Towards a Construction Site Control System – Task Management in Construction Operations and Intralogistics

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Abstract –
The operation of automated construction equipment and autonomous construction robots depends on contextual information regarding the job to be carried out. Therefore, robots as well as equipment require a task-based construction site control system. Such a system also provides some advantages for construction managers. However, some prerequisites must be met prior to implementation. This paper positions the construction site control system concept in the current and future task management on construction sites and compares approaches from autonomous intralogistics with those of the construction sector. The paper then examines the required functionality of a construction site control system in detail and closes with the demonstration of an exemplary construction site control system (CS²).

Keywords –
Construction Site; Control System; Task Management; Construction Robotics

1 Introduction

Standardized processes and the application of autonomous construction equipment are innovative, high-performing and versatile approaches and represent the key elements in the digitalization of the construction site. Autonomously operating equipment implies the need to efficiently assign explicit tasks to such equipment. However, task assignment on construction sites is currently hardly automated. In most cases the whole communication is verbal and informal. In order to meet the growing demand for automated task assignment, the concept of a control system can be adapted from other industries. A control system provides equipment with significant data and tasks before and during operations. The aim of such a system is to manage operations efficiently, to detect disturbance variables at an early stage and thus to realize a smooth, excellent construction process. Additionally, a control system infrastructure enables the exchange of environmental information between autonomous equipment, which simultaneously forms a uniform data basis for cooperative operations. In addition to the necessity for increasingly automated equipment operation, there are a number of positive effects on the management of construction processes. Coordination efforts for reoccurring tasks and misunderstandings when passing on tasks between site manager, foreman and vehicle driver are eliminated with a CS². Furthermore, job results are automatically reported from the autonomous equipment to the CS², reliably documented, and made accessible to authorized users. Site managers and foremen can thus focus on managing inevitable, unforeseeable changes. In the future, the meta-data generated during the processing and reporting of tasks can be used for project control and enable process mining approaches on the construction site.

2 Research Method and Structure

Motivated by the vision above, the overarching research question of this paper is: *How does an applicable and sustainable control system concept for the automated construction site look like?*

In order to approach this research question, expert interviews with various construction stakeholders and equipment manufacturers have been carried out. They form the basis for the process analysis described below and the assessment of applicability. Subsequently, an interdisciplinary expert workshop on the understanding and functionality of a CS² was conducted as part of a research project. Additionally, literature on task management and control systems applied on construction sites was systematically reviewed to classify existing solutions. In order to sustainably address future fields of action in autonomous construction, other, more automated, sectors were also consulted. With intralogistics, a suitable industry was found in which autonomous transport systems are already integrated into the warehousing process. The comparison of task management in both industries provides structure for defining and conceptualizing a CS² and, moreover, an established template for implementation. Finally, parts of the template were implemented in a small case study, to demonstrate practicability.

3 State of the Art

This section covers the state of the art regarding the research matter and is divided in four parts. First, some fundamental concepts are defined in this section to familiarize with the topic and create a universal understanding. Second, the current task management process and state of control systems on construction sites based on expert interviews is depicted. Subsequently, a systematic literature review depicts the current state of research regarding task management and control systems in construction. Finally, the fourth section covers an excursus to the advanced control systems of autonomous intralogistics.

3.1 Fundamentals

It is important to clarify the two fundamental concepts of task management and control systems before going into more detail.

First, task management is defined as the process of managing tasks, specifically planning, testing, tracking, and reporting, in order to accomplish a collective or individual goal [1]. Adherent to this definition, it composes an element of project and process management [2]. Second, a control system can be defined as a "system that can command, direct or regulate itself or another system to achieve a certain goal" [3]. More specifically in the ISA 95 [4] automation pyramid, industrial control systems are divided into 5 levels, from production process (Lvl. 0) to business planning and logistics (Lvl. 4). The scope of control systems regarded in this paper spans from level 2: Monitoring and Supervision to level 3: Manufacturing Operations and Management. Typical systems for these levels are Supervisory Control and Data Acquisition (SCADA) for level 2 and Manufacturing Execution System (MES) for level 3.

