AUTOMATIC LATERAL CONTROL OF A MODEL DOZER

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Key words: Kinematic measurements, total station, closed loop system, dozer steering model

SUMMARY

Control of construction machines for road building is a task already implemented in practice, but leaving various fields of research still open for investigations. Tracked vehicles like dozers differ from wheeled vehicles with regard to the steering model. This contribution presents the steering model for tracked vehicles. There the rotation angle of the dozer is controlled by the velocity difference of the two tracks.

The implementation of the closed loop system at the Institute of Engineering Geodesy at the University of Stuttgart (IIGS) comprises a total station for acquiring the position of the dozer, a Kalman Filter based on the dozer steering model and a PID controller with pre-control. The realization was effected using a software simulator as well as a hardware-in-the-loop simulator that is based on a 1:14 model of the dozer in the laboratory. Therefore the calibration of the simulator is required and explained.

Test drives on given trajectories were realized using the automatic total station Leica TCRP 1201 with and without pre-control. Under ideal conditions in the laboratory the results deliver a lateral control accuracy of 2 mm. This result is comparable to the one achieved for wheeled vehicles using the bicycle model.

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1. INTRODUCTION AND REQUIREMENTS

Machine control and guidance is one of the current research topics in engineering geodesy. But it is a truly interdisciplinary field, where control engineering, mechanics, electronics and informatics as well as agriculture, construction and engineering geodesy are collaborating to find solutions (see Schwieger et al., 2012; Schulze-Lammers & Kuhlmann, 2010; Ingensand & Stempfhuber, 2008). From the point of view of a geodesist positioning, data management and automation of processes are the main fields of investigations. Some of the geodetic scientists deal with complete closed-loop systems to improve their positioning and filtering results in a real environment (e.g. Kuhlmann & Wieland 2012). Table one presents accuracy requirements for different road construction machines. Dozers, diggers and milling machines may be equipped as tracked vehicles. This means that the accuracy requirements reach from 50 mm in position up to 5 mm in height.
At the Institute of Engineering Geodesy at the University of Stuttgart (IIGS) a hardware-in-the-loop simulator including a complete closed-loop system has been built up during the last years (Gläser et al., 2008; Schwieger & Beetz, 2007; Beetz, 2012). Up to now, positioning was realized with different tachymeters and the vehicle simulator was restricted to wheeled vehicles. The positioning instrument is not changed for this paper, but the simulator is extended to tracked vehicles, thus the respective theoretic knowledge has to be available as well as the implementation of a real tracked vehicle model has to be realized.

Table 1: Accuracy requirements (standard deviations) for selected construction machines

Machine	height accuracy	position accuracy	velocity	available systems
Grader	10 - 20 mm	20 - 30 mm	up to 9 m/s	I+II
Dozer/Scraper	20 - 30 mm	20 - 50 mm	up to 3 m/s	I+II
Digger	20 - 30 mm	20 - 50 mm	-	I
Asphalte Paver	5 mm	5 mm	up to 0,16 m/s	I+II+III
Concrete Paver	5 mm	5 mm	up to 0,05 m/s	I+II+III
Curb&Gutter Pav.	5 mm	5 mm	up to 0,08 m/s	I+II+III
Milling machine	5 - 10 mm	10 - 20 mm	up to 0,30 m/s	I+II
Roller	-	10 - 20 mm	up to 3 m/s	I+II

2. TRACKED VEHICLE MODEL

2.1 Steering Systems for tracked vehicles

Since this paper focuses on lateral control, the steering system is the most important part of the dynamic model representing the respective construction machine. In contradiction to wheeled vehicles working with front, rear, articulated or all-wheel steering, tracked vehicles are divided into two-, three- or four-track crawler chassis. Figure 1 gives an overview of these different steering models taking into account the typical movements available for the respective track number. It includes the center of rotation of the tracks as well as their instantaneous centre of rotation with respect to the different crawler and movement types.

