguish between circle or clothoid).
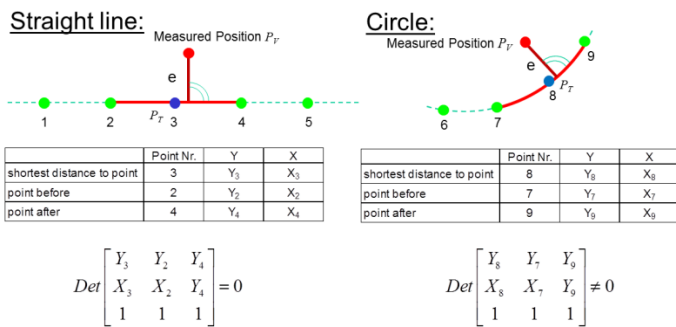

Figure 6. Decision of Trajectory Element (r = 1) [4]

3. The algorithms for the computation of the normal on a straight line or circle always uses the three points of the second step. This means the element of the trajectory will be described with these three points.

Due to the clothoid parts which are identified as circles too, the computation of the normal is only an approximation. The approximation error depends on the equidistance between the reference trajectory points. In [4] it could be shown that this error can be neglected if an equidistance of 10 cm is

chosen. Further information on the algorithms can be found in [4] and [5].

E. Controller used in the System

The implemented closed-loop system uses the lateral deviation as control deviation $e(t)$. In the simulator system several controllers are available. For the subsequent test drives a PID-controller in combination with a feed forward control will be used. The values for the PID-controller are:

Proportional gain (P-control):	$K_P = 12.000$
Reset time (I-control):	$T_n = 0.500$ min
Rate time (D-control):	$T_v = 0.001$ min

The controller combination used computes the steering angle as regulation variable $u(t)$. The feed forward control uses the information of the reference trajectory $w(t)$ and computes the assumed steering angle δ_{ffc} in case the lateral deviation is zero [5]. According to [14], the following equation describes the used controller mathematically:

$$u(t) = K_P \cdot \left(e(t) + \frac{1}{T_n} \cdot \int e(t)dt + T_v \cdot \frac{\Delta e(t)}{dt} \right) + \delta_{ffc} \quad (1)$$

In Fig. 7 one can see the implemented control-loop. The wheeled remote-controlled vehicle is the plant. The position (control variable $y(t)$) of the moving vehicle will be measured by a tachymeter. An additional Kalman filter uses the information of the regulation variable $u(t)$ to predict and estimate the filtered control variable. Information on the implemented Kalman filter can be found in [3], [15] and [16].
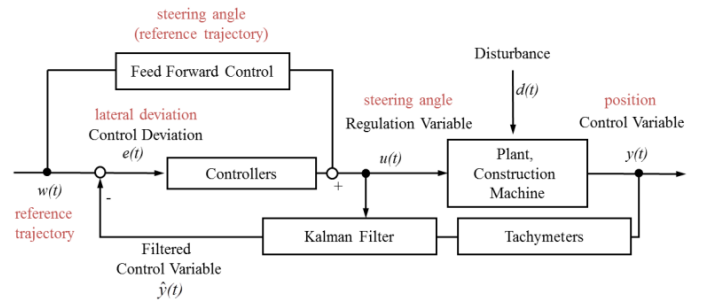

Figure 7. Closed-Loop System [3]

III. QUALITY ASPECTS OF CONTROL

A. Definition of Control Quality

Many different quality parameters for closed control-loops are known in control theory. For example a good guiding behavior, a fast damping of the oscillations, a stable behavior or a good dynamic behavior of a closed-control loop are important. One way to describe these different parameters in one overall parameter is the computation of the area enclosed by the driven trajectory and the set point w (cf. Fig. 8). The demand for good quality is to minimize this area ($A1 + A2 + \ldots + A_n$ = minimum).
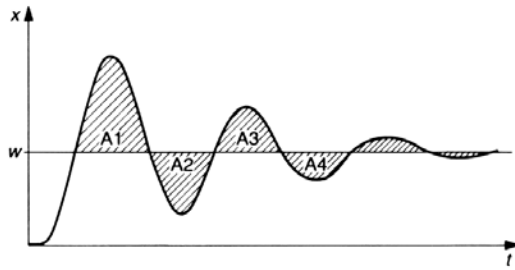
Figure 8.   Area enclosed by the driven trajectory [17]

