AUTOMATED CONSTRUCTION

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ABSTRAKT

Tento článek popisuje vývoj robotizace stavebnictví. Nejprve se věnuje očekávaným budoucím požadavkům na proces výstavby a současným možnostem architektury, kde je možné dnes funkčně užívat parametrický design a umělou inteligenci. V článku je popsáno systémové bednění běžně užívané u pozemních staveb a zdůrazněny jsou jeho výhody a nevýhody. Díky dostupnosti prototypovacích technologií je umožněno navrhnout, postavit a naprogramovat konstrukčního robota, například pro stavbu kleneb. Dále jsou popsány 3 open source řešení a nastíněn další vývoj práce. V rámci popisu jsou uvedeny i systémy řízení a dílčí komponenty. V závěru je kriticky zvážena možnost nasazení robotů na staveniště a naznačen další vývoj a výzkumu prototypů, například pro prefabrikaci.

KLÍČOVÁ SLOVA

Robotická ruka • Arduino • Beton • Betonové konstrukce • Parametrická architektura • Bednění

ABSTRACT

This article describes the effort to robotize construction. Firstly, the expected future requirements for the construction process and the current architecture options where parametric design and artificial intelligence are shown. The paper describes the formwork systems, that are commonly used in buildings construction and emphasizes the advantages and disadvantages. Thanks to the availability of rapid prototyping technologies, it is possible to design and build a construction robot for vaulting (example). Than 3 open source solutions are described and controlling systems are outlined. Finally, the possibility of robots being deployed on the construction site and the further development of research and prototyping is described and were critically considered.

KEYWORDS

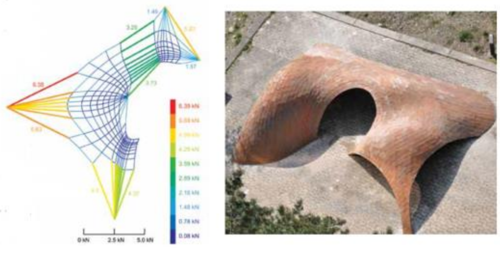
Robotic arm • Arduino • Concrete • Concrete structures • Parametrical architecture • Formwork

1. INTRODUCTION

We are nowadays facing the rapidly changing world in the relation to new technologies and possibilities. The most talked is from the year 2013 new industrial revolution – Industry 4.0. Industry brings the autonomous algorithm-based systems with wide scenarios of behaviours, internet of things, robotic surgery, nano-tolerance manufacturing, rapid prototyping and more. The civil engineering sector due my humble option will be part of these revolution. We are witnessing progressive movements in architecture such parametric design and ideal form finding are being used. There is possibility, that one day our conventional software for static analysis won't be able to accept difficult and complex structural models of designed buildings and construction companies won't be able to construct such structures, because of lack of adaptability of so far known formworking systems. Zero toleration of the constructed members measurements of the final structure will soon be appearing. Increasing speed of construction will be surely demanded and lack of capable workers will affect the civil engineering region. This state of requirements on the construction will lead to "robotization" of the process and part of common labourers will be replaced by various autonomous machines and robots.

2. STATE OF THE ART

Faced situation is challenging due to numerous of offered opportunities. The pressure from the reformist groups of architects that are using parametrical design method and artificial intelligence for ideal form finding due to required pre-defined properties is going to be stronger in the future as the complex and widely efficient design of structures will be demanded by public and private investors.



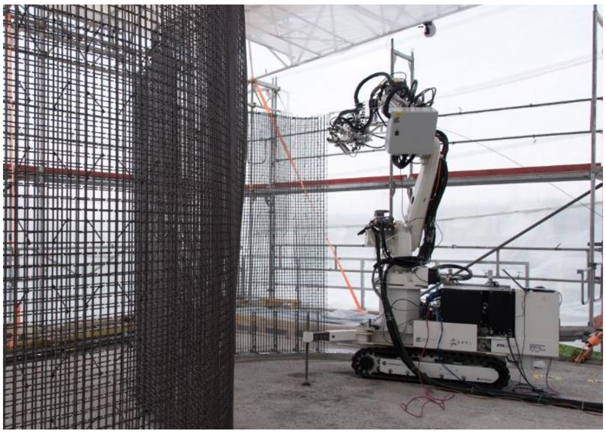
Picture 1: *Parametrically designed vault*

* Školitel: prof. Ing. Petr Štemberk, Ph.D., D.Eng.