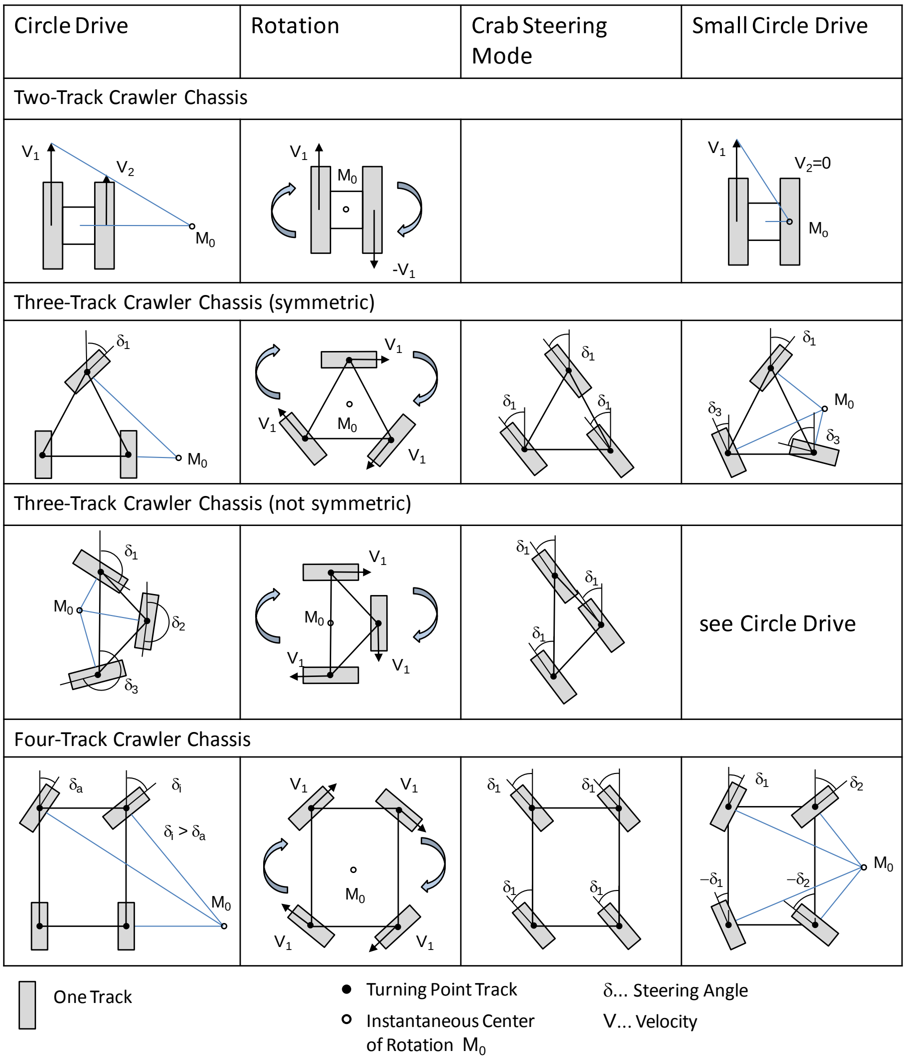

Figure 1: Overview of different crawler chassis

In this paper the authors concentrate on the two-track crawler chassis used for dozers. Here, any change of direction or any circle drives are realized by different velocities of the two tracks. This procedure is called differential steering. The difference in velocity has a direct influence on the driven radius: a bigger difference result in a smaller radius. If the tracked vehicle should rotate on a spot the tracks have to run in opposite directions. For small radii one track is retarded completely.

2.2 The dozer model

The two-track crawler chassis is the typical realization available for dozers. To steer, guide and control a dozer one needs to have a steering model for the respective vehicle type. Le (1999) developed a model for dozers with and without slip. The simple model does not consider slip and therefore can be used for slow velocities and high static friction. In all other cases the model including slip has to be preferred. In general a circle drive is the model assumption for the driving behaviour, as it is the case for wheeled vehicles. For the two-tracked vehicles like the dozer the velocities of the current right v_r and of the left track v_l influence the steering that can be parametrized through the radius of the driven circle R and the orientation change $\Delta\varphi$. Additionally the distance between the two tracks B essentially influences the steering. Figure 2 shows the geometrical relationships.

