STEERING PROBLEMS AND SOLUTIONS DURING CONSTRUCTION OF ROADS

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Abstract: This paper deals with some problems and their solution which have occurred in automated steering of construction machines during road construction. Position and orientation of the construction machine are determined by sensors and will be instantaneously compared with reference data of the road planning. Hydraulic cylinders of the machine will then be addressed in a way that the geometry determining part of the machine, as e.g. the blade of a grader, can establish the reference geometry of the layer to be incorporated. For this measuring and controlling procedure different sensors are being used which are located in many different places of the machine. It all happens while the machine is moving so that problems with the temporal synchronization of the sensors and the machine inertia must also be considered.

1. INTRODUCTION

Information technology, digital data communication and sensor systems are nowadays used for construction work of traffic lines [4]. Benefit potentials of this technology is well known [3], for earth work it is proven [2]. Only in Germany some hundred kilometres were build in the last years using machines with automated steering facilities[1]. When constructing a road certain geometric requirements must be met. Conventionally these requirements have been guaranteed by setting out guide wires or similar guiding devices. Nowadays larger construction works do already without those guide wires. The geometry will be established via sensor combinations, especially by using GPS or tacheometer. This means major operational advantages as interferences do not occur anymore because of the guide wire. Additionally an inspection of the guide wire geometry is no longer necessary.

New in-depth studies have shown that automated machine steering has become a standard procedure in larger construction works in Germany, especially for layers with less accuracy requirements such as foundation course and frost layer [1]. Table 1 provides a survey of the systems commercially available on the market.

Manufacturer/ Developer	Systems	Maschines	Links
Leica / Moba	1D-Systems 3D-Systems	Bulldozer Digger Grader Paver/Finisher Moulding Cutter Roller	www.leica-geosystems.com www.moba.de
Trimble / Wirth	1D-Systems 3D-Systems	Bulldozer Grader Paver/Finisher Digger Roller Compressor	www.trimble.com www.wirth3d.de www.cat.com
Geodynamics	RTK-GPS	Roller	www.geodynamics.com
BOMAG	GPS	Roller Compressor	www.bomag.de
CIRC	Circom CirPav	Roller Paver	www.pges.fr
OSYRIS	O.-Machine	Roller Paver/Finisher	www.osyris.org

Table 1: Systems available

2. SYSTEM CONCEPT OF CONSTRUCTION MACHINES

The geometric steering of construction machines is a kinematic measurement process in order to eliminate current disadvantages of conventional methods and in order to aim for an optimisation of the workflow regarding efficiency and accuracy. Although the currently used measurement systems do only meet the kinematic requirements inadequately (cf. 3.5). There have been, however, solutions which allow to steer dynamic construction processes reliably and according to the requirements of the code of practice. Although there are specific requirements for each construction which can be derived from the topography, the subgrade but also specific building codes, the same basic principle of navigation will be used for the kinematic, automated steering: positioning, guidance, comparison to reference values, correction calculation. Application-oriented there will be the pattern shown in Figure 1.

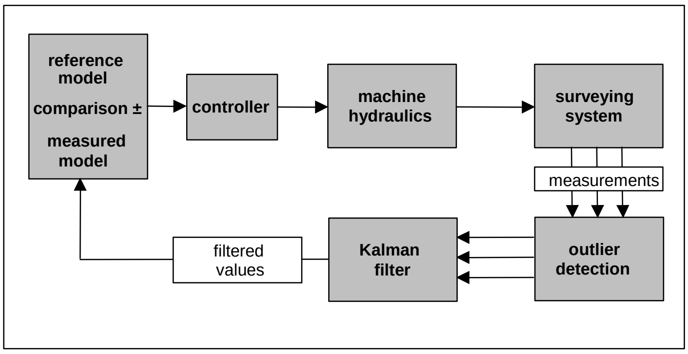

Figure 1: Control loop of steering process

In this control cycle the surveying system presents a component which delivers measurements for a real time filtering process, e.g. a Kalman filter. From this geometric actual values can be determined in discrete time intervals. The actual model again can be compared with the reference model. From possible differences the controller derives certain values which set respective control variables by the machine hydraulics. The efficiency and functional capability of this control cycle does largely depend on the synchronisation ability, the sampling rate of the measurement components, on the communication ability of all system components and lastly on the dead time, i.e. the typical interval for a new provision of the control variable. The dynamic behaviour of the control cycle is influenced by typical changes (movements) of mechanical processes and of the site or the reference geometry of the construction.

