An Ontology for Process Information Modeling

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ABSTRACT

So far, the use of Building Information Modeling (BIM) to support automatic prefabrication and on-site assembly processes during a construction project has been limited. The modeling and management of information concerning the diverse elements involved in these construction processes, such as activities, objects, flows and operations, has not been sufficiently studied. In order to support the proper handling of construction process information and improve productivity, a process information modeling framework is developed in the present research.

This paper presents an ontology model for supporting information handling of off-site automatic prefabrication and on-site assembly, which can incorporate manifold aspects (e.g. geometry, functionality, physicality) of building production sub-systems. The object-oriented framework can support the semi-automatic preparation of digital information for off-site component prefabrication, and the simulation of the production process while considering variables such as the geometry of building components, material attributes and production speed.

The framework can also support the definition of a project specific assembly activity and the simulation of on-site assembly activities such as component unloading, mounting, hoisting and positioning, while considering construction engineering constraints such as the lifting capacity and speed of cranes. As a result, the 3D model of the building component is updated to reflect its actual motion on the site during assembly processes.

Keywords – Process Information Modeling Framework, Application Ontology, Construction Automation

1 Introduction

Buildings are extremely complex products, in terms of the number of different components they contain, and the different relationships that exist between those components. Moreover, the processes in which buildings are constructed are dynamic by nature: they involve frequent changes in activities and the resources that they require, and the simultaneous movement of equipment, workers and materials along different paths on site. The combination of a highly complex product and dynamic production processes make it a challenge to plan efficient construction projects.

A key step towards increasing the efficiency in construction projects is the application of automated prefabrication and onsite assembly processes. In the construction industry, BIM has been widely used for project planning, designing, scheduling, and estimating. However, the use of BIM to support dynamic prefabrication and assembly processes during a construction project has so far been restricted. Therefore, the objective of this study is to develop an information modeling framework that will support the detailed planning of such automated processes, and the management of information concerning the diverse elements involved. Such elements include activities, objects, flows and operations. Since the decision whether to produce a component on or off-site is project and context-specific, the framework addresses both on and off-site processes, and the dynamic interactions between the resources they require. The framework will support the detailed planning, simulation and optimization of prefabrication and assembly processes.

In information sciences, ontologies formally represent knowledge, and can be used to model it. *Domain ontologies* define the constructs used in a specific domain. *Constructs* refer to the concepts which are used to characterize a phenomenon and describe problems within a domain (March and Smith 1995). A domain ontology also defines the properties of each construct, and the relationships among the different constructs in the domain (Guizzardi 2007). In addition to domain ontologies, *task ontologies* define the constructs related to a generic task or activity, and application ontologies define constructs depending both on a particular domain and a task. Application ontologies are often specializations of the related domain and task ontologies (Guarino 1997). Thus, domain ontologies define the fundamental constructs in a relatively large domain (such as construction), while *application ontologies* focus on sub-domains of a major domain (such as the planning of construction processes) (Lima et al. 2005).

In this paper, an application ontology is presented for construction process information modelling. The definition of the ontology is a first step in the development of an object-oriented framework that will support the detailed planning of dynamic construction processes in general, and of automated prefabrication and assembly processes in particular. The definitions of the constructs, their properties and their relationships in the ontology will be used to define the objects in the framework, which are not included in existing Building Information Models.

2 Related Works

2.1 Ontologies for construction planning

A number of previous studies were aimed at developing general domain ontologies for the construction industry (El-Gohary et al. 2010; Grobler et al. 2008; Lima et al. 2005; Zhang and Issa 2011). Among those, Zhang and Issa [3] developed an information extraction method, using an ontology model, with the aim of obtaining specific information from a BIM file or document to support different use cases in the construction domain. None of these ontologies are specific enough to support the detailed planning of dynamic construction processes. In other domains, Chang et al. [11] developed and utilised ontologies for Design for Manufacturing (DFM). They demonstrate that the ontology can facilitate the reuse of data, reducing the effort required for populating the knowledge base of the ontology. Park et al. [10] analysed and evaluated the shipbuilding fabrication process, based on an enterprise ontology, to support process management. This illustrates that one of the applications of ontologies is to take an enterprise wide view of an organisation, in order to achieve effective integration and effective business planning.

