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SIMULATION OF AUTOMATED CONSTRUCTION USING WIRE ROBOTS

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ABSTRACT

Despite a high potential to improve the productivity, quality and safety and also to reduce costs, automated technologies are not widely spread in the construction sector. This paper presents a simulation-based approach to analyze the technical and economic feasibility of wire robots for automated construction in future investigations. Masonry buildings are considered as an appropriate application case due to repetitive construction procedures and high demands concerning accuracy of construction. A simulation model representing the fundamental mechanics of a wire robot is created. Special focus lies on creating collision-free motion profiles which can be exported to the robot control system. BIM models can be used to set-up the simulation model and to prepare the required input data. Following a modular structure, the model can be applied with different purposes in the exploration of the approach. The construction of a one-story masonry building serves as case study proving the concept's functionality.

1 INTRODUCTION

In mechanical engineering branches like automobile and consumer goods fabrication, the automation of processes has reached a high level. Development and production processes have been established towards standards, tools and interfaces that allow for the application of robots and automated production lines. Nowadays, even individualized products are aspired in the upcoming Industry 4.0 approach. While automated techniques are widely spread in the manufacturing industry, construction work is mainly conducted in a conventional manner. In general, construction projects are characterized by a high number of individual boundary conditions. Except for the prefabrication of building components, automated construction techniques are rarely applied. With regard to the typical processes of construction projects, the size of a building lot makes the application of robots extremely demanding. Thus, the integration of robots in the construction of buildings has always been challenging.

Due to the potential to save working time while increasing work quality, automated construction by using robots is worth being investigated. Still, many past initiatives did not succeed, most because of two major conditions (Cousineau and Miura 1998):

- As a masonry building is a large product, no conventional robot technology is known to cover it entirely. Accordingly, the robot base needs to move, which is usually avoided for industrial robots due to cost and robustness reasons.
- Masonry buildings are usually unique projects. In conventional planning, this is associated with drawings that are not prepared for automated processing and production planning.

The latter has dramatically changed with the emergence of Building Information Modeling (BIM) in the last decades. A detailed overview on BIM and its benefits for the construction industry can be found in Borrmann et al. (2015). Automatization techniques may now benefit from detailed and precise information provided in BIM models. Thus, the ongoing development of BIM can be regarded as key motivation for examining the application of robots for automated construction. In this regard, repetitive work patterns are particularly suitable for automatization. Considering the construction of domestic buildings, the creation of masonry buildings represents a practicable example. The lack of large-scale robots has also recently been resolved by the demonstration of huge wire robots. This novel robot concept created by a set of computerized winches that are connected with the payload allows building robots that can easily cover the base area of a masonry building.

However, challenges evolving with the application of robots need to be investigated. These can be divided into technical and economic challenges: For example, in the path planning, collisions between robot parts and other elements need to be avoided. Furthermore, the robot workspace needs to be adjusted to the dimensions of the created building. Stiffness and load calculations are necessary to compute and optimize accuracy, while the installed actuator power determines the required time for the single robot operations. Finally, the economic efficiency of the concept needs to be proven based upon these findings. An evaluation of the developed concept can be achieved by the help of process simulation. Following this approach, conducting time-consuming and cost-intensive practical tests at early project stages can be avoided. In this paper a concept for the simulation-based validation of wired robots for automated construction is presented.

The paper is structured as follows: Section 2 gives a brief overview concerning the background of the general idea. Special focus lies on recent developments concerning robot application for construction – especially wire robots, process simulation for construction as well as processing information from BIM models. Section 3 contains basic information concerning wire robot modeling. In section 4, the developed framework is presented in more detail. A case study conducted with the discrete event simulation can be found in the last section.

