Advanced Process Control for Infrastructure Building Processes

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Purpose In this research, novel information integration technology and advances in wireless communication, positioning and machine control systems were combined into a general control method for an improved multi-contractor infrastructure building process. More intense competition and new environmental regulations in the field of infrastructure building are forcing companies to revise and intensify their processes. There is a clear need for tools enabling more efficient process management. In this research, the objective was to find out how to improve process management through more efficient information exploitation. **Method** We conducted a literature review and interviews with professionals in the field to find out requirements for improvements in process management. **Results & Discussion** Based on the requirements revealed by the literature and interviews, the developed control method exploits common ontology models to integrate design and construction time process data with the help of advanced communication, positioning, and machine control applications. In addition to construction time process control, the utilization of the developed control method also potentially intensifies operations before and after the project. The developed method for example makes offer requesting, project control and maintenance potentially more efficient and therefore makes processes safer, more cost-efficient, eco-efficient, and greatly helps the product data management. The development of the method is the first step and the results will be verified in a next research phase by practical implementation.

Keywords*: infrastructure building, information integration, semantic methods*

INTRODUCTION

The infrastructure building companies among the other industry nowadays are facing a huge pressure to strengthen and intensify all the processes due to hard competition, the new regulations and public demand for more pro-environmental processes. Talking about the large scale infrastructure building projects they are less organized and formalized due to more badly measured process parameters, lower technical status of factors of the process and sometimes quite complicated subcontractor chains. The technology variety and technology knowledge of different subcontractors in the same site cause difficulties to project and process control. Infrastructure project consists several parallel processes where machine break down or other kind of interruption can cause delays and unplanned costs. A random interruption in the process including several parallel sub-processes may cause problems in large scale. These interruptions should be handled immediately preferable automatically as fast as possible. However, in many cases in the infrastructure building, process data is handled slowly and manually by error-prone human operators without knowledge from every affecting process parameter. The implication of the aforementioned example is that in infrastructure building process, control is difficult. Difficulties in control leads to the situations where the status of the sub-processes are worse known, making the overall process control and dynamic reaction to the changes impossible and therefore processes are more inefficient, hazardous, expensive and slower.

According the description above, there is a clear need in the infrastructure building industry for the deployment of more intelligent process control methods concerning both the information of the original plan and the dynamically changing construction time process parameters. The research problem was to develop suitable control method to answer the need. The developed method allows integration of the most important subcontractor process information to be used by main project coordinator for more efficient process control and reaction to the changes in the field. The main benefits of the method are more efficient, cost-effective, more environmental friendly and safer infrastructure building projects through the improved production data management. The most important facilitators of the control method are novel technologies in the areas of the machine control systems, data formats, location systems, information management technologies and finally general Web technologies.

In this study, a novel method for the improved process control was developed. In the method, the management of the design data, automatic dynamically changing and manually added process data is formalised in a way that it could be easily integrated as a whole and where the information format provides also means to successfully do automated data fetching and inferring.

State-of-the-art

Commercial state-of-the-art products of construction project management offers proper tools for data storage, data analyze and instant messaging, but components for open, vendor-independent data integration tools are missing.

In the academia, the infrastructure building topics are also vastly researched. In the mid-1990's Navon et al. begun to research construction industry management. Industry related state-of-the-art research has been conducted in Israel[1]. Navon and his colleagues focused in their researches on automated productivity measurements using GPS-data and the concept of work envelopes[1,2]. In the same time Navon state that in the beginning of 2000 century the background for the construction process control was thin and all the actions were done by manually made calculations[1].

Later on two German research projects has started to study the ways to improve construction processes and management. Researched focus areas were e.g. improving the total construction process and optimizing the workflow with help of machine control, logistics planning, virtual phase visualization, documentation and data management. State-of-the-art technology like PDM-systems and close range identification were used to help reaching the targets[3-7].

Several academic researchers have also researched lately the potentials of ICT-related construction management[8-10]. The common factor of these ICT-related researched mentioned above is the use of novel ICT technology for process measurement and follow-up.

