Construction Automation Process Development – Advancing the Collaboration between Finland and California

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Abstract

This paper presents the total process model of automation for construction and maintenance, with a focus on roads and bridges. This multi-phase model includes: initial measurements, product modeling and design, construction control and machine guidance, quality assurance and control, and lifecycle operations and maintenance. The paper then provides detailed discussion of current applied research results from Finland and California. The paper gives a summary of the key findings of Finland and California, noting areas of commonality and areas for further investigation. Finally, the paper presents plans for further collaborative research between the University of Oulu and the University of California – Davis.

1. Introduction: The Total Process Model

Automation of infrastructure construction is based on the use of different information models in the different phases of the total working process. For example, the needed machine control models ("control model") can be processed from the related product design ("product model"). The product model is designed and optimized based on measured "initial data models". Constructed structures and products are measured and stored as "as-built models." On-going maintenance and operations of the infrastructure will need different functional measurements ("maintenance model"). In the end-of-product lifecycle, residual value measurements ("residual value model") can be utilized in the long-term planning and development of products and working processes (Heikkilä and Jaakkola 2006). This total process model provides a formal framework for the current and future collaborations between Finland and California.

1.1 Initial Measurements

The automated road construction process starts with on-site input data measurements. In road construction projects, the key input data includes variations in terrain and elevation and soil features. Recently, laser scanning from an airplane, helicopter, or on the ground has developed greatly and become increasingly popular (Hiremagalur *et al.* 2007; Hiremagalur *et al.* 2009). The resulting 3D point cloud adjusted to the relevant coordinate system can be imported into a semi-automatic analysis application that can be used to model not only the contours of the terrain but also tree stands, road alignments, structures, and buildings. However, 3D modeling of underground soil features and conversion into a digitized format is technically far more complicated than above-ground terrain modeling.

1.2 Product Modeling and Design

In product design, a model and instructions for the implementation of the product are created out of the input data. Typically, the products are large 3D objects. If the input data is 3D, design can be carried out 3-dimensionally using CAD tools. The 3D geometric model can be used to produce images for 2D drawings. With improved efficiency in design, it is also essential to be able to make use of the design model for physical construction. If the geometric model is accurate and based on the site coordinate system, it can be used directly for controlling measurements and construction machines. This imposes additional requirements on the quality and accuracy of design.

While geometry is an essential aspect of the model, and represents the focus of the discussion in this paper, other data types must be considered throughout the process. These include road structural layers, pavement characteristics and performance, soil conditions, hydraulic characteristics, existing or anticipated traffic patterns, right-of-way and utility issues, and operational and maintenance issues and measurements.

1.3 Construction Control and Machine Guidance

In the future, there is a very strong view that machines used in civil construction will be increasingly controlled by automated systems. The most advanced systems presently available permit partial automatic control of the machine blade based on 3D positioning and 3D models. However, the functional performance of the systems varies, usually because the corresponding geometric data is not managed completely. Full control of the 3D geometric data and, in particular, inclusion of other property data in the control system remains as future goals.

Previous research and experiments indicate that the control of construction machines and blades requires active coordination by the operator. In this system, the blade position is adjusted automatically with reference to the control model, permitting the operator to select among various options to optimize the process according to the situation at hand. Evidently, pre-calculated paths of travel can seldom be followed.

Typically, 3D point, curve and triangulated surface model models provide sufficient geometric control data for finishing surfaces. However, their data content is not sufficient for a control model for work operations such as the reinforcement of the road bed or stabilization of structural layers, where the objective is to modify the properties of the materials.

1.4 Quality Assurance and Control (QA/QC)

QA/QC is an essential part of the construction automation process. Modern sensing technologies, including 3D laser scanning, robotic total stations, and a variety of pavement quality sensors, can be combined with the CAD data and models used for machine guidance (Kilpeläinen, Heikkilä and Parkkila 2007). Real-time monitoring as well as post-production validation will be necessary to assure the appropriate levels of quality, and compliance with job requirements and specifications.

1.5 Lifecycle Operations and Maintenance

For the safest and most efficient operations and maintenance of the infrastructure, data- and model-driven methods must be applied throughout the lifecycle. Numerous advanced sensing, software, and robotics and automation technologies have been developed and proven by the AHMCT Research Center (AHMCT Research Center 2008). For example, mountain pass road opening benefits from sensing and driver assistive displays based on a GPS/GIS model of the roadway (Yen *et al.* 2008). Several of these systems are now commercially available and are being deployed into infrastructure operations and maintenance (AHMCT 2008; TRAF-tech 2008).

2. Finland Applied Research

Finland is quite active in the field of Road Construction Automation, with on-going cooperative efforts between the University of Oulu, Tekes, the Finnish Road Administration, and numerous private partners. A sampling of these efforts is provided here.