2 BACKGROUND

According to AbouRizk (2010), construction simulation comprises developing and experimenting with computer-based representations of construction systems to understand their underlying behavior. Focusing on the construction sector, the application of simulation techniques has experienced significant growth over the last decades. AbouRizk (2010) states that simulation plays a central role in a modern vision of automated project planning and control. Several projects focus on the application of simulation for increasing the efficiency of construction management and control. Research projects focus on various sectors of the construction industry. Alzraiee et al. (2015) developed a method that realistically estimates project duration, productivity, and cost while considering a project's dynamic and uncertain boundary conditions. By using a hybrid simulation platform, realistic performance estimates were achieved. Furthermore, the understanding of the project's dynamic was improved. Changing project conditions in highway construction represented the focus of the model proposed by Ozcan-Deniz and Zhu (2016). Objectives included time, cost and environmental impact of the examined construction method. After having conducted a case study, the model was found effective in selecting the most feasible construction method. Site layout planning and supply chain management represent a common application case for simulation. For example, a simulation-based approach to model the size of temporary facilities can be found in RazaviAlavi and AbouRizk (2015). The main intention of this model is quantitatively analyzing the impact of facility size on project time and cost. El-Rayes and Khalafallah (2005) present the development of an expanded site layout planning model that is capable of simultaneously maximizing construction safety and minimizing the travel cost of resources on site. Zhou et al. (2009) integrated general purpose simulation for modelling space, logistics and resource dynamics. Genetic algorithms were applied for optimizing the layout of a tunneling jobsite which is influenced by various constraints and rules. By applying process simulation, Scheffer et al. (2014) enable a transparent evaluation of possible logistic strategies or project setups for tunneling jobsites.

The current development and application of BIM can be seen as key motivation for investigating automated construction techniques. In the most desirable case, a BIM model contains precise information on the building geometry and construction method. Hence, in the context of automatization, the model can be used as a digital construction plan. In recent decades, several research projects focused on the use of BIM for prefabrication and automatization. For example, Buswell et al. (2008) state that BIM is likely to become a key element for information delivery in the context of Rapid Manufacturing principles. An exploration of a new BIM-based automation construction system (BIMAC) can be found in Ding et al. (2014). Based on the technique of Additive Manufacturing (AM) techniques, BIM model layer data are converted to specific Computerized Numerical Control (CNC) codes enabling an automated manufacturing of building components.

BIM-based simulation mainly includes areas of sustainability analysis for design factors such as day-lighting, climate control, and energy usage (Issa et al. 2009). However, several findings concerning BIM as an input source for process simulation have been made. Wang et al. (2012) presented the idea to automate the extraction of building information that can be subsequently used in evacuation simulations. A BIM-based approach to model and simulate spatial requirements of construction activities was proposed by Marx and König (2013). Scherer and Ismail (2011) developed a process-based discrete-event simulation library for construction project planning. In this context, BIM is used for the automated generation of detailed project schedules. The results of the literature research prove the wide range of possible applications of BIM. Due to a high potential for increasing efficiency, BIM models can be regarded as a data source of the simulation model. The following section contains a brief overview concerning recent concepts to use robots in the field of construction. Additionally, projects combing BIM and robots are presented.

Only a few projects focus on the application of robots for construction tasks. Choi et al. (2005) present a construction robot that can be used for window glass mounting or panel fixing. Chu et al. (2013) introduced a robot-based construction automation system for high-rise buildings and describe its application for robotic beam assembly. Dolgui and Borangiu (2012) describe an open control architecture for a mobile platform with inclination control moving in construction sites and carrying a robotic arm for bricklaying services. Besides the possible integration of the BIM method in the context of automated construction techniques, several researches focus on combining BIM with robot applications. Vähä at el. (2013) conducted a survey on potential sensor technologies and robotics use for construction projects. They distinguished between manufacturing prefabricated components and assembly work. In this context, BIM can be used for guiding the assembly work by providing component reference values and other assembly related information. Lee et al. (2009) developed a robotic crane system deploying a laser-technology-based lifting-path tracking system which requires the application of BIM. The tracking system receives an identifier for material to lift from a central database that stores a construction schedule and a 3D BIM model.

The concept of wire robots was developed in 1985 by Landsberger (Landsberger and Sheridan 1985). Extensive theoretical work was done since then, while the industrial application of the technology was focused only in the last few years. Wire robots are intrinsically modular machines (see Figure 1). They are composed of identical winches that share the weight of the payload and the power needed to move the robot. Usually, the winches are attached to the ground and coil the wire. The wires are led through a series of pulleys mounted to a supporting frame and are attached to a platform carrying the payload. The winches are controlled by a computer that runs an advanced control system. Modern control approaches use model-based feedback control to ensure a proper tension in the cables and a precise guidance on the payload. As cables can be extremely long – dozens of meters are easily possible – very large robots can be built. A detailed introduction on the recent state-of-the-art for wire robots is given in Bruckmann et al. (2016).