A method for information integration in infrastructure building was developed by El-Diraby et al. in few related studies[11,12]. In these studies, semantic methods are used to formalize information as well as relations between those information instances. The study, presented in this paper exploits some of the main ideas of these studies like creation of ontologies for different sub-processes for information formalization.

RESEARCH METHODS AND METHOD ENABLERS

The base research method for the improved building process control that has been developed was quite straightforward. It was based on a state-of-the-art study, the contractor and their employee interviews, industry partner workshops and worksite visits. The deployed information integration method is based mainly on the semantic methods but the utilization of the method in the real world case would not be possible without new technology advances like open data formats, automated machine control systems, automated positioning systems and wireless mobile technologies.

Technology state-of-the-art and research partner practice surveys

The need for the novel process control method and its type were researched in several different ways. In the beginning the state-of-the-art survey were done for developed similar systems among the commercial products and academy researches to verify the need and to find already developed corresponding methods. Then the key position personnel were interviewed among the main and subcontractor companies taking part to the research project and the work site observation were done. Also two workshops among the project partners to discuss the topic were held. Finally, the potential technology enablers were studied and the most suitable were chosen to be used.

Semantic technologies

As a main technology for realizing the improved process control system, Semantic Web related technologies were utilized. Semantic Web is a concept for the next generation WWW in which information is given well defined meaning[13]. The underlying technological infrastructure of Semantic Web is referred to as Semantic Technologies[14]. Semantic technologies contain for example ontology tools, dynamic mediation tools, inference tools and thesaurus tools[15]. Ontologies and ontology tools are in central role in information integration.

In information integration the semantics of information is preserved while the context is transformed. Semantic technologies, especially the usage of ontologies, offer a way towards solving the information integration challenge[16]. Ontology captures consensual knowledge in a generic way to be reused and shared across software applications and by groups of people[17].

In ontology based model the semantics of information is modeled as classes and relations between those classes. The W3C's Semantic Web activity has developed many related technologies such as Resource Description Framework (RDF), RDF Schema (RDFS), Web Ontology Language (OWL), and SPARQL to realize the ontology based interoperability in the WWW. In this research, all the process data from the design to the real-time process data is stored to the triplet database to be easily deployed with the help of inferring when needed.

Open design data formats

New open design data formats for the building processes make it possible to reuse design data in different CAD and other applications. These new data formats are in many case well documented and XML-formatted making it even easier to be exploited in general. The developed process control method exploits one of the lately developed formats called InfraModel2 that is based on LandXML specification and targets i.e. road, street and water route design[18]. XSLT transformation were used to convert the design file to RDF type ontology.

Automated machine control systems

The recent commercial machine control systems have opened a completely new era in the some of the sub-processes in the infrastructure building. With help of the wireless communication technologies, machines can now receive work instructions and send up-to-date process data on-demand enabling better real-time process control on their behalf.

Wireless mobile technologies

Realization of the control method described in this study would not possible without the novel wireless mobile communication technologies like wireless operator networks. The requirement to transfer larger amounts of data wirelessly more frequently is clear if the greater level of real-time behavior is wanted. Although the needed data transfer will be small if only machine guidance, survey, status and mass transfer related data is transferred.

