3D Excavator Application in a Future Jobsite

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3D guidance for operator of an excavator is a daily life in a modern infrastructure jobsite that is utilizing 3D production models. The guidance application creates a real time view of production model and inner-state of a machine. This view helps the operator to finalize the task without external measurements. When measurement task is performed by the machine operator instead of surveyor, new methods are required for geodesy and quality assurance issues. The use of 3D applications in the jobsite increase the performance of an individual task typically 15%. When novel telemetry and fleet management methods are applied to the 3D guidance, even better performance is reached due to online jobsite management. The level of automation grows in the different applications over time. However, the tasks performed by excavator are usually very difficult by their nature to automate. When other applications in the jobsite increase the level of automation, the machine with guidance system and the operator might be in danger. Therefore the challenge of accurate human detection needs to be solved before full automated machines can enter to the same site with machines operated by humans.

3D machine guidance systems automate the external stake out measurements of the jobsite. The automation is done by creating a real-time Virtual Reality of production model and inner-state of a machine. Automation of external measurement typically decreases the overall measurement cost, but total efficiency boost is coming from the increase of the quality in the end product and increased autonomy of a work machine.

Excavator

Excavator is a machine that is used for various different tasks. It can load the material to the dumber or it can receive the material to construct a road or other product. Excavators are also used for loading the material to the rock crushing stations. The most used actuator in the excavator is a bucket. However, excavator is a handy platform for special applications like drilling, lifting, crushing, screening or action alike due to availablity of a hydraulic power for the actuator. Excavators are used in multiple different environments, such as civil construction, dredging, mining and forestry.

Excavator Machine Control Hardware

The typical components of a 3D excavator guidance system includes inclination sensors for excavator booms and machine body (1), RTK GNSS receiver(s) for 3D positioning (4), Communication system (5) and a computer system for processing and Graphical User Interface (2,3).

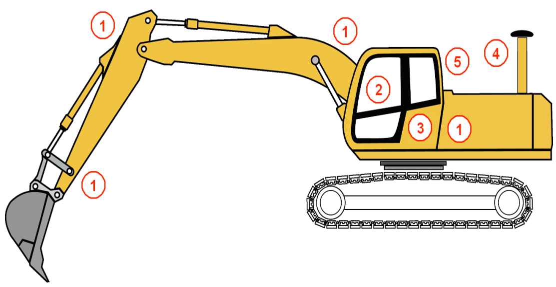

Figure 1: 3D Excavator Application

Inclination sensors are usually built by using MEMS technology, which is used to measure the boom angle in respect to the gravity of Earth. Digital signal processing is needed in order to get fast and accurate results. Inclination sensors typically use a CAN bus for communicating the inclination data to the computer system. Novatron utilizes CAN tranceivers and CAN buffers that fulfil the Bosch v.2.0B CAN specification. The higher layer protocol implements Novatron prorietary protocol.

Measures of the machine are calibrated in to the system and the position of an actuator, such as bucket, is determined by means of forward kinematics. Machine control system that is not including positioning sensors is called a 2D system. 2D system is capable of performing relative measurements in respect to the machine body. Even though such system has its limitations, the efficiency of 2D system is improved greatly by using rotating laser transmitter and receiver for calibrating the height of the machine body. When machine is moved to another place in the jobsite the laser corrects the position of the actuator in level.

Positioning

3D system requires the use of 3D positioning sensor, such as Real-Time Kinematic Global Navigation Satellite System (RTK GNSS) or robotic total station. RTK GNSS is based on satellite systems and a separate base station that sends correction messages to a moving rover unit. Robotic total station is an optical instrument that follows a reflective prism by servomotors. The encoders in the motors and a built in Electronic Distance Meter (EDM) enable the digital angular and distance readings. These readings are used to calculate the 3D position of the reflector.

The sufficient precision, lower cost and ease of use prefers the RTK GNSS technology over robotic total station. On the other hand, robotic total station offers even more accuracy - millimeter level instead of centimeter level, and gives coverage also when machine is working indoors, where RTK GNSS system does not operate.

RTK GNSS system offers a precise, global coordinate in WGS84 ellipsoid. Before it can be used in a 3D machine control system, it needs to be converted from the geographic, geocentric coordinates to the cartesian coordinates that are used in the surveying coordinates, production models and in the inner-state kinematics. A Map projection methods are used to convert the geographic coordinates to a cartesian form. The most used map projection is called a Transverse Mercator. New coordinate reference systems, such as European Geodetic Reference Systems (ETRS89), have a defined relationship between these two worlds and are therefore simple to use in 3D application. However, there are older coordinate systems that are not compatible with direct conversion. These systems needs to be calibrated to WGS84 world, where positioning device operates. This calibration could be done by using a Helmert 7-parameter transformation that adjusts the translations, rotations and a scale of source and target systems. Usually five or more point pairs are needed from source and target in order to calculate a robust transformation parameters. [7]

The reached calibration accuracy of a 3D system in a medium-sized excavator is typically better than three centimeters in plane and two centimeters in height.

