1D AND 3D SYSTEMS IN MACHINE AUTOMATION

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Abstract: Over the past 15 years, kinematic measurements in the area of Engineering Geodesy have seen a significant upturn. Around 1990 the first automatic tracking total station Geodimeter 4000 [Hennes, 1992]) was developed, also around this time the first GPS receivers became commercially available. After a short period it became clear that terrestrial and global surveying instruments could be used for tracking the trajectory of a moving object [Stempfhuber, 2001]. During this period the first machine control systems began to be used on construction sites. In the middle of the 90's various companies attempted to control the kinematic processes for paving and finishing operations (e.g. stringless 3D slipform paving www.wirtgen.de/de/darchiv/). In the following years the first prototypes of such a control system upgraded the conventional "stringline" method with "stringless technology".

Today there is a large range of potential markets for new machine automation applications, which will lead to the development of a range of new products in the tunnelling, construction, mining and agricultural industries. The use of machine automation in these applications will alter the workflow of data collection, data processing, creating designs, uploading and transforming data, controlling machines without stringlines, checking the as-constructed output of the operation and documenting these results. This needs a completely different approach to that which is currently used today.

1. Definition of Machine Automation

By combining kinematic measurement systems such as total stations, rotation lasers and receivers, slope sensors and Global Positioning Systems (GPS), many new applications in the area of Engineering Geodesy are feasible. This coupled with the use of machine control systems for precision farming in the agricultual industry have enabled a high growth potential in the market of more than 10% a year.

The term "Machine Automation" is now synonymous with various construction applications including those used on motor graders, dozers, excavators, trimmers, profilers, compactors, and aspalt and concrete pavers. These applications in the field of construction may comprised 1D or 2D guidance systems (e.g. machine left or right, plate or bucket up and down are considered 1D control systems), 1D plus slope control systems, semi-automatic or fully automated 3D control systems merge all of these applications. To structure these various machine automation groups the following definitions can be made:

- **1D or 2D Guidance Indication Systems**
  The System indicates the height with or without slope or steering information to the machine operator,

Leica Applications are:
MC200 Digger or MC200 Depthmaster for excavators and the Basic Panel Systems for Dozers and Motor Graders.

The kinematic measurements for these applications are obtained via a rotation laser (such as the Leica "Rugby" series) used in conjunction with dual grade slope sensors. This provides the basis for the calculation of the correction values to be compared to the design data. The results are then displayed to the operator on a user panel to indicate the required movement of the machine, which is carried out manually. A common misconception is that 1D plus single or dual grade slope sensors being referred to as a 2D system, however within the geodetic frame of reference this is an incorrect notion.

- **Semi-Automatic Control Systems**
  The system indicates the actual position to the operator and controls the height and slope of the machine automatically. Alternatively an existing surface is measured with a sensor and will be used to guide height control.

  Leica Geosystems systems include the MOBAmatic 1D system (manufactured by MOBA Controls GmbH), combined with slope sensors for height control. This system is used on asphalt pavers, rollers and profilers and is also incorporated into the LMGS_P control system. For earthworks applications, Leica's MC1200 System is designed for Motor Graders and Dozers. To control these semi-automatic systems no geodetic 3D sensor such as GPS or a total station is needed. Therefore the handling of the unit is relatively easy to operate for a non-surveyor and compared to full 3D systems with RTKGPS receiver or total stations the semi-automatic control systems are relatively "low-cost-systems"

- **Automatic Control Systems**
  The machine automation system automatically controls the steering and height hydraulics.
  Leica Application is the LMGS-S 3D system for mainline concrete slipform pavers, curb & gutter slipform paving and fine-grade trimmers

The working sequence for a construction project using machine automation applications incorporates many surveying techniques such as establishing a geodetic reference network, data collection, data processing and design. This information is then transferred to the relevant Machine Automation application before construction takes place. The use of Leica's complete range of geodetic instruments and software solutions for this sequence can be seen in the example of a new motorway project. See Figure 1