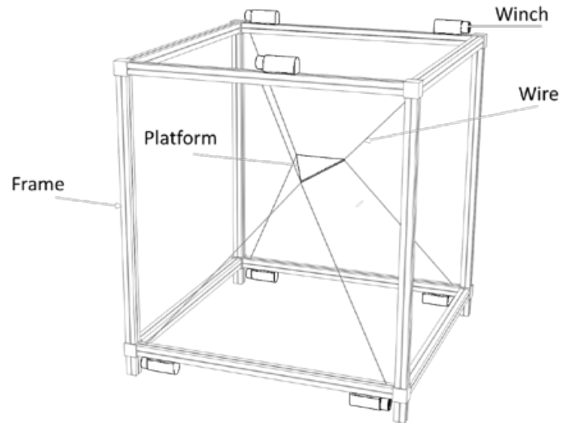

Figure 1: Wire robot principle based on Bruckmann et al. (2008).

3 WIRE ROBOT MODELING

As cables are flexible, they can only pull but never push. Accordingly, to fix the pose of the platform with n degrees-of-freedom, at least m cables are needed, i.e. $m \geq n + 1$. This type of cable robot is called a fully tensed wire robot (see Figure 2).

This creates actuation redundancy that allows to actively vary the tension in the system: If for a given pose one cable increases the tension, the others can react with an appropriate force and establish the force equilibrium again. Additionally, this allows to fully constrain the payload and to suppress vibrations effectively. Noteworthy, cables coming "from below" the platform may be an issue. Therefore, moveable pulleys are advised.

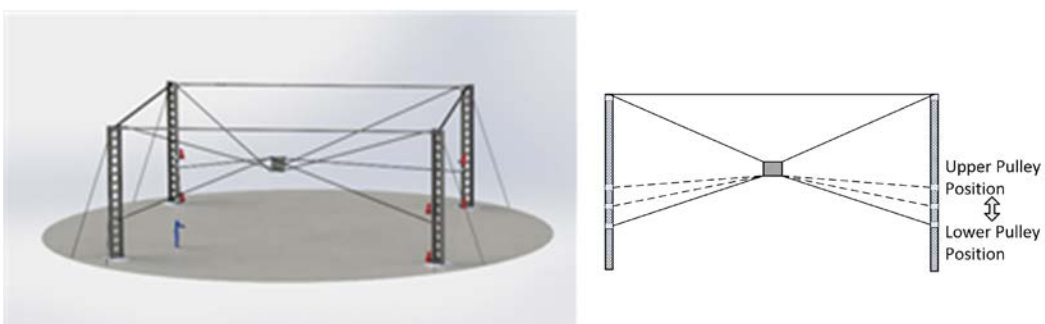

Figure 2: Fully tensed wire robot (left) and variable pulley position (right).

The force equilibrium for wire robots is defined as follows (see Figure 2): Assuming vectors $l_\mu; \mu = 1, \ldots, m$ from the platform to the pulleys, cable forces (or tensions) f_μ and a vector of platform forces and torques w (including inertia and gravity), it holds:

$$\underbrace{\begin{bmatrix} \nu_1 & \cdots & \nu_m \\ p_1 \times \nu_1 & \cdots & p_m \times \nu_m \end{bmatrix}}_{A^T} \underbrace{\begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix}}_{f} + \underbrace{\begin{bmatrix} f_p \\ \tau_p \end{bmatrix}}_{w} = 0, \quad (1)$$

$$\text{where } \nu_\mu = \frac{l_\mu}{\|l_\mu\|_2} \quad (2)$$

As this is an underdetermined system of equation (m unknowns, n equations and $m \geq n + 1$), the changeability of the tension level is obvious. It is a demanding task for the control system to determine the appropriate set of values for the cable tensions in real-time (Gouttefarde et al. 2015).

For first experiments, a fully tensed robot is proposed due to its superior mechanical properties. Primarily, its higher stiffness is desirable: For moving and installing bricks, a certain level of precision is required. Since the cables, the drivetrains of the winches and even the controller show an elastic behavior (with changing elasticities over time), the stiffness of the platform might be an issue for accuracy and therefore needs to be carefully investigated and optimized. Otherwise, disturbances such as wind forces can lead to insufficiently accurate results. Since usually cables are usually employed below the moving platform, collisions might be an issue. Actively movable pulleys are suggested to avoid this problem which gradually increases with the construction progress. The left side of Figure 2 shows a simplified side view of the fully-tensioned robot and possible positions of the movable pulleys.