Log Data

When the machine is able to measure the precise 3D coordinates it can be used for logging data. The log data has multiple purposes. The most common purpose is to use it to define an as-built status of a project. The operator of an excavator simply places the bucket or other actuator to a finished surface or a point and tells the system to store the location. Location data typically has attributes, such as point code, layer and name that identifies the measured object. When the as-built data is transferred to the office it can be used to follow the progress of the site.

Another use for data logging is to survey the tasks that are dangerous or otherwise hard for surveying personnel to measure. Best examples for such operation are underwater works, deep soil removal operations and rock blasting. Data logging also increases the efficiency in the cases where surveying is needed fast in order to proceed in the selected task. Examples of such operation include measuring the unpredicted rock for blasting or measuring the installed underground structure, such as pipe or cable.

Production Model

Logging data is one purpose for 3D excavator application. However, the more important feature is that the production model of a road, building foundation or basicly any construction job can be transferred in to the system for measurement purpose. The model is used for measuring deviations between the actuator and the model. The graphical appearance and deviation information is presented for the operator of an excavator. The information is used to perform the measurement of the end-product in real-time over the model.

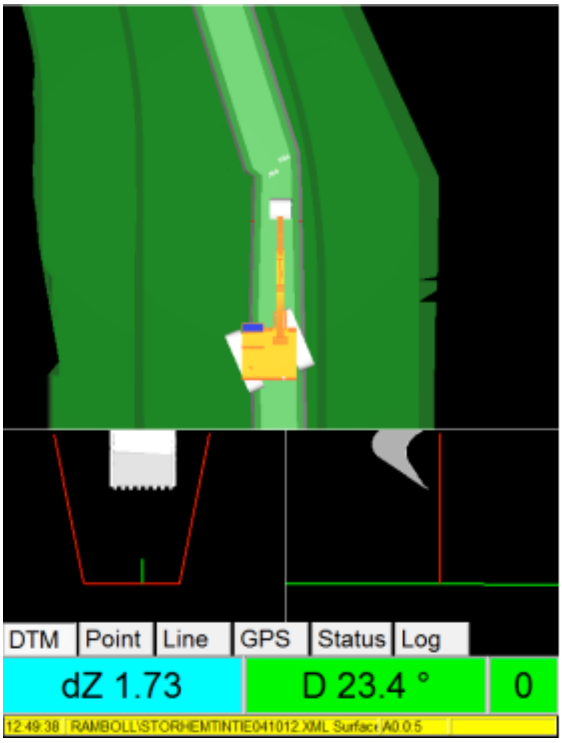

Figure 2: Digital Terrain Model in the 3D Excavator Application

There are different methods for presenting the production model. The most used method is a triangle mesh that is called a Digital Terrain Model (DTM) in surveying business. DTM describes the surface by triangles that have a references to points in a point cloud.

More advanced way to describe continuous models, like roads, is to use a line model. In the line model, each side line is presented in a polyline or in a mathematical form by presenting different elements that are connected to each other. The elements include typically lines, curves and different kind of spirals. The side lines are connected to each other and they define a surface, like DTM. The power of using a line model lies in the fact that it includes less data but more information than DTM. For example it is possible to measure the sideway distance between the side line and the actuator of a machine. Such operation by using a DTM requires a lot of processing and guessing, because the information about the breakline does not exist.

Other type of models include background drawings and points. Drawings are normally used for pointing out existing underground objects, such as electrical cables. Drawings are also used for presenting a map of a jobsite for an operator. Some objects are most powerful to model as points because of their simplicity and unambiguous. Light pole standings and manholes are good examples of objects that are possible to install with very simple point model and by using a 3D guidance system.

Quality Assurance

There are multiple error sources for measurement accuracy in the 3D Excavator Application. A biggest problem is that some actuators wear over time and so also the measurement accuracy of a system changes over time. When operator of a machine performs the measuring task instead of a surveoyr, who has an education and skills to analyze the performed work, the quality of a end product has a chance to fail. A common practice is that the accuracy of the actuator is checked daily on a check point and results are stored to quality assurance documents. When the machine is performing the measurement, the need for end-product surveying drops down dramatically. 3D Excavator Applications use mainly RTK GNSS positioning systems. The best way for end-product quality assurance is to use another positioning technology, such as robotic total station for surveying the end-product. If optical measurement and satellite measurements match, the end-product is built in to the correct place with high certainty.