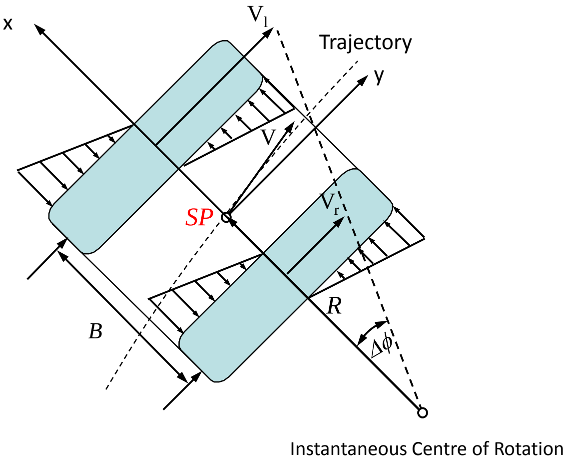

Figure 2: Tracked vehicle model without slippage considered (after Le 1999)

First the velocity can be determined by averaging the right and left velocities

$$v = \frac{v_l + v_r}{2} \tag{1}$$

then the driven distance s between two samples can be calculated, since the sampling interval Δt is known

$$s = v \cdot \Delta t. \tag{2}$$

In the following R can be computed using the intercept theorem

$$R = \frac{B \cdot v}{v_r - v_l} = \frac{B \cdot (v_l + v_r)}{2 \cdot (v_r - v_l)}, \tag{3}$$

for $\Delta\varphi$ the arcustangens function can be used

$$\Delta\varphi = arctan\left(\frac{(v_l - v_r)\cdot\Delta t}{B}\right). \quad (4)$$

The computation of R can be realized using s_l and s_r instead of the velocities. Since the following equations

$$v_r = r \cdot \omega_r \text{ and } v_l = r \cdot \omega_l \quad (5)$$

show the relationship between track velocities and angular velocities ω_l and ω_r of the driving roller using the radius of the roller r, these angular velocities can be used too.

If static friction is low and/or velocities are fast, the slip has to be considered. According to Endo et al. (2007) the amount can be determined by measuring the track velocity at the driving roller v' and the actual velocity v. In general, slip values for tracked vehicles i_l and i_r are given in percentage leading to the equations

$$i_l = \frac{v_l - v_l'}{v_l} \text{ and } i_r = \frac{v_r - v_r'}{v_r}. \quad (6)$$

With regard to our simulator these parameters can be neglected because of the low velocity. Information about the determination of these values can be found e.g. in Le (1999) or Moosavian & Kalantari (2008), if one is aiming to consider the slip in the model. Figure 3 shows the relationships following Le (1999). In contradiction to the model without slip, the real centre of rotation and the centre of gravity differ by the distance D. For computation of circle radius and orientation change only the velocities have to be computed taking into account the slip values

$$v_r = r \cdot \omega_r \cdot (1 - i_r) \text{ and } v_l = r \cdot \omega_l (1 - i_l)\ . \quad (7)$$

The remaining calculation procedure is identical to the model without slip consideration. These models are integrated into the closed-loop system described in sections 3 and 5. The relationships are important to derivate the regulating variable for the dozer model from the lateral deviation determined before.

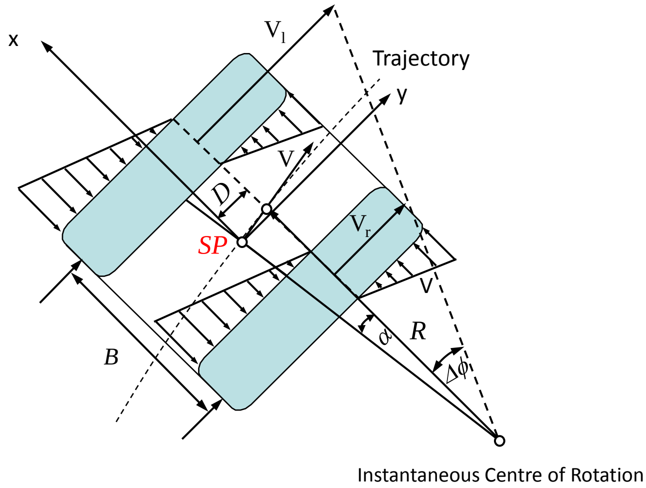

Figure 3: Tracked vehicle model with slippage considered (Le 1999)

3. IMPLEMENTATION OF DOZER MODEL INTO SIMULATOR

3.1 Hardware-in-the-loop simulator

The IIGS is building up has a hardware-in-the-loop simulator. It is the final stage of a three level simulator concept developed at IIGS (Beetz, 2012; Schwieger & Beetz, 2012). Up to now the simulator included a front steering wheel vehicle using a bicycle model (e.g. Beetz & Schwieger, 2007; Beetz & Schwieger, 2008). In the following, the general structure of the hardware-in-loop simulator is described. It consists of a remote control, a model construction machine (scale 1:14), a robot tachymeter as position sensor, an interface between a PC and the remote control. The robot tachymeter measures the current position of the model machine. This position is compared to the given position on the control computer resulting in a lateral deviation. This lateral deviation is transformed into a steering angle and finally into a voltage value for the remote control that influences the steering of the model caterpillar. Finally the position of the model is measured again by the robot tachymeters to close a loop. During this process the velocity is kept constant.