4 OVERALL FRAMEWORK

Analyzing wire robot use for automated construction requires a multi-disciplinary approach. Principles of construction technology and scheduling as well as jobsite conditions need to be combined with the fundamental laws of mechatronic system modeling. Furthermore, the approach needs to be evaluated concerning economic efficiency and safety. Figure 3 shows the overall structure of the chosen approach which is divided into different work packages: simulation, optimization and evaluation. In the following, a brief overview on the single work packages and their meaning concerning general project intention is given. As the project is at an early stage, this paper focuses on objectives and interaction of discrete event simulation and continuous simulation.

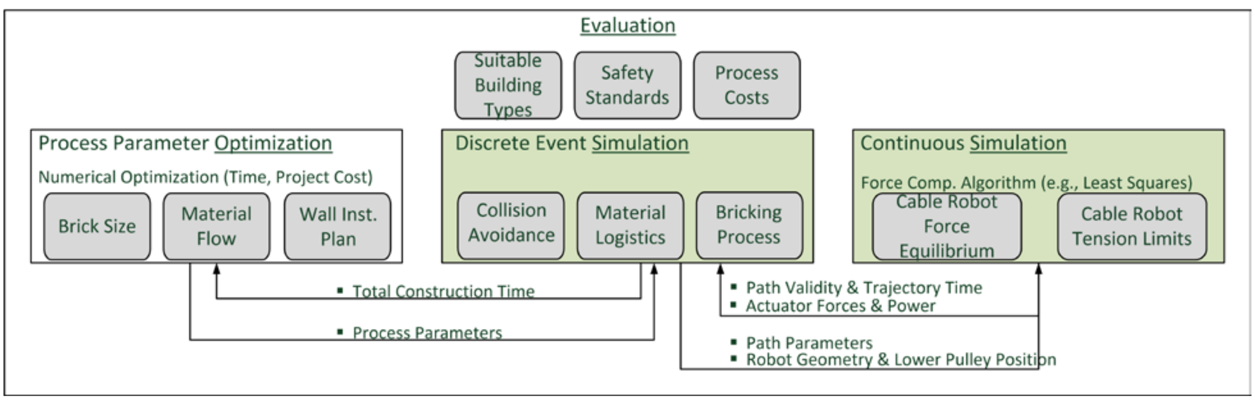

Figure 3: Proposed evaluation, optimization and simulation framework.

The feasibility of the robot operation represents a key factor for project success. In this regard, several technical performance requirements need to be fulfilled:

- The workspace may not be left during a required robot motion. For wire robots, this mainly implies the selection of the cable connection points on the platform, the frame dimensions and the (moveable) pulley positions (all summarized in the wire robot design) plus the needed actuator torque.
- Collisions between the robot and other elements on the jobsite need to be avoided at any time. This needs to be reflected by path planning and may need to move the pulleys during a motion.

The discrete event simulation mainly focuses on calculating collision-free paths. For this purpose, the bricking process needs to be represented in accordance with the chosen construction method. The results of the discrete event simulation serve as input for the continuous simulation. This application includes a computation algorithm covering force equilibrium and tension limits combined with a simplified dynamics model. The continuous simulation provides feedback concerning path validity especially focusing on resulting actuator forces and power as well as compliance with the robot workspace.

The results from the discrete event simulation represent the input for the process parameter optimization. In this process, different types of bricks are proposed and the parameters will be analyzed using the simulation model. The feedback is the total construction time. Following an iterative approach, an optimal brick size and a construction method will be found. The work packages to be addressed in the near future include optimizing the chosen layout concerning time and cost by referring to the simulation results. Boundary conditions like site layout and brick size could be varied and examined concerning their impact on project performance. To achieve practical relevance, the overall approach needs to be evaluated concerning suitable building types, economic aspects and work safety. According to the focus of this paper, the following sections describe the simulation-based work packages in more detail.

