Automated Construction of Masonry Buildings using Cable-Driven Parallel Robots

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Abstract

This paper presents an approach of using cable-driven parallel robots for automated construction. Masonry buildings are considered as appropriate application case due to repetitive construction procedures, high demands on quality as well as accuracy of construction, and handling of small and lightweight material. In this context, the application of Building Information Modeling (BIM) as data source is proposed. Furthermore, a simulation model representing the operation method of a wire robot is created to analyze the process of assembling a masonry wall. Special focus lies on creating collision-free motion profiles that can be exported to the robot control system.

Keywords – Automation and Robotics, Building Information Modeling (BIM), Mechatronics, Simulation

1 Introduction

Due to the potential to improve productivity, quality, safety and to reduce cost, automated production has been established in many industrial sectors. Today, Computer Aided Design (CAD) system modeling as well as automatic assembly methods are frequently applied in industries such as aerospace, ship building or automobile [1]. Concerning the construction sector, however, automated technologies have emerged in the 1990s. One of the most attractive aspects of automated production is the opportunity to reduce personnel costs, while at the same time achieving a constantly high production quality. In many cases, robots or electronically controlled machines are applied to increase production efficiency. Focusing on the construction sector, however, automated production techniques are still limited to the sector of prefabrication (e.g., the production of precast concrete elements). With the development of Building Information Modeling (BIM) in the last decades, the application of automated construction techniques needs to be reconsidered. In this context, BIM represents a comprehensive data source by enabling a high amount of precise information concerning a building's construction phase.

The intention of this work is to present a concept for applying cable-driven robots for automated construction. The results of a literature research show possible application cases of BIM in the context of automated production, site layout planning and work safety (Section 2). In addition, several projects that combine BIM and robotics are presented. Recent approaches to use wire robots in large scale manipulation projects are examined and provide first ideas for possible application cases in the construction industry (Section 3). A simulation model is created to validate the concept concerning feasibility, efficiency, and work safety (Section 4). In the following, the background of developed concept is presented in more detail.

2 Related Work in the Context of BIM

On the basis of digital building models, the design, construction, and operation processes can be significantly improved. The focus is on three-dimensional digital models that consist of individual building components characterized by rich semantics. BIM models can be applied and extended for various planning and analyzing tasks. During project execution, typical application cases comprise clash detection, cost estimation and construction scheduling. Further applications also deal with the simulation and control of detailed construction and logistics processes. In this context, BIM can also be an enabler for developing new approaches to use robots in construction projects frequently.

In the following, current applications of BIM for automated construction processes are presented. With regard to the purpose of this paper, special focus lies on prefabrication and automated assembly of building elements, site layout planning and work safety. Additionally, several projects that combine BIM with robotics are described.

2.1 BIM for Prefabrication and Automated Production

The growing application of BIM contributes to the potential for increased use of prefabrication and modularization [2]. Costa et al. connected building components catalogues with BIM models by using semantic technologies and tested the concept on concrete components [3]. Thus, they facilitated the participation of manufacturers in the design and building process. Buswell et al. focus on large scale processes for construction applications based on Rapid Manufacturing principles [4]. They state that BIM is likely to become a key element for information delivery in this context. An exploration of a new BIM-based automation construction system (BIMAC) can be found in [5]. 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. Babič et al. aimed at integrating mass production prefabrication processes with construction site activities [6]. BIM was used as a link between an enterprise resource planning (ERP) information system that supports manufacturing processes and construction object related information. By introducing their approach to a construction company, they observed an increase in transparency between production and construction for the purpose of project monitoring and material flow tracking. Moghadam et al. developed an automated model for the design and manufacture of modular construction that applies both Building Information Modeling (BIM) and lean concepts on a modular construction manufacturing (MCM) process [7]. The described projects prove the possibility to use data from BIM models for prefabrication and automated production of single building elements. In contrast to the proposed robot application, assembly work needs to be performed manually resulting in decreased working precision.