For the case we are discussing in this paper, the construction machine is a caterpillar suitable for the dozer model with its two-track crawler chassis (Figure 4). At the moment the IIGS simulator can integrate three tachymeters: the Leica TS30 and TCRP 1201 as well as the Trimble SPS930. All three belong to the instruments showing the best performance and accuracy available on the market for tracking of moving objects. Leica GRZ 101 is the prism used to achieve the results in section 5.

The complete software toolbox is developed with LabView©. The given trajectory being the base for the results of section 5 is stored as discrete points in a text-file and has a length of 11 m. The circuit consists of two straight lines, four clothoids and two curves. The distance between the stored points is 0.1 m. Further details of the simulator and the guidance system are described in Gläser (2007) and Beetz (2012); e.g. the other given trajectories are shaped like an eight and a kidney respectively (Beetz , 2012).

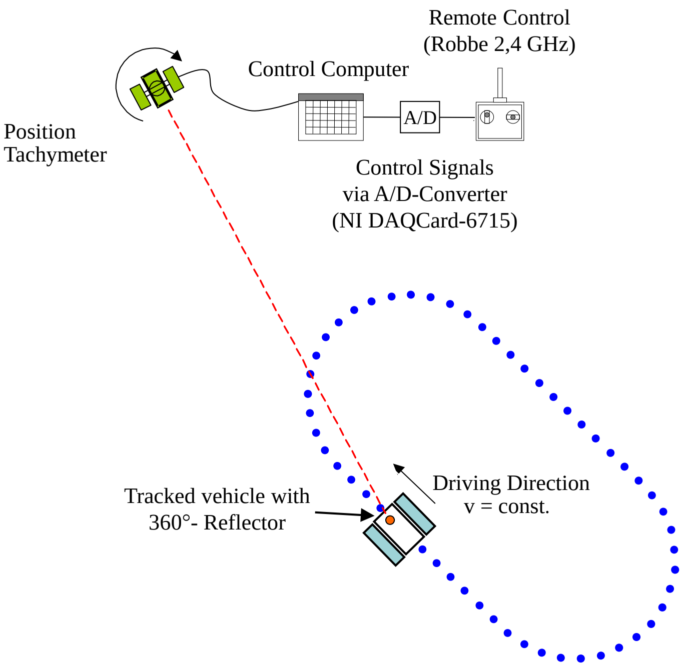

Figure 4: Situation in laboratory

3.2 Integration into the closed-loop system

In general, a closed-loop system consists of a reference signal w(t), a controller, a controlled system and a measurement system. The closed-loop system presented here is completed by a pre-control (e.g. Gläser 2007, Kehl 2007) and a Kalman filter. In general, the reference signal is compared to a measured or filtered variable $\hat{y}(t)$ to determine the control deviation $e(t)$. In our case the positions of the given trajectory and the measured and filtered positions are used to compute the lateral deviation. Then the controller converts the control deviation into a regulating variable $u(t)$ that specifically influences the controlled system. Here a PID controller generates the steering parameter p in percentage that has a direct influence on the model dozer, in case the reference signal is time-invariant. The parameter p indicates the percentage of the right track velocity in comparison to the left one. Since the machine model is driving with constant velocity on the trajectory, the reference signal is time-variant, e.g. a clothoid follows a straight line. The steering parameter delivered by the trajectory is included and summed up with the one delivered by the PID controller to get the final steering parameter p as regulating variable. The reaction of the controlled system is defined as controlled variable $y(t)$. The controlled variable is measured and compared again to the reference signal or filtered before the comparison. As written before, the measurements of the positions are carried through by a robot tachymeter. The following Kalman filter is described in detail in Schwieger & Beetz (2007) and will not be discussed here.
The main difference to the bicycle model is that instead of voltage values the steering parameter p in percentage is introduced and the steering angle δ in degree is replaced by the curvature as the reciprocal of the radius in 1/m. In following we have to describe the equation to determine the parameter p:

$$p = \frac{v_r}{v_l} \cdot 100. \tag{8}$$

As only the ratio of the velocities of the right and left track is of importance and not the respective absolute values, the parameter p can be used directly to steer and control the model caterpillar. Therefore equation (3) in section 2 can be rewritten into

$$R = \frac{B \cdot v}{v_r - v_l} = \frac{B \cdot (1 + \frac{p}{100})}{2 \cdot (\frac{p}{100} - 1)}. \tag{9}$$

For left curves the resulting radius R may have a minus sign. This fact should be interpreted in the right way.