In [18] the parameter of the enclosed area could be enhanced to *RMS* as a quality parameter in the simulator system. Here the requirement is a constant sample rate during the testdrive. The *RMS* will be computed with *n* measured lateral deviations *e*.

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

The advantage of using the *RMS* is the posibility to compare test drives with different lengths [18].

B. Hypothesis test for the Evaluation of Control Quality

For further investigations it is necessary to know which tachymeter is able to measure the correct control quality. Or in other words, which *RMS* is statistically proved to represent the control quality. To ensure this, two *RMSs* will be computed and compared to each other. RMS_1 will be computed with lateral deviations of the measured tachymeter positions. RMS_2 is the reference and will be computed with lateral deviations of a sensor with much higher position accuracy. If the two *RMSs* are statistically equal, the control quality can be computed within a confidence level by means of the respective tachymeter. The following variance test used is given in [19]:

The test hypothesis statements:

Hypothesis accepted: H_0: $RMS_1^2 = RMS_2^2$

Hypothesis rejected: H_A: $RMS_1^2 \neq RMS_2^2$

For this test an *F*-distribution has to be used. The quantile of the statistical test depends on the degree of freedom of the respective *RMS*. Due to the large number of the later measurements (>17000) both degrees of freedom can be assumed as infinity => $f_1 = f_2 = \infty$. In this case the quantile results in (error probability = 5%):

$$F_{+\infty,+\infty,1-\frac{a}{2}} = F_{+\infty,+\infty,97,5\%} = 1.001 \qquad (3)$$

The test value will be computed as the quotient of both *RMS* squared. As well the following relationship is required:

$$F = \frac{RMS_1^2}{RMS_2^2} > 1 \qquad (4)$$

The decision of the hypothesis statements takes place with:

If $F \leq F_{+\infty,+\infty,97,5\%} \Rightarrow$ Accept H_0, both *RMS* are equal.

If $F > F_{+\infty,+\infty,97,5\%} \Rightarrow$ Reject H_0, both *RMS* are different.

IV.   THE MEASUREMENT SETUP

A. Description of the Measurement Setup

In order to measure the real trajectory of the model vehicle with much higher accuracy than the tachymeters, a laser tracker was used. With a laser tracker a 3D position accuracy of better than 0.1 mm can be reached [20]. To measure an identical trajectory with the tachymeters and the laser tracker, the reflectors of the tachymeters and the laser tracker will be mounted exactly on the top of each other. To reach an accuracy of better than 0.1 mm with the laser tracker, the measurements have to be carried out by means of a special reflector [21]. For this Leica offers different Corner Cube Reflectors (CCR). A CCR has the disadvantage that its opening angle is only ± 30°. In other words, an overall opening angle of 60° from the CCR in the direction of the laser tracker must be assured. Alternatively, the so-called "CatEye" is available, which has an opening angle of ± 60°. Beside the poor centering accuracy, which plays a minor role here, this reflector has a weight of about 700 g. This makes it almost impossible to adapt the "CatEye" to the truck model used. For this reason, an arrangement was chosen which enables the tilted laser tracker to observe the model truck during the whole trajectory from above. In so doing, an interruption of the incident laser beam into the tracker reflector during the measurements can be avoided (a 360°-reflector for laser tracker is not available). So the measurements were carried out in the foyer of the building in Keplerstraße 17 in Stuttgart. Here, one can look from the first floor to the floor below and the lower floor has enough space to act as test area. These conditions allow a total height of the laser tracker of 5.40 m above the model truck. The laser tracker is thus able to observe a test area of approximately 5 x 5 m for carrying out kinematic measurements with the CCR. The aperture of the CCR is oriented in the zenith direction and the cutting edge is approximately perpendicular to the vertical axis (cf. Fig. 9).
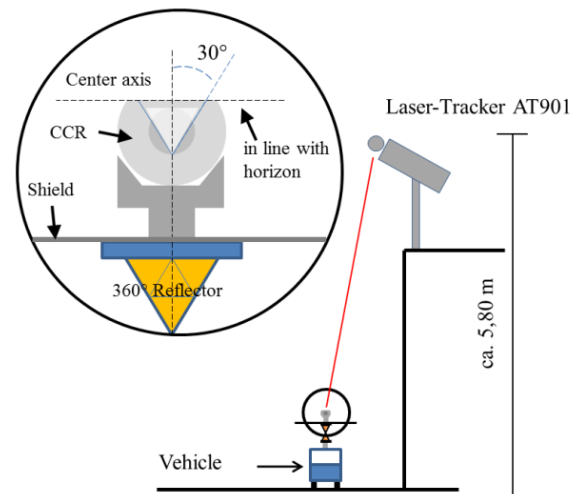

