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NAVIGATION OF CONSTRUCTION AND AGRICULTURE MACHINERY

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Abstract. Over the last two decades terrestrial and global 3D measurement sensors in the field of engineering geodesy have seen a significant upturn. With modern measurement techniques, a 3D trajectory of a moving object can be determined within a few centimetres (mostly with Global Navigation Satellite Systems, GNSS), under certain circumstances and with an overall understanding of the applied method accuracies of within 5 to 10 millimetres can be achieved (tracking total station). New application areas have been now created in the fields of construction, mining and agriculture. The guidance or control of heavy machinery demands a navigation sensor with an appropriate measurement rate and accuracy, as well as stable and reliable performance. The 3D position, together with the orientation as well as the long and cross inclination information is hereby just one part of the absolute machine guidance or control unit. Data collection, verification, management and interaction of the position information with the 6 degrees of freedom, together and the machine controller, are needed for the overall system. Rotation ring sensors for height control or height guidance are well-known amongst construction jobs and have been in use for more than 20 years. The first GPS-based guidance system for yield mapping was used 15 years ago (Auernhammer 1995). Optimization and improvements in efficiency are the principal reasons for the current developments in the area of 3D-based machine control and guidance. This paper will describe the state-of-the-art and general approaches as well as the real-time 3D measurement techniques in construction and agriculture environment.

Keywords: machine guidance and control, 3D measurement sensor, construction and agriculture.

1. Definition of machine control and guidance

1.1. Construction engineering

Heavy construction machines are used for many applications in civil or underground engineering, such as roads, tunnels, railways and airports. Conventional control methods use stringlines to navigate the machine along a predefined reference (Fig. 1). The disadvantages of such a height and/or position references for earthmoving or paving application are apparent. Therefore the motivation for an increased use of stringless technology is generated by the fact that stinglines:

- are expensive, time-consuming and error-prone,
- are easily damaged during the workflow,
- are easily misaligned (errors increase costs),
- are a significant site safety hazard (e.g. paving operation during a road maintenance job),
- interfere with site logistics (e.g. concrete delivery time), increase haulage costs and reduce productivity,
- are faster during complex designs.

By using and combining modern kinematic measurement technology such as tracking total stations, dual frequency GNSS receivers, dual slope sensors and still rotation ring lasers, the conventional method will be discontinued. From an economic prospect, this means that survey costs can be reduced up to 50% and overall application and project productivity related can be increased by approximately 20 to 50%. Additional reasons for a wide spread distribution of machine control and guidance systems on construction sites are the improved accuracy and logistics aspects. Furthermore, there is the benefit of direct dataflow from the first survey through to design data (2D or 3D polylines or triangulated irregular network, TIN) up to the final grading or paving layer. The digital project documentation and the as-built check complete the application.

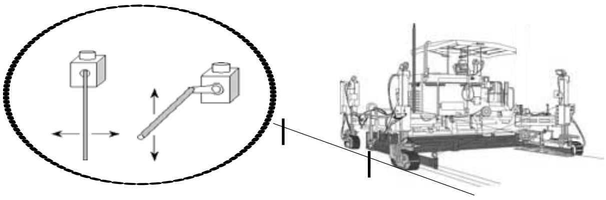

Fig. 1. Mechanical scanning of stringlines
(Leica PaveSmart User Manual)

Currently, the machine control and guidance technology are used with motor graders, dozers, excavators, trimmers, profilers, rollers, asphalts and concrete pavers and can be defined as state-of-the-art. The classifications are:

1.2. 1D and 3D guidance systems

This means a height indication with or without single or dual inclination information of an excavator bucket, dozer or motor grader blade. The machine operator is guided along the predefined reference. In this case, the measurement and guidance system has no hydraulics linked to the machine. For basic systems, a rotation ring laser combined with a laser catcher is used to give the absolute height information. Dual slope sensors (dozer and motor grader) or boom angle sensors (excavators), together with the machine geometry, are used to calculate the reference value (Fig. 2). Display panels provide the operator with the deviation along with additional information, e.g. the amount of material or machine related parameters. The 1D indication systems are so-called low cost entrance units which are easy to operate and install. Such rotation ring laser-based solutions have been well accepted for more than 15 years.

