Use of a Machine Control & Guidance System, Determination of Excavator Performance, Cost Calculation and Protection Against Damaging of Pipes and Cables

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Abstract

The construction industry is confronted with permanent pressure regarding costs due to:
• increasing expenses, especially those affecting labor and energy;
• shortened schedules for completion of projects;
• a highly complex legal system with a growing number of official laws and standards.

Possible solutions include efforts to make engineering construction more efficient – i.e. by the introduction of industrial production methods to building practices. It is intended to achieve further improvements of performance. Attention is focused on the earthmoving and road construction areas. The adoption of GPS-referenced machine guidance systems based on a digital terrain model (DTM) can significantly contribute to cost reduction. Much progress has been achieved in these areas in the recent years: the introduction of laser-referenced 1-D machine guidance systems, as well as 3-D machine guidance, tachymetrically referenced and GNSS-based guidance systems for graders, bulldozers and excavators.

A DTM-based machine guidance system for excavators using GPS positioning has been developed at the University of Applied Sciences, Coburg, Department of Civil Engineering.

Keywords


1 INTRODUCTION

Why machine guidance?

The construction industry is confronted with permanent pressure regarding costs due to:
• increasing expenses, especially those pertaining to labor and energy;
• shortened schedules for completion of projects;
• a highly complex legal system with a growing number of official laws and standards.

What can be done to handle the increasing cost pressure?
Possible solutions include efforts to make engineering construction work more efficient - that is, to introduce industrial production methods into building practices as a means to achieve further increases in productivity.
Techniques of working with DTM-based machine guidance systems will have considerable effects on working practices of construction engineers and surveyors [w.a.07]. This development should be kept in mind when training students.

1.1 History

For earthmoving, the surface contours of the construction site of an embankment were visualized to the machine operator by means of profile templates, visors, stakes etc. The visible templates provided the operator with an image of the finished surface and the excavator bucket's edge approaching the grade height ever more accurately. Therefore support by a site worker was required and work was restricted to daylight times.

This well known central function must be integrated into a user-friendly machine guidance system. Apart from that it is necessary that the operator gets a three-dimensional image of the work to be done. Nowadays, digital terrain model based machine guidance systems are a suitable resource.

1.2 Basic ideas

In the beginning of the development of the DTM-based machine guidance system, it was intended to improve the productivity of construction machines, such as excavators. The excavator was chosen, because it is the geometrically most complicated machine for machine control applications. Possibilities to improve the productivity are:

- The improvement of the autonomous operating capabilities of an excavator. The operator of an autonomous, stakeless, operating excavator needs total information of his excavating job.
- The excavator should operate 24 hours a day without the assistance of any worker.
- Digging accurately in order to avoid over-excavating. The excavated material has to be moved only once.

A means to realize the 3-D machine guidance system is the GPS-system. The continuous development of the GPS receivers has made them easier to handle, more efficient and has improved the accuracy in the determination of their position.

2 SYSTEM DEVELOPMENT

2.1 System architecture

At first, the structure of the machine guidance system was determined. To avoid over-excavation the operator's main information is the difference between the planned depth and the actual depth at the edge of the bucket. This difference is zero, when the planned depth is reached.
We started with the development of:

- Hardware and software for calculating the current position, the $X_{BE}$, $Y_{BE}$, $Z_{BE}$ - coordinates of the bucket’s cutting edge
- Software to calculate the set-height (planned) coordinates $Z_{DTM}$ from the current coordinates $X_{BE}$, $Y_{BE}$ and the DTM.
- Hardware and software to visualize the altitude difference to the operator (depth control).

We continued with the development of the visualization on the screen of the on-board PC:

- Software for visualizing the plan view. The plan view enables the operator to see the current position of the excavator in relation to the digital description of the job, including the position of pipes, cables and other structures.
- Software for the profile view. With the profile view the operator gets an image of the finished excavation works.
- Software for the sensor-manager. It allows the permanent monitoring of the system sensors.
- Logging tool as a basis for the determination of the excavators daily productivity.
2.2 Basic conception

2.2.1 Calculation of the current coordinates $X_{BE}$, $Y_{BE}$, $Z_{BE}$ at the bucket’s edge center

The excavator has been equipped with 2 GPS receivers and one tilt sensor TS1. The GPS antennas A1 and A2 were mounted at the boom at a large mutual distance. The receivers calculate the positions of their antennas A1 and A2.

The triangle, shown in figure 1, consisting of the points A1, A2, G1, is the basis for calculating the current 3-D coordinates $X_{BE}$, $Y_{BE}$, $Z_{BE}$ of the bucket’s cutting edge center.

The on-board computer calculates these coordinates $X_{BE}$, $Y_{BE}$, $Z_{BE}$, taking into account the machine geometry, as detected by the two angle sensors G1 and G2 (encoders) and the known length of the stick and the bucket height. There was no need to use further sensors to cover the complexity of the excavator’s kinematic system.

During the development of the machine guidance system, various sensor geometries were tested. The described sensor geometry with a large mutual distance between the two GPS antennas gave the most accurate results.

2.2.2 Calculation of the planned depth

In order to obtain the planned depth of the grade, the database of the site DTM, downloaded on the on-board computer, is permanently queried. The queries yield the height $Z_{DTM}$ for the current position (coordinates $X_{BE}$ and $Y_{BE}$). The difference between the current height of bucket’s cutting edge $Z_{BE}$
and the planned height $Z_{DTM}$ provided by the site DTM is the height deviation. It is visualized in several ways, on the computer screen and on a stick mounted LED bar display. For the operator's convenience the LED bar provides an analog display of the vertical and lateral deviation. At a glance the operator can ergonomically see the moving bucket and its deviation from the planned depth.