Figure 9.   Combination of reflectors and position of laser tracker [3]

The holder of the CCR can be fixed on the 360°-reflector of the tachymeter through a special adaptation. Due to the manufacturing tolerance, the difference between the central axis of the CCR and the 360°- reflector does not exceed 0.1 mm. An additional shield has to be fixed between CCR and 360°-reflector, so that the laser tracker does not aim at the 360°-reflector during measurement. Fig. 9 shows the configuration of the CCR and the 360°-reflector and the measurement setup of the laser tracker. The height distance between center of CCR and center of 360°-reflector is about 10 cm. If a centering accuracy of less than one millimeter is to be guaranteed, the model truck must not roll more than 0.5°. To minimize the rolling of the vehicle, wooden plates were laid on the floor to compensate its unevenness.
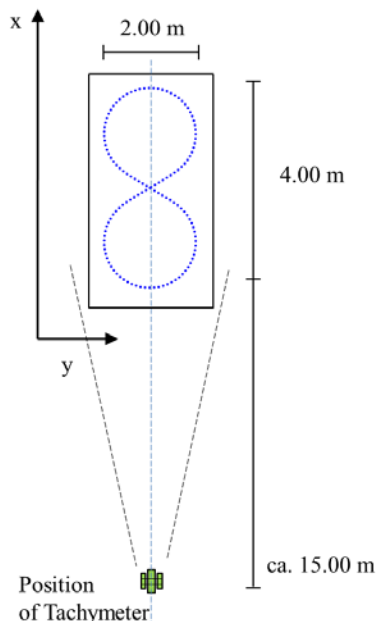

Figure 10. Test Area [3]

The position of the tachymeter is defined along the center axis of the reference trajectory (cf. Fig. 10). Here, the measured distances are between 15 and 19 m.

B. Realization of the Measurement Drives

The control objective is to guide a vehicle on a given reference trajectory. To achieve this, a PID controller is used, since the best results so far were obtained with this controller. As already mentioned, for the reference trajectory the design of an eight is chosen.

With the test drives all three tachymeters are examined regarding their attainable measurement accuracy in the control loop. The control quality should be determined as well, for which one a statistically based value can be delivered. This requires that values of the control quality and of the measurement accuracy are to be considered separately. Previous results of the control quality with respect to the used simulator always included both parts, so that up to now it was not possible to determine the control quality exactly. By using the simultaneous measurements of the laser tracker, now a reference measurement is performed and an exact value can be determined for the control quality.

As there was no time reference available between tachymeter and laser tracker, a direct comparison between the measured positions of the tachymeter and of the laser tracker is not possible. Thus only a geometric comparison between the driven trajectories was done, which is sufficient for the determination of the control quality.