3.2 Sate of Practice

Before going deeper into the above defined theoretical concepts, the current state of task management and control systems on construction sites is reviewed. Therefore, expert interviews with various stakeholders of the construction industry have been carried out.

Task management on today's construction site can be divided into three levels: project management, work instruction and execution. Today, the information exchange between these levels is based on direct, verbal dialogs. At the project management level, the site manager translates the general project data (e.g. timetables, plans) into concrete instructions for action and passes them on to the foreman (see Fig. 2).

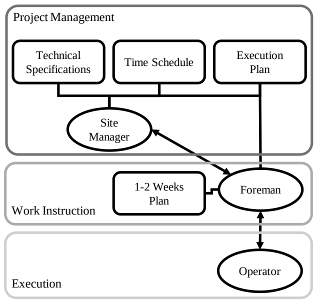

Figure 2. Task management on today's construction sites

The foreman, in turn, uses this data to create a one- to two-week plan and passes on the practical instructions verbally to the equipment operators. The equipment operators as well as the foreman keep monitoring the progress on the task and verbally report any deviations or task completion to the site manager. As this task management process is mainly verbal and unstructured, it depends heavily on the involved persons. Digital tools are hardly used in this context. Technical challenges are the standardized description of tasks, transparent, open interfaces and ongoing digitalization as well as automation. Introduction and training of the necessary processual and technological changes is the main non-technical challenge in this context. However, machine control vendors today offer systems to automatically transfer digital terrain models (DTM) to automated earth-moving machines [5]. These can be interpreted as early forms of control systems. More automated scenarios are still a field of research.

3.3 State of Research

In order to get an overview of current research on task management and control systems in construction, a systematic literature review has been conducted. The results have been classified according to their contributions to the topic. The search strategy for the systematic literature review is shown in Figure 3.

AND

	Aspects		
	Activity	Object	Environment
Synonyms (OR)	Task Management	Control System	Construction Site
	Operations Management	Guidance System	
	Task Monitoring	Operating System	
	Task Supervision	Execution System	
	Task Reporting	Fleet Management System	
	Task Planning		

Figure 3: Search strategy for the literature review

The keywords were searched for in the Scopus database with aspects being combined through the Boolean "AND" operator and synonyms being differentiated by the "OR" operator. A number of 94 literature sources was initially obtained. For filtering out relevant sources, first the titles (43 sources) and then the abstracts (22 sources) have been examined regarding their topical relevance. The identified literature either motivates the design and implementation of a CS² (3.3.1), sets requirements on such a system (3.3.2) or presents a prototype control system (3.3.3).

3.3.1 CS² Motivation

The need for a CS² is subject of two main groups of publications: construction planning and construction robotics literature.

In construction planning, better project operating systems are expected to increase productivity by controlling equipment, machinery, and processes in complex situations automatically [6]. Therefore, researchers work on integrating established task planning techniques like Building Information Modeling (BIM) and the lean construction Last Planner System (LPS). They find that "software support is not treated thoroughly" [7]. In this context Cai et al. [8] identify state of technology gaps between academic research and products, products and on-site application as well as the construction and robotics industry. In order to foster the on-site take-up of construction automation and robotics, they propose the joint development of robots and automated construction systems [8]. A CS² is a viable instance in this context.

The same need for integrating process automation efforts and robot development can be observed in construction robotics literature. Meschini et al. [9] stress the need to integrate construction planning and robot task planning platforms in order to derive robot tasks from construction information systems. Other sources, like Seo et al. [10], Ha et al. [11] and Kim et al. [12], develop single-task construction robots and thereby identify a lack of task planning systems, capable of equipping the construction robot with the necessary job information to cope with the task at hand. While, integrating the development of a task management system in the development of a single-task construction robot is state-of-the-art, Melenbrink et al. [13] envision a future system that is capable of coordinating among heterogenous machines performing many different tasks. They find that coordinating operations between different robot systems has been largely neglected in research. Gharbia et al. [14] support this claim by stating that only a few papers propose an integrated robotized construction site, while most of the papers studied single construction tasks. Research into the design for automation is essential to create integrated systems of on-site robotics, capable of transferring the digital design data directly to operations [14]. Ha et al. [11] states similar aspects to achieve cooperative operations of unmanned platforms in earthmoving. Vahdatikhaki et al. [15] stress that such systems could help achieve potentials in collaborative and post-mortem learning, leading to continuous improvement in construction project performance.