3D indicate systems are mainly GNSS-based excavation units. Two dual frequency rover GNSS receivers at the machine frame provide the absolute position (transformed WGS84 GNSS data from a flat job site coordinate system), height and chassis orientation (Fig. 3). The first patents for such an approach were submitted in 1995 by the excavator manufacturer Caterpillar in the United States. The calculation of the bucket 3D position is based on the GNSS rover data, the angle measurements and the constant distance between each boom (similar to the 1D system).

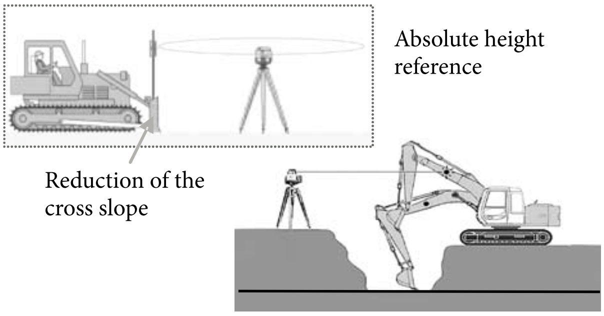

Fig. 2. Rotation ring laser for dozer / Basic excavator system (Stempfhuber 2006)

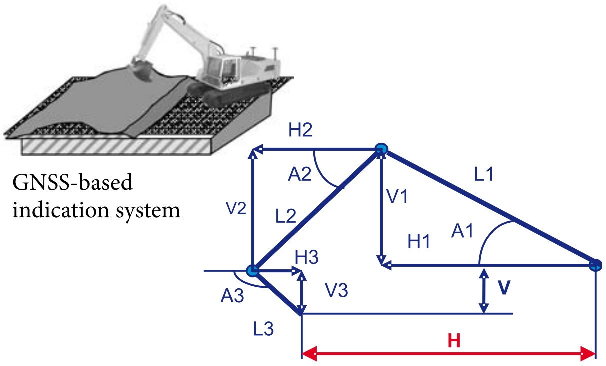

Fig. 3. Calculation of the excavator bucket (Leica digsmart user manual)

The position and height offset is given by:

$$V_i = L_i \cdot \cos(A_i) \quad \text{and} \tag{1}$$

$$H_i = L_i \cdot \sin(A_i), \tag{2}$$

$$V = \sum V_i \quad \text{and} \tag{3}$$

$$H = \sum H_i, \quad i = 1 - 3. \tag{4}$$

So the excavator geometry form the master GNSS rover antenna to the first boom. GNSS-based roller guidance systems such as the Hamm HCQ GPS-Navigator (www.wirtgen-group.com) or the Bomag GPS Variocontrol (www.bomag.com) are used to increase the complex compaction of grading or asphalt layers.

1.3. Semi-automatic or full automatic control systems

Semi-automatic systems (also called grade control) are developed to control a trimmerhead, the asphalt mould of a paver, a dozer or a motor grader blade. For homogeneous plates, horizontal or with a tiny long and cross slope, a rotation ring laser is a sufficient sensor. Neither a design with the 3D machine position, nor geodetic knowledge is required. For irregular surfaces, the absolute height of the blade in relation to the design position, from the 3D trajectory of a GNSS or a tracking total station, must be calculated. The deviation from the reference height or digital terrain design determines the output values on the machine controller. The mobaMatic (www.moba.de), with more than 80% of the worldwide used control systems are the most used interface between the machine hydraulic and the 1D or the 3D measurement sensors. The calculation method will be explained in the following chapter.