2.2 BIM for Site Layout Planning and Work Safety

Besides the application of BIM for automating construction processes, many researches concentrate on BIM-supported site layout planning. When using wire robots for construction tasks, the site layout needs to be modified accordingly. In the best scenario, basic information on site layout are directly derived from the BIM model. Several projects of the past focused on this aspect. For example, Kumar et al. generated an automated framework for creating dynamic site layout models by utilizing information from BIM models [8]. Taking into account actual travel paths of on-site personnel and equipment allowed optimal utilization of the available space. Wang and Zhang developed an integrated approach which combines BIM and Firefly Algorithm (FA) to automatically generate an optimal tower crane layout plan [9]. A BIM-based simulation can be created to visualize and evaluate the chosen layout.

Using a wire robot results in high demands concerning work safety. Collisions between robot parts and workers may result in an increased risk of injuries. Consequently, checking work safety represents an important step when validating the proposed concept. In addition to the above described application areas, BIM represents a viable tool to check work safety and identify possible hazards. Schwabe presented concepts for possible software solutions using rule checking algorithms for construction site layout planning [10]. Prototypical implementations demonstrate to what extent currently existing BIM software is able to realize the existing concepts. Zhang, Teizer et al. developed an automated safety rule checking platform based on BIM models including automated hazard identification and correction [11]. In [12], a BIM-based approach for activity-level construction site planning is presented enabling an improvement of construction safety. An automated hazardous area model was proposed by Kim, Lee et al. [13]. It is based on the deviation between the optimal route (shortest path) which is determined by extracting nodes from objects in a BIM model and the actual route of on-site personnel collected from a real-time location system. Based on this information, the developed identification module identifies potentially hazardous areas in laborers' paths. Combining information form the BIM model (e.g., 4D construction schedules) with the path planning of the robot may help to increase work safety at all project stages.

2.3 BIM and Robotics

Vähä, Heikkilä at el. conducted a survey on potential sensor technologies and robotic applications for construction projects [14]. They distinguished between manufacturing of 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, Kim et al. developed a robotic crane system deploying a laser-technology-based lifting-path tracking system which requires the application of BIM [15]. The tracking system receives an identifier for material to lift from a central database that stores a construction schedule and a 3D BIM model. Lee, Cho et al. present a tower crane navigation system that provides three-dimensional information about the building and surroundings and the position of the lifted object in real time [16]. Besides various sensors, a BIM model is applied and linked to a real-time construction progress management system. The results of a case study indicated that crane operators preferred the crane navigation system to a text-based anti-collision system.

The results of the literature research prove the wide range of possible applications of BIM. This ongoing development can be regarded as key motivation for examining the application of robots for automated construction. Automatization techniques may now benefit from detailed and precise information provided in BIM models which can be used as digital construction plans. Thus, the application range of the presented concept is extremely increased. The following section contains a brief overview concerning existing concepts to use robots in the field of construction.

3 Application of Wire Robots for Construction

When examining 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. At the same time, in mechanical engineering, the automation of processes has reached a high level thanks to widely used series production. Consequently, both development and production processes have been established towards standards, tools and interfaces that allow for the application of robots and automated production lines. Nowadays, the introduction of Industry 4.0 even aims at the fully automated production of individual items and products.

Today’s standard industrial robots hardly cover workspaces of more than five meters in radius. Accordingly, even fundamental processes like the stacking of bricks to rise a wall are impossible to realize without the need to move the whole robot. This process requires recalibration, takes time and drives the costs. These are only some of the reasons why many approaches failed, most of them during the first wave of automation attempts in the 1990s.

Today, some novel approaches for bricking based on serial robot manipulators are under development. The Australian company Fastbricks Robotics currently develops a large-scale manipulator called Hadrian that could be large enough to move bricks along the manipulator arm to any desired position on the construction site. In parallel, the American company Construction Robotics is developing the SAM robot that is basically a conventional serial robot on a moving platform, equipped with a wide range of pose sensors. Both approaches still need their broad applicability. On the level of innovative fundamental research, Kohler presented approaches based on flying drones and moving industrial robots [17, 18].