Project Start
e.g. *New Motorway*

Surveying, DTM and Reference Network
Leica GPS and TPS System 1200, DNA03/10 Level

Asphalt Paver and Roller
Leica LMGS-P or Mobamatic

As-Built Measurements
integrated
Leica GPS and TPS System
1200, DNA03/10 Level

Data Processing, Planning and Design
Leica GeoOffice LGO, Liscad,
MobileMatrix, ATK RoadRunner

Concrete Sub-ground
Leica LMGS-S for
Slipform Paver

Earthworks
Leica MC200 Digger, MC1200 Dozer
with Rugby 400

Fine Grading, preparing the Sub-ground
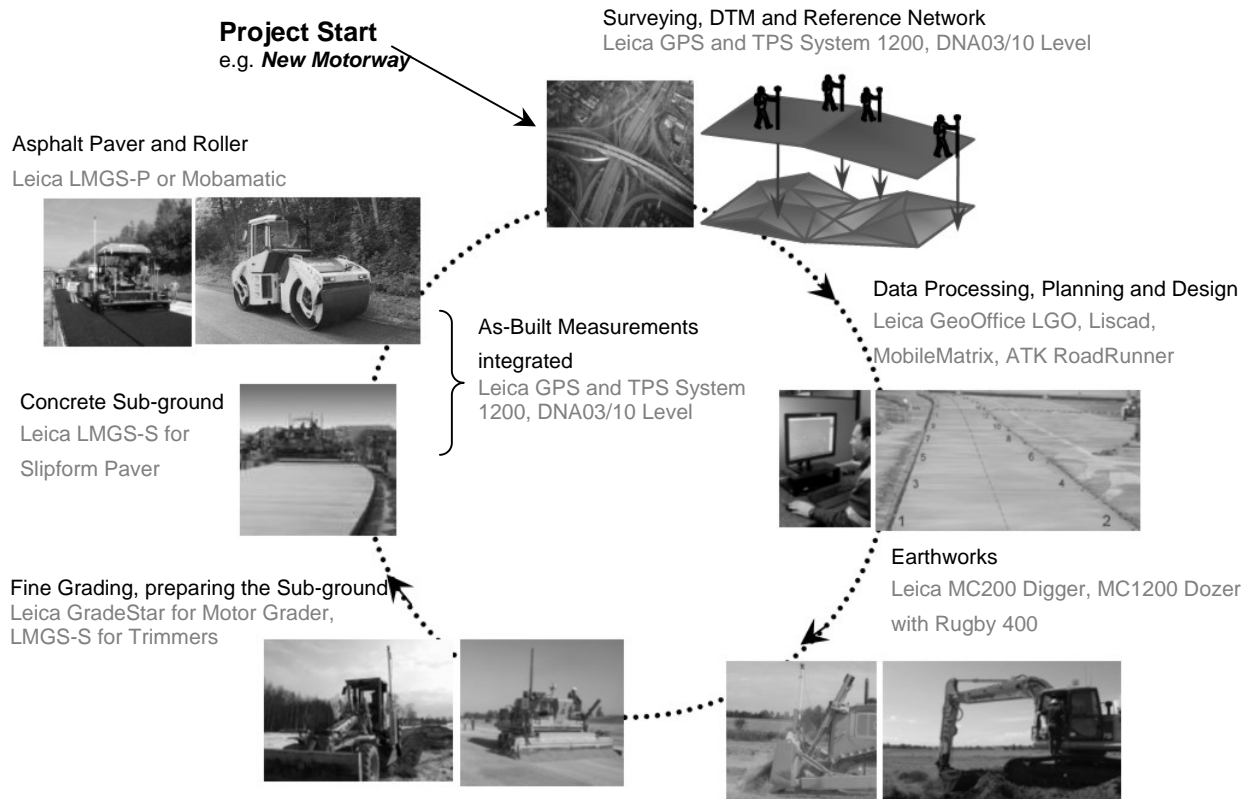Leica GradeStar for Motor Grader,
LMGS-S for Trimmers