The numerical analysis of parametrically designed vaults can be found in the work Prof. Dr. Philippe Block (Assistant Professor, Institute of Technology in Architecture, ETH Zurich). Several catatalan brick laid vaults was constructed in Switzerland and Italy. (Picture 1)

With the problematics of robotization of construction industry was dealing A. Warszawski (Head, Building Research Station, Technion I.I.T., Haifa, Israel) in 1985 in the US. He pointed out that construction industry is very important for GDP. However, the robotization does not exist, despite the fact that robotization could enormously increase effectiveness of the construction industry. He had seen enormous potential for growth. In the year 1985 was in the US in industry employed 15 000 robots, 0 in construction industry.

On the ETH Zurich was developed "In-situ Fabricator" (Picture 2), semi-autonomous robot able to prepare reinforcement rebars for double curved walls, laying bricks and more. As studies from ETH shows, the effectiveness of robotic construction systems is based mainly in the complicated designed shapes of the structure, where in the complex costs / benefits analysis are robots more efficient than classical construction labourers. For simple structures, such as planar walls and slabs, the common construction labourers are still more suitable.



Picture 2: *In-situ Fabricator*

2.1. Architecture – The Swarm Tower

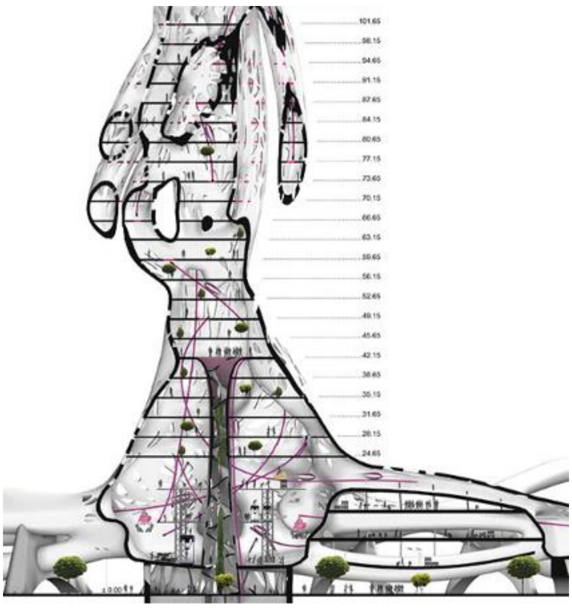
As example is shown project called The Swarm Tower from Ing. arch. Jan Petrš (Faculty of Architecture, CTU; Institute of Building Structures and Structural Design, University of Stuttgart). The tower shape was roughly defined based on the entry points of personal rapid transit and basic statical scheme. Around these boundaries, the final shape was morphed.

Picture 3: *The Swarm Tower*

All the other processes of design were made by computing and the organic appearance was obtained (Picture 3). Computing design procedures used:

- multi-agent system due that was main vectors of corridors defined
- meta-balls, due that was 3D shape defined
- parametric design, due that was additional structures defined (windows, etc.)

Worth mention that not negligible part of script was written directly by Ing. arch. Jan Petrš.



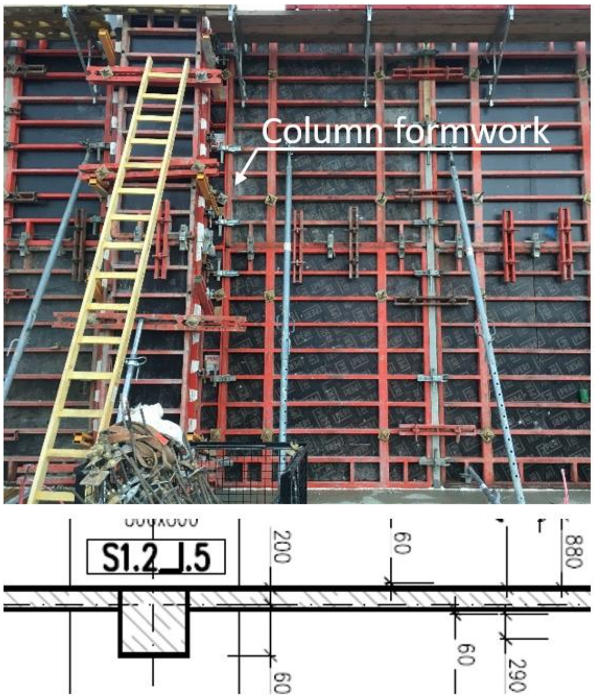
Picture 4: *The Swarm Tower – cross section*