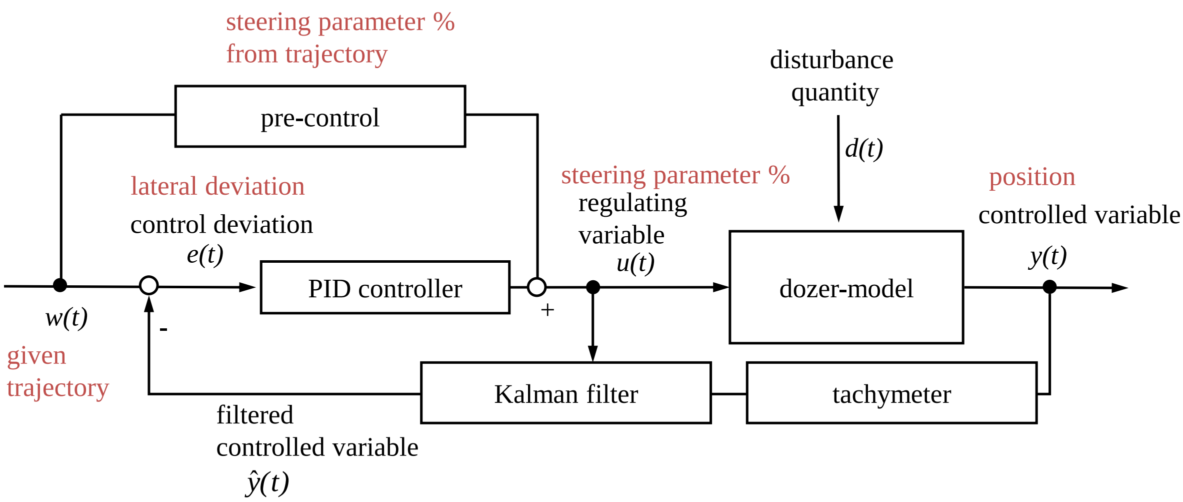

Figure 5: Closed control-loop for lateral control of a dozer-model

Besides steering the radius given by the equations (8) and (9) using the parameter p, one has to consider that the velocity v should be constant during the drive. If the ratio between the two velocities is the only steering parameter, one could e.g. break down one track without changing the velocity of the other track. In this case the general velocity v will decrease. To keep the velocity constant one needs to consider these problems. The general velocity is the average of the two track velocities v_l and v_r:

$$v = \frac{v_l + v_r}{2} = \frac{v_l \cdot (1 + \frac{p}{100})}{2}. \tag{10}$$

Finally, the two track velocities will be determined by the following equations:

$$v_l = \frac{2 \cdot v}{1 + \frac{p}{100}} \quad \text{and} \quad v_r = v_l \cdot \frac{p}{100}. \tag{11}$$

These velocities will be converted into voltage values and then transmitted to the caterpillar model via remote control. Additionally, the algorithm assures that none of the two track velocities may exceed the maximum possible track velocity. For a more detailed derivation the authors refer to Beetz (2012).

4. CALIBRATION OF STEERING

In general, the velocities for the left and the right track are known according to the equations described in section 3. To get a continuous calibration function also at zero-crossing, the relationship of p to curvature and not to radius has to be determined (radius will be infinite, if p=0). The general procedure was developed by Beetz (2003) and Gläser (2007). Since the procedure was rather time-consuming, it was automated by Su (2009) and Beetz & Schwieger (2010). For further details the authors refer to the mentioned publications. In the following the general procedure for a wheeled vehicle is described.

The first step is to drive circular arcs of minimum a quadrant using constant voltage values (Beetz & Schwieger, 2010). Different voltage values are driven, so that equidistant values for the whole measuring range of the potentiometer are available. In the second step outliers are eliminated. The third step consists of a least-square adjustment that delivers the central point and especially the radius of each of the driven circular arcs. Finally a calibration function between voltage and steering angle or another steering parameter is determined. For the bicycle model of the wheeled vehicle this relationship was linear.