4.1 Discrete Simulation

Analyzing the feasibly of wire robot use for automated construction represents the main objective of this work. Special focus lies on calculating collision-free moving paths of the robot. To achieve reliable simulation results, both the robot geometry and the operation method need to be represented correctly. The BIM model of the project provides information concerning building geometry and material and thus, decisively influences the robot operation. With regard to reutilization, the simulation model can be used for different building projects provided that the BIM model is available. Robot and site layout (e.g., the position of the brick storage) are regarded as significant input parameters. Due to a modular, component-based structure the model can be easily adapted to different working conditions. Figure 4 shows the general structure of the simulation model.

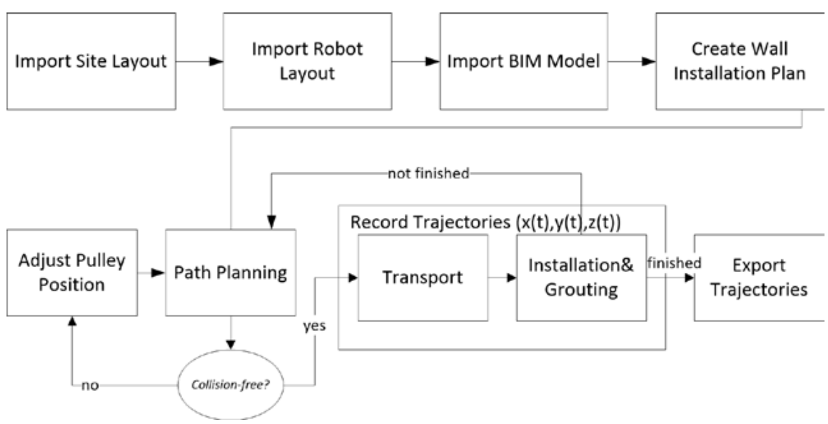

Figure 4: Discrete-event simulation concept.

Input data is derived from the site layout plan which also restricts the maximum size of the wire robot. The BIM model delivers information concerning building geometry and material. By using the neutral IFC format, restrictions concerning the applied modeling software do not apply. As most software tools only support modeling walls instead of modelling single bricks, a wall installation plan needs to be created. In this case, manufacturer specifications form the basis for developing such wall installation plans. Figure 5 shows a wall installation plan which is composed of different brick types. In this case, the original plan is modified and expanded by layers and steps to install the bricks.

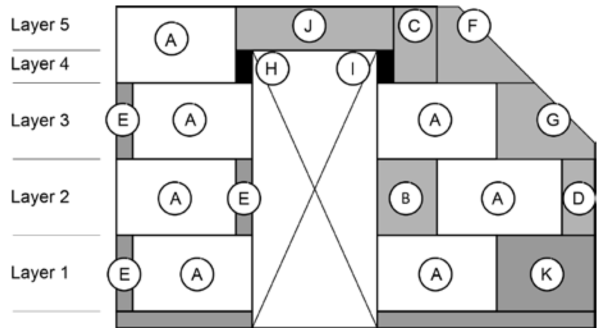

Figure 5: Wall installation plan with layers based on KS-PLUS Wandsystem GmbH (2014).

The described approach has been implemented using the commercial simulation software AnyLogic which offers state charts to model processes for discrete event simulation. Main objects of the simulation model are the wire robot, the workspace (determined by the position of the beams) and storage areas. The dimensions and positions of the implemented objects form the basis for calculating and recording collision-free moving paths. By exporting the resulting trajectories to the continuous simulation, the chosen robot movement speed can be tested concerning feasibility. Currently, the movement speed is chosen in accordance with common standards.

Focusing on robot operation, path generation and collision detection are of particular importance. For this reason, each brick is assigned a target position in (x, y, z)-direction which corresponds to its position in the wall installation plan. The single robot operation includes picking one brick from the storage and transporting it to its target position (see Figure 6). In a first step, the shortest route between the storage and the target position is determined. The movement of the robot starts while continuously checking for collisions with other elements on site. The position of all moving objects (especially the robot and wire position) is continuously updated. The distance between robot parts and other elements is of special importance. In case this value falls below a project-specific safety level, the path needs to be adjusted. In practice, supplying the robot with a LiDAR system would be helpful for measuring the distance to surrounding objects and safety reasons. There are two options of solving collision problems. One possibility is vertical movement of the robot in order to overcome the obstacle. In case of collisions between the lower wires and other objects, adjusting the position of the movable pulleys may represent a more effective solution. Both approaches are implemented in the model. The collision-free and project-specific moving path of the robot is documented as trajectories in the format $[x(t), y(t), z(t)]$. In the next step, the trajectories as well as pulley position are imported to the continuous simulation.