The construction part was not deeply solved in this diploma thesis therefore, it is architectural work. Nevertheless, was expected, that the load bearing structure will be prefabricated in construction parts and in-situ completed.

2.2. Reality of Construction (buildings)

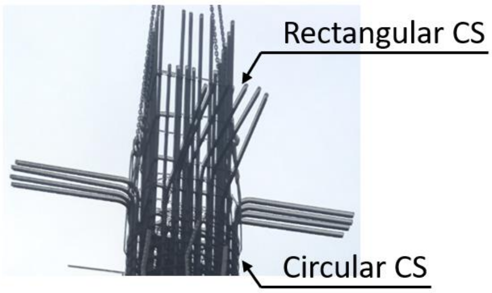
Formworks, that are used on the construction site belong to the system formwork category and it is supported with a classic formwork praxis (prisms and planks), that is used for more than 2 000 years. Basically, is system formwork maximally used and the difficult parts of designed structure are shuttered with prism and planks.

Vertical formwork and horizontal system formworks allow easily construct direct members with rectangular and circular constant cross-section. These formworks work in the system of members, that are joint together with multiple types of fasteners and stabilized with supporting members of formwork (Picture 5). Proper stabilization and usage of radial bars that bonds both sides of vertical formwork together are necessary. The pressure of concrete column can be calculated on site or manufactures of frame formwork systems provide basic pressure diagrams. However local collapses and excessive deformation of formwork frames may be found from time to time during concreting on site. Often it is seen for unusual type of structures and details. As an example (Picture 5) the wall with rectangular columns is shown, despite of the fact that it is not complicated shape, following complications appeared. Stabilization perpendicularly to a plane of the wall is locally difficult in the part where wall is connected to column and edge formwork parts (corners) are used. There are used extra parts of system formwork for stabilization, but still, deformations of frame formwork parts are visible. On the other hand, turnability of system formwork is spectacular and allows very fast construction of geometrically simple members.



Picture 5: *Wall with integrated column*

Cross-section (CS) of the designed vertical members is changed usually, according to good practice, in the ceiling slab. (Picture 6), due that we are able to avoid curved structure with changing cross-section along the height of the column. When is, due to project documentation, demanded something else, for example axis of vertical member is not situated with 90° angle with slab, is the usage of system formwork very difficult and the timbering is necessary.



Picture 6: *Changing cross-section in the width of slab*

The way, that The Swarm Tower (Picture 3 and Picture 4) was designed eliminates usage of known system formworks (usage of system slab formwork is possible). Designing of reinforcement of the structure like Swarm Tower is challenging and suitable documentation is most likely impossible without using of 3D models.

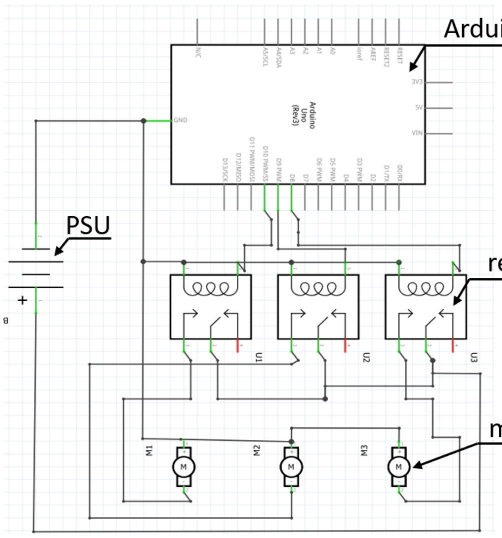
3. DEVELOPMENT AND POSSIBILITIES

Thank to availability of 3D modelling software, 3D printers, CNC mills and single-board microcontrollers with wide offer of accessories and growing coding community, the development of prototypes is possible. The idea of constructing robot for vaults therefore is not far away to find.