Altogether the steering system for construction machines is characterised by the following components (see Figure 2):

- Machine operator and machine,
- internal sensors (adapted to the machine),
- external sensors,
- controller system (position, comparison to reference value),
- actuating elements (hydraulic systems) of the construction machine.

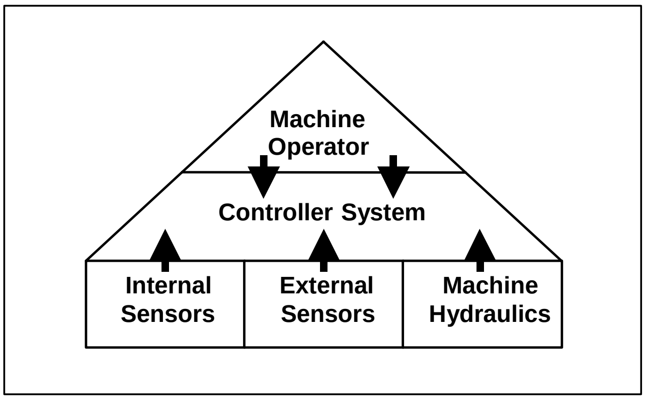

Figure 2: Components of steering system [8]

On the one hand the complexity of the control loop is dependent on the number of measurements and on the other hand on the number of steering elements as well as necessary control variables.

3. CHARACTERISTICS

Subsequently all relevant characteristics of the above mentioned system will be illuminated.

3.1. 3D-Problem

The construction of a road is a 3D problem. The road surface has changing longitudinal and lateral inclinations which are, however, rather minor. Cross slope changes do occur in ramps so that a torsion of the surface will result. Different accuracy demands do exist for the three coordinate directions due to the requirements of drainage and driving dynamics: The altitude component h is much more important than the horizontal position (x, y). Regarding position the transverse component is important because of the driving dynamic requirements. The accuracy requirements of the longitudinal component are irrelevant. On the basis of those facts it is possible and necessary to steer the altitude as a function of position:

$$h = \varphi(x, y) \tag{1}$$

The accuracy to be kept is either just a few centimeters for the foundation course up to a few millimeters for the road surface depending on the layer to be incorporated. Does a section show constant inclinations a 1D steering will be possible for the height component. For this a reference plane is usually being transmitted to the construction machine by a rotating laser. A detector at the vehicle reacts to altitude changes (in a certain measurement range) and displays qualitatively or quantitatively whether e.g. a further degradation or filling should be carried out. This can be done manually or automatically dependent on the technical equipment, provided that the indicating device does still have an access to the hydraulics. Altogether these systems can easily be installed and handled.

