Multi-Sensor Systems for Machine Guidance and Control

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Key words: Machine guidance, Multi-sensor systems, 3-D guidance, sensor integration, Kalman filter.

ABSTRACT

New developments in construction industry in recent years have led to an increase in productivity of construction works and corresponding cost savings. Starting from a classification of machinery employed for road and railway construction, suitable systems and sensors have to be assigned to solve a specific task. In modern systems for construction machine guidance, multi-sensor systems are employed that consists usually of a 3-D surveying system, i.e., either RTK GPS or total stations with automatic targeting and tracking, and additional sensors, e.g., electronic inclinometers, gyro compass, etc. In a comparison with conventional systems, their main advantages and disadvantages and major applications are highlighted.

For guidance of the machine along the defined path, the position and orientation of the machine in a 3-D coordinate system, e.g., the coordinate system of the construction site, has to be determined continuously in real-time. This problem can be solved by defining a so-called machine coordinate system (or body frame) that is embedded in the machine or machine blades. Then the orientation and rotation of the frame in 3-D space are described by three attitude parameters. The position and attitude parameters are obtained in the evaluation process from the observation of all sensors of the multi-sensor system. A modified approach based on optimal linear estimation methods (Kalman and Wiener filter) for the determination of the machine blade movements will be discussed and analysed briefly.

ZUSAMMENFASSUNG

Neue Entwicklungen im Baubereich, vor allem im Zusammenhang mit modernen Baumaschinen, haben in den letzten Jahren zu einer wesentlichen Steigerung der Produktivität und zu entscheidenden Kosteneinsparungen beigetragen. Ausgehend von einer Klassifizierung von modernen Baumaschinen für den Straßen- und Eisenbahnbau werden in diesem Beitrag die Komponenten und Sensoren für moderne Systeme zur Maschinensteuerung bzw. -führung beschrieben. Im Prinzip sind diese Systeme sog. Multisensorsysteme, wobei für die dreidimensionale Positionierung entweder Tachymeter mit automatischer Zielerfassung und -verfolgung bzw. GPS-Echtzeitsysteme in Verbindung mit anderen Sensoren, wie z.B. elektronische Neigungsgeber und Kreisel, zum Einsatz kommen. In einem Vergleich mit herkömmlichen Systemen (Rotationslasersysteme, Einsatz von Führungsdrähten) werden die Vorteile dieser modernen 3D-Steuerungssysteme dargestellt und deren Hauptanwendungen vorgestellt.

Für die Steuerung der Maschine längs einer vorgegebenen Trasse muss deren Position und Orientierung in Echtzeit kontinuierlich in einem übergeordneten Koordinatensystem (z.B. dem Koordinatensystem der Baustelle) bestimmt werden. Diese Aufgabe kann durch die Festlegung eines sog. Maschinenkoordinatensystems gelöst werden, das in der Schar der Maschine gelagert wird. Die Ausrichtung der Achsen des lokalen Koordinatensystems im übergeordneten System wird dann durch drei Orientierungsparameter beschrieben. Seine Lage und Orientierung kann im Auswerteprozess aus den Messungen aller Sensoren des Multisensorsystems bestimmt werden. Ein Algorithmus basierend auf optimalen linearen Schätzverfahren (wie Kalman und Wiener Filter) für die Bestimmung der Bewegung der Schar der Maschine wird kurz vorgestellt und diskutiert.