Figure 1: Process to build up a new Motorway (Leica Product Range for Construction)

The advantage of a closed or proprietary system is that the entire dataflow is compatible. Leica provide only three different data formats in the DBX database (Fixpoint job, DTM job and Road job). For tunneling a fourth DBX job exists.When converting data, each subsystem can be integrated and when used in a complex constration project with different contractors data can be shared. Each working process is linked with the previous and the next steps. Focusing on the machine automation application surveying is only one subsystem of the overall process. All components are connected to the machine computer (MPC) which is the main control unit. The MPC with the control software is therefore the database (stored all design and reference data), the data collection unit (3D position, long and cross slope), the data procession unit, the steering and height control unit and the as-built unit.
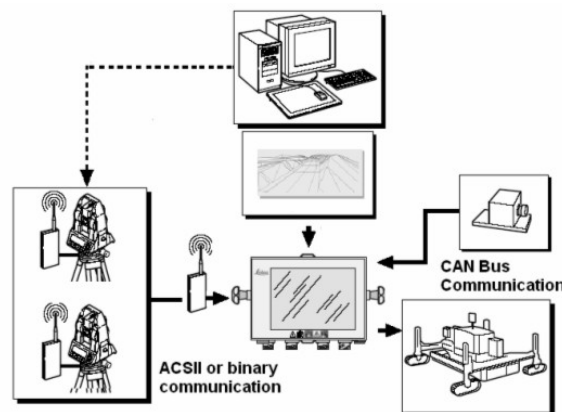

Figure 2: Key Components of a Machine Control (e.g. for Slipform Paver)

The communication with the position sensor is through an ASCII or binary format file, while slope sensors typically communicate via CAN-Bus. The direct or indirect (e.g. MC1200 or Mobamatic) communication with the hydraulic cylinders of the machine is also realised via CAN-Bus interface. The definition of the machine automation in this chapter was mainly based on 3D Systems. The principle of a 1D is similar and the following chapter will describe the 1D, 1D with Slope and also the 3D systems in more details.

2. 1D without or with Slope and 3D Applications

Beside the precision farming market, machine automation applications for construction projects are a huge business with a total volume of several hundred million dollars per year, with an increasing potential of more than 10 % per year. To get a complete overview of the whole solutions this paper will summary the current systems.

1D Guidance Systems

The first group is composed into the 1D applications. These products are guidance systems (called Basic Systems), which indicate the reference value to the machine operator. A good example for this application is the new Leica Solution MC200 Digger combined with a rotation laser for excavators or the basic panel systems for Dozers and Motor Grader. A similar solution for a completely different application is the Leica MC200 Digger. The depth and slope control is an efficient and productive product with additional features including:

- Weighing function from a boom pressure sensor
- On the fly Laser Reference Catcher (Constant work flow guaranteed)
- Tilt brackets
- cm-Accuracy