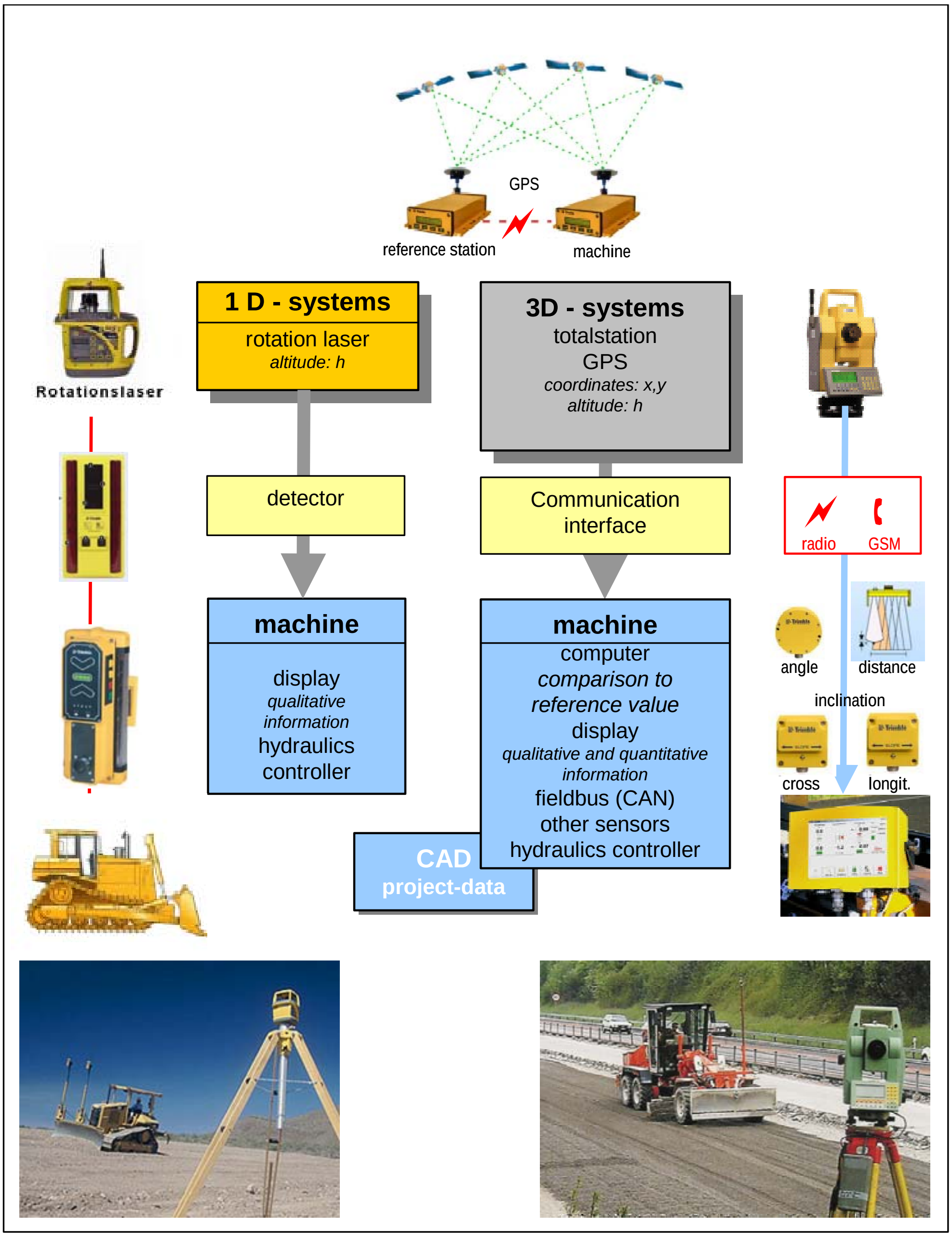

Figure 3: 1D vs. 3D controlling

In 3D steering the coordinates of the construction machine are determined by external sensors and are transmitted to the controller (Figure 3). By means of additional inclination devices and distance sensors the machine can as well be positioned absolutely in a given coordinate system as relatively to neighbouring objects and areas. Compared to the 1D steering system the reference geometry (CAD) of the construction or project data must be deposited in the computer for a comparison to reference data. In order to start the automated steering of machine elements such as the shield of a caterpillar or the blade of a grader according proportional hydraulic valves must be addressed via special valve interfaces in order to regulate the hydraulic elements.

3.2. Kinematic Procedure

As only GPS operates in a precise and generally available time scale it is necessary and convenient to relate all other more or less asynchronously acquired measurements to this reference. By certain techniques like time stamp or interpolation comparable measurements in a given time frame can finally introduced into the analysis and controlling process. The higher the kinematics of the entire system, the higher are the requirements for a good synchronisation. A delay of 0,1 sec. e.g. at a speed of 1 m/s and a slope of the road of 10% yields an altitude deviation of 1 cm.

Apart from the measurement registration the kinematic procedure does also have an influence on the analysis: In static and kinematic measurements the observations may include random and systematic deviations or even gross errors. The aim of any analysis is to reduce the noise, to largely eliminate the systematic errors and to detect respectively to abandon blunders. This happens via geometric redundancies in form of a degree of freedom. Characteristic for positioning of moving objects by GPS or tacheometer is, however, that the redundancy in every epoch is very small. Redundancy and also controllability are not available in every single epoch. They only arise from the sequence of the positions, i.e. the object trajectory: this must meet certain principles. The formulation of those principles in a kinematic model and its integration in to the analysis is therefore mandatory regarding the pointing out of errors. As shown in Figure 1 this is often done with a Kalman filter.