RESULTS

Method requirements

In addition to the state-of-the-art review and field study observations, personnel of the in involved project partners were interviewed to get a better idea of the process control method requirements. The interviews of the study covered personnel basically from each sectors of typical actors from large scale infrastructure building project. Among the interviewed key personnel there were representatives from a builder, a designer, main contractor as well as subcontractor system supplier companies. Subcontractor system supplier companies covered a design tool provider, a mass transportation management system provider, a machine control system provider and road measurement system as well as end users of those systems. Amount of the interviewed personnel were only about 2 persons per company type, except the main contractor where around 5 persons were interviewed. Since the amount of the interviewed persons was quite few, the interview results are not all-covering, merely giving a basic idea of the system requirements. Sub-topics of the interviews covered partner's recent official practices concerning project-wide and inter-partner information flow, future plans and interviewee's own opinion of the way practices should be realized. The interviews and the questions were tailored according the interviewee type. The answers included direct suggestions how to improve practices as well as indirect observations that were translated to requirements by authors. E.g. one of the answers of the main contractor explained what the most important observed process parameters are and what the preferred update interval for them is. The interview results completed the information received from worksite observations, a partner workshop, the state-of-the-art review and the authors' experience from the other related projects. The requirements of the system contain both the exploitation possibilities of the information and the overall integration system requirements. The most important requirements for the intended control system are listed in *Table 1*. The list reveals that an efficient control system for the purpose includes at least some of the following features: soft real-time, decentralization, system independency pre-agreed subcomponent interfaces and decision-making capabilities. State-of-the-art survey revealed us that there is general purpose information integration method developed in academia suitable for the infrastructure building processes[12]. However, there was no such a case found where the general information integration method was used for construction time process control purposes. There are also many different examples how different sub-processes or special focused needs could be covered, but none of really matching the needs mentioned above.

Table 1. The most important requirements for the developed method

Need	Explanation
Semi real-time	Response time should be within tens of seconds.
Easy system integration of different actors needed without custom programming	Common data models for both design and run-time process data provider parties are needed.
Automated decision making	Data formats supporting machine based inferring.
Non-system dependent	Using information management system should be done using common, platform independent technologies.
Possibility for decentralized system	No need for Common repository for process data.
Selected site parameter monitoring	Necessary function of the concept, concerning proper site progress monitoring.

Method description

The process control method presented is based on the described requirements. As we have studied in earlier chapters, one of the most important matters in order to realize an advanced process control system seems to be general data interoperability that can be realized e.g. with pre-agreed common data formats that enables ease assembling of smaller portions of data to usable wholeness. Those data formats should also be machine understandable. Also important properties of the control system are system independency and possibility to realize system with decentralized architecture. The main idea of the developed method is to develop and use common ontology model that contains sub-ontology for each subcontractor type of the infrastructure building process. For example there should be different sub-ontologies for the design and different process data providers like mass transport or excavating companies. Sub-ontologies contain only relevant data instances and their interrelations. *Figure 1* illustrates a simple snippet of subcontractor resource ontology model.

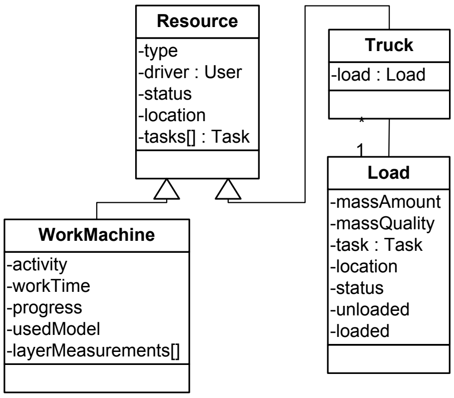

Fig. 1. An ontology snippet of sub-contractor resource

The common ontology guarantees the information interoperability and possibility to do inferring based on the data relations. Using the developed method, all the ontologies were described in OWL format to enable easy ontology combination from the different fragments.

Method utilization prerequisites

In order to realize an efficient process control method based on system requirements described in previous chapter, there are some initial prerequisites to be fulfilled. These prerequisites should be taken into consideration in the very early phase of agreement concluding between the project participating companies. The most important prerequisites are explained in *Figure 2* and *Table 2*. These prerequisites are needed since at present there are no standard ontology templates for different actor types.