The tachymeter and the reference trajectory are situated in the same coordinate system. To transform the laser tracker coordinates system into the reference trajectory coordinate system, six identical points were measured before the test drive. Fig. 11 shows the positions of the identical points.
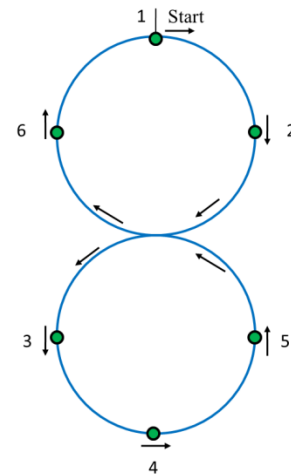

Figure 11. Identical Points for Transformation [3]

Each point from 1 to 6 was measured with both sensors. The point accuracy in that initialization phase of the tachymeter is between 1-2 mm. Since at least two test drives were carried out for each tachymeter, 12 identical points were available for a 7-parameter-transformation. The sample rate of the laser tracker was twice that of the tachymeter, due to the sampling theorem from Nyquist-Shannon [22]. This sample rate was also chosen to get a small approximation error for the

computation of the lateral deviations with respect to the reference trajectory (cf. II.D).

For the investigations of the three tachymeters the following scenario was used:

- The vehicle was moving with a speed of 10 cm/s. This corresponds approximately to the speed of an asphalt paver during bituminization,

- a PID controller with and without Kalman filter was used. The PID controller was optimized for the used velocity (P=12.0; T_v=0.5 min.; T_n=0.001 min.),

- 4 laps were driven with a constant velocity,

- each test drive began at point 1 and ended at the same point.

C. Description of Analysis

For the comparison of the measured laser tracker coordinates and the tachymeter coordinates a 7-parameter-transformation with Gauss-Helmert model [19] must be computed in a first step. In this case the measured identical points and the open source program JAG3D [23] was used. The standard deviations of the transformed points were consistently less than 1.3 mm. In the next step, the lateral deviations of the transformed tracker coordinates to the reference trajectory and of the measured coordinates of the tachymeter to the laser tracker trajectory were computed. The lateral deviation of the tachymeter coordinates to the reference trajectory can be stored during the test drive with the control module. The lateral deviations of the laser tracker data were computed with the lateral deviation algorithm of the simulator system (cf. II.D). According to [4] the expected approximation error for the lateral deviation during the test drives is smaller than 0.1 mm. For calculating the tachymeter coordinates on the laser tracker trajectory, which has equidistant point distances of 2.5 mm (Trimble® SPS930) and 5 mm (for Leica tachymeters), the approximation error is smaller. This guarantees an accuracy of 1 mm for the computation of lateral deviation. After computing the respective lateral deviations, the laps of each test drive were selected and the *RMS* for each trajectory element was computed. Here the first lap was eliminated due to transient oscillations during the start-up of the system. In Fig. 12 the three steps of the analysis are shown.
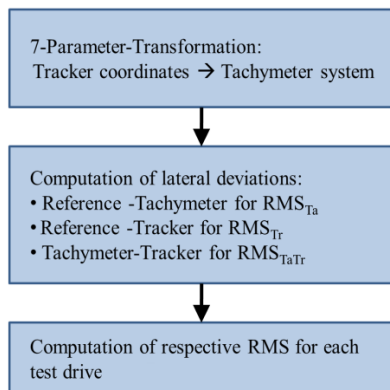

Figure 12. Workflow of Analysis [3]

V. RESULTS

A. RMS of the Test Drives

In Tables II-IV the achieved accuracies are shown. The displayed *RMS* were computed with the lateral deviations of the whole test drive (3 laps). The *RMS* in the table is listed for each individual trajectory element and for the total trajectory. The overall trajectory *RMS* is highlighted.