Typical working speed is between 0-40 km/hr. The steering of the construction machine is done while it is moving. It therefore is a kinematic procedure. This has consequences on the measurement and analysis technique used. The sensors must also be suitable for kinematic problems. This applies in particular to the sampling rate and the temporal synchronisation amongst all sensors. Even for slow construction machines sampling rates of 8 Hz or more are necessary due to the required real-time regulation and the inertia of the machine. Especially the tacheometers reach their limit at that stage. Disturbance accelerations affect the sensors due to the machine motors. This does in particular apply to the inclination sensors. Appropriate damping will be unavoidably. The requirement of the temporal synchronisation of the sensors does not only apply to the measurement itself but also to the data transmission on the machine and to additional external sensors.

3.3. 3D Moving Body

A construction machine is a three-dimensional body which moves within space. The reference geometry to be built is available in the superordinate construction site coordinate system. To create this with the machine the following information will be necessary:

- The coordinates of the reference point x,y,h,

- the attitude α, β, γ of the vehicle axis related to the local perpendicular direction and the chosen coordinate system (azimuth, roll, pitch),
- as well as time t which must be assigned to a.m. parameters.

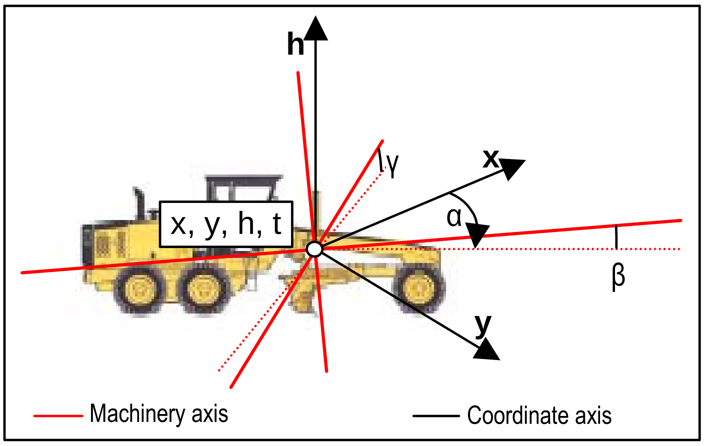

Figure 4: axis and orientation of building machine

The external sensors (mostly tacheometer or GPS) determine in discrete intervals the coordinate differences related to the according target / antenna point on the machine which is generally visibly fixed to a mast. These measurements must then be reduced to the reference point of the machine coordinate system. The measurement of the internal sensors (e.g. inclination sensor) are additionally related to the controller reference point (blade). One cannot rule out that several controller reference points must be defined. Once the controller reference points have been calibrated into the machine coordinate system, the current externally determined coordinates of the reference point can be transformed to the respective controller reference point (actual value). In order to do the comparison to reference data afterwards, the respective target value of the controller reference point must be interpolated out of the digital model. The deviations (target-actual) can then be incorporated into the controlling process in order to minimise those.

It becomes apparent that the transformations of the sensor coordinate system into the machine coordinate system and from the machine coordinate system into the construction site system are necessary. The second transformation is always dependent on time due to the machine movement. The necessary parameters must be determined by the sensors used. But also the first transformation can e.g. be subject to temporal changes because of changes of the inner machine geometry such as the abrasion of the blade.

Both transformations are therefore closely connected with the calibration of the entire system. Only if that has been properly done during installation and in regular intervals the accuracy of steering and the comparison to the reference data can be guaranteed. The following targets should be pursued:

- Determination of a suitable machine coordinate system (s. figure 4),
- geometric determination (calibration) of all measurement and controller reference points,
- calibration of all sensors installed.

In anticipation of paragraph 3.5 it should be noted that the determination of the azimuthal orientation (yaw angle) of the machine does quite often result from a sequence of positions. Roll and pitch are often directly measured using inclination sensors.

3.4. Dynamic System

Based on its dimensions and limited steering possibilities a construction machinery is a dynamic system with a certain inertia. An erratic change of the reference value can cause the dynamic behaviour of the filter to react as follows:

- An asymptotic approach to the reference value,
- a single overshooting over the reference value and after that an asymptotic approach,
- swinging around the reference value with abating amplitudes.

It is obvious that these effects, especially in connection with the measurement frequency and dead time, do significantly influence the quality and accuracy of the construction process.