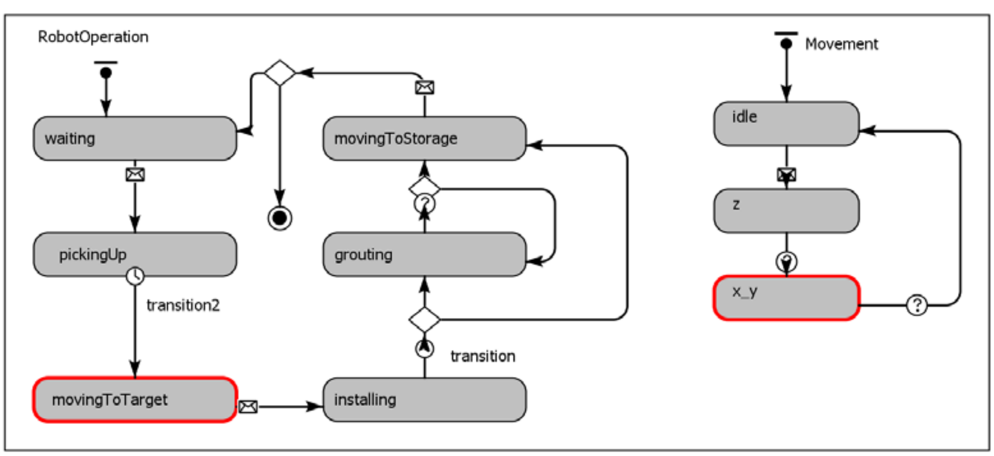

Figure 6: State charts representing robot operation and movement.

4.2 Continuous Simulation

The dynamics of the motion of the wire robots is analyzed by a continuous simulation (Figure 3). The simulation model is based on the force equilibrium introduced in (1) and (2). For a typical robot design with $m \geq n+1$, this describes an underdetermined system of equations. While this leaves the freedom to vary the tension in the system for a given pose within the workspace, tension force limits must be considered: On one hand, it must be ensured that all cables are at least under a tension $f_{\min}$ greater than zero to avoid slackness, i.e. $0 < f_{\min} \leq f_\mu \forall \mu = 1, \dots, m$. On the other hand, the cables have a breaking load and the actuators provide a maximum cable force, so an upper limit $f_{\max}$ needs to be defined, i.e. $f_\mu \leq f_{\max} \; \forall \mu = 1, \dots, m$. Additionally, for control purposes, it must be guaranteed that during the motion of the robot, continuous set cable forces are computed. Accordingly, the selected solutions must be continuous. It was proven by Verhoeven (2004) that a proper solution can be found by solving the constrained linear least-squares problem:

$$\text{minimize } g(f) = \|f\|_2 = \sqrt[2]{\sum_{\mu=1}^{m} f_\mu^2} = \sqrt[2]{f_1^2 + f_2^2 + \cdots + f_m^2}$$

$$\text{subject to } \underbrace{\begin{bmatrix} v_1 & \cdots & v_m \\ p_1 \times v_1 & \cdots & p_m \times v_m \end{bmatrix}}_{A^T} \underbrace{\begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix}}_{f} + \underbrace{\begin{bmatrix} f_p \\ \tau_p \end{bmatrix}}_{w} = 0 \text{ and } 0 < f_{\min} \leq f_\mu \leq f_{\max} \; \forall \mu = 1, \dots, m. \qquad (3)$$

While this is generally a well-understood problem, its solution under real time conditions for control may be demanding. Nonetheless, the approach is well-suited for simulations. As introduced, the loads w are determined by the gravity and inertia according to the Newton–Euler equations for the moving platform. Thus, the chosen velocity and acceleration profiles [*x(t), y(t), z(t)*] for the trajectory of the platform motion directly influence the required cable forces. As these cable forces are bounded according to (3) and only a limited actuator power can be provided, the computation of the minimum trajectory time for a given path again leads to an optimization problem. Its solution delivers the time needed for a given motion. If the required forces w cannot be balanced by the cable tensions, the desired path is not realizable and outside the robot workspace.