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1. INTRODUCTION

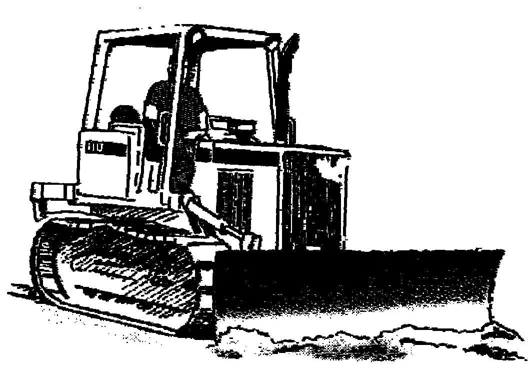
The major applications for machine guidance systems can be found in construction industry and mining for the guidance of dozers, motor graders, excavators, scrapers as well as in agricultural applications for the guidance of tractors and harvestors. Modern 3-D guidance systems have been developed starting from laser based machine guidance systems. In general, the 3-D systems use either robotic total stations with automatic targeting and tracking or RTK GPS systems for position determination. To guide the machine and/or the machine blades along the defined path, the position and orientation of the machine in a 3-D coordinate system (e.g. the coordinate system of the construction site) has to be determined in real-time. Therefore a so-called machine coordinate system (or body frame) is used that has its origin in the rotation point or centre of gravity of the machine. Then the orientation and rotation of the machine in 3-D space are described by three attitude parameters. These attitude parameters can be obtained using either three measurement points on the machine defining the body frame or in combination with observations of other sensors, e.g. using an electronic inclinometer and/or gyro compass.

2. CLASSIFICATION OF CONSTRUCTION MACHINES

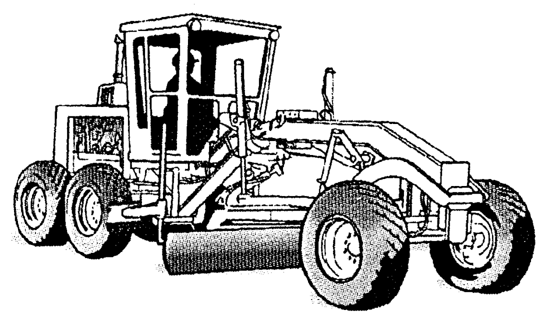
Many types of construction machines are available that can be employed for different tasks. For the construction of road and railways some of the main tasks for the employed machinery are:

- Bulk earthworks and earthmoving,
- Topsoil stripping,
- Sub base formation,
- Bridges and structures earthworks,
- Abutments and ramps,
- Embankments and noise embankments,
- Course grading of materials,
- Soil stabilizing,
- Soil or asphalt compaction,
- Asphalt or concrete pavement.

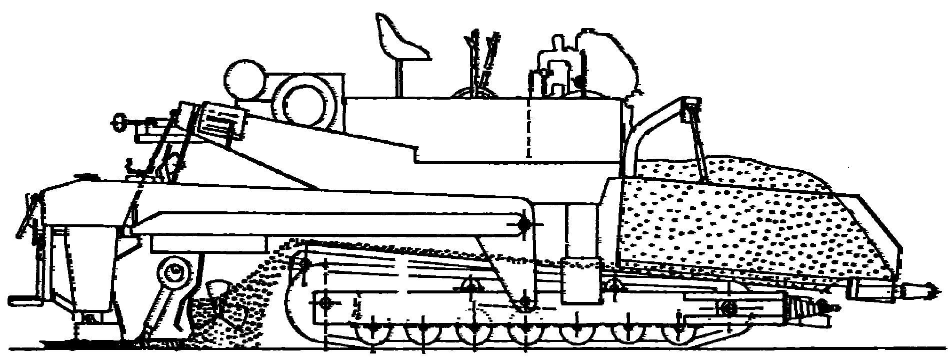
Typical machinery developed for earthworks and earthmoving, grading and pavement are shown in Figure 1. For these types of construction machines a variety of guidance systems have been developed. Dozers are usually employed for bulk earthworks and earthmoving, the construction of abutments and ramps, embankments, etc. It can be distinguished between wheel dozers with with rubber tires and and the more common crawler dozers with steel tracks (Figure 1 a). The blade is mounted at the front of the machine. Motor graders (Figure 1 b) are equipped with rubber tires and the machine blade is mounted behind the front wheels. The blade can be rotated and tilted by the machine hydraulics to achieve any given alignment and inclination. Graders are usually employed for fine grading, course grading of materials, sub base formation or sideslope work. The asphalt or concrete surface of a road can be built using paving equipment. The type of paving machine shown in Figure 1 c can be employed for highways, city streets, county roads, lane additions, industrial sites, parking lots, overlays and other production-sized paving jobs. It can be distinguished between pavers with rubber tires and steel tracks. Concrete slipform paving machines are also used in the construction of the trackbed for high speed railway lines or airport runways and taxiways. Table 1 summarizes the application areas, the precision requirements and the usual employed guidance systems for the three different types of construction machines.