2.1 In the field of Road Construction the results of the Development of an Overall Functional Process Utilizing 3D Data Models and Automation for Rehabilitation of Road Structures – CASE VT4, Haurukylä–Haaransilta (3D-ROAD) project implemented in 2006–2009 in Finland

The main objective of the 3D-ROAD research project is to develop a 3D functional process for enhancing road structures, utilizing automation, and improving the efficiency and quality of the measuring, design and construction processes (see Figures 1-3). The partial objectives enabling achievement of the main objective are: to complete the research tasks required for the development of an overall functional process; to model the overall functional process in order to complete a full-scale test project; and to complete an experimental implementation of automation, i.e. the overall functional process, in an actual construction project.

The Finnish Road Administration (FRA) was also participating in the research project in co-operation with the University of Oulu, aiming to develop subphase-specific requirements to speed up the implementation of new technology as part of the 3D-ROAD project. The requirements were be included in the requests for bids, enabling the actors to present their own implementation solutions as part of their bids. The test project gave the companies an opportunity to develop and test automation technology.

The common objective of the University of Oulu and the FRA was to complete the construction on the actual test site, setting a global standard in utilization of progressive 3D automation. The project was completed using the best technology and skills available today. The first aim was to get the companies to start developing their automation technology. The second aim was to acquire more comprehensive and accurate initial data utilizing accurate 3D positioning. The third aim was to design and model new 3D road geometry as part of the structural rehabilitation project. The fourth aim was to utilize 3D machine control in the construction of the pilot project.

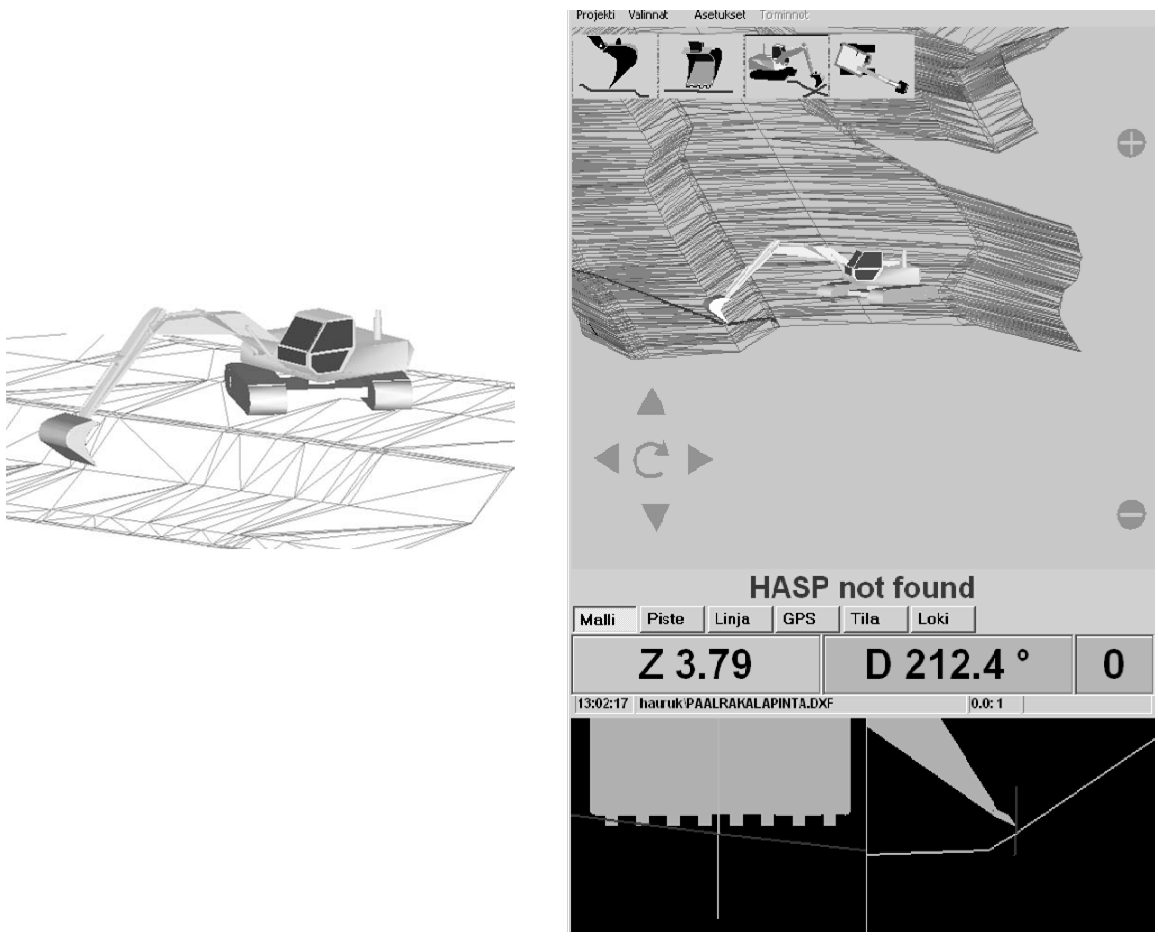

Figure 1: Examining the quality of machine control models in the user-interface of 3D measuring application software

Finland has about 150 3D machine control systems currently in use. Software used includes Tekla Xstreet, Novapoint, and Bentley Inroads for road design tasks. Vehicle-based laser scanning systems have been tested and used, and helicopter-based laser scanning has been in wide use. Finally, 3D GPR measuring has been tested and partly used in construction projects.