For the dozer model the final step is different and needs some explanation: here the relation to be calibrated is between curvature and percentage value p. As written before, the curvature replaces the radius which was used for wheeled vehicles. The value p is a function of the ratio of two velocities (compare equation 8) and therefore of two voltages, if the relationship between voltage and velocity is constant for given velocities. This was proven empirically for the velocities driven. The main characteristic is the non-linear calibration function leading to new approaches in comparison to e.g. Beetz & Schwieger (2010). The simplest possibility would be a polynomial regression. This may lead to the problem of overshooting. Improvements are expected by cubic spline interpolation. Here the function can be differentiated two times at all support points (voltage-radius-pair). Nevertheless, the function may not be estimated in a smooth way at all places. A small overshooting may remain. This is eliminated using the Hermite interpolation. Figure 6 shows the difference of the two interpolation variants and highlights the advantage of the Hermite interpolation. The equations are given in Beetz (2012). Further details can be found in Herrmann (2007), Engeln-Müllges et al. (2005) and Fritsch & Carlson (1980).

For the calibration, the estimated radii are converted into curvatures. Then these curvatures are set into relation to the parameter p. The Hermite interpolation is realized for different velocities v. Figure 6 shows a typical example. The velocities driven are 6 cm/s and 10 cm/s, this corresponds to voltages of 0.86 and 1.075.

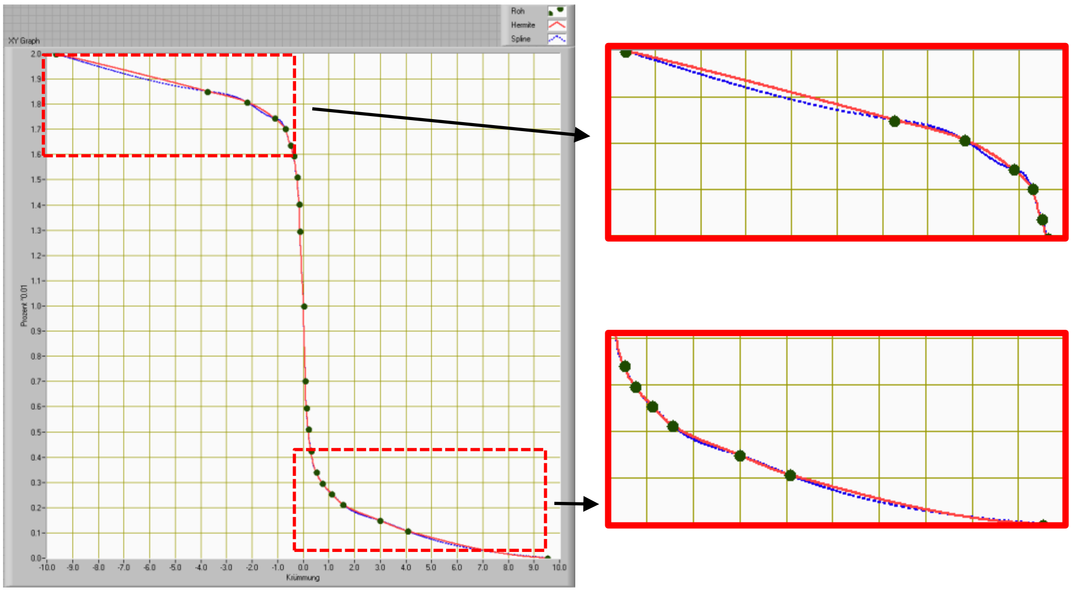

Figure 6: Calibration function of dozer comparing Hermite interpolation (red) and spline interpolation (blue)

5. RESULTS

All drives are carried through on the oval described before. The used robot tachymeter was the Leica TCRP 1201 including the Leica GRZ 101 prism. The PID-controller parameters are given in Beetz (2012). In figure 7 the dozer model is visualized in the scale 1:14.