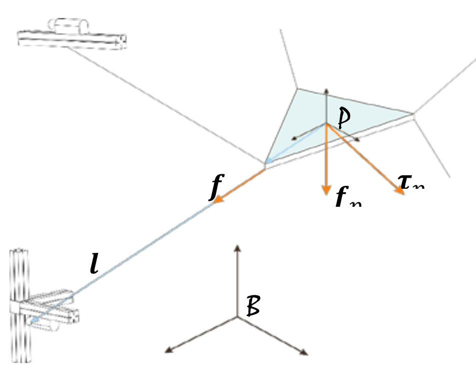

Figure 7: Force equilibrium at the moving platform based on Bruckmann et al. (2015).

5 CASE STUDY

In this case study, a possible scenario for using wire robots to create a masonry building will be explained. Due to the focus on the simulation model, several assumptions and simplifications are necessary. The presented case study is limited to the automated bricking process. Wire robot installation and demolition and their effect on conventionally performed processes are excluded from the analysis.

Concerning working precision, the influence of external factors (including forces, elasticities, inertia) is neglected. For example, it is assumed that the jobsite supply chain works properly. Required material is always available and the single bricks are delivered and stored according to the wall installation plan. To achieve a firm connection between the bricks, a specific mortar is applied on the horizontal joints. This work step is also performed by the robot and will be explored by further studies. Figure 8 shows two fictitious and simplified site layout plans – conventionally planned without and planned with wire robot. However, on the most job sites, cranes are used for different tasks. In later working steps, it needs to be investigated whether an additional crane is required. To prevent collisions with the wire robot, a crane would have to be arranged outside the wire robot working range.

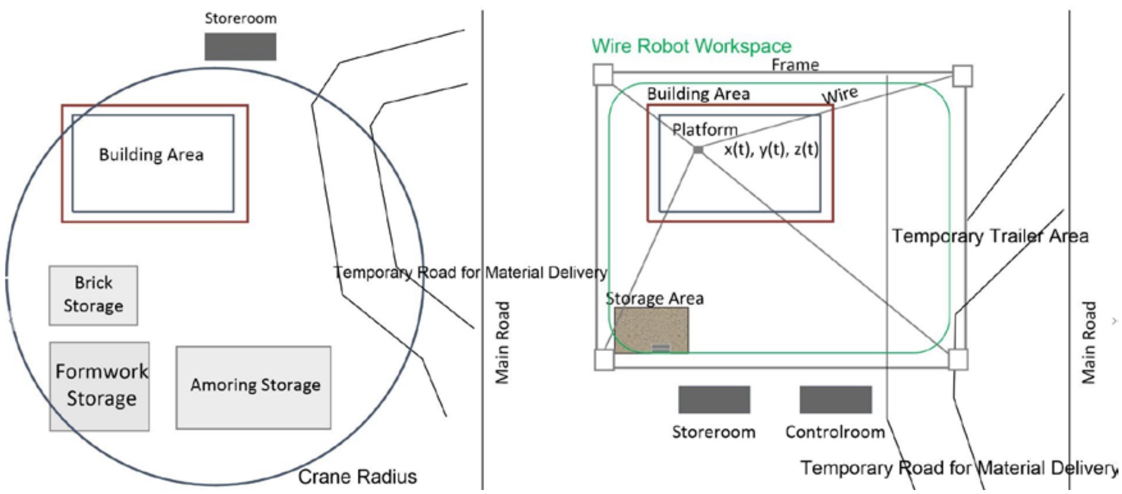

Figure 8: Exemplary building site equipment (without and with wire robot).

When comparing the two site layout plans, the most striking differences are the shape of the workspace and the position of the storage areas. Especially the rectangular shape of the robot workspace makes a new construction site facility necessary. The following issues need to be considered:

- The robot workspace needs to cover the whole building floor area.
- Storage areas must be enclosed by the working space of the robot.
- While the robot is working, no persons are allowed to work within its working space.

Table 1 shows the most influential input data of the case study. Except for the brick size, the parameters are based on technical experiments with wire robots. Robot and site setup correspond with the site layout plan shown in Figure 8.

Table 1: Parameters of the case study.