For the analysis three *RMS* values were determined. Firstly the RMS_{Ta}, computed with the lateral deviations of the reference trajectory and the tachymeter coordinates. The RMS_{Ta} includes the control quality and measurement accuracy. The RMS_{Tr} is computed with the lateral deviations between the laser tracker coordinates and the reference trajectory. The RMS_{Tr} represents the control quality without the influence of the accuracy of the tachymeter. Thirdly the RMS_{TaTr}, which is computed with the lateral deviation of the tachymeter coordinates and the trajectory of the laser tracker coordinates. The RMS_{TaTr} represents the measurement accuracy. In this investigation it should be determined how much the influence of the measurement accuracy affects the result of the control quality. The results are presented in the range of mm-level, since the accuracy of the reference coordinates (because of systematic effects) are at most 1 mm.

At first glance, the Trimble ® SPS930 shows the best result. The control accuracy RMS_{Tr} results in 2 mm with and without Kalman filter. The measurement accuracy RMS_{TaTr} can be improved up to 1 mm by using the Kalman filter. The Leica tachymeters' accuracies are only slightly worse. Here the measurement accuracy RMS_{Ta} is better by 1 mm compared to the control quality RMS_{Tr}. The reason for this will be explained in the following chapter. An improvement of the control quality RMS_{Tr} can be reached with TS30 by using the Kalman filter. This tachymeter is slightly worse than the TCRP 1201 without using the Kalman filter. This is due to the fact that the TCRP 1201 is designed better for kinematic measurements than the newer TS30. Nevertheless, the results of the TS30 correspond to the technical data sheet [9]. The SPS930 has a much better position accuracy than the values of 1 cm indicated by the manufacturer [10]. The same applies for the Leica TCRP 1201 [8].

TABLE II.   LEICA TCRP 1201 (MGUIDE, 8-10 HZ) [3]

	with Kalman filter [m]			
	Line	Clothoid	Circle	Total
RMS_{Ta}	0,003	0,003	0,002	**0,002**
RMS_{Tr}	0,003	0,003	0,003	**0,003**
RMS_{TaTr}	0,003	0,003	0,002	**0,003**
	without Kalman filter [m]			
RMS_{Ta}	0,002	0,002	0,002	**0,002**
RMS_{Tr}	0,003	0,002	0,003	**0,003**
RMS_{TaTr}	0,002	0,003	0,003	**0,003**

TABLE III. TRIMBLE® SPS930 (20HZ) [3]

	with Kalman filter [m]			
	Line	Clothoid	Circle	Total
RMS_{Ta}	0,002	0,002	0,002	**0,002**
RMS_{Tr}	0,002	0,002	0,002	**0,002**
RMS_{TaTr}	0,002	0,001	0,001	**0,001**
	without Kalman filter [m]			
RMS_{Ta}	0,002	0,002	0,002	**0,002**
RMS_{Tr}	0,002	0,002	0,002	**0,002**
RMS_{TaTr}	0,003	0,002	0,002	**0,002**

TABLE IV. LEICA TS30 (MGUIDE, 8-10 HZ) [3]

	with Kalman filter [m]			
	Line	Clothoid	Circle	Total
RMS_{Ta}	0,002	0,003	0,002	**0,002**
RMS_{Tr}	0,004	0,004	0,002	**0,003**
RMS_{TaTr}	0,004	0,004	0,002	**0,003**
	without Kalman filter [m]			
RMS_{Ta}	0,004	0,004	0,003	**0,003**
RMS_{Tr}	0,005	0,005	0,003	**0,004**
RMS_{TaTr}	0,004	0,004	0,002	**0,003**

B. Evaluation of the control quality with respect to the measurement accuracy

Using the presented statistical test in chapter III.B it is now possible to decide which tachymeter can be used for the determination of control quality. According to the test, the RMS_{Tr} and the RMS_{Ta} must be identical to meet the statistical equality. This case only happens using the Trimble® SPS930 (cf. TABLE III.). In the next step the range of quality will be investigated to determine in which range the control quality is guaranteed.