A rotation laser is used in conjunction with a laser catcher, which is mounted on the bucket arm of the excavator to give the reference height for the systems. Several angle measurement sensors are located on the boom of the machine are used to calculate the height of the of the machines buckets to cm accuracy. The operator's panel indicates the deviations from the reference value of the machine and guide production. All components communicate via CAN-Bus technology to the MC200 computer. The following diagram illustrates the excavator system.
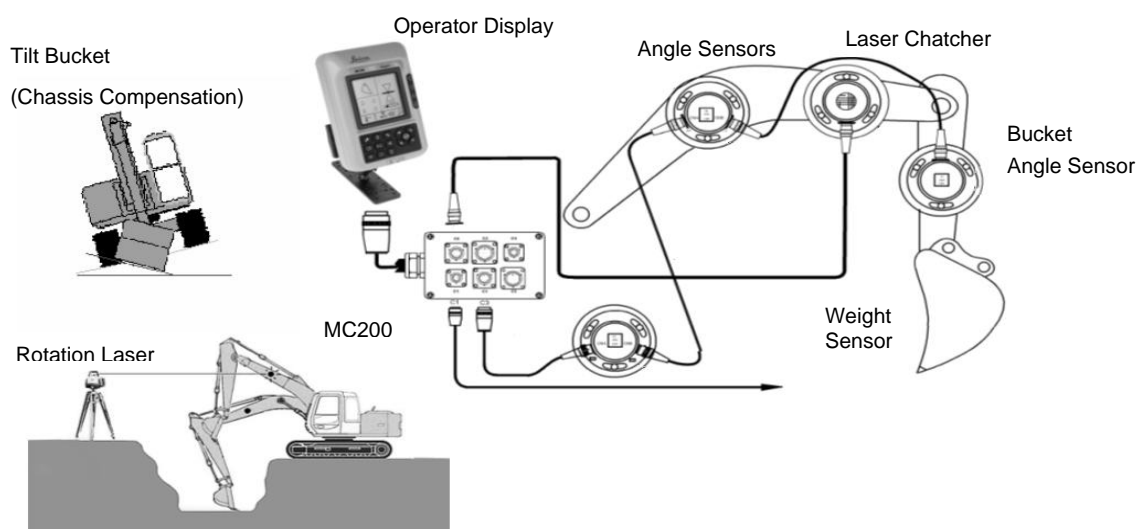

Figure 3: MC200 Digger

The components of the system are the rotation laser, the laser receiver/catcher, the rotation sensors, the machine controller and the user panel with the indicator display. An optional single or a dual slope sensor can be used for the inclination measurement.

1D Control Systems

1Dimensional control systems refer to height control with manual driving of a machine. The Leica System MC1200 is a good example to illustrate such a solution. The rotation laser and the laser receiver control the precise height of the machines blade. The driver is free to track across the site with the height of the blade being continually adjusted relative to the rotation laser (similar to the excavators system).
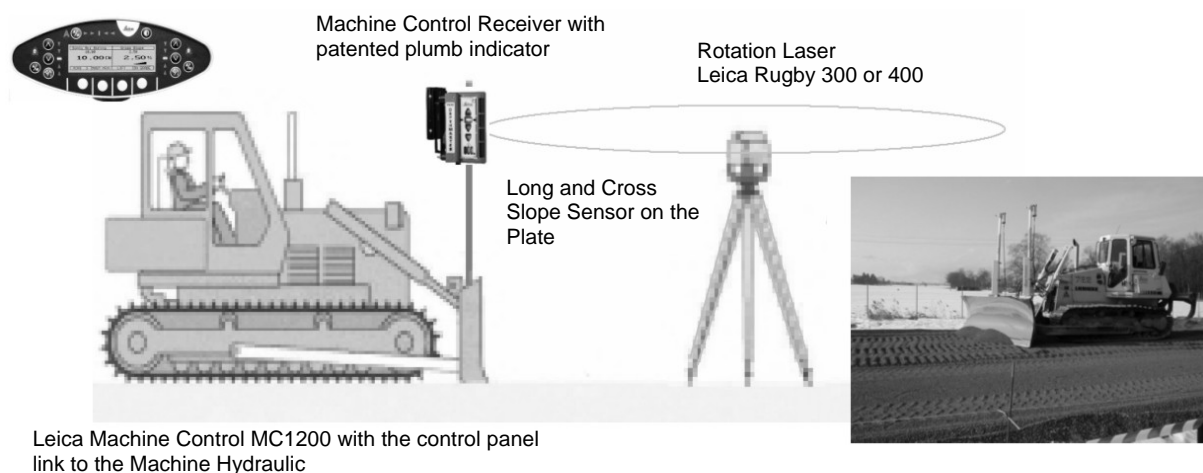