Parameter	**Value**
Total wall area	ca. 43.23 m²
Brick Size	1000 mm × 500 mm × 240 mm
Robot Layout (Measurements of the Frame)	16 m × 20 m × 10 m
Lower Pulley Position	5 m
Movement Speed of the Robot Platform	0.5 m/s
Pick up Brick	30 s
Brick Installation	30 s

The case study is limited to the creation of a single masonry wall (see Table 1). Figure 9 shows collision-free moving paths in *x-y*-direction, *x-z*-direction and *y-z*-direction as well as in 3D. Data presentation is limited to the installation process of four bricks (#11 - #14), while the 3D-representation shows the moving path for brick #11 and #12. In total, the automated wall assembly took about three hours. Being represented as cubic splines, resulting trajectories can be directly exported to the continuous simulation. The following work steps include proving the technical feasibility of the calculated paths.

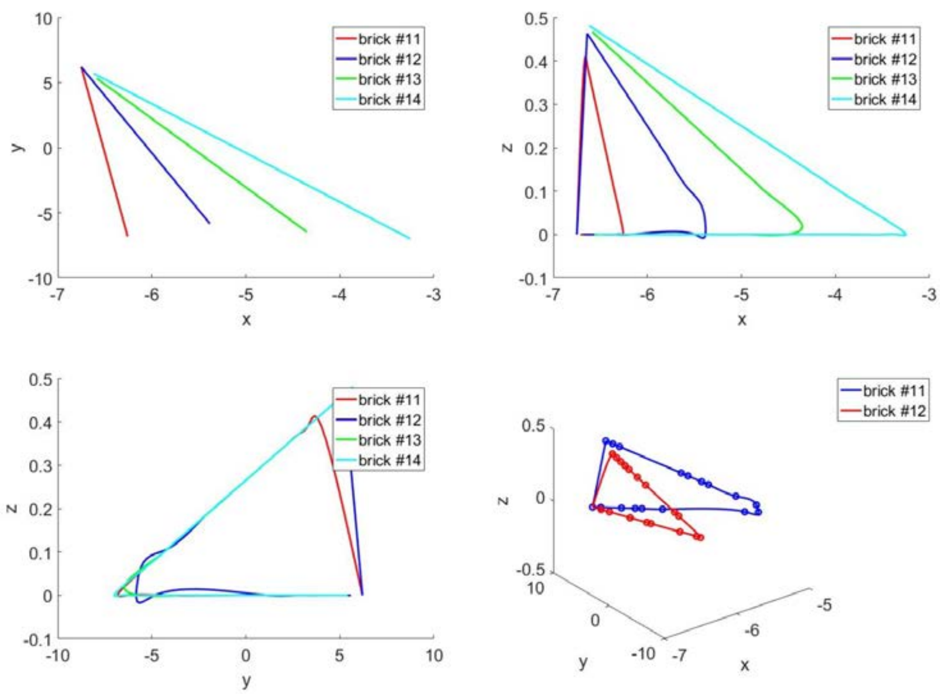

Figure 9: Exemplary trajectories as spline curves (collision-free).

The results of the simulation using a wired robot are compared with conventional performance factors. In this case, the wall can be constructed by two workers in 13.4 hours using the performance factor 0,31 h/m² (KS-PLUS Wandsystem GmbH 2014). The simulation results show that the wire robot needs only three hours for the same result. With regard to the high interdependency between project cost on overall success, this result proves the efficiency of the developed concept, however more studies are needed.

6 CONCLUSION AND OUTLOOK

This paper presents a simulation-based concept to use wire robots for the automated construction of masonry walls. The main focus lies on the interaction between a discrete event simulation used for calculating collision-free paths and a continuous simulation providing feedback concerning path validity. Due to use of BIM models as the main simulation input, the application range of the model is immensely increased. Furthermore, BIM is an essential precondition for achieving high levels of working precision despite unique project conditions. After determining the most effective robot setup and moving speed, the next steps will include optimizing the construction method by referring to the simulation results. Boundary conditions including site layout and brick size will be examined concerning their impact on the total project duration and cost. To achieve practical relevance, the overall approach needs to be evaluated concerning suitable building types, economic aspects and work safety. Furthermore, several factors need to be considered in future research to allow an assessment of the economic performance of the approach. Some of them are as follows:

- Interference with conventionally performed work steps (scheduling of robot installation and demolition, blocked workspace during robot operation).
- Exact duration of robot processes (e.g., movement speed, time for picking up and installing one brick).
- Effects of external influence factors with special regard to working speed and precision.

After having implemented the simulation-based framework, practical experiments will serve to test the concept under realistic conditions.

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