Benefits of 3D Machine Control

3D excavator system automates the measurement task in the jobsite. Traditionally the investment for 3D excavator system is considered to payback by reduced cost of a surveying personnel. Traditional measurement requires a surveyor to stake out the slopes and heights on the ground. When the work is implemented with stakes, a separate person or the operator of the excavator measures the end-product on the ground.
Automating the measurement is a true saving, but only the first level of the accomplished value. The biggest advantage is that every modeled task can be completed with a higher level of accuracy due to real-time measurement. This leads to better quality, tighter building tolerances and savings in material cost. Another advantage is that the operator of the excavator does not need to wait for the stake outs made by the surveyors, the job can be done continuously and independently.
Another benefit of using a 3D system is the increased safety. Increased safety is reached due to reduced number of people on the ground. [6]

BIM

Traditionally the interoperability between product design and construction has been very poor. It is common to use Computer Aided Design (CAD) in three dimensions to design and analyze civil construction product. It is very common that a 3D model is not shifted digitally to a construction phase at all. Sometimes the design work has started a decade or two earlier and there is nothing more than paper prints available for construction work. The 3D machine control pioneers have had their own competence to create the 3D models from drafting-centric plans for construction phase. This has been a competitive advantage for companies who have had skills for such operation.
Building Information Modeling (BIM) is a process that enables the transfer of digital product model from one phase to another in the project life-cycle without loosing relevant data from the model. BIM has proven its performance in the building construction business, where it has been used already many years. One basic idea of the BIM is that the design effort is increased, because the ability to impact to the cost is highest in the earlier steps of the project (Figure 3). The job is modeled, analyzed and virtually constructed before the real work implementation takes place. One important part of the virtual construction is a clash detection analysis where designs of the multi-technical project can be verified to work seamlessly together.

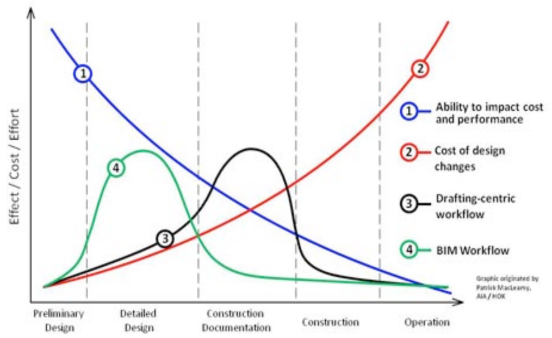

Figure 3: Ability to impact cost and performance [5]

The knowledge transfer from the building business to the civil construction can not be done directly. The principles of the process applies, but the tools and the models are very different by their nature. One major difference is that the buildings are usually built by blocks that can be presented as solids. In civil construction the modeled object could be continuously changing mathematical roadway that has lots of design rules. Such object could not be modeled by solids nor the design rules could be easily transferred from one CAD system to another.
The BIM methodology in civil engineering leads to standardized formats and processes. The availablility of production

models for construction companies will increase and that will be a significant driver for machine automation and 3D applications in construction. [1]

Site Management and Production Control

The management of the jobsite utilizing 3D applications requires a novel management tools for Chief Surveyors and Site Supervisors. In traditional way the supervisors located themselves by using the stake out markings. Now when the markings do not exist in the 3D site the location of the human in respect to the production models needs to be solved otherwise. Latest achievements in this field include cloud-based services that take care of the jobsite production model updates, collection and visualization of as-built data and visualization of the production models in the low-cost tablet PC.

There are already signs that next level of jobsite automation involves the fleet management and production control features. Controlling the construction process always needs a plan and feedback from as-built status. Two basic methods for following the as-built progress are following the truck or dumper traffic or following the machine that is finalizing the end-product. The challenges for the truck option include either complicated fully automated system or a simple system that requires an accurate user input. Following the machine requires less from the control system and the amount of needed devices in the ground drops down, but the challenge remains in how to separate the movement in a real finished surface from the movement done for refueling or service of the machine. Novel algorithms for as-built reporting needs to be developed. [2,3,4]

Increasing the level of automation

Level and slope control is very common in screed type of machines, such as an asphalt paver and a motorgrader. Automating the excavating movement in the excavator is not a simple task. Today, human is more efficient to finalize the work due to nature of tasks performed with excavator. However, there are solutions and patents introduced for semi-automatic excavating functions. Semi-automatic systems might be able to improve the efficiency of the machine so that it is reasonable to retro-fit hydraulic valves and a controller in to the machine.

Automating the measurement function increases safety because external measurement people are not needed that frequently by the machine. When systems are automated and machines start to move either autonomously or in the human surveillance, safety is always the first concern. Even though a machine could be automated to work autonomously in civil construction jobsite, the problem lies in the domain. Civil construction work is usually performed nearby civilian settlements. In many cases it is impossible to restrict the jobsite by a fence. A random civilian could enter the jobsite without wearing a dedicated safety system and risk his or her life.