2.2 Planning dynamic construction processes

BIM can be exploited in the design of prefabricated building components, for example in providing dimensional information on building components. This information can be used for controlling the manufacturing process and for quality control (Boukamp and Akinci 2007). During the on-site assembly of prefabricated building components to the building facade, BIM can be used for guiding the assembly work by providing component reference values and other assembly related information according to the defined assemblage order (Case et al. 2014). Thus, a virtual trial assembly of a complex steel structure based on data extracted from BIM can lead to considerable savings in terms of time, cost and logistics, when compared with the physical trial assembly. Wu et al. [2] presented a method for automatically generating time schedules for bridge construction projects based on the discrete-event simulation of construction works, by considering the interdependencies between individual tasks and the available resources (building elements, required materials, machine and manpower resources and technological pre-requisites of the activities). Benevolenskiy et al. [1] proposed an ontology-based process modelling with a rule-based process configuration, in order to improve the consistency of construction process modelling and to improve the modelling time. The proposed system can support the generation of process schedules for construction projects.

2.3 Dynamic operations for moving components and material

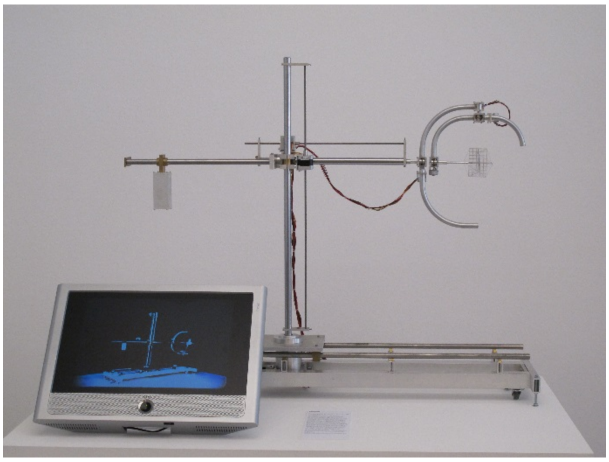


Figure 1. Geometrical Tests of LOM, TU Munich, [9]

A number of previous studies have focused on the application of practices and theory from robotics in construction. Bock et al. [8] found an economic potential in using robots for mounting and finishing operations in construction and suggested kinematic structures for the corresponding operations. In addition, movement planning and formation of the laws of drive control were taken into consideration in this research.

Previously, Konrad Wachsmann et al. developed a “Location Orientation Manipulator (LOM)”, which was a prototype for architectural assembly assignments by allowing the free coordination of an object in time and space [7]. This work is of relevance to the present research, since the LOM underlined the feasibility of fully industrialised and automated building systems, by defining an automated assembly system and by using assembly process concepts and an appropriate mathematical model.

3 Application ontology for construction process information modelling

3.1 Ontology for construction processes

Both off-site manufacturing and on-site assembly in construction are basically related to the interaction between components, materials, equipment and workers. These interactions involve the delivery of building components and materials from one place to another and the connection of components to each other.