Machine Control Receiver with patented plumb indicator

Rotation Laser
Leica Rugby 300 or 400

Long and Cross Slope Sensor on the Plate

Leica Machine Control MC1200 with the control panel link to the Machine Hydraulic

Figure 4: 1D System with a dual Slope Sensor, e.g. MC1200 Dozer System

Semi-Automatic Control System

The next group of machine automation solutions is the semi-automatic control (or "guidance only") system with precise position information; therefore a precise 3D position is needed. According to the accuracy of the application total station or RTK GPS is used (see chapter 3). The critical component is exclusive the height and this is also the only component which will be automatically controlled. The operator steers the machine manually by comparing the actual position of the machine or the tool to the reference position. Such height control systems are commonly used in earthworks (dozers), fine grading (motor grader and trimmer), paver, milling machine and roller. Both dozers and motor graders can be controlled by the Leica GradeStar solution. This modular system can be installed with a GPS receiver, with a total station for a very accurate fine grade tasks or with ultra sonic sensors for copying existing surface. With the machine controller the MC1200 GradeStar application can be installed on any machine type. The blade (e.g. on a motor grader) can be shifted or rotated in all directions GradeStar software provides several features which are unique in this field.

Figure 5: GradeStar for Dozer and Motor Grader

Full 3D Control Systems

One challenging field for fully-3D machine automation control applications is in concrete slipform paving, and has to-date only been realised by the Leica LMGS-S system. Conventionally, paving machines are controlled by stringlines which have many disadvantages. Nowadays more and more companies in the concrete paving market are switching to 3D control which is also known as "stringless paving". The principal driving forces behind this switch to stringless systems is the dramatic improvements the system offers in logistics and the reduction in the workflow for the operator prior to paving.

Many different paving machines are able to benefit from this stringless technology including mainline slipform pavers, barrier pavers, and curb and gutter machines. The general components of each of these systems are similar (See Fig. 6), however the size and shape of the mould varies between each machine and each application. Large slipform pavers may have a mould of up to 15 meter wide and are always controlled by two total station and two dual grade slope sensors. Barrier pavers and curb and gutter applications are generally steered with one instrument in combination with one dual grade slope sensor, the reason for this is mainly due to the rotation or twist experienced in the frame of the machine while under stress. Another significant difference between these applications is the production speed of the paving operation and the design radius the machine is required to manoueuvre around.
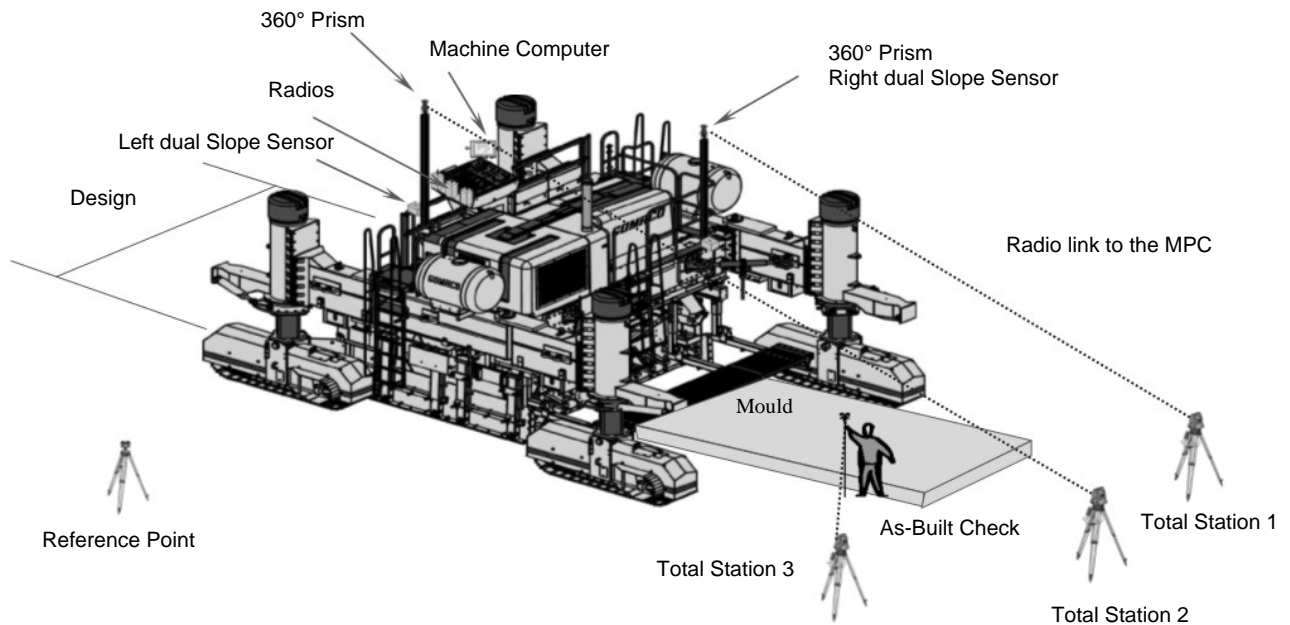
Figure 6: System overview Concrete Paver