But besides the development of BIM, also robotics research explored revolutionary concepts and new types of robots. One of them is the so-called cable-driven parallel robot or simply wire robot, similar to a Steward-Gough platform. This type of robot completely eliminates the aforementioned drawbacks. A wire robot uses a set of wires (or cables) in a tensed configuration to guide a payload along a predefined path.

3.1 Overview on Wire Robots for Large Scale Manipulation

The concept of the Steward-Gough platform – a parallel kinematic machine – has been used since the 1950s. In the last decades, several approaches were taken to transfer some of its advantageous properties like high stiffness and good precision into industrial applications. However, its drawbacks like high manufacturing costs and limited workspace appeared as major issues and prohibited its success on a broader level. Only within niches like simulator motion systems, the Steward-Gough platform became a popular solution. To overcome the described drawbacks, in 1985 Landsberger [19] proposed to replace the stiff linear actuators of the conventional Stewart-Gough platform by cables. These cables are attached to a moving platform (the payload), guided by pulleys on a supporting frame and wound up by motor-driven winches on the ground. This results in a so-called cable-driven parallel robot, often simply called wire robot. In a certain sense, a wire robot is a combination of computerized cranes that act in a synchronized manner, keeping the appropriate cable lengths and cable tensions to precisely move materials to the desired position. From a certain perspective, the concept resembles a 3D crane system. A wire robot shows some remarkable advantages:

- Extremely large workspace: Since cables can be easily wound up for dozens of meters, a wire robot covers the complete building lot.

- Simple and cheap mechanical elements: Only winches, pulleys and cables are needed. These elements are traditionally widely used on building lots.
- Easy to install: The wire robot just needs a supporting cuboid frame which can be easily erected in place.
- Extremely lightweight and fast: Since a wire robot has nearly no mass except from the payload, it can move very fast as long as human safety is not affected. At large dimensions, the frame may be constructed by lattice girders.

Starting with the 1990s [19], the wire robot has been tested for several applications. Recently, the application of wire robots for large-scale applications has been extensively addressed.

Figure 1: Storage Retrieval Machine based on Wire Robot Technology

In 2010, the project "Storage and Retrieval machine based on the Stewart-Gough-Platform" – funded by the German Federal Ministry of Education and Research – started to develop a storage retrieval machine that effectively uses the advantages of a parallel wire robot [20]: While conventional storage retrieval machines have a mass of one to two tons to move a payload of 20-50kg, the wire robot only moves 100kg including payload. Besides the University of Duisburg-Essen (Germany), the project included eight globally leading industrial partners from the logistics industry to realize a full-scale demonstrator (see Figure 1).

In 2009, the Chair of Mechatronics at the University of Duisburg-Essen and the Technical University Hamburg-Harburg realized an active suspension system for wind tunnels based on wire robots [21]. The system is currently in normal operation and performs well. In 2011, a large initiative on European level started: Within the European Union Seventh Framework Program FP7/2007-2013, the project CableBOT was realized. Its objective was the investigation of wire robots for large goods handling and manipulation. In the frame of the project, wire robots were explored for two key application examples: First, the maintenance of airplanes together with EADS Innovation Works (now Airbus group). Second, the production of large prefabricated steel parts for facades. Within the project, the Chair for Mechatronics was involved in the development of an advanced control system.

Nowadays, wire robots are used commercially to move cameras e.g. above a sports stadium. This is a simple application example from a robotics point of view, but very demanding from the requirements for safety and reliability.

3.2 Robot Design

Wire robots are intrinsically modular machines: They are composed by identical winches that share the weight of the payload. This allows to adapt wire robots to a given task in a very wide range.

As cables are flexible, they can only pull but never push. Based on this, researchers fundamentally distinguish between two types of wire robots that are composed by the same principle, but show very different properties. These two types are explained in the following.

3.2.1 Suspended Wire Robot

This type of wire robot needs external forces like gravity to tense the wires and is e.g. used to carry cameras. The options to vary the tension in the cables for a given robot pose are very limited. As an advantage, usually the cables come "from above", i.e. the area below the robot is not occupied (see Figure 2). This dramatically reduces the problem of collisions.