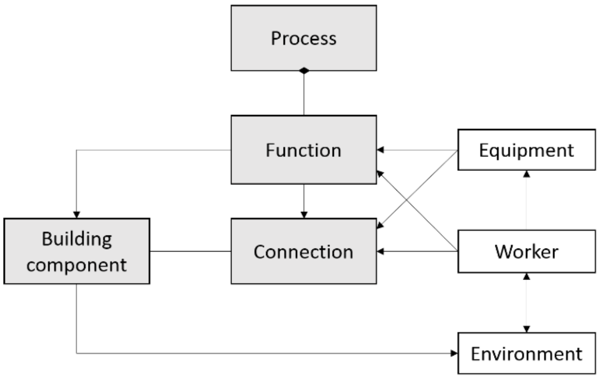
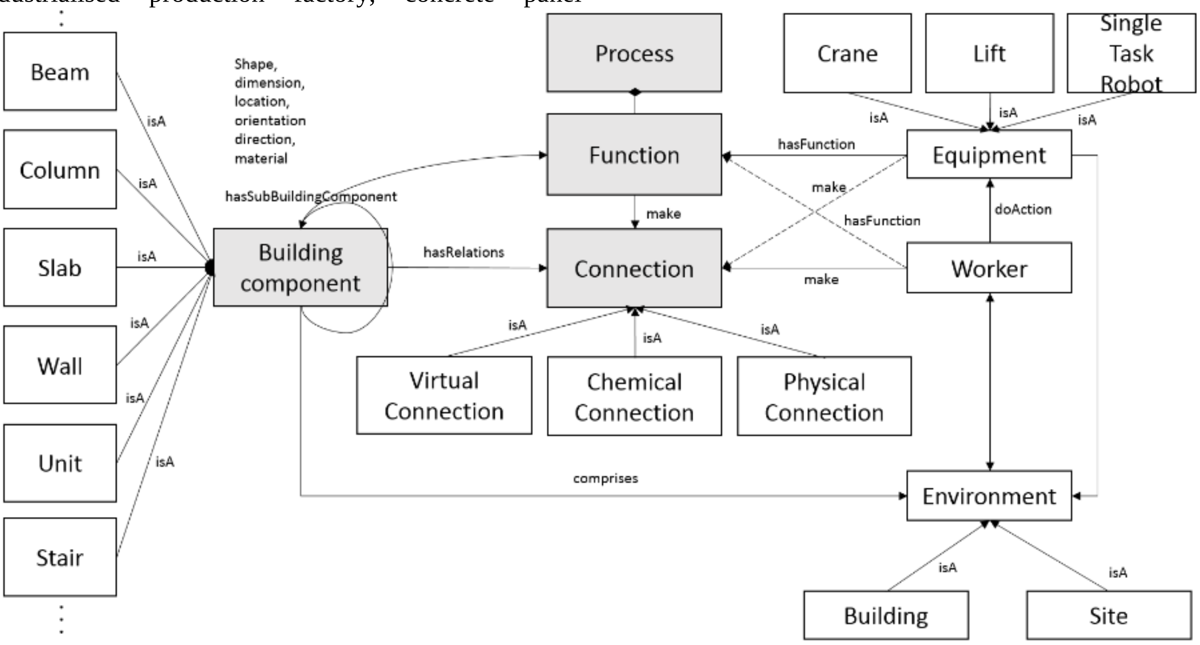


Figure 2. A basic application ontology for construction process

Figure 2 depicts a basic application ontology for construction processes. Concrete panel production can be used as an example for off-site manufacturing. In a highly industrialised production factory, concrete panel production goes through multiple steps: formwork, rebar installation, concrete casting, separation of formwork and delivery. In general, this process involves diverse activities such as material handling, displacing, connecting, separating, and so on, which are carried out by equipment and workers. Quite similarly, we can continue to use this scheme to explain precast concrete (PC) panel installation process in an onsite construction workplace. Once the PC panel is transported to the supply point, a tower crane lifts the panel and delivers it to the demand point for final assembly. The equipment and its operator (worker) perform a series of activities to assemble (connect) the component with other building component(s). In the meanwhile, before the final assembly of the component on the demanding point, obviously there is a temporary connection between the component and the crane.

Even though construction processes are related to material flows and the interaction between the entities involved, currently available BIM applications are limited in the ability to define this information, and it is therefore difficult to use them to plan dynamic construction processes. In order to support such planning, it is necessary to model detailed information on the construction process. Figure 3 and 4 provide broader view of the application ontology for construction processes and function ontology, respectively. 'Action' is defined as individual motions or control, which represents the most detailed behaviour such as one horizontal move, one vertical move, holding, rotation on the axis, etc.