Therefore the achieved accuracy of RMS_{Ta} = 2.00 mm. Assuming a normal distribution (quantile k = 1.96) the control quality at a 95% confidence interval can be guaranteed with a minimum of

$$RMS_{Ta} \cdot k = 3.92 \, \text{mm} . \quad (5)$$

As shown in TABLE III. the measurement accuracy can be enhanced by using a Kalman filter. With the same confidence interval used before, the control quality can be guaranteed with

$$RMS_{Ta} \cdot k = 1.96 \, \text{mm} . \quad (6)$$

In spite of the good results, it must be kept in mind that the RMS_{Ta} is influenced by systematic effects. Normally the RMS has to be corrected to reduce these effects. Presently this is not possible, because for doing so the exact viewing direction of the reflector has to be known [24]. The influence of the reflector during the test drives will be explained in the following chapter.

C. Influence of the 360°-reflector

From [24] and [25] it is known that 360°-reflectors have systematic deviations, when rotating. These systematic deviations influence the position accuracy during a movement of the reflector. From this point of view, further investigations will be done focusing on the movement of the reflector during the test drive. In Fig. 13 the viewing direction of the reflector during the test drive is shown.
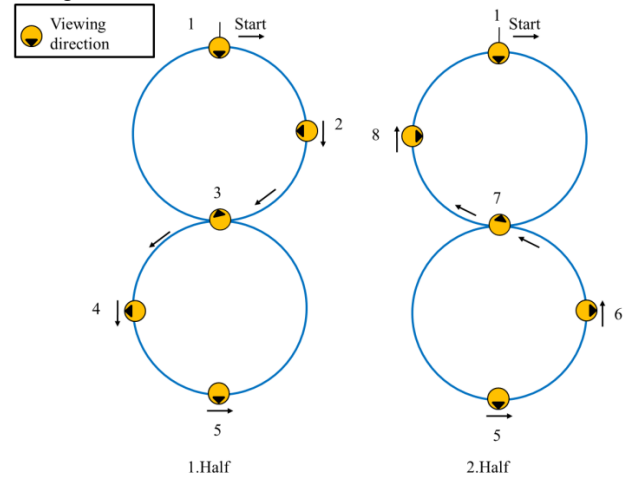

Figure 13. Reflector Movement and Viewing Direction [3]

The start of measurement is at point 1. Up to point 3 the reflector has done nearly half a turn. After that, the reflector moves to point 5 and rotates back into the initial position of point 1. From point 5 to point 7 the process is the same, but in the opposite direction. A complete rotation of the reflector does not occur.