Above mentioned, multiple needs for a CS² motivate the conceptualization of such a system in this paper. The next section gives an overview of requirements towards the system under development.

3.3.2 Requirements on a CS²

Literature lists manifold requirements towards a CS². The main requirements are enlisted below with a short description from literature.

1. Generate standardized tasks automatically

A CS² should be capable of deriving standardized tasks automatically from planning data. Bock and Linner [16] emphasize that even today the construction task has to be split up in a multitude of subtasks that are complicated to coordinate. Dallasega et al. [16] also find, that a main shortcoming of current construction planning concerns, the lack of detailed modelling of the execution process in terms of workflow, dependencies or locations. Schimanski et al. [7] therefore propose the Should-can-will-did (SCWD) scheduling logic consisting of five steps with increasing level of detail. Complementary, Sacks et al. [18] see the generation of construction tasks as one functionality of BIM.

2. Integrate machines and robots

Ha et al. [11] require a CS² to allocate subtasks among several (automated) platforms, perform a shared task in association with other platforms, manage and prioritize events, to cooperatively handle more sophisticated tasks with higher efficiency. Melenbrink et al. [13], Gharbia et al. [14], Seo et al. [10] and Kim et al. [12] need a CS² to be capable of equipping construction robots with the necessary job information, as a basis for robot operations (e.g. trajectory planning, navigation, etc.) and handle the robot's sensor data backflow into overarching project management and documentation systems. In this context, Part four of the ISO 15143 facilitates the exchange of site topology data between earthmoving machine control systems and proposes the exchange of job description and process data between machines, vendor integration systems and a central site control system [19]. Thereby, a machine-readable representation of the surrounding world, similar to building representations through BIM or point clouds in high-rise construction is provided [12,20].

3. Facilitate on-site coordination and communication

Antwi-Afari et al. [21] see critical success factors for construction projects adaptable to the CS² in "coordination and planning of construction works" and "collaboration of simultaneous access of construction work". Akpabio et al. [22] formulate several software requirements towards a construction management software, among them “allow for efficient communication” and “give a platform to effectively collaborate and team up to achieve stated goals”. Tezel and Aziz [23] state that a project production control system should be directed towards mobile systems and enable work units to compare what is actually planned and what is actually done. They propose virtual visual control boards, similar to Kanban boards. According to Dallasega et al. [17] a CS² should support a frequent monitoring of the work on-site and base the scheduling of the execution process on it. Oskuie et al. [24] add the monitoring of construction processes, and real-time evaluation of productivity, as BIM-related functions.

4. Support overall project management

The connection of the CS² to more general project management tools is subject to requirements by Akpabio et al. [22] and Dallasega et al. [17]. Sacks et al. [18] stress the online communication of product and process information towards BIM. Furthermore, Antwi-Afari et al. [21] see improved construction project performance and quality as well as integrating project documentation/bid preparation as critical success factors incorporated by a CS².

5. Feature the supply chain

To support construction execution control, according to Dallasega et al. [17] a CS² should not only be focused on construction work but it should also consider the supply chain. In more detail, Akpabio et al. [22] demand that materials on site should be effectively managed to reduce wastage and improve efficiency.

6. Adapt to changes

Rouhana et al. [25] investigate the emergence of ‘new tasks’, which should be manageable through a CS², in construction planning. They divide the inevitable causes behind the emergence of ‘new tasks’ into three categories: the realm of planning, ongoing construction, and uncertainties. Ghasemi Poor Sabet et al. [6] add “untracked planning/scheduling (poor project control)” as a potential root of poor productivity and list “updating and adjustable planning for microplans in case of overlooked requirements and troubleshooting” as a productivity fundamental.

These six requirements along with the results of the expert workshop on a CS² form the basis for the assessment of existing control system prototypes in the next section and the concept development of the CS² described in section 4.