a) Crawler dozer



b) Motor grader



c) Paving machine

Fig. 1: Main construction machine types

Depending on the application, different accuracy requirements in position and height have to be fulfilled from the employed machinery. In the case of road and railway construction, especially high accuracies in height have to be achieved for the finished surface. Thereby different surface layers can be distinguished in the construction process that have corresponding requirements for the height accuracy. Typical accuracy requirements in height for the different layers are summarized in Table 2. The employed measurement systems have to guarantee these high vertical precision and careful control of the formation.

	Dozer	Grader	Road paving machine	Slipform paving machine
Major application field	Bulk eartworks and earthmoving	Fine grading, sideslop work	Asphalt surface for highways, concrete surface for runways	Concrete surface for highways, high speed railways, runways
Precision requirements	up to ± 2 cm	up to ± 5 mm	up to ± 5 mm in plane ± 3 mm in height	up to ± 5 mm in plane ± 2 mm in height
Guidance systeme	3-D systems: GPS or total station	Laser systems 3-D systems: total station	String lines or stakes Laser systems 3-D systems: total station	String lines or stakes Laser systems 3-D systems: total station

Tab. 1: Comparison of differnt types of construction machines

Surface layer	Vertical precision
Finished Surface	< ± 6 mm
Base course	± 6 mm
Upper road surface	± 8 mm
Road base	± 15 mm
Sub base	± 10 mm – 30 mm
Formation and cap	± 20 mm – 30 mm

Tab. 2: Vertical precision requirements for road surface constructions (after Houghton, 2001)

By comparing Table 1 with Table 2, suitable construction machines and guidance systems can be selected for a specific task. The high precision requirements in the case of the construction of highways and high speed railway lines or runways on airports are very challenging for the employed paving machines and the guidance systems. The most commonly used guidance systems are described in detail in the following section.

3. MACHINE GUIDANCE SYSTEMS

The methods developed for the guidance of construction machines can be distinguished depending on the level of automation they achieve. The highest level of automation is achieved with modern 3-D guidance systems and automatic blade control. In this case, the navigation parameters and deviations of the machine blades from the designed surface are obtained from a comparison with the given alignment of the road. The given alignment is usually based on a digital terrain model. If a correction is required, the parameters are automatically sent to the machine hydraulics to maintain the design elevation and cross slope. Visual control is provided for the machine operator using a navigational display. Some machinery employ also manual blade control. Then the guidance of the blades is controlled by the operator. In the following, the principle of operation of modern 3-D guidance systems is discussed and in comparison with conventional methods their advantages are highlighted.

The main component of 3-D guidance system is a positioning unit which is able to track the machine movements continuously. Due to the availability of modern RTK GPS systems and total stations with automatic targeting and tracking such systems could be developed. They are able to determine the 3-D position of the machine continuously with a high frequency of up to 10 Hz, i.e., 10 times per second. The kinematic sequence of machine positions represents the trajectory of the machine. Figure 2 shows the main components of a 3-D machine guidance system. Apart from the positioning unit, usually additional sensors are included into the system design, e.g. electronic inclinometer or tiltmeter to measure the pitch and roll of the machine or the blade.