Existing and new machines can be easily upgraded from stringline paving to the 3D Control Systems. Currently four companies manufacture large paving machines (Gomaco, Wirtgen, CMI Terex, Guntert & Zimmerman). Currently only Gomaco and Wirtgen machines are 'plug and pave' compatible with the Leica control system.

All the components of the systems are linked to the 3D machine control computer which is in turn connected to the paver controller via one direct cable making the installation process simple. The 3D system controller is in turn connected to three ruggedised radios for bi-directional communication with the total stations, and two CAN Bus dual-grade slope sensors with individual identification signals to establish the left and right inclination of the paver. One CAN Bus cable is used to collect all this information, and relay it to the machine controller.

Three Leica TPS System 1000, 1100 or 1200 total stations are used with special onboard software called Mguide. These are linked via remote radios to the MPC onboard control computer. Two of the instruments are used to permanently measure the (x, y, z) position of two prisms, mounted on each side of the mold. A third total station is also connected to the system and is used to monitor the as-constructed concrete slab being extruded from the paver (the crucial geodetically-independent check). This gives the operator the ability to make small corrections of the mold possition to allow for external factors such as the varying nature and consistancy of the concrete. The as-constructed information is also recorded for quality documentation and may be used for asset recording.

After the surface control is carryed out the third instrument is then used to control the system. This allows one of the controlling instruments to be removed from the process and moved closer to the paving production. This is carried out to maintain high accuracies in the measurments being collected by the system as the paver moves away from the initial controlling total station position. This is an iterative process which is carried out throughout the paving process and is euphemistically known as "leapfrogging" the instuments. The orientation of the instuments is typically carried out by a resection function with three or more known fixed points, or by a known point with a back sight orientation.

To control such a machine six values, the so-called six degrees of freedom, are required. Each corner of the mould must be compared to the design height (= four height values) and two control points for the steering are determined (deviation form the design orientation). This requires the precise geometry of the machine to be known. Measurements are made during the installtion and subsequent callibration of the machine to determine the relationship between the two prisms and the four corners of the mold. This is used for the 3D control of the machine.

Another important step during the installation of the 3D kit is the tuning of the output values for the hydraulic cylinders. The control algorithm, calculates deviations from the design in millimeters, through a predefined fuzzy logic the deviation is transformed into a CAN-Bus output messages and transmitted to the machine controller. During this calculation loop several safety checks are made (stop rules, measurement timeouts, measurement checks, etc.) to safegaurd against any erroneous data. One of the main factors in a succesfully producing a smoothly finished concrete surface is to minimise the length and number of machine stops.