3.3.3 Control System Prototypes

In the existing literature, nine control system prototypes were identified. In this section, they are briefly introduced and assessed regarding the requirements enlisted in section 3.3.2. Akpabio et al. [22] present requirements on and the development of a web-based construction management software. It consists of a task, document, materials handling, budget and messages module. Abdelmegid et al. [26] integrate simulation modeling with the LPS. They utilize information available in the LPS, especially the phase schedule, to define activities and their relationships. An exemplary activity list for the renovation and expansion of a public stadium is demonstrated. Future research can include applying the framework on the complete operations of a construction project in realtime. Corucci et al. [27] present a three-level control system for an autonomous demolition robot. The system consists of a high-level planner identifying subtasks and robot base positions, a medium-level planner defining demolition style and contact points, as well as a low-level planner computing a collision-free trajectory. On top of the control system, they propose a convenient representation of the surrounding world, in order for the robot to be situational aware. Thereby, they solve the trade-off between a representation rich enough for reasoning but simple enough for real-time processing through down-sampling of 3D sparse point clouds and semantical identification of objects. Sriprasert et al. [28] differ between three levels of planning: project or product level, process or operation level, and assignment level. They propose a new construction planning technique called “Multi-constraint planning”. The technique is supported by an information management system: Lean Enterprise Web-based Information System for Construction (LEWIS). It derives process data from interfaces to project planning and scheduling software. Schimanski et al. [7] introduce a conceptual model for BIM-LPS integration. The original LPS model is extended by the BIM part which serves both as input and output visualization instrument. Additionally, a (digital) Kanban system is proposed, to optimize flow and improve visual management. They also stress the positive pull effect of the Kanban method, enabling higher productivity. Seo et al. [10] develop an intelligent excavation system along with an excavation task planner. Therefore, they use an earthwork design model and project management information systems. Vasilyev et al. [29] integrate QR-code exchange data technologies into a construction control system based on BIM, providing availability of data, security and mutual cooperation on a construction site. Kim et al. [20] investigate the task planning process of an autonomous excavator. They assume the availability of a digital terrain model (DTM) and its compatibility with the task planning system. Kim et al. [12] present a robot task planning system that can generate behaviors of robots based on the project information from BIM and the construction schedule. They use an IFC-SDF converter to link BIM and ROS for a wall-painting robot. The next version of their system should incorporate a diverse list of construction tasks and mobile robots that can be simulated in the created virtual environment. Vahdatikhaki et al. [15] combine location-based guidance systems and safety management methods in a multi-agent system in order to improve equipment operations, safety and equipment management. Table 1 assesses the introduced control system prototypes regarding the requirements from section 3.3.2.

Table 1. Control system prototypes from literature assessed against requirements on a CS²

Prototype	R1	R2	R3	R4	R5	R6
Akpabio			x	x	x	x
Abdelmegid	x		x	x	x	x
Corucci	x	x				
Sriprasert	x		x	x	x	
Schimanski			x	x	x	x
Seo	x	x				
Vasilyev			x	x	x	
Kim_20	x	x			x	
Kim_21	x	x				
Vahdatikhaki	x	x	x	x		

In summary, current control system prototypes either focus on supplying a robot or automated equipment with machine-readable, standardized tasks or focus on coordination and communication on a project management level. None of the existing prototypes combine task management on the equipment level with the project management level.

3.4 State of Practice in Intralogistics

As the assessment of the control system prototypes in Table 1 has shown, very few control systems from the construction sector fulfill the multiple requirements from equipment automation and project management. In order to prepare the CS² concept development in the next section, this subsection looks into the more advanced control systems of the autonomous intralogistics sector.

Intralogistics can be analogously to current task management on construction sites (see 3.2) divided into three levels. One difference is that instead of the first level being project management, warehouse management preceedes the work instruction and execution levels in intralogistics. The automated information exchange between these levels is based on digital interfaces standardized in industry standards like the VDA 5050 [30]. At the warehouse management level, a warehouse manager configures the warehouse management system, which in turn transfers data to a control system. The control system creates tasks from the data received and transmits them to the autonomous mobile robots (AMR) or automated guided vehicle (AGV). After successful execution of the task, it is acknowledged by the AMR/AGV. In addition to task information necessary for its execution, the AMR/AGV sends and receives information about the operational environment to a shared environment model available to each robot in the network. Figure 4 summarizes the task management environment in intralogistics.