2.2 In the field of Bridge Engineering the results of the Bridge Product Modeling and Construction Automation Development (5D-SILTA) project implemented in 2004–2007 in Finland

5D-SILTA was an umbrella project under which various separate R&D projects were carried out in cooperation between the actors in the consortium (Pulkkinen, Karjalainen and Heikkilä 2008). In the project, 5D technology refers to the production, transfer and utilization of data in more than three dimensions throughout the total operating process of bridge building. The research and development focused on the development of 3D laser scanning and GPR scanning of bridges, the transfer of measurement results and road geometry to the 3D product modeling of bridges (see Figure 4), the development and improvement in the efficiency of road design based on product modeling, the diverse utilization of product model data in quantity surveying and cost accounting, scheduling, and procurement planning and management of construction work, and in 3D measurements used to control and validate (QA/QC) construction.

Figure 2: 3D control of excavators in the test of 3D ROAD

Figure 3: 3D control of excavators in the test of 3D ROAD – user interface

Three-dimensional laser scanning enriches the geometric measurements taken during various stages of bridge construction and improves their efficiency and precision. By utilizing the developing technique of bridge scanning, the measurements of the starting data can be expanded further and thus produce more information for the planning of bridge repairs. In bridge design, the shift to 3D product modeling increases the efficiency and speed of design work, reduces design flaws, improves change management, and directly serves the various aims of visualization. A contractor can utilize a product model directly in quantity surveying and bid calculations, procurement operations, schedule management, and even in measuring. Thus, 5D technology integrates the designer and contractor into a more interactive and continuous process of cooperation. The client can utilize the product model when checking plans, for example, and in later maintenance and repair stages.

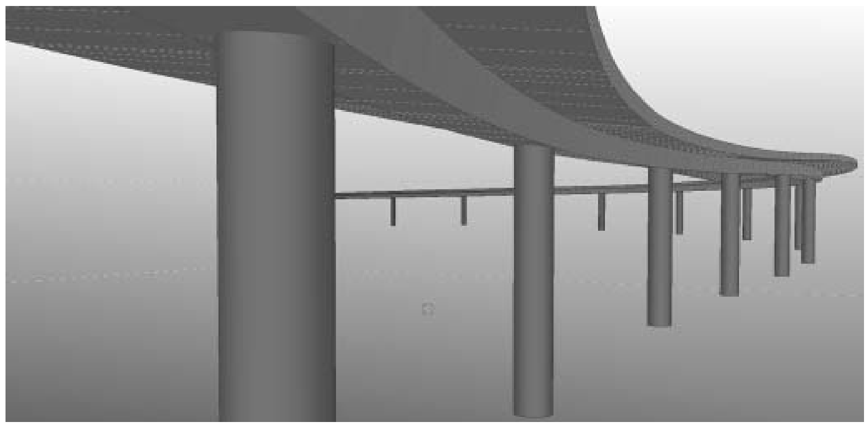

Figure 4: An arched concrete slab modeled in a Finnish test (Tekla Structures)

3. California Applied Research

The California Department of Transportation (Caltrans) current design process is to produce 2D drawings for roadway and bridge construction by in-house engineers. A small portion of the designs are done by engineering firms. Roadway designs are developed using a combination of CAiCE (Autodesk, San Rafael, CA.) and Bentley MicroStation (Exton, PA.) Bridge designs are done using in-house modified and commercial software. The completed 2D plans are used for bidding and building the projects. Contracts are awarded through a competitive bid process and contractors are by law not allowed to be preselected. This prevents the contractor from collaborating with the designer before the project is awarded. Although 3D design data exists, it is often not in a complete and edited 3D model. The creation of a full 3D model is not a required design product at this time.

Caltrans began receiving requests for electronic design data, in addition to the 2D plan sheets, from contractors in 2001-2003. Vendors also demonstrated the use of their equipment for construction automation. However no data was presented, then or now, to conclusively show that automated construction saved time and/or money on highway projects. Construction automation was seen by some Caltrans employees as just another way to use the data that was currently being produced and no workflow change was needed.