Figure 3. An extended application ontology for construction process



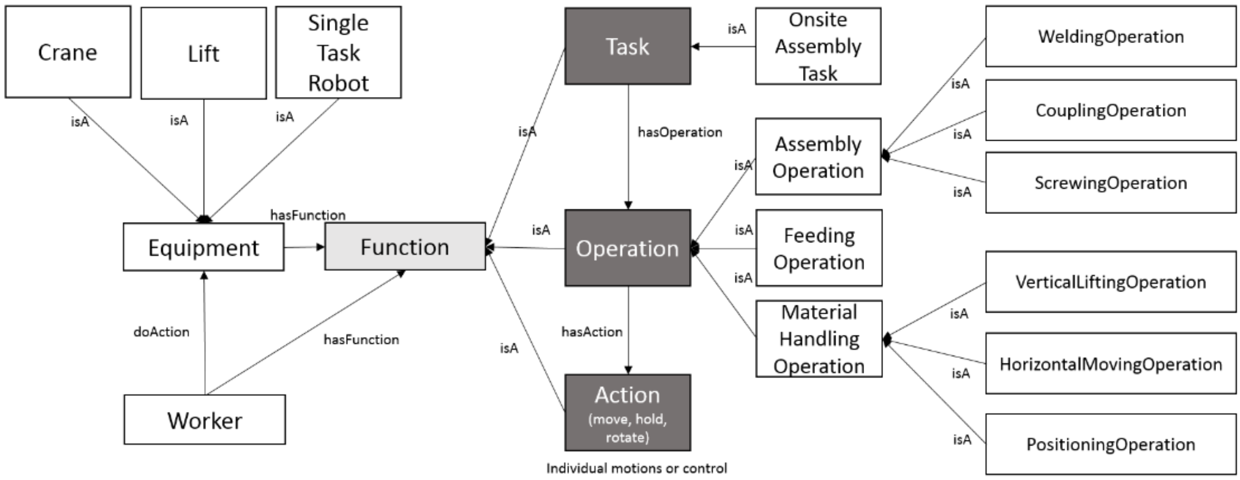


Figure 4. Function ontology for construction process

'Operation' is a collection of 'Action'(s) that represent intermediate procedures to put building components together. For instance, 'FeedingOperation', 'AssemblyOperation', 'MaterialHandingOperation', etc. are subclasses of 'Operation'. 'WeldingOperation' is defined as a kind of 'AssemblyOperation'. 'WeldingOperation', 'CouplingOperation' and 'ScrewingOperation' are subclass of 'AssemblyOperation'. 'MaterialHandlingOperation' contains 'VerticalLiftingOperation', 'HorizontalMoving Operation' and 'PositioningOperation' as its subclasses. Similarly, 'Task' is composed of a series of 'Operation'(s) in order to conduct construction components assembly. For example, in case of an 'OnsiteAssemblyTask' for a RC panel assembly, a series of 'VerticalLiftingOperation' and/or 'HorizontalMovingOperation', and 'CouplingOperation' are conducted by a crane.

3.2 Two mathematical representations

The representation of the dynamic construction process in a spatiotemporal dimension is required as well. To technically support the modelling based on the overview of the application ontology, two mathematical representations are required. One is transformation vector in order to represent movement, and the other is a graph in order to represent connections between entities.

The basic constructs of the mathematical model representing the moment in time t of the transformation are as followings:

- A node b representing the component or a point on the component undergoing the transformation
- A position vector of node b at time t:

$$\vec{p}^{(b)} = (x, y, z),\ \vec{p}^{(b)} \in \mathrm{R}^3 \quad (1)$$

- A displacement vector for transformation c:

$$\vec{d}^{(c)} = (\Delta x, \Delta y, \Delta z), \vec{d}^{(c)} \in \mathrm{R}^3 \quad (2)$$

By representing the movement path with displacement vectors we can:

- Calculate the total displacement for the component by summing up the vectors:

$$\vec{d}^{(Total)} = \vec{d}^{(c)} + \vec{d}^{(d)} \quad (3)$$

- Calculate the length of each vector:

$$\|\vec{d}\| = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \quad (4)$$

- Calculate the work w (in Joule) by multiplying the displacement vector with a force vector $\vec{f}$:

$$w = \vec{d} \cdot \vec{f} \quad (5)$$

The dynamic graph representing the product that is being assembled is defined as $G = (N, L, T)$ where N is a set of nodes representing the product's components, L a set of links representing connections between the components, and T is a set of discrete assembly phases in which these connections are created or removed. A time step $G_t = (N_t, L_t)$ of G consists of the nodes and links present in the graph at time $t \in T$. A_t is an $M \times N$ adjacency matrix representing time step G_t. The 3D "adjacency cube" is a representation of the dynamic graph G created by stacking T adjacency matrices in chronological order, one for each time step. The cube has two node dimensions and one time dimension. An entry $e_{mnt} \in (M \times N \times T)$ exists for each link l_{mnt} between nodes m and n at time t. Entries in the same row and column across all matrices form a time vector c that describes the evolution of the connectivity between two nodes m and n in the T

time steps:

$$\vec{c}^{(mn)} = (e_{mn1},\ e_{mn2}, \ldots, e_{mnT}). \quad (6)$$

Entries in the same row or column in matrix A_t form a neighbourhood vector:

$$\vec{v}^{(n)} = (e_{m1t},\ e_{m2t},\ \ldots,\ e_{mNt}) \quad (7)$$

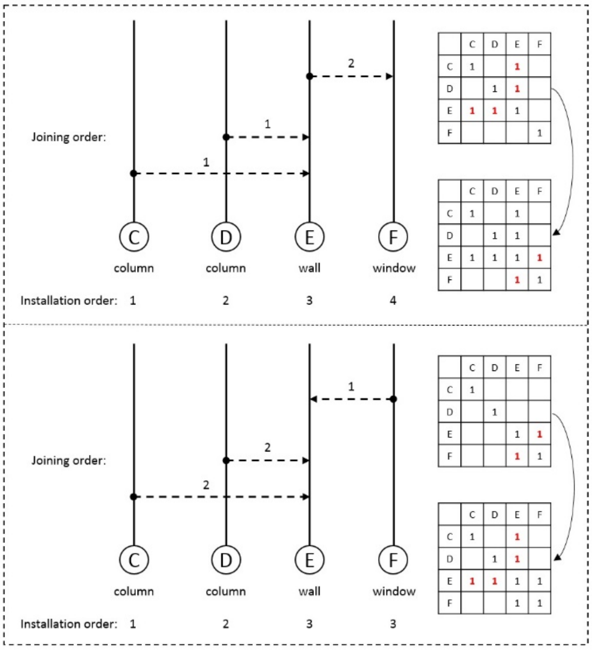


Figure 5: An example of different connection sequences for the same assembly

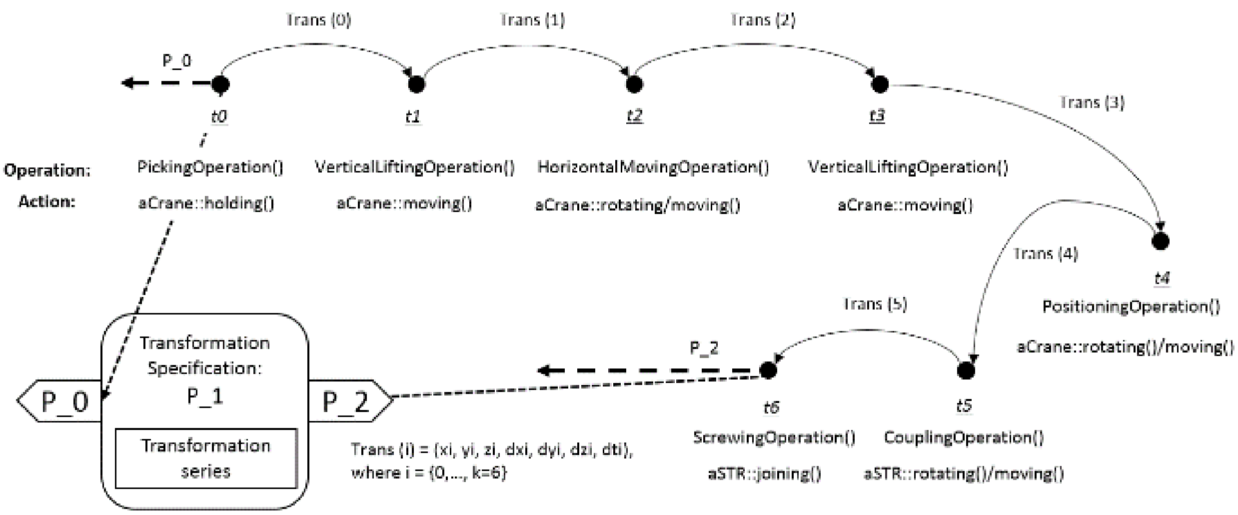


Figure 6: An example of dynamic transformation of a RC component by using a crane and a single task robot

This vector describes the neighbours of node *m* at time *t* (i.e. the nodes to which node *m* is directly linked in that time step). Figure 5 is an example of two different connecting scenarios among two columns, a wall, and a window. In the first scenario a window attached to a wall after it is connected to two columns. In the second scenario a window is connected to a window first, and then they are both connected to two columns.

3.3 A case study of assembly operation using the application ontology

To demonstrate how the proposed framework can support the dynamic construction process, a simple example of an on-site assembly task is introduced, as shown in Figure 6. This example shows a dynamic transformation of a RC component by using a crane and a single task robot (This single task robot conducts a screwing operation at t6). This example represents an 'OnsiteAssemblyTask' of a RC component, which is the construction process from a supply point to a demand point. Here, 'P_0' points a previous operation and 'P_2' points a next operation among others.

A series of actions from t0 to t6 represents a single 'AssemblyOperation' by using a crane and a single task robot. From t0 to t4, kinematic operation of a crane can be modeled and from t4 to t6, that of aSTR (Single Task Robot).

4 Conclusion

Currently, BIM is restricted in its ability to support the planning of dynamic processes during a construction project. Therefore, the development of an application ontology for construction process information modelling is of importance to enable dynamic information management and the detailed planning of on- and off-site prefabrication and assembly processes. An ontology-based approach is used in this research to capture the data on the construction processes and represent it hierarchically.

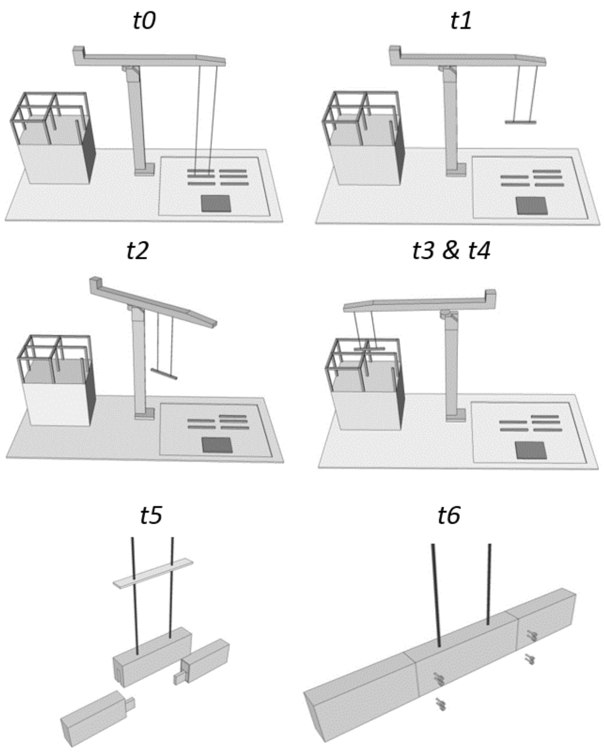


Figure 7: A pictorial example of Operations and Actions performed for a dynamic transformation in Figure 6

As a result, the definition of constructs, their attributes and relations are described concisely. To represent the dynamic construction process in a spatiotemporal dimension, two mathematical representations are introduced: a transformation vector for representing movement, and a graph for representing connections between entities.