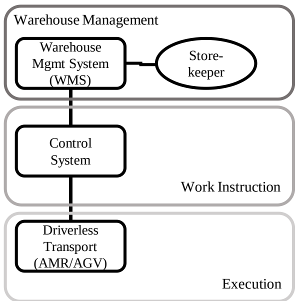

Figure 4: Task management in intralogistics

4 Construction Site Control System (CS²)

Picking up on the excurse to autonomous intralogistics, the formulated requirements and the motivation for a CS², this section proposes an applicable and sustainable control system concept for the automated construction site of the future. Therefore, the CS² is located in the task management environment of future construction sites. Subsequently, the functional concept of the CS² is examined in detail, before the subsection closes with an exemplary implementation of the CS².

The following concepts are founded on the results of an expert workshop on task management and control systems in the construction sector as part of an interdisciplinary research project on the digitalization of the construction site as well as the findings of expert interviews and the literature review presented in the previous section.

In the future, task management on the construction site can still be divided into the levels of project management, work instructions and execution. Nonetheless, the automated information exchange between the three levels is based on digital interfaces. In addition, there is a verbal information exchange between the site manager and the foreman for task management issues, like changes or emerging tasks, as well as the overall project management. Tasks are generated from the job description of the object under construction. More specifically, the information sources will be information rich building information models (e.g. 5D BIM) and project management simulation systems (e.g. Discrete Event Simulation). The CS² is responsible for task management and the digital supply of the autonomous equipment with the information required for task execution. At the work instruction level, the foreman can interact with the CS² to manage tasks, similar to a task backlog or Kanban board. Figure 5 shows the task management environment of future construction sites with the CS².

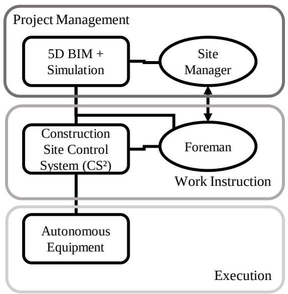

Figure 5: Task management on future construction sites

4.1 CS² - Functional Concept

The CS² connects the project management and execution levels, as shown in Figure 5. The individual functions and their interactions are broken down in Figure 6.

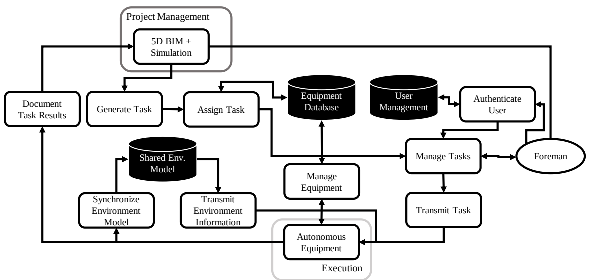

Figure 6: Functional concept of the CS²

First, a task is generated from the project data stored in building information models and project management simulation systems. The construction task is segmented into subtasks suitable for the specific piece of equipment (Generate Task), whereby the task design and the added data differ depending on the equipment. In order to facilitate a project management, an assignment to the job description and an execution period should be specified with each task. After the task has been created, it is assigned to a piece of equipment that is available in the execution period (Manage Equipment) and that matches the task requirements (Assign Task). The foreman, as the main user of the CS², can manage and manually edit the orders (Manage Tasks) after authentication (Authenticate User). The task is then transmitted to the autonomous equipment, including all the necessary data (Transmit Task). Likewise, relevant environmental information from a shared environmental model is sent with the task to the equipment (Transmit Environment Information). The sensor data of the autonomous equipment collected during task execution synchronizes a shared environment model (Synchronize Environment Model). After successful execution of the task, the work result is documented and transferred to the project management level (Document Task Results).