One project that attempted to use construction automation was on I-15 near Barstow (see Figures 5 and 6). New lanes were being added to the existing roadway in both directions for 15 miles. The paving subcontractor attempted to use construction automation to control the concrete paver. Two total stations were tracking retro-reflective prisms on the paver and providing XYZ positioning. The weather was hot (air temperature 105^{o} F) and the concrete was setting up very quickly, the paving crew was inexperienced with the equipment, and the contractor wanted both grade stakes and control for the total stations. This additional survey control created demands on the survey department that they could not meet. Ultimately, the contractor returned to using the traditional grade stakes on the project. This combination of environment and experience factors limited the effectiveness of the equipment and showed that the technology might not work in all cases.

In 2003 a Machine Guidance Committee was formed by members of the Caltrans Divisions of Design, Construction, Computer-Aided Design and Drafting (CADD), Office Engineers, Legal, and Surveys. The committee discussed construction automation and it became apparent that there were several challenges.

Caltrans current road design software does not use a full 3D model during design. The software relies on cross-sections as the basic design tool. Full 3D lines are developed through a separate process once the design is finished. Lines are not interactive with the cross-sections, and if a flaw is discovered they must be recreated. New road design software is being evaluated but has not yet been purchased. A change in software should make it easier to create files needed by the contractors.

Figure 5: Concrete paver, automated construction on I-15 near Barstow, CA

There were many concerns about delivering electronic data to contractors. The electronic files might not match the 2D plans, additional claims could be based on the discrepancies, the lines created from cross-sections may contain defects, unknown translation errors could be introduced by different software, and no design file will ever be perfect. These concerns have been addressed but still remain a concern to engineers. Non-standard Special Provisions have been added to contracts to allow delivery of electronic files to contractors but this has been on a case-by-case basis.

The committee developed a set of guidelines based on delivery of electronic files after award (Caltrans 2005). A pilot project was developed in District 11 on the second stage of a bypass around the town of Brawley in Imperial County (Caltrans 2004). State Routes 78 and 111 are being rerouted to reduce traffic on city streets. Originally the electronic design files were to be provided to bidders on the project before award. Due to concerns by the Division of Construction the files were delivered after award. Construction did not start until June 2007 and is expected to be completed by 2010. A “lessons learned” document will be completed when the majority of the work is done.

Figure 6: Robotic total stations tracking retro-reflective prisms on the paver and providing XYZ positioning

Another pilot project was started in 2008 in District 3, around the small town of Tudor, in Sutter County on State Route 70. The design files were included in the bid package and the contract was awarded. Major construction has yet to begin.

There have been many projects done with machine automation around California. Contractors have been given existing electronic design files, or the created their own from existing 2D information. These projects have been poorly documented because of the time pressure to get the projects built. Caltrans management does support developing policy for the use of machine automation.

Caltrans is also looking to other DOTs, the American Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB) to share information. Caltrans has an active representative on AASHTO's Automated Machine Guidance (AMG) Technology Implementation Group (AASHTO 2008). A Request for Proposal to identify guidelines for the use of AMG was sent out and was due on 12/2/2008 (NCHRP 2008). The finished study should be valuable to all DOTs. The TRB subcommittee AFB 80 (Geospatial Data Acquisition Technologies in Design and Construction) is also investigating machine automation (TRB 2008).

In conclusion, Caltrans is investigating machine automation, but the real champions of this new technology are our construction contractors. The major challenges have been producing an electronic design file, changing existing workflows, developing new contract language, purchasing better road design software, overcoming organizational and personal resistance to change, and documenting the results. A compelling case for cost and time savings to Caltrans would make all the difference.

4. Conclusions and Future Research

The total process model for automation for construction and maintenance is expected to provide substantial benefits for transportation infrastructure. Research, development, and pilot testing in both Finland and California have demonstrated the feasibility and many of these benefits, and have also identified areas for further investigation and improvement. The model will allow us to identify key features and requirements for Caltrans and its contractors to appropriately apply machine guidance and construction automation. As noted with respect to California's results, a critical need is a detailed business case analysis demonstrating the cost-benefit for machine guidance and the use of a total process model for the complete infrastructure lifecycle.

The AHMCT Research Center at the University of California and the Research Unit of Construction Technology at the University of Oulu have identified a number of areas for cooperative research in construction automation, machine guidance, and model-driven lifecycle operations and maintenance of transportation infrastructure. We plan to pursue a carefully orchestrated pilot project with Caltrans, structured in a manner to properly evaluate and document the benefits and costs of these technologies in a well-controlled environment. In addition, we are investigating application of GPR for the pro-active evaluation of bridge deck health. We also intend to collaborate on the application of 5D technologies, and the evaluation of their benefits to the DOT. Finally, we plan to develop an on-going series of workshops bringing together government agencies, researchers, and industry, to accelerate the application of innovative and beneficial automation technologies for highway construction, operations, and maintenance.

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