The following figures show the lateral deviations of the tachymeter positions in relation to the tracker coordinates during 3 laps. The deviations are smoothed with a moving average filter in order to distinguish the profile of the deviations. The filter has a span of 30 values. The colored bar below the lateral deviations indicates the respective element of the reference trajectory (straight line = red, clothoid= green, blue = circle). The results of the TCRP 1201 with GeoCOM, the TCRP 1201 with MGUIDE, the SPS930 and TS30 with MGUIDE are shown successively (cf. Fig. 14 and Fig. 15).
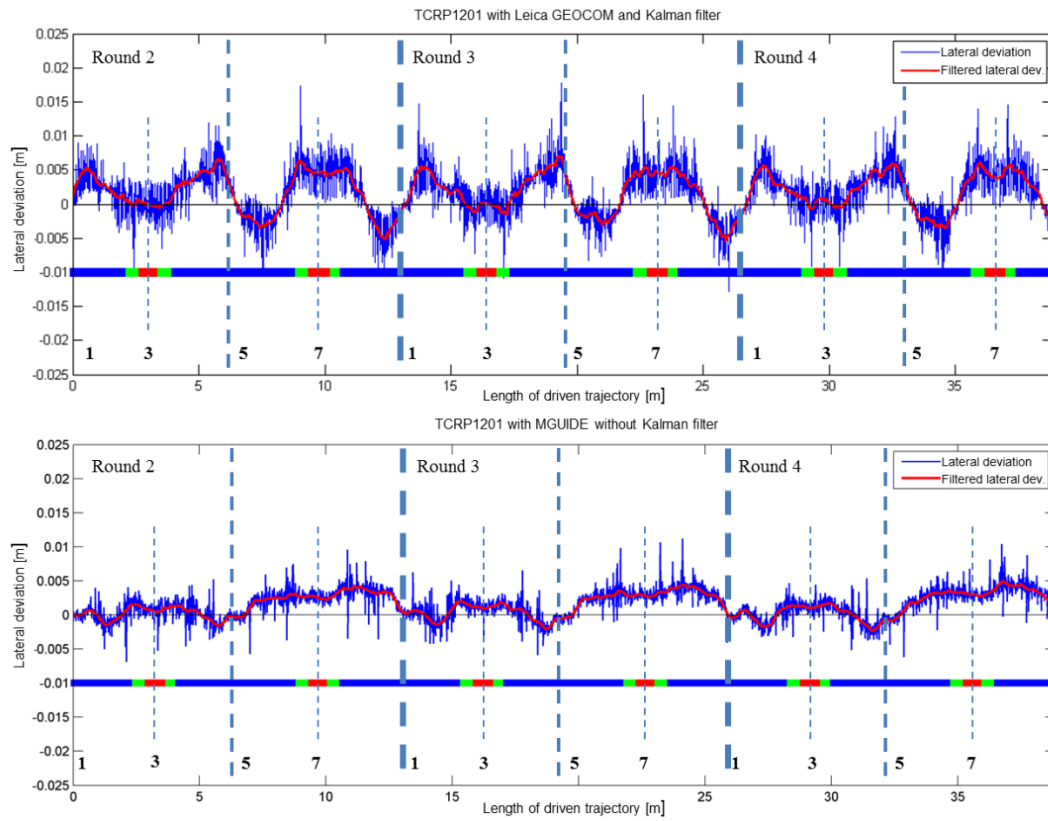
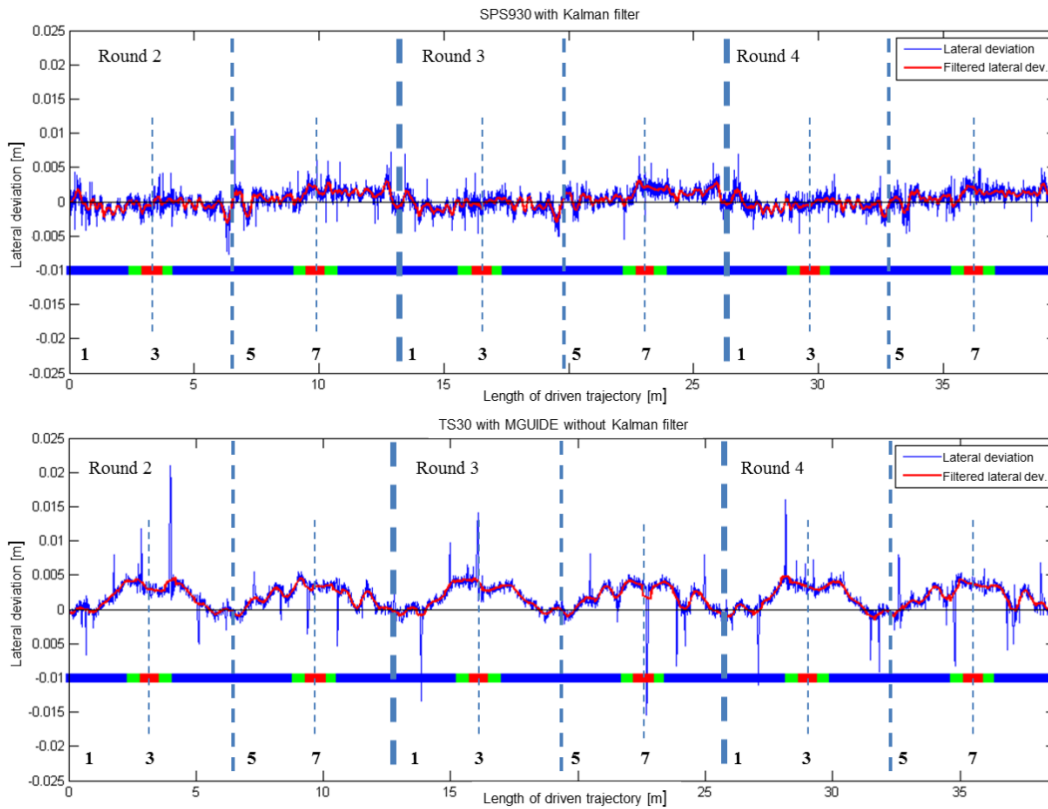Figure 14. Control Quality of Leica TCRP1201 with GEOCOM and with MGUIDE [3]