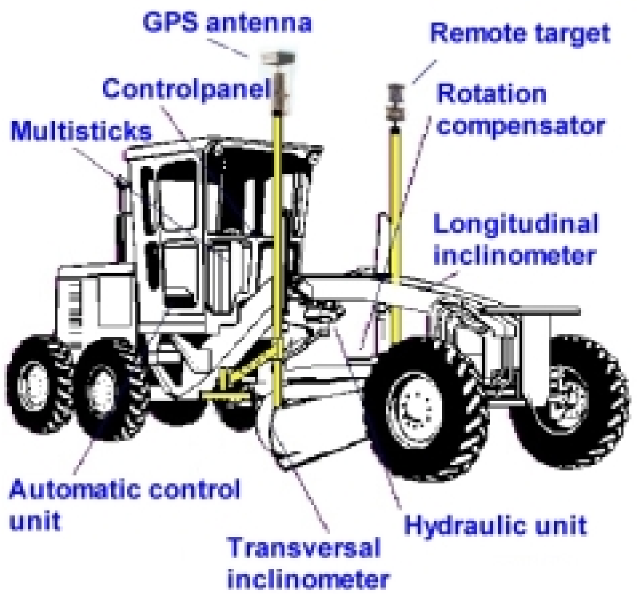


Fig. 2: Main Components of 3-D Machine Guidance Systems

Inclinometers or tiltmeters are employed to measure the longitudinal and transversal tilt (i.e., pitch and roll) of the machine and/or its blade. The longitudinal sensor (so-called long slope sensor) measures the vehicle pitches in the direction of travel and hub for all system sensors. The transversal sensor is a highly dynamic measuring unit that determines current lateral blade inclination for exact control of lateral inclination. In addition, a precise determination of blade rotation using a so-called rotation compensator provides for optimum lateral inclination compensation (see e.g. Moba, 2002). This sensor is in principle an electronic gyro compass or heading sensor. All the sensors are integrated with the positioning unit in the sense of a multi-sensor system.

As an alternative, the current lateral blade inclination can also be determined using two prisms or GPS antennas which are mounted on each side of the machine blade (see Figure 2). A GPS guidance systems especially developed for dozers uses two GPS antennas connected to one receiver. The unique dual GPS antenna system indicates the exact position, slope and orientation of the cutting edge (Trimble Site vision GPS, Trimble 2002 c).

Table 3 compares the 3-D guidance systems using total stations and RTK GPS with traditional methods based on string lines and stakes or the use of rotating lasers.

The conventional systems require surveyors to provide the interface between the engineering design and the machine operator on site. This can be achieved by using grade stakes that are placed at strategic locations around the site and indicate the level of cut and fill required at that point. Machine operators then have to use their experience to interpolate the grade between the stake locations. Grade stakes can be replaced by string lines (see Figure 3) where the machine is guided along the line using detectors such as ultrasonic or laser tracers. Their main disadvantages, however, are that grade stakes or string lines are often knocked out by the machines during the course of the daily work and that they are very labour intensive in setting out and maintenance. On-site surveyors are required to stake and re-stake, to check the resulting surface, to calculate the volumes of earth moved and deviations from the desired design surface (see e.g. Carlson et al., 1999; Anderson 1999).

	String lines or Stakes	Rotating Laser Systems	Robotic Total Station	GPS
Dimensions	3-D	1-D (height only)	3-D	3-D
Reference stations required per construction site	Many tachymeter stations required for setting out	One or more; site dependent	One per machine	One
Setups per construction site	Not applicable	Multiple times per site	Multiple times per site	One
Number of machines supported by reference station	Not applicable	Unlimited in one plane	One per total station	Unlimited
Maximum range	Sensors work in close-range	up to 300 m depending on line of site	up to 700 m depending on line of site	Several kilometres
Usability under bad visibility conditions	Not affected	Reduced	Reduced	Not affected
Accuracy	mm - level	mm - level	mm - level to cm - level	cm - level
Major applications	Guidance of road and slipform paving machines	Precise height control for graders; Guidance of road and slipform paving machines	Guidance of graders, excavators, scrapers or dozers	Guidance of dozers and scrapers, Precise Farming

Tab. 3: Comparison of machine guidance systems

Fig. 3: Guidance of paving machines using string lines (after Anderson, 1999)