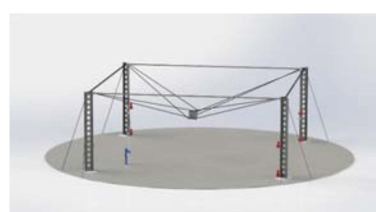

Figure 2: Suspended Wire Robot

3.2.2 Fully-tensed Wire Robot

Here, the cables needed to suspend the payload are completed by a set of cables that counteract the others. This allows to actively vary the tension in the system: If 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. Assuming the payload needs to be moved in n degrees-of-freedom, at least m cables are needed, i.e. $m \geq n+1$. Since usually also cables below the moving platform are employed, collisions might be an issue. As an option, sliding pulleys in rails can help to avoid this.

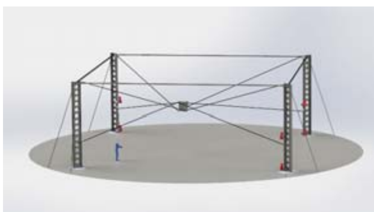

Figure 3: Fully-tensed Wire Robot

For first experiments, a fully-tensed robot is proposed due to its superior mechanical properties and its higher stiffness. For the production of buildings, a certain level of accuracy is required. Since the cables, the drivetrains of the winches and even the controller show an elastic behavior (with possibly 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, all disturbances like e.g. wind forces lead to bad accuracy results. Based on numerical optimization, a design with a cuboid supporting frame is proposed. It shows a remarkably large workspace of the wire robot, see Figure 4. Currently, the design is optimized with respect to workspace shape, volume and especially stiffness to increase the accuracy of the system. To avoid the danger of collisions, movable pulleys should be used in the future.

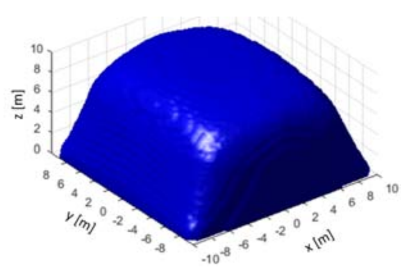

Figure 4: Workspace of the Wire Robot

3.2.3 Planning and Trajectories

The planning of paths and the generation of motion profiles over time – called trajectories – is a key issue of the planned wired robot. The robot control system needs to generate all necessary motions to create buildings using material elements like bricks, steel parts and prefabricated modules. Path planning needs to include a number of features:

- Completeness: For each single material element, a trajectory must be generated that moves it from its storage or delivery location to its mounting position.
- Efficiency: To successfully enable the automated wire robot approach, the production of a building must become cheaper. Usually, this is related to the reduction of the construction time, i.e. the robot must be fast or should move large material elements. Accordingly, the sum of the generated trajectory times must be minimal and tweaked. This can be solved e.g. by numerical optimization.
- Sequences and Collisions: The path planning must include the position of all material elements at all times. This is required due to two facts:
  - Building material is often delivered in a stacked manner, e.g. palletized. Only the top layer is usually accessible for the robot.
  - Many building structures can only be created bottom-up in layers. Accordingly, the production sequence needs to be considered.
- During the production process, the building intrinsically changes its shape. The wire robot and its payload may not collide with storage, delivered parts, the building, other machinery or itself (self-collisions). As most of these obstacles also change dynamically their size and/or position, this becomes a complex task that usually cannot be solved in real-time and therefore needs to be solved in advance of the production process.

4 Concept of BIM-based Construction Planning using Wire Robots

The planning of the construction process is based on the virtual 3D-model of the building. By providing detailed information concerning building structure, geometry and materials, BIM models represent a valuable source of information. Furthermore, the BIM-based approach allows the consideration of complex restrictions making each construction project unique. Connecting the digital model with information from the construction schedule enables the detection of processes that can be performed by wire robots. Those are described in Section 4.1.