**Figure 3**: Operator's view of the on-board computer screen. The cross hairs show the position of the bucket's cutting edge in real time on a heading up map display. [ScDi01]

### 3 DETERMINING EXCAVATOR PRODUCTIVITY

The information age has definitely arrived and in fact it has just begun to affect the business processes of the construction industry. Apart from navigating the excavator, the machine guidance system provides users also with valuable real time information based on safe estimations in order to avoid guesswork.

Performance assessment serves to indicate whether the actual excavator’s performance is according to plan. The determination of actual performance during operation has advantages for construction companies in terms of operational planning, invoicing, and deriving revised cost calculations from comparable machine operations. Determining productivity is the essential step to a controlling system for construction sites. Such a system monitors production, controls the solvency and the profit of a construction site [Wirt01].

Excavator performance can be calculated from volume and surface data. The machine guidance system's volume and surface determination software uses the following working principle. Two digital terrain models are determined:
1. A basic DTM (blue), namely DTM$_0$ at time $T_0$ before the excavation work begins, and

2. A temporary DTM (red), namely DTM$_1$, at the moment $T_1$ of performance assessment, after the excavating job is finished.

**Figure 4:** System for determining the excavated volume

At time $T_0$ when work starts, all surface points have the original site coordinates, which means that all DTM$_0$ data are valid.

At time $T_1$ of the first volume assessment, the actual coordinates of characteristic points on the site are recorded by the excavator operator as a temporary base area, while the working movements of the construction machine are recorded and automatically stored.

The machine guidance system’s CAD program creates the temporary DTM$_1$ from the actual coordinates just measured: this data is stored for subsequent use. As soon as excavating work is completed, the temporary DTM$_1$ becomes the target DTM. By comparison of the two DTM values (DTM$_0$ and DTM$_1$), the volume $V_{0,1}$ excavated during time $T_1 - T_0$ can be determined (DTM-green).

In the same way as for excavated volume $V_{0,1}$, the subsequent excavated volumes $V_{1,2}$, $V_{2,3}$, etc. at measuring times $T_2$, $T_3$, etc. can be determined.

They can be computed, processed, stored and evaluated. It is also possible to send them to an ERP-system which can analyze the data with powerful tools [Nebe03]. The data is very useful for planning and preparing construction work. It provides a basis for post-calculation of important service components on the construction site and is useful for calculating subsequent bids for similar construction projects.
Figure 5: System for calculating the direct unit cost
Use of the calculated excavated volume to determine operating data

With the aid of the calculated excavated volume or the surface covered and additional machine operating data, the operating data for the “excavator cost estimation” can be determined.

Additional data can be saved and processed in the machine’s computer: details of machine operators’ wages, cost of fuel and related operating materials, cost of the machine itself (depreciation A, interest charges V, and average repair charge rate R), costs of wear and tear, and miscellaneous costs.

Regarding all these parameters the excavator’s hourly costs can be divided into separate cost.

ERP Interface

As we have already mentioned ERP-Systems offer powerful tools to analyze the collected data. Because of that the developer team has implemented an SAP ERP interface. The interface is based on so called Business Application Programming Interfaces (BAPIs). BAPIs allow access to SAP-Business-Objects, which makes it possible to add data to the ERP database. To set up the ERP interface we used the SAP tool “Legacy Systems Migration Workbench” (LSMW). Alternatively we could have used another powerful SAP technology which is called „Exchange Infrastructure“ (XI). The advantages and disadvantages of the tools are discussed in [WiGr03; StOr05; NiFN06]. Due to availability reasons and the fact that XI would have entailed additional license costs we decided to use the LSMW. With the implemented interfaces data collected by the machine guidance system can be transferred to the ERP system. It can be analyzed by the project system, the controlling and the finance component. It is also conceivable to use business intelligence tools for further analysis.

4 PROTECTION AGAINST DAMAGING OF PIPES AND CABLES

Another important feature is the protection against damaging of pipes and cables. By integrating cable and grid network plans into the site DTM displayed on the monitor screen the operator can see the distance between a cable and the bucket edge. Interruptions of work due to cable or pipe damage can be avoided. Hence the excavator performance will be improved.

In Germany, every year, a lot of cables and pipes are damaged, caused by digging works. The bills for repairs and claims for compensation amount up to 400 million Euros a year - a huge waste of material, time and money. A reduction of this amount could be realized by a combination of magnetic detection, better grid data and a machine guidance system.
Figure 6: CAD software DTM-Designer showing a plan view: Ditch for the foundation with crossing gas and water pipes.

Figure 7: Machine guidance software DTM-Navigator. Operator's plan view with gas and water pipes. Actual distance: Bucket’s center to the gas pipe: 2.00 m
The DTM-based machine guidance system provides the on-board computer with the 3-D-coordinates of the current local position of the bucket’s cutting edge. It is possible to make the cable and grid network plans available for the on-board computer which enables a superimposed view. With a layer technique, the operator can see the current cable situation and the site plan in a single view. If a collision is imminent, the operator is warned by an audible signal.

5 CONCLUSIONS

In this paper a new generation of machine guidance systems is presented. Its additional features are:

- Determination of excavator performance
- Protection of cables during excavation work
- Possibilities to analyze productivity and costs

This leads to the following benefits:

- More accurate schedules and estimates
- Less surveying work
- Fewer interruptions of work caused by cable and pipe damages, thus saving labor and material costs

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