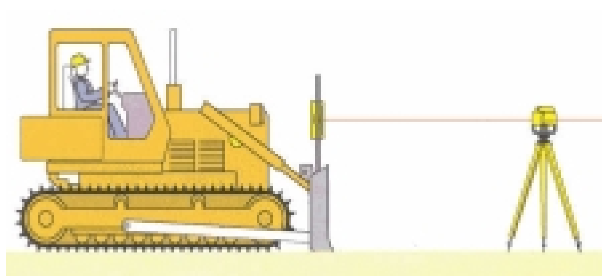


Fig. 4: Operation principle of rotating laser systems

Compared to the conventional methods, the use of rotating laser systems has led to an increase in productivity and cost-savings. Their principle of operation is shown in Figure 4. With the rotating laser beam a horizontal plane is defined and the deviations from the plane can be observed. The laser detectors are usually mounted on the blade of the machine. Using laser systems, height control can be performed with high precision. Their application, however, is limited for areas with small changes in gradient. Otherwise new setups of the laser instrument are required very frequently. Rotating laser systems are mainly employed for precise height control of graders.

The major applications for 3-D machine guidance systems can be found in construction industry and mining for the guidance of dozers, graders, excavators, scrapers as well as in agricultural applications for the guidance of tractors and harvesters (see Table 3). Depending on the accuracy requirements, RTK GPS systems or robotic total stations are employed. Systems are available on the market from several companies (e.g. Leica, 2002; Gomaco, 2002; Trimble, 2002). The high precision requirements for the guidance of road and slipform paving machines, however, are still very challenging for 3-D guidance systems. In recent case studies 3-D systems using two robotic total stations have been tested. The systems still need further improvements that conventional and labour intensive methods can be replaced totally.

4. MACHINE TRAJECTORY DETERMINATION AND BLADE GUIDANCE

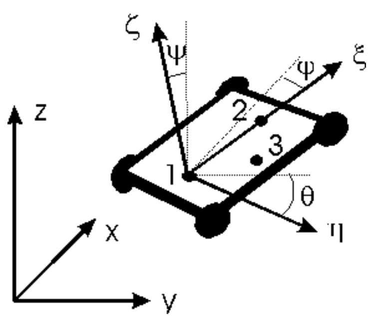


Fig. 5: Attitude parameters describing the machine orientation in the site coordinate frame (x, y, z)

For machine guidance the 3-D position and attitude parameters (i.e., orientation or heading φ, longitudinal tilt or pitch ψ and transversal tilt or roll θ) of a construction machine and its blade have to be determined continuously in a 3-D coordinate frame (x, y, z), e.g. the coordinate fram of the construction site which is used for the survey. Figure 5 shows the situation where on the machine a reference frame (ξ, η, ζ) is defined and its position and orientation is described in respective to the site coordinate frame (x, y, z). The machine reference frame (ξ, η, ζ) can be defined using measurement points where the ξ-axis runs from measurement point No. 1 to point No. 2, the η-axis points to the left and the ζ-axis forms a right-handed system with the ξ- and η-axes. Its origin can be located either at the centre of masses (or gravity) of the machine or at the machine blades. As described in the previous section, most systems use only one measurement point equipped with a GPS antenna or prism for determination of the absolute machine position. Then dual-axis electronic inclinometers can be employed to measure the pitch ψ and roll θ directly. The unknown parameters can be obtained from a transformation of the the machine reference frame coordinates (ξ, η, ζ) to the site coordinate system (x, y, z) (see e.g. Kahmen and Retscher 1999; Retscher 2001).

To guide the machine blades automatically, the deviations of the current blade position and inclination from the given alignment have to be determined. The blade movements and orientation should therefore be described in relation to the designed alignment. Figure 6 shows the relationship between the machine frame (ξ, η, ζ) and the designed alignment at a certain epoch k. At the beginning, a reference point P is chosen in the given alignment and the location of the origin P_k at a certain epoch k of the machine reference frame is described in relation to the track alignment in the site coordinate system (x, y, z) using the coordinate differences Δx, Δy and Δz. As the axis of the machine frame (ξ, η, ζ) also vary, the changes in the attitude parameters Δφ, Δψ and Δθ will be referred to the tangent system in the reference point P. In the elevation procedure the coordinate differences and the changes of the attitude parameters are estimated together.