One of the most important steps of this project is proving the feasibility of the developed concept. A simulation model is created for analyzing the robot operation method instead of conducting expensive and time-consuming practical tests. To achieve reliable results, process-relevant objects and interactions with the robot need to be implemented. Following a modular structure, the model can be used for different application cases (e.g., different building geometries or robot designs). The implementation is mainly based on the developed catalogue of automated processes (cf. Section 4.1) as well as the BIM model of the building. Restrictions considered in the simulation model include site and robot layout. Conventionally performed work steps are not considered explicitly. In the following, processes and elements implemented in the model are described in more detail. Furthermore, the data flow between BIM model, simulation and robot control is presented.

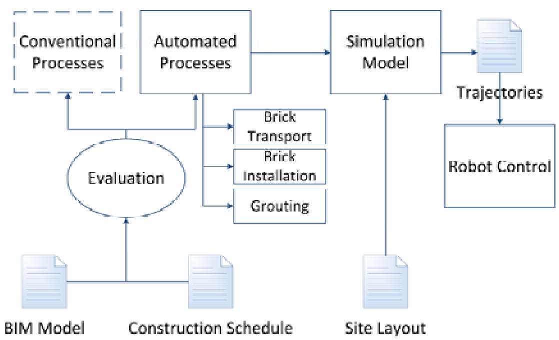

Figure 5: Basic Concept and Data Flow

4.1 Automated Processes

The first step comprises creating a catalogue of building processes and associated materials that can be automatized and performed by wire robots. Processes are examined concerning materials to be moved, required equipment and desired working precision. Due to its high potential for automatization, the creation of masonry buildings represents the focus of this project. In this context, a fully-tensioned wire robot transports and assembles bricks to create a masonry building. After having completed one row of bricks, a special grouting system is applied to create a firm bonding between the single bricks. This work step is also performed by the robot. Processes that are unsuitable for automatization need to be performed in a conventional manner and are not regarded explicitly. Figure 6 shows the operation method of the wire robot which comprises the automated processes of brick transportation, brick installation and grouting.

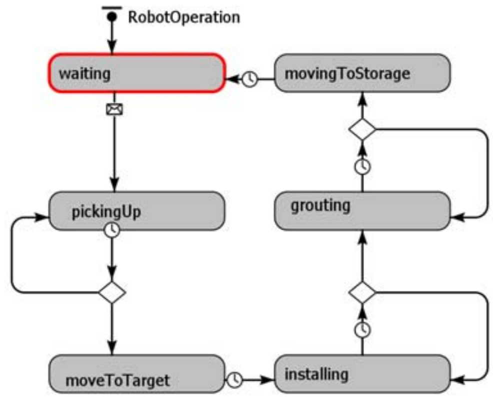

Figure 6: State chart: Robot Operation Method

4.2 Data Exchange

The BIM model represents the major data source concerning building geometry, material and installation position of the single components. Focusing on the automated construction of masonry buildings, wall elements are extracted from the BIM model which is provided in the neutral IFC format. Relevant information on walls (material, position, length, height and thickness) are imported to the simulation model. However, within BIM models, walls are defined as coherent elements. To simulate the assembly procedure, they need to be divided into single bricks. Furthermore, a formal language is developed and implemented to define transport units moved by the robot. The installation sequence of the single walls corresponds to the construction schedule of the project. As the transportation of building material represents the major part of the robot operation, moving paths are recorded paying attention to the requirements mentioned in Section 3.2.3. The resulting trajectories can be used as input source of the crane control system and to check the robot operation for possible collisions.

4.3 Simulation Model

The described approach was implemented using the commercial simulation software AnyLogic. This Java-based software offers state charts to model processes for discrete event simulation. To create a realistic model, system-relevant elements are implemented as AnyLogic “Active Objects” which can be easily modified by adding Java code. Figure 7 shows the most important elements of the simulation after the completion of the first masonry wall: Wire robot, workspace, cables, and storage area.