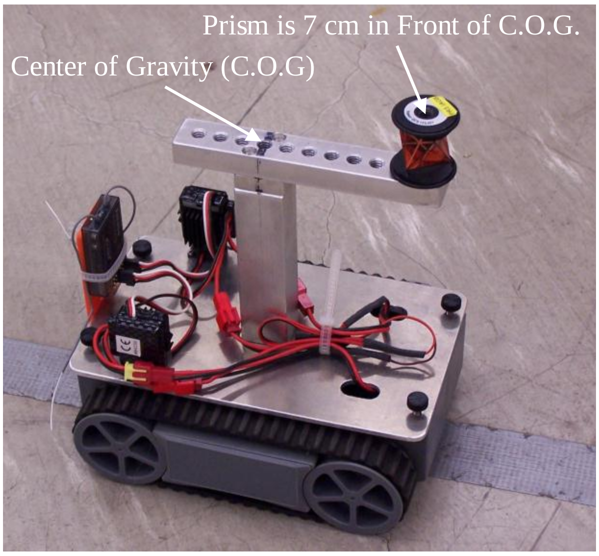

Figure 7: Setup of dozer model

The prism is installed 7 cm in front of the center of gravity to realize a higher control quality, especially in case of direction changes, which may occur in curves. This is the mechanical

realization of the anticipated computation point. For further details the authors refer to Schwieger & Beetz (2007). The concrete value of 7 cm is determined using the software simulator available at IIGS (Beetz, 2012). This shifted prism is the essential part of the pre-control introduced in the system presented in figure 5, too.
Figure 8 and table 2 are obviously indicating the advantages of the integrated pre-control. In general four laps on the oval were driven. The first one was eliminated due to inhomogeneous overshooting. Figure 8 shows the lateral deviations for straight line (red), circle arc (blue) and clothoid (green). For the pre-control almost all deviations are smaller than 5 mm, but without pre-control values up to 15 mm are reached only. The positive influence of the pre-control integration is obvious.

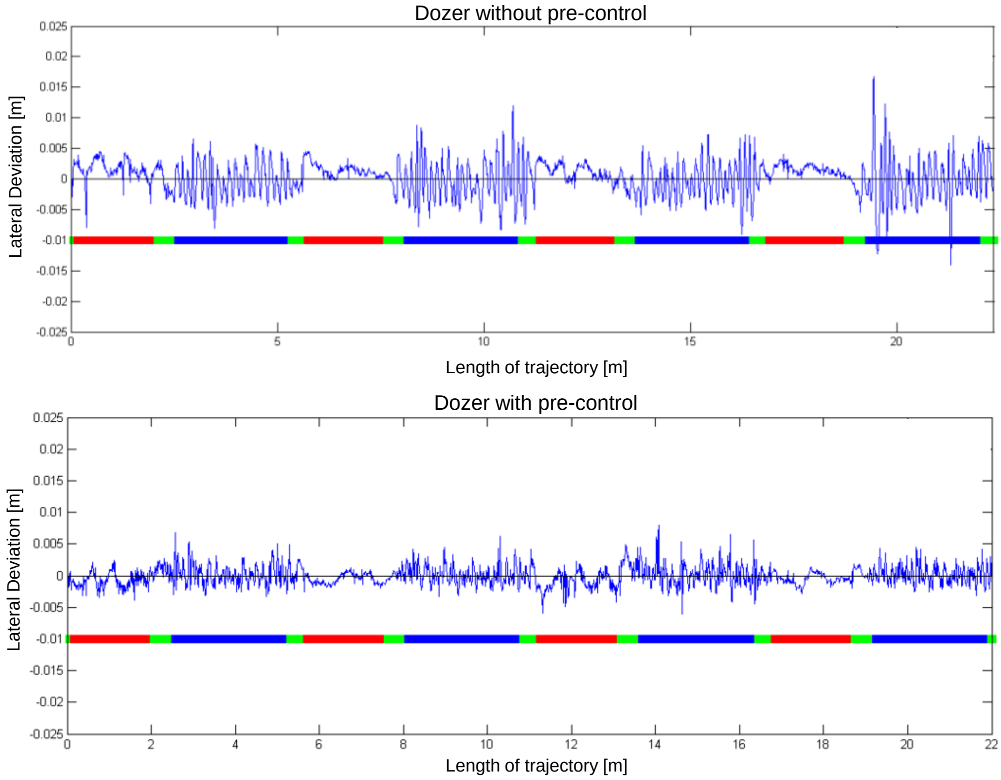

Figure 8: Comparison of two test drives with and without pre-control

Table 2 shows the quality control indicated as RMS of the lateral deviations. For the drives without pre-control the 4th lap could not be considered due to logistical reasons. The improvement leads to a total RMS of 2 mm instead of 3 mm without pre-control. Additionally outliers are fewer as visible in figure 8.
Another test drive was the comparison of laps with and without integrated Kalman filter. The authors realized that no improvement of RMS could be quantified. But the filter led to a smoother trajectory not improving the RMS but surely the driving dynamics. Figure 9 shows the raw trajectories and the Kalman-filtered trajectories for a part of a test drive. Obviously the Kalman filter results in a smoother trajectory and consequently in a better driving behaviour.