A full automatic system controls the machine autonomous in 3D (in height and position). Currently the only application is a slipform paver (mainline paver for highway and airport jobs, barrier, curb & gutter or offset paving) plus a few trimmer applications. Leica Geosystems (based on tracking total stations) and Topcon (based on combination of GNSS with rotation ring laser as mmGPS) provide such sophisticated 3D control solutions. Both have implemented the control protocol of the main machine manufacturers (Gomaco and Wirtgen), thus meaning that the system concept and installation are very simple. This also means that only one cable is connects the control unit with the machine controller. Only four height and two control parameters send the correction values to

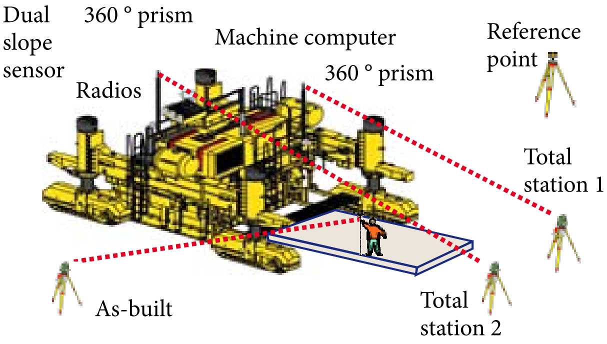

Fig. 4. 3D Control, example of a mainline paver (Stempfhuber 2007)

the machine CAN Bus. An example of the total station-based system setup is shown in Fig. 4.

The main improvements compared to convensional methods can been clearly seen in logistics and the reduction in overall jobsite workflow.

1.4. Agricultural applications

The approach taken in all agriculture tasks are also driven by similar optimisation, ergonomic and economic reasons. A further motivation for precision farming or precision agriculture systems are the environment protection with savings in seed, fertiliser, pesticide, fuel, overlap and skip expenses. Fleet management systems, yield or soil mapping and field robotics, such as automatic tractor steering systems, are state-of-the-art techniques which use geo-reference GNSS measurement (stand alone, difference or dual frequency real time kinematic).

Many system requirements in precision farming or precision agriculture are similar to construction machine control or guidance. A calculation is allways made between the reduced 3D position and reference data at one or a few control points. Therefore, kinematic measurements systems are required to determine the trajectory in real time.

2. Kinematic measurement sensors

Both areas of application, construction machines as well as agriculture machines are based on geodetic measurement systems (Fig. 5). The main difference is that in precision farming the height component is only of secondary relevance and vice versa in machine control or guidance of construction machines. A further point is that GNSS receivers are the common and well accepted sensors because of their obvious advantages over tracking total stations based on angle and distance measurements. Both applications are mainly related to the overall accuracy with different focuses, the measurement frequency and the stability according to the number of measurement timeouts of the sensor (Stempfhuber 2004). A sufficient measurement frequency is needed to correct all bumps. The Nyquist–Shannon sampling theorem allows the minimum sampling rate to be determined.

$$f_{\max} \le \frac{1}{2\cdot\Delta t}. \tag{5}$$

Other critical parameters are the relative or absolute latency of the 3D position output and therefore the reaction time of the machine. The discussion of the appropriate 3D sensor is generally based on the accuracy of the measurement system. Error-free and optimized terrestrial measurements with a tracking total station can achieve 5 mm at a range of up to 50 m. A relative comparison of the two different machine control and guidance measurement systems shows the performance. This can be interpreted as an indication of which measurement is the most suitable to choose for an individual application.

As a consequence of the height plot (Fig. 6), GNSS measurement cannot be used for precise grade or milling applications and definitely not for paving applications, even with a good satellite constellation. Applications with an absolute height accuracy around 5 mm can only be achieved, if the whole setup of a tracking total station is optimized. The required parameters are:

- lock stability of the automatic target recognition,
- interaction tracking regular,
- velocity of the motorisation,
- stability data link,
- prism search / prism identification,
- tilt sensor integration during tracking,
- measurement frequency,