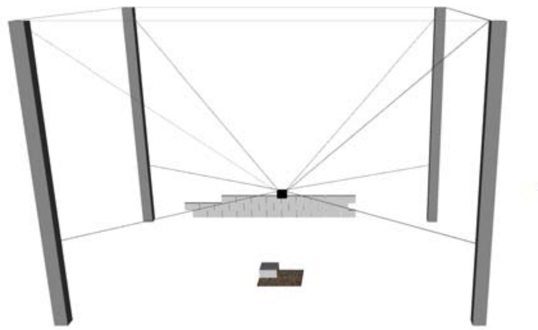

Figure 7: Screenshot of the Simulation: Creation of a Masonry Wall

The design of the wire robot and the positioning of the frame corresponds to the chosen robot type and setup as well as the given construction site layout. Position and geometry of the single bricks derive from importing wall elements provided in the BIM model. In a second step, the exact installation position of each brick is calculated in accordance with brick format (height, width and thickness) as well as grid design. In order to avoid cross joints, every second brick row is displaced by a half stone. Storage position and capacity correspond with the prevailing site layout. As the main focus lies on analyzing the robot operation method, it is assumed that the required amount of bricks and grout is available at any time of the construction phase.

4.4 Results

Analyzing the robot operation method represents the main intention of conducting simulation experiments. By conducting case studies on simple building structures, the robot motion profile can be examined concerning feasibility, efficiency and work safety. Figure 8 shows the moving paths in x- and y-direction while creating the first row of a masonry wall. The single bricks measure 1000mm x 500mm x 240mm and the center of the storage is set to be in the point (0;0). Concerning the aspect of feasibility, for example, the simulation can help to check whether all building materials are positioned within the workspace of the robot. In addition, the model can be applied to record movement paths required to create the exemplary building structure. The feasibility of the developed concept is validated if the resulting trajectories are collision-free. Collision-free motion paths can be used as input for the robot control system and thus, support an efficient and safe work progress.

The current underlying model is purely based on geometric assumptions and thus limited to kinematic properties. Accordingly, errors arising from dynamic effects (including forces, elasticities, inertia) cannot be covered, but the resulting paths can serve as input for first experiments on a prototype that will indicate the accuracy for practical applications.

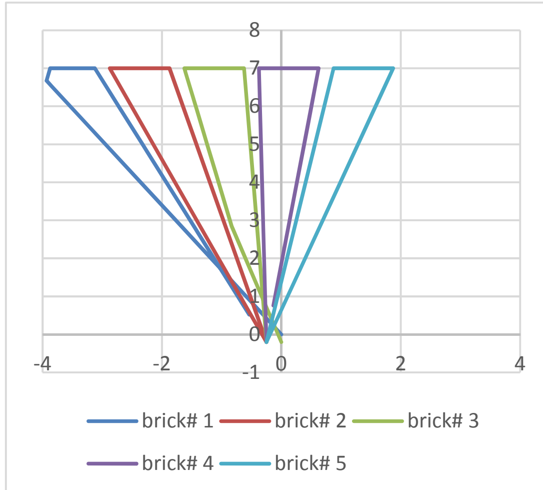

Figure 8: Resulting Moving Paths for the First Row of a Masonry Wall

5 Summary and Outlook

This paper presents an approach of using wire robots for the automated creation of masonry walls. The developed concept represents a first step towards automatizing construction work by the use of robotics. By combining the advantages of BIM and automated production techniques, quality as well as production rates can be increased. In a first step, construction processes which are suitable to be performed by wire robots were detected. This evaluation mainly depends on the BIM model and construction schedule of a construction project. Furthermore, recent applications of robots, especially in the construction industry, were analyzed. Due to its superior mechanical properties, a fully-tensioned wire robot was chosen for the transportation of bricks. A simulation model was created to represent the robot operation method in detail. In this context, BIM was included as main data source for building geometry and material while the construction schedule provided further information on the installation sequence. Next steps comprise the development of a rule checking language to develop a collision-free motion profile. Subsequently, a common data format for exporting moving paths to the control system of the wire robot needs to be developed. The accuracy of the developed approach will be examined by conducting experiments with a prototype of the robot. Additional application cases of the simulation might include optimizing storage position and size and thus, leading to a reduction in project makespan and costs. Focusing on the application of wire robots, the achievable level of working precision needs to be investigated which might result in higher demands concerning platform stiffness.

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