Table 2: RMS of test drives with and without pre-control

Dozer without pre-control [m]				
	straight	clothoid	circle	total
Lap 2	0.002	0.003	0.003	**0.003**
Lap 3	0.002	0.003	0.004	**0.003**
All Laps	0.002	0.003	0.004	**0.003**

Dozer with pre-control [m]				
	straight	clothoid	circle	total
Lap 2	0.001	0.001	0.002	**0.002**
Lap 3	0.001	0.003	0.002	**0.002**
Lap 4	0.001	0.002	0.002	**0.002**
All Laps	0.001	0.002	0.002	**0.002**

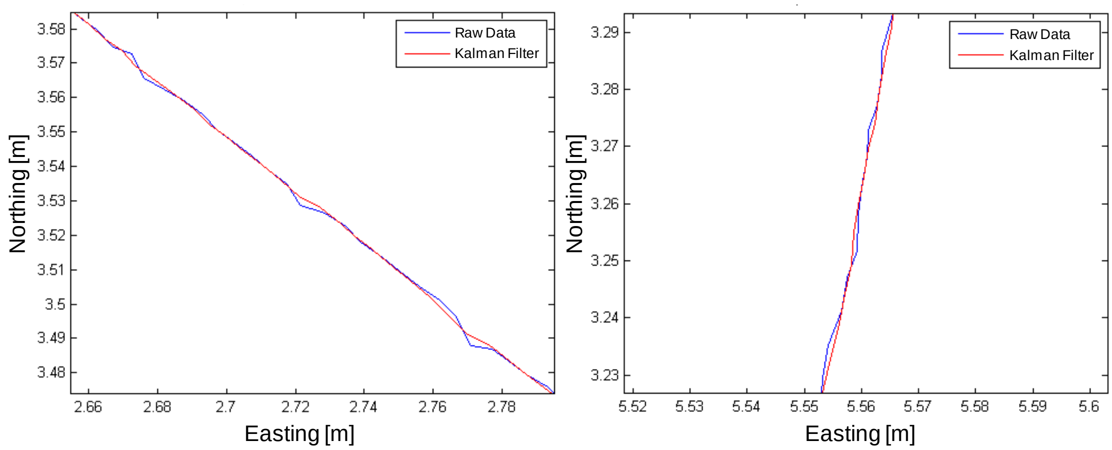

Figure 9: Behaviour of Kalman filter during the test drive

6. CONCLUSION AND COMPARISON TO WHEELED VEHICLES

In this paper the authors could show that the control quality for a dozer model in the scale 1:14 can reach 2 mm, if pre-control is introduced. The results are based on Leica TCRP 1201 tachymeter measurements. Another component helping to reach this high accuracy is the steering calibration using a Hermite interpolation between curvatures and velocity differences of the tracks. The Kalman filter does not show an improvement for the RMS, but for the trajectory smoothness.

Therefore two questions are remaining. First: Can the same accuracy be achieved for dozers as for wheeled vehicles. Here, the authors refer to Beetz (2012) and Beetz & Schwieger (2012) and table 3. Obviously, the same accuracy can be achieved, since different models are adopted.

Table 3: Comparison of test drives with dozer to wheeled vehicles

	straight	clothoid	circle	total
Front Wheel Steering (Beetz & Schwieger 2010) PID-controller with pre-control	0.001	0.002	0.002	**0.002**
Dozer (Beetz 2012) PID- controller with pre-control	0.001	0.002	0.002	**0.002**
Rear Wheel Steering (Beetz 2012) Multi-value controller with disturbance transfer function	0.002	0.003	0.004	**0.003**

The second remaining question is, if these accuracy levels will be kept in real construction outdoor environment like sandy areas or stony underground as well as deep potholes. These questions cannot be answered clearly for the moment. It has to be assumed that accuracy and reliability would decrease, but no prove could be shown up to now. This is the reason why an outdoor simulator is built at University of Stuttgart and why the research will continue in the future.

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