Generally it can be said that the transmission behaviour between geometry deviation and the resulting machinery action for the steering system shown in figure 1 must be known. This is determined by experience following the theory of the linear dynamic systems and is supported by keeping the sampling rate of the system adequately short. Practical problems do occur if the transmission behaviour is not constant. This can be the case with changing ground or with different amounts of the material to be used. Methodically this would lead the somewhat complex theory of the non-linear dynamic systems [7]. In practice this is usually being solved by the intervention of the machine operator. Controlling therefore doesn’t happen fully automatically. The assignment of machine operators on construction vehicles is necessary anyway due to the robustness towards breakdown and security aspects.

3.5. Multi Sensor System

The determination of the coordinates of the reference point is generally being done by means of GPS or an electronic tacheometer (external) in discrete time intervals. The attitude angles and additional measurement information as e.g. distance and inclination measurements can – redundant if possible – be obtained through additional (internal) sensors.

As already indicated above all sensors of the entire system must meet certain requirements in order to determine the required „filtered actual parameter“ in the expected specification scope. Without going into the single construction machinery typical sensor combinations just now, table 2 will give a survey of sensors and characteristic features.

This compilation shows that there are different sensors for comparable measurements. Furthermore you can see that the sensor „electronic tacheometer“ has a relatively high latency period and can therefore only be used in a real time system under certain conditions. In future it can be expected that the manufacturers of geodetic equipment will minimise or eliminate this disadvantage. Altogether the prior area of application will still be in relatively slow construction processes.

Sensor	Measurement	Range Meas.Range [m]	Meas. Inaccuracy	Meas. Frequency [Hz]	Latency [ms]
GPS (Differential)	Coordinates x, y, h	0 – 5000 m Radio, GSM dependent	1 – 3 cm	< 50 Hz	20
Electr. tacheometer	Coordinates x,y, h	1,5 – 700 m Radio dependent	< 5 mm	0,1	150
Rotational laser	Altitude	1 – 1000 m	2 mm/100 m	10	< 10
Inclination sensor	Inclination (absolute)	± 60°	< 0,01°	> 100	< 10
Prop.Laser receiver	Change of altitude	25 - 75 cm	< 0,01 m	>3Hz	< 40
Potentiometer Altitude controller	Change of altitude	± 70 mm	< 1 mm	> 3 Hz	< 40
Gyro	Rotation rate	360°	< 0,1°	> 100	< 10
Tactile angle sensing device	Angle (altitude)	± 70 mm	0,5 mm	> 100	< 10
Ultrasound sensor	Distance (absolute)	20 –100 cm	< 2 mm	> 100	< 10
Opto-electronic sensing device	Distance (relative)	1 – 50 cm	< 1mm	> 100	< 10
Cable winch sensor	Distance (absolute)	0 – 100 m	0,1 %	> 100	< 10

Table 2: Sensors for machine control

GPS on the one hand has the advantage of a higher measurement frequency, on the other hand accuracy and reliability are closely connected with the necessary satellite visibility. In contrast to that an electronic tacheometer can generally only control one construction machine whereas the GPS reference station can serve more users. Therefore the best sensor combination must be chosen depending on application area and accuracy requirements in order to determine the essential parameters of the construction machinery (see Figure 4). For a comprehensive survey of possible sensors see [4].

3.6. Legal Problems

Apart from the technical problems mentioned so far there are also administrative problems with the automated control of construction machinery. The performance performed by the contractor must be checked and approved by the ordering party. With regard to the geometry of the road this was previously done by means of simple measurements relative to the guide wires set. As these guide wires are no longer in use, the examination requires extraordinary efforts. Additionally some materialized reference information in form of a guide wire no longer existent which leads to acceptance problems at the construction site [8]. There is much convincing still to be done. An opening of the shielded software packages is also necessary. It should also be mentioned that the available measurement data with a high sampling rate present a much better examination possibility than in former times. This does in particular apply to the evenness of the road.

4. Conclusion

To conclude it can be said that nowadays the geometric steering of construction machinery of all types - dozer, straight rolls, pavers, etc. has a good command of appropriate companies. The different system configurations with respective links are shown in table 1. The important problem is still the practical application: Not every machine system has – as shown above – the best configuration for each range of use. Especially for accuracy demands in the millimetre range is still some work to do.

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