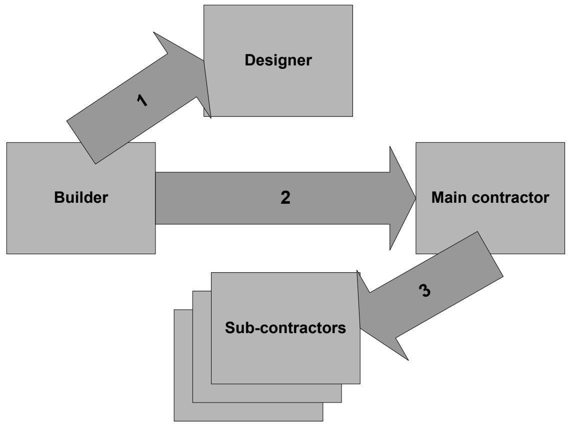

Fig. 2. Initial prerequisites of the control method

Table 2. Explained method prerequisites

Pre-requi-site	**Explanation**
1	The builder should order a product design either directly in common ontology format or easily converted one supporting also machine control system conversions for better design data compatibility, exploitability and better general reuse. Designs or more specifically machine guidance models should be divided into part's suitable for developed concept.
2	The builder should order the main contractor to log the most important process parameters in common ontology format for more efficient quality control, traceable billing and maintenance purposes.
3	The main contractor should demand subcontractors to provide the produced process parameters to be available in common ontology for better information and project management, safety, cost-efficiency and eco-efficiency.

System architecture

In the developed method, the main contractor is the party that is coordinating data collection and reuse. Both decentralized and centralized methods can be used. In decentralized method, all the other participating companies just give the main contractor an access to their remote information repository containing generated process data in OWL format and the main contractor fetches data from there and combines them when necessary. In our study however, the centralized method is the one that is in the focus. In the centralized method, all the parties send their design and process data in correct format to the server provided by the main contractor in agreed intervals and the main contractor takes care of the data exploitation and its possible distribution and reuse. *Figure 3* shows a simplified architecture and the data transfer principles of the centralized version of the developed information integration method.

Designers deliver design related information, like construction and schedule design, to main contractor's server as well as information about any changes made to the design information during the project. Subcontractors transfer process related data to the main contractor's server; this information may contain e.g. excavation status and mass transfer data with related machine location data. Subcontractors are able to receive realization information about project and for example work instructions through information system. Main contractor adds its own process related data, which is combined to subcontractors' data. The developed system offers the integrated information to main contractor through information integration system's user interfaces. All the data transferred to main contractor's server is formatted according to agreed ontology model. The ontology is realized using OWL.

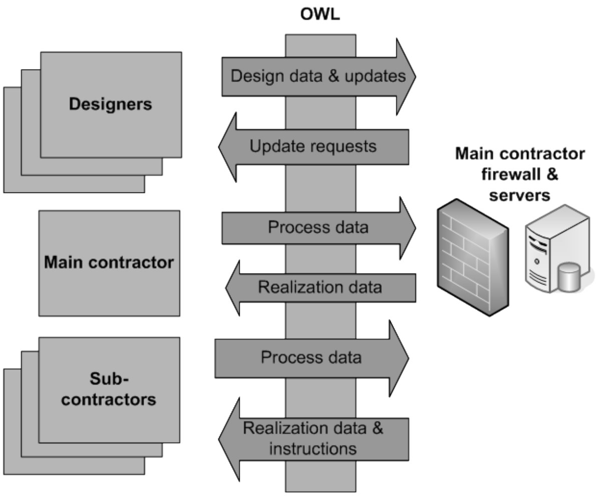

Fig. 3. The control system architecture

Illustrative Use Case

An illustrative use case describes the planned use of the new control method concept. Use case is divided into three parts and it considers three actor types (designer, main contractor and sub-contractors). First phase of the use case is initial state and the following phases are operational. Presented use case is ideal and heavily simplified. Use case presents the use of the control method in a road construction case. The use case will be implemented for real-life implementation in the next phase of this research.

Initial state

In the initial state all needed road designs, machine guidance models, mass hauling plans and schedules are uploaded into the server following the researched prerequisites, see *Table 2*. Initial state models, plans and schedules have designed by group of designers and verified by construction site operating officer.

Execution

Execution phase is divided into two parts; cut-and-fill and mass hauling. Therefore execution phase considers only two actor types (excavator and truck). Excavator is equipped with state-of-the-art machine guidance system with wireless data transfer technology. Cut-and-fill is done by instructions from a machine guidance model. Mass hauling trucks record every load they transport using a mobile application. Recorded mass hauling data is sent in real time to the server, where it has been compared to plan.