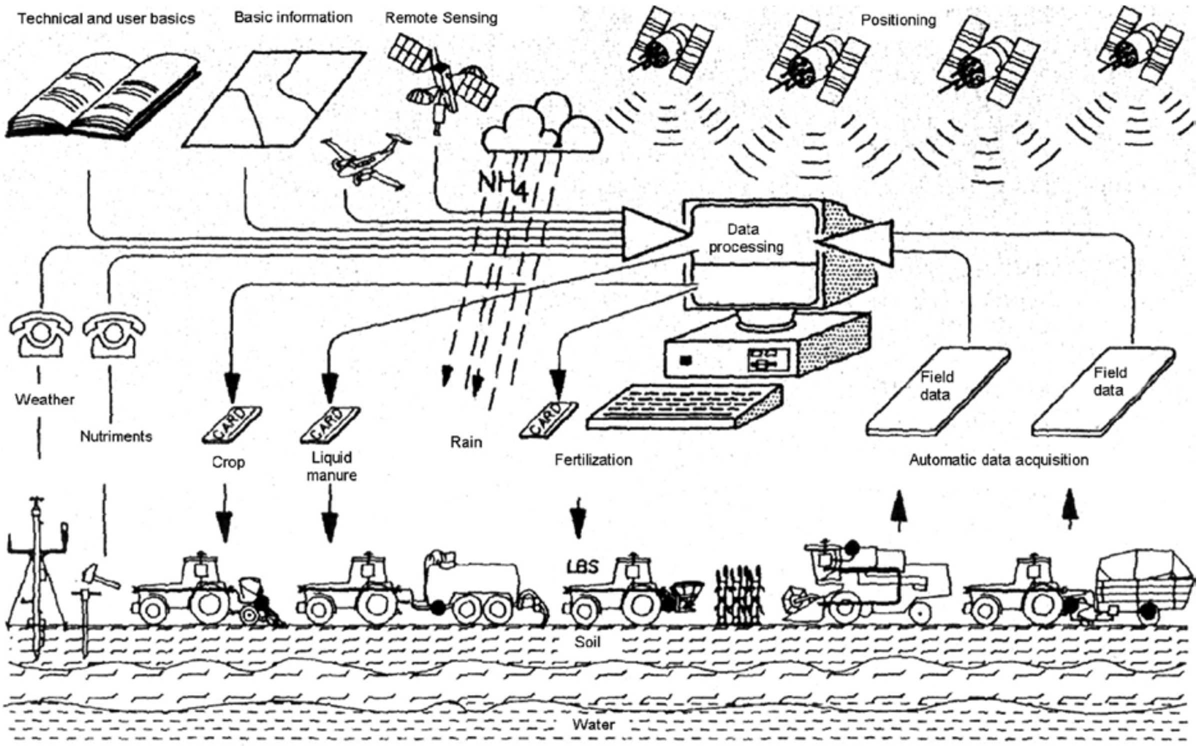

Fig. 5. Overview of the precision farming applications (Auernhammer 1995)

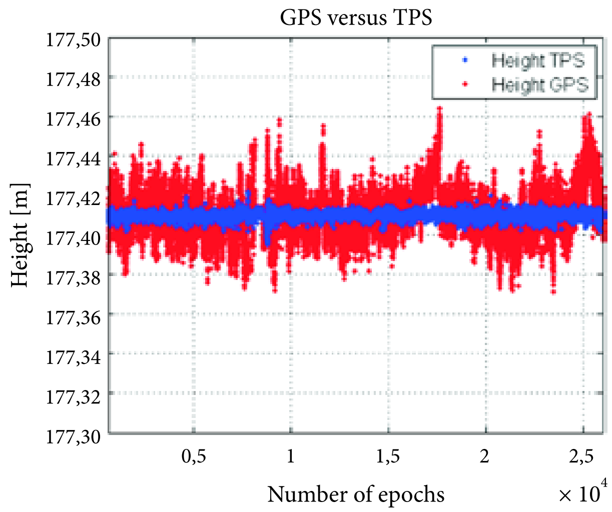

Fig. 6. Comparison of GNSS versus tracking total station

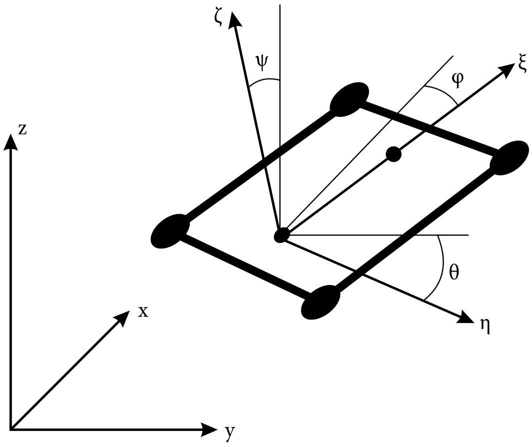

Fig. 7. Calculation of the Control Point (Retscher 2002)