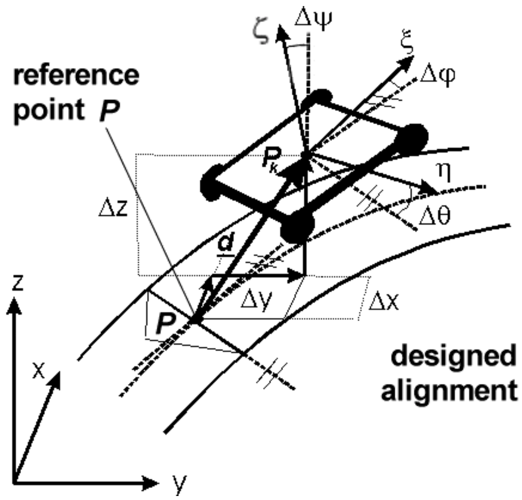


Fig. 6: Relationship between the machine frame (ξ, η, ζ) and the designed alignment at epoch k

The evaluation algorithm has to perform three main tasks, i.e., the combination of the measurements from the 3-D positioning unit (robotic total station or GPS) and other sensors (e.g. inclinometer, rotation compensator), the filtering of the measurements and the prediction of the positions and inclination of the machine blades between two measurement epochs. Thereby all incoming information should be used in such a way that an optimal estimate of the position and attitude parameters is available at any time. For an optimal estimation of the unknown parameters the use of a modified Kalman filter or Wiener filter was firstly suggested by Kahmen and Retscher (1999) and further developed by Retscher (2001). For real-time evaluation the Kalman filter is usually employed. The observation vector in the filter algorithm contains the coordinate differences Δx(k), Δy(k) and Δz(k) of the origin P_k from the reference point P in the given alignment and the changes of the attitude parameters Δφ(k), Δψ(k) and Δθ(k) at the epoch k. For more detailed information on the evaluation procedure the reader is referred to (Retscher 1998; Egbonu and Retscher 2000; Retscher 2001).

5. CONCLUSIONS

Due to the use of modern surveying techniques in combination with advanced filter algorithms construction machines can mainly be controlled and guided automatically. 3-D guidance systems will significantly reduce times for surveying and therefore achieve cost savings while increasing productivity of construction works. If either a Kalman or Wiener filter approach for the estimation of the position and orientation of the machine reference frame embedded in the machine blades is employed, then the trajectory of the machine can be described in the coordinate frame of the site in respective to the designed alignment and the blades can automatically maintain their design elevation and cross slope.

Nowadays, the major application of 3-D guidance systems can be found in construction industry and mining for the guidance of dozers, graders, excavators, scrapers as well as in agricultural applications for the guidance of tractors and harvesters. Thereby systems using RTK GPS are not as accurate as systems using robotic total stations. For the guidance of road and slipform paving machines, however, the very high precision requirements especially for the height component are still very challenging for the 3-D guidance systems. To achieve this level of precision and to replace conventional labour intensive methods in this application completely, the 3-D systems still need further improvements.

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BIOGRAPHICAL NOTES

Dr. Günther Retscher is employed at the Vienna University of Technology, Austria, since 1992 and is Ass.-Prof. at the Department of Applied and Engineering Geodesy at the same University since August 2001. During March 1997 to August 1998 he was lecturer at the Department of Land Surveying and Geo-Informatics of the Hong Kong Polytechnic University. He received his Ph.D. at the Vienna University of Technology, Austria, in 1995. His main research and teaching interest are in the fields of engineering geodesy, satellite positioning and navigation, application of multi-sensor systems in machine guidance and navigation. He has published more than 30 papers in international journals and conference proceedings. As Secretary of IAG Special Commission 4, Section I (Positioning), on "Applications of Geodesy to Engineering" and member of the Working Group 1 in the same commission on "Mobile Multi-Sensor Systems" as well as Vice-Chairman of Ad-hoc Group WG-5.33 "Multi-Sensor Systems" of FIG WG 5.3 on "Kinematic and Integrated Positioning" he is actively involved in the work of these international organizations.