Through this functional structure, the CS² covers all requirements from section 3.3.2 (see Table 2). Standardized tasks are automatically generated from BIM and other sources of planning data (R1). These tasks are broken-down and transmitted to automated equipment and robots (R2). Through a Kanban board like interface for task management, the on-site coordination and communication is supported (R3). Results of the executed tasks are fed back into overarching project management solutions, like BIM (R4). With this interface to BIM and other planning data, the supply chain can be incorporated in task generation or work results can be considered in supply chain controlling (R5). As the foreman is a crucial part of the CS² the whole system can react to changes by managing or creating tasks, fostering on-site flexibility (R6).

Table 2. CS² assessed against the requirements from section 3.3.2

Prototype	R1	R2	R3	R4	R5	R6
CS²	x	x	x	x	x	x

4.2 Exemplary Implementation

The introduced functional concept of the CS² is partly implemented to validate the concept. Autonomous machine integration and a shared environmental model are not implemented in this case study. In this specific case study, which can only be briefly addressed here, the focus is on earthwork (e.g. digging, grading, compaction) and transport tasks (e.g. bulk material, unit loads).

The exemplary system can create tasks either through importing a standardized job description (German GAEB-xml-format) or manually through the task creation function. Attributes for specific tasks (e.g. digging or transporting) are predefined and can be automatically or manually filled with the respective information. After a task is created, the task is allocated to an equipment. Therefore, the machine database "Equipment Information System" (EIS) and a fleet management platform are connected to the web-service through APIs. In these systems, equipment can be administrated and managed. Figure 9 shows the system architecture, which is based on the client-server pattern, with the web browser taking on the role of the client. The client sends a request to the server, which then responds and transmits the desired information. At the core of the architecture is the server with the associated database. In addition, two services (equipment information and fleet management) are currently integrated, however further services can be seamlessly integrated if necessary. During operations, the foreman can move the task through the states (backlog, in progress, on hold, in review, done) on the Kanban board (Fig. 9) or, in a more automated scenario, the robot automatically feeds back his current state of work. The foreman can always intervene and stop, review, comment or reopen tasks, staying in full control of construction.

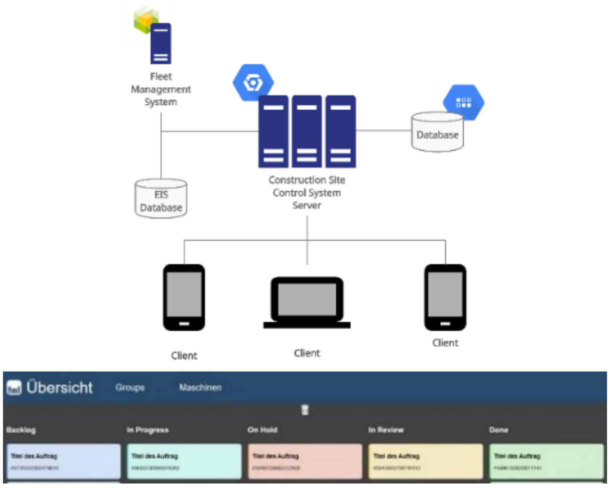

Figure 9: CS² system architecture and Kanban board with task states

5 Conclusion & Outlook

A CS² is necessary for autonomous equipment and brings numerous advantages in construction robotics as well as construction planning and management. However, some functional requirements must be met for a successful implementation. This paper classifies the CS² in the current and future management of tasks on the construction site and enhances existing approaches from a systematic literature review in construction research with those of autonomous intralogistics. The paper then goes into detail about the necessary functionality and demonstrates a partial implementation of the CS² to foster the development of a sustainable control system for the construction site and validate applicability.

This paper thus forms the basis for the implementation of a complete CS² in the near future. Under way is the complete demonstration of the CS² with the integration of autonomous equipment. Additionally, the enclosed literature review reveals a trend towards single-task construction robots. On the one hand, future research should therefore focus on coordinating mixed robot fleets in physical challenging environments with varying tasks. On the other hand, robotics should also investigate the development of multi-functional robots that can be configured for several tasks in a general construction workflow (e.g. inner-city construction).

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