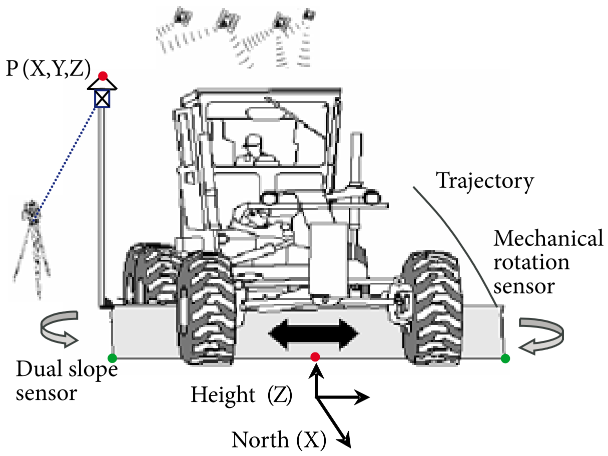

Fig. 8. Calculation of two control points (Stempfhuber 2007)

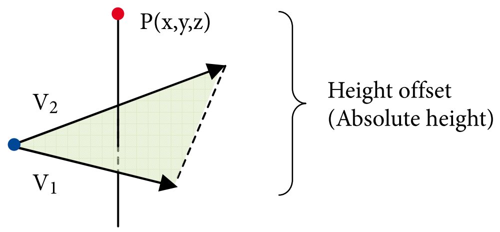

Fig. 9. Calculation – absolute height with a triangle design

- latency (relative and absolute),
- quality of the 360° targets,
- EDM mode,
- suitable data formats and interfaces.

With all the current tracking total stations from the manufacturers Leica, Trimble, Topcon and Sokkia, it is possible to achieve the following measurement result, with a kinematic fine tuning system.

3. Calculation procedure

The main task is to calculate an absolute 3D position in x, y, z together with the dual inclination and the machine orientation in order to determine control points which are used for the deviation computation. This is always a translation and a rotation around a predefined system origin (Fig. 7).

3.1. Automatic steering system of tractors

Only the correction of the 3D GNSS position is considered. The nadir is calculated with the GNSS antenna height, the orientation or heading φ from the trajectory history and the long- and cross-inclination (roll Ψ and pitch θ angle) by:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \cdot R(\varphi,\psi,\theta) \cdot \begin{pmatrix} \xi \\ \eta \\ \varsigma \end{pmatrix}. \qquad (6)$$

If the antenna is not centred, a cross offset must be considered. Only one control point is needed for calculating of the hydraulic control values. Additional sensors are sometimes used to determine the front wheel angle.

3.2. Height or grade control

Two absolute control points are required for the height control of asphalt moulds, trimmerheads, dozer or motor grader blades. With the following method, left and right control points are calculated in real-time around 10 to 20 times per second. This closed calculation loop is implemented in the core algorithm of each software. Fig. 8 illustrates the example of a motor grader.

Calculation loop (Figs 9–11):

- obtain 3D position in the jobsite coordinate system (TPS / GPS transformation needed),
- get orientation from the history track,
- correct long and cross slope use slope sensor reading and the mast height,
- use local machine plate dimension (height, long & cross offset, size),
- correct side shift offset (lateral offset),
- correction of the plate rotation,
- transformation of XYZ position into the design model,
- find corrected point in the TIN (def. local window), via extrapolation of the triangle,

$$E : \vec{x} = \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} + r \begin{pmatrix} V_{1x} \\ V_{1y} \\ V_{1z} \end{pmatrix} + s \begin{pmatrix} V_{2x} \\ V_{2y} \\ V_{2z} \end{pmatrix}, \tag{7}$$

$$G : \vec{g} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} + k \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}. \tag{8}$$

- calculation of the height difference,
- extrapolation of the absolute height left right,
- use machine tuning parameter.