In the execution phase main contractor can monitor and control the execution task progress by comparing the schedules and realization models since they are part of the same common ontology model. Progress is presented graphically enabling easy project status observation. If realization seems too fast or slow the supervisor can react accordingly.

Quality assurance and task approving

In a quality assurance and task approving phases the executed work is recorded by machine guidance and mass hauling systems and results are delivered to the server as an as-build model. After comparing the as-designed and as-built models the main contractor can approve the task and give the permission to start the next phase of the construction.

DISCUSSION

The driving factor of our research was the lack of proper general tool for project management concerning the site officer, who is in charge of daily construction actions. The general process control method was developed for that purpose. Utilization of the developed control method could also affect in many different sub-topics in the infrastructure building sector as well as to other domains with scattered contractor chains and not formalized production methods. The gained benefit comes due to formalized, easily combined data formats ensuring the better interoperability and enabled automatic inferring and decision-making based on the collected data. The design data could be used more effectively when it is used as an initial data to be compared to the realization data which improves process follow-up. Also the collected process data is easier to integrate in order to enhance the process monitoring, quality control, faster reaction, safer and more efficient processes and after the project for maintenance focusing and improvement. The collected data could also be used after the project as a reference for a more efficient offer requesting processes and descriptions. The semantic way to present project data with internal relations eases also the exploitation of novel PDM-systems.

The developed method is quite scalable, general purpose and easily deployable. Each company taking part to a construction project could use their best known software technology and platform and take part to information chain. The developed method is also usable in other related tasks e.g. invoicing process as for example the realization of a certain mass hauling task may be allocated to certain a subcontractor. This reduces need of human work in invoicing as it reduces paper handling. This also gives better opportunities to main contractor to order extra machines for example for mass hauling. During development of the information integration method also maintenance after construction was taken into account.

Previous and currently running research projects have been studied. Methods how to monitor and manage processes and how to gather liable status information from the infrastructure building projects were researched. In many cases automated data gathering and GNSS-positioning systems are the main factors of the developed concepts, but the way how this gathered data is analyzed and used again varies between different projects. Nowadays the common way is to develop an algorithm that monitors automatically where the assets are moving and realizes which part of process is in progress. The control method developed in this research exploits also GNSS-positioning and other novel ICT technology, but the main focus is in the ontology based information formalization and its utilization for information integration purposes. Several lately conducted researches have same kind of integration approach where enterprise level systems and software's are integrated to concept database. Developed methods have also same key features like web-based platforms, databases and mobile accessories which are noteworthy technologies because the latest developments in wireless network and other ICT-related areas. There are also examples where ontologies are used for information integration purposes in the field of infrastructure building processes. These examples however did not point out how to use them to the process control purposes and neither there were explanation what kind of extra prerequisites were needed to fulfill to really deploy them.

During research process couples of drawbacks were recognized. Since the infrastructure building process is quite scattered concerning to level of the used technology among the subcontractors there will be problems to add all the needed parties to the system in practice. Also the utilization of the semantic methods demands high technology orientation from the using party with the skilled personnel before the routines to use the method evolves. Due to quite heavy data formats and system structure the method does not allow hard real-time utilization. Of course the possible production system using the developed method would demand heavy standardization process for development of real common ontology. One drawback is also the lack of clear earning principles. Of course, if the benefits are high enough for the main parties, the demand for method from the main builder side would speed up the process. At the moment the current sub-contractor software data formats do not support ontologies described in this research, causing an issue demanding data format converter or specific interface for every subcontractor counterpart.

As pointed out the need for additional research is clear. Since there is already few main example ontologies developed, the proof-of-concept implementation system should be done including the integration of the design data, scheduling data and some important process data. Also a tool improving the construction time process management with user interface should be included. The implementation should be tested concerning the performance and utilization experiences from real users. Also the business model to motivate additional funding for research should be clearly pointed out.

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