Figure 15. Control Quality of Trimble®SPS930 and Leica TS30 with MGUIDE [3]

A comparison between the different diagrams shows that the results of the Leica tachymeters have deviations of up to 4 mm. One can see that the shape of the deviations is repeated after each lap. Also a mirror symmetry is visible in certain points. Here, the axes with the numbers 3 and 7 can be seen as mirror axes. The numbers of the axes in Fig. 14 and Fig. 15 correspond to the positions in Fig. 13. A half-turn of the reflector from point 1 to point 3 can be detected. Then the reflector rotates back and at point 5 it has the same orientation as at point 1. Thereafter, the reflector rotates in the other direction. This results in different figures, depending on the direction of rotation. The figures keep on repeating themselves in every lap.

The systematic lateral deviations are only visible if the positions of the laser tracker as reference are used. This systematic effect disappears, if the RMS_{Ta} is computed since the controller does "not know" this effect. The controller only uses the information of the computed lateral deviation (tachymeter – reference trajectory) and tries to reduce this lateral deviation to zero. Hence, from the controllers point of view the lateral deviation is zero, but in reality due to this systematic effect the vehicle is outside the reference trajectory. If the lateral deviation is falsified by the shown systematic effects, this has a direct influence on control quality. The result is lower control quality, although smaller lateral deviations have been computed in the system. To this reason, the RMS_{Ta} of the Leica tachymeters (tachymeter– reference trajectory) is smaller than the calculated RMS_{Tr} (tachymeter– laser tracker) since here the shown systematic effects are included.

VI. CONCLUSION AND OUTLOOK

In this paper, it could be shown that with the presented measurement setup and analysis procedure it is possible to separate measurement accuracy from control quality. Further the influence of systematic effects of the reflectors can be shown. In addition it was demonstrated that for example the tachymeter Trimble SPS930 is able to measure the control quality with an accuracy of 4 mm (target distance 15-19 m, error probability 5 %).

Here it must be considered that all results were reached in laboratory conditions. Using the tachymeters on construction sites, the position accuracy deteriorated because the measurements are affected by other influences, for example by refraction. For continuing investigations with respect to these influences an outdoor simulator is under construction at the Institute of Engineering Geodesy (IIGS).

Since the results derive from measurement drives of only one single day, it is planned to repeat the experiment for verification. For future investigations it is important to enhance the accuracy of the identical points for the transformation. Therefore a special adaption will be developed at IIGS. Further, the synchronization of the tachymeters and the laser tracker has to be solved to investigate the measured data (e.g. horizontal angle or slope distances) and positions directly. For the coming test drives

the IIGS can use its own laser tracker, which will be available at the end of the year.

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