=> send correction to the hydraulic controller.

With simulated data the height of an extrapolated TIN can is verified.

3.3. Full 3D control

Different machines in the concrete paving applications are slipform pavers, barrier pavers, curb and gutter machines. All of them have a rectangular mould. In order to control such a mould, only four values at each corner for the height control and two values are needed to steer along a polyline. These six control values are basically the parameters between the measurement unit and the machine controller plus a few safety routines.

A similar approach to the semi-automatic control is used but the machine orientation is measured with a second prism and the height calculation is extrapolated to each corner. The two steer positions can be defined in the centre, left or right. These 6 control values correct the 4 hydraulic cylinders which is the same as a stringline control.

Each algorithm is based on the same method by using 6 degrees of freedom, which means that only one general 3D calculation platform would be needed. This is just one obvious motivation, in addition, to the overall system setup and a lot of similar software panels to guide or control every machine with a selection of various measurement sensors and only one common algorithm.

4. Outlook

Both systems in the field of construction and agriculture use machine control and guidance to optimize the applications. This "new technology" is well accepted but has not spread worldwide. In construction jobs, 3D applications are often project-related. There is no doubt that this business has a high rate of growth, so a lot of further improvements and system developments will take place in the near future. This fact is not only driven by the system provider but also by the system user. A large number of open questions have to be discussed by both academic research and system and kinematic sensor manufacturers. Next few years, immense developments in improving and facilitating operating methods for overall systems, an increased integration of the whole workflow plus suitable measurement sensors will promote this technology more and more.

This ambitious target can be reached only if all experts from the engineering geodesy and the machine and control experts exchange their knowledge. A potential occasion is the 1st International Conference on Machine Control & Guidance at the ETH (www.mcg.ethz.ch). All topics described above will be discussed in a technically based manner.

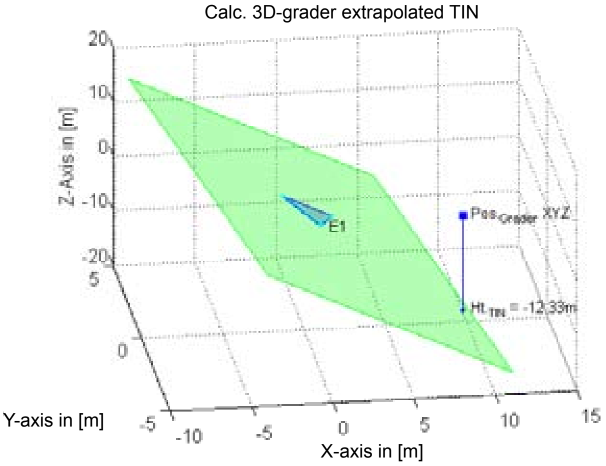

Fig. 10. Calculation of height in one TIN triangle

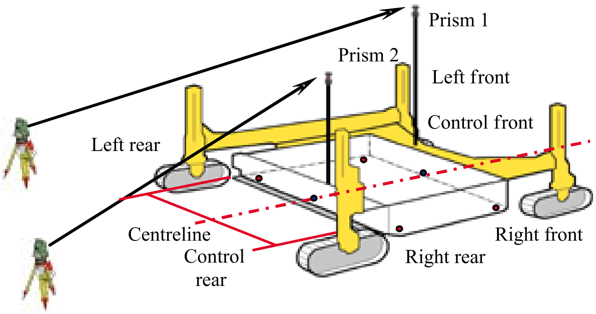

Fig. 11. Control points – mainline concrete paver (Stempfhuber 2007)

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Research interests: machine control and guidance, precision farming, engineering geodesy and geodetic measurement techniques.