Research Project FAMOUS

Novatron Oy has been one of the industrial partners in the research project “Future Semi-Autonomous Machines for Safe and Efficient Worksites” (FAMOUS). FAMOUS is a part of research program “Energy and Life Cycle Cost Efficient Machines” (EFFIMA) that is totally worth ca. 41 million Euros. EFFIMA programme is managed by Finnish Metals and Engineering Competence Cluster (FIMECC). FIMECC is one of the Strategic Centres of Science, Technology and Innovation (SHOK). SHOKs are a cooperation platforms for companies and research institutes. Target of a SHOK is to create world class results and expertise in a very close relationship to a business life.

There are thirteen idustrial partners and four research partners in FAMOUS. The industrial partners are coming from the different businesses. There are companies that supply technology, such as software, sensors, controllers or HMI's and companies who produce complete machines. The machines work in various different industry domains. Project started in 2010 and will last for 2014. The project includes following tasks:

1) SENSIBLE - Sensing Technology

2) SECO - Safety Concepts

3) OPE - Operator assistance

In SENSIBLE the target is to research and develop new sensing technologies for machine and human positioning and mapping. There is not a single sensor in the market that alone could be used for machine navigation or finding a human in all environmental conditions. Safety augmentation is another reason why multiple sensor technologies should be found for every required environmental condition. Because of amount of different use case scenarios and required environmental conditions, the project participants decided that a universal sensor rig should be built for data collection and processing. When data is collected from multiple sensors at the same time, the Situational Awareness can be improved by means of sensor fusion. The sensor rig system includes following sensors:

- RTK GNSS
- Inertial Measurement Unit (IMU)
- 3D LIDAR
- High dynamic range cameras
- Infrared camera
- High resolution camera
- Directional microphones
- Automotive radar
- Ultra-Wide Band ranging (UWB)

The sensor rig is used to collect the data in various different use cases and in different environments. The data is used for machine navigation, mapping and for location of the human. Humans can be detected passively by using perceptive sensors or actively by using a tag. In the domain of civil construction the passive detection is preferred.

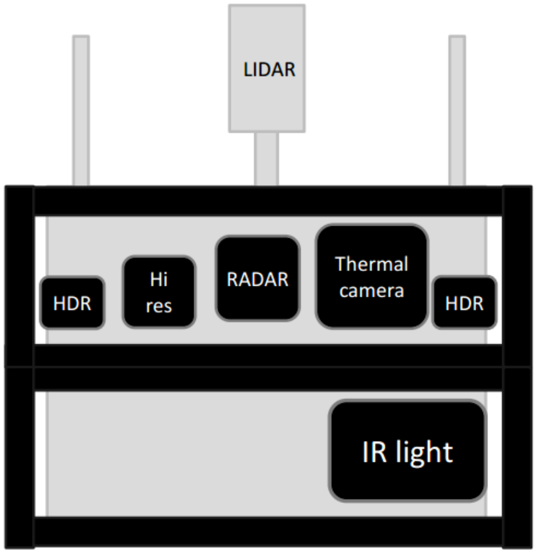

Figure 4: Himmeli

The focus in SECO task is on safety research. The goal is to find new adaptive safety concepts for human-machine collaboration. Traditionally safety means stopping machines if there is any chance for accident. However, in many safety cases the ideal solution would be that most of the machines continue with full or reduced speed even if human enters the automated work area. Inventing such adaptive safety methods for machine control would lead to more efficient but still safe sites.

OPE task focuses on operator assistance matters. When machines get smarter, novel operator assistance methods are required. The researched topics include 3D pointing technologies, augmented reality (AR) and Machine to Machine Communication (M2M). Also Situational Awareness model was developed in OPE for machine fleet safety system.

In the first half of the project Novatron focused on development of position and IMU sensors in SENSIBLE task. The project will end to final demonstrations in spring 2014.

Future of the Excavator Application

3D Machine Control application for excavator automates the measurement functions of the jobsite. Automation of the measurement increases the safety because number of people on foot is reduced. Excavator work is not simple to fully automate by its nature. In the future there are needs to keep excavator safe from other machines that might have a higher level of automation. Excavator can also be placed to the site where it can cause danger to itself and others by moving to places it should not go. Such places are found for an example from rail road rehabilization project where track is closed one way and has full traffic in the next lane. Some tasks, such as machine service, require that the operator of the excavator goes outside from the cabin. It is also possible that civilians enter the civil construction site without a warning. When autonomous machines are working on the civil contruction site, there is an immediate need for perceptive human detection. Accurate, safe, augmented positioning solutions and safety concepts need to be invented and applied also to the excavator application.

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