An example of the utilization of the proposed framework for an on-site assembly task is introduced to demonstrate how the dynamic construction process can be modelled.

Future research will focus on a detailed analysis of the proposed modelling framework in more complex construction process scenario. Based on the analysis, the proposed framework will be expanded to support the detailed planning, simulation and optimization of prefabrication and assembly processes. In addition, diverse construction process ontologies must be developed to support common construction processes.

Acknowledgement

The first author (Seongki Lee) is supported by AUSMIP+ program.

References

[1] Benevolenskiy A. Roos K. Katranuschkov P. and Scherer R.J. Construction processes configuration using process patterns. Advanced Engineering Informatics, 26(4):727-36, 2012.

[2] Wu I-C. Borrmann A. Beißert U. König M. and Rank E. Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation, Advanced Engineering Informatics, 24(4):379-388, 2010

[3] Zhang L. and Issa R. Ontology-Based Partial Building Information Model Extraction, J. Comput. Civ. Eng., 27(6):576–584, 2013

[4] Case F. Beinat A. Crosilla F. and Alba I. M. Virtual trial assembly of a complex steel structure by Generalized Procrustes Analysis techniques. Automation in Construction 37(0):155-65, 2014.

[5] Boukamp F. and Akinci B. Automated processing of construction specifications to support inspection and quality control, Automation in Construction 17:90-106, 2007

[6] Camazine S. Franks N.R. Sneyd J. Bonabeau E. Deneubourg J.-L. and Theraula G. Self-Organization in Biological Systems. Princeton University Press, 2001.

[7] Bock T. and Lauer W.V. Location Orientation Manipulator by Konrad Wachsmann, John Bollinger and Xavier Mendoza, 27th ISARC:704-712, 2010.

[8] Bock T. Parschin D. and Bulgakov A. Robotization of mounting and finishing operations in building, Robotica, 20: 203-207, 2002.

[9] An Author's own photo (T. Bock).

[10] Park J.-H. Kim K.-H. and Bae J-H. J. Analysis of shipbuilding fabrication process with enterprise ontology, Computers in Human Behavior, Volume 27(5): 1519-1526, 2011.

[11] Chang X. Rai R. and Terpenny J. Development and Utilization of Ontologies in Design for Manufacturing, J. Mech. Des. 132(2):021009 (12 pages), 2010.

[12] El-Gohary, N. M., and El-Diraby, T. E. Domain ontology for processes in infrastructure and

construction. Journal of Construction Engineering and Management, 136 (7):730-744, 2010.

[13] Grobler F. Aksamija A. Kim H. Krishnamurti R. Yue K. and Hickerson C. Ontologies and shape grammars: communication between knowledge-based and generative systems. In: Design Computing and Cognition '08, Springer Netherlands:23-40, 2008.

[14] Guarino, N. Semantic matching: Formal ontological distinctions for information organization, extraction, and integration. In: Information Extraction, A Multidisciplinary Approach to an Emerging Information Technology. Springer, Berlin:139-170, 1997.

[15] Guizzardi, G. On Ontology, ontologies, Conceptualizations, Modeling Languages, and (Meta) Models. In: O. Vasilecas, J. Edler, A. Caplinskas (eds.), Databases and Information Systems IV. IOS Press, Amsterdam:18-39, 2007

[16] Lima C. El-Diraby T. and Stephens J. Ontology-based optimization of knowledge management in e-construction. Journal of IT in Construction, 10:305-327, 2005.

[17] March S.T. and Smith G.F. Design and natural science research on information technology, Decision Support Systems, 15(4):251-266, 1995.