When working with other types of pavers such as curb and gutter or barrier pavers beside the number of instruments required to control the paver the size and the position of the mold on the machine is also different and the workflow and logistics of the operation is also slightly different.

The upper left picture shows a Wirtgen SP1600 slipform paver with a mast on each side of the mold. The upper right picture is a typical Curb and Gutter application with one prism on a Gomaco GT 3200 machine paving around a dam wall in Japan. The same application with a very small radius (around one meter) is illustrate in the lower right picture in the US. The lower left picure is a barrier paving application on a motorway in Belgium with a Gomaco Commander III in transport mode.

Figure 7: Leica LMGS S System, Slipform Paver, Barrier Paver, Curb and Gutter Application

3. Geodetic Sensors

From a geodetic point of view the measurement sensors are the key components in a machine control system. The result of any earthworks, grade or paving job is mainly related to the accuracy, quality, measurement frequency, number of timeouts and the stability of the respective measurement experienced by the sensor. RTK GPS has a number of advantages compared to terrestrial measurement systems, but for precise grade, milling or paving applications the stand-alone RTK GPS height accuracy is not acceptable. Another limitation of the RTK GPS sensors is the vertical visibility to the satellites. The combination of the GPS with a rotation laser provides a promising approach, but the reality shows that this solution has various limitations including the horizontal and vertical range of the laser receiver. A transformation is typically also required between a local job site coordinate system and a WGS coordinate system when using RTK GPS measurements. This can be carried out on the MPC or directly on the GPS Rover utilizing the Leica specific NMEA Message LGG (Local Grid System).

For all machine control system with absolute height accuracy requirement (or construction tolerance) of less than 3-5 cm a total station is needed. This sometimes leads to user confusion because the total stations are design for a geodetic task and the instrument architecture is designed to suit a geodetic workflow. To provide all functions for machine automation application, onboard software for the total station is needed. This is the reason behind using the MGuide software on the total stations to optimize the various function of this total station. A height accuracy of 3-5 mm can be achieved, but is a function of many variables including the quality of the prism, the bi-directional communication with the machine computer (This means the interference of the radio signal must be reduced to zero. With the new radio handle at the TPS System 1200 the radio performance is clearly increased.), other critical parameters are the measurement frequency, the synchronization of all subsystems in the total station and the latency of the measurement value [Stempfhuber, 2004].

The following table recommends the suitable measurement sensor for the different application. Some decision must be made individually by the requirements of the job.

	Height accuracy	Position accuracy	Max. Speed	Guidance System	Control System
Motor Grader	10-20 mm	10-20 mm	35 km/h	√	(only Height)
Dozer	10-30 mm	20-50 mm	12 km/h	√	(only Height)
Excavator	20-30 mm	20-30 mm	static	√	X
Asphalt Paver	3 mm	5 mm	10 m/min	X	(only Height)
Concrete Paver	3 mm	5 mm	2 m/min	X	√
Curb & Gutter	5 mm	5 mm	5 m/min	X	√
Milling Machine	3 mm	5 mm	15 km/h	X	(only Height)
Roller	3 mm	10 mm	10 km/h	X	(only Height)

Table 1: GPS/TPS kinematic Parameter in Machine Automation

4. Outlook

During the 1980s automation ambitions were focused only in areas with large production quantities and with a fixed production location (e.g. the automation of car manufacturing). In the last 10-15 years great advances in target-tracking total station and RTK GPS technologies have taken place, which offer clear advantages for the construction site and machine automation applications. An important improvement has been in the fleet management and in job site network (remote control of the different application) due to this many of all the difficulties in the logistics and data management and exchange can now be solved.

Machine automation, which can now be distinguished as a specialist application field within the realms of the Engineering Geodesy discipline, has become more and more important, in terms of both its commercial viability and the academic rigour required to solve the unique kinematic challenges of various construction machines. Machine Automation offers unique challenges and unlimited potential for future technological and workflow advances.

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