3.1. Robotic prototyping

For controlling the prototype of robot that is capable to lay bricks in vault is used Arduino microcontroller. Arduino is capable to run a pre-defined code loop, has 14 digital pins a 6 analog pins for the inputs and outputs. The example of Arduino circuit is shown on Picture 7. This circuit was used for sensor driven 12V DC pumps, powered by external PSU through relays series, actuating the origami muscles during the “Soft Actuated Environments” Workshop held on CTU in Prague, Faculty of Architecture in the FLOW Atelier (doc. Ing. arch. Miloš Florián, Ph.D).

For possible moving and orientation on the site will be considered rail and belt chassis. For further application the enchanted circuits and control solution will be demanded including sensors and real-time image analysis tools.



Picture 7: *Example of Arduino circuit*

3.2. Robotical Arms

First constructed was a small-scale robotic arm (Picture 8) with 4 degrees of freedom. This arm was actuated by 4 pieces SG90 small servo motors. The structure is laser cut from acrylic plate. Command loop was added directly to the code and arm performed pre-defined orders due the loop setup in the code. As shown, these types of servos are not reliable and for further investigation not suitable. As well has shown, that large scale experiments are necessary to be done.

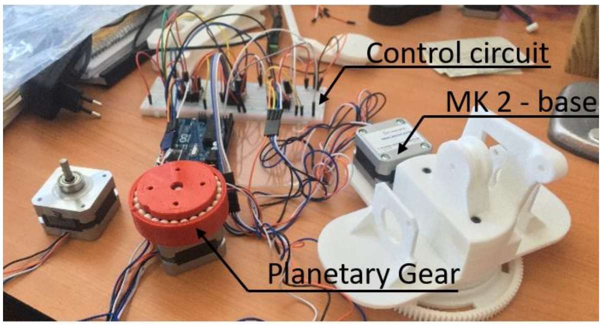
Picture 8: *First robotic arm made*

Second chosen is open source robot arm "Robot Arm MK2" (Picture 9) with 4 degrees of freedom. The model is available online and the parts could be easily printed on common 3D printers, that takes approximately 30 hours of printing time, depending of setup of the 3D printer and demanded accuracy and surface quality.

Arm is actuated with 3 stepper motors NEMA 17 and one servo motor used for the gripper. Stepper motors are moved by controlled electric current in the series of coils in stator. Rotor is equipped with permanent magnets. Due to response of permanent magnets on changing magnetic field of sequentially activated coils, motion is generated. Arm is controlled with Arduino board and stepper motor drivers. Stepper motors are externally powered with 12 Volts of Voltage.

Picture 9: *Robot Arm MK2*

This robotic arm (Robot arm MK2) is currently under construction and testing of the controlling of stepper motors is done. (Picture 10) Perfection in using Arduino and motor equipment is purpose of this construction. For functional prototype more degrees of freedom are needed.



Picture 10: *Production and testing*

Third robotic arm that is in preparation state of realization is "WE-R2.4 Six-Axis Robot Arm". This opensource robotic arm is inspired by nowadays industrial robots, the parts are available online and can be easily 3D printed as it was in case of "Robot Arm MK2". There is 6 stepper motors and one tower servo designed for controlling the gripper of the arm. In this case are planetary gearboxes installed (Picture 10). Gearboxes are transmitting axial movement with the leverage 38,4:1. That is efficient due to working diagram of the stepper and the precision of final movement. The size of step of the stepper motor is defined as 1,8°, so the full rotation is divided into 200 steps. The further dividing of the steps is possible and depends on used motor driver in the electric circuit. For example, driver DRV8825 is able to divide full rotation into 6400 steps maximum. It means that basis 1,8° step is divided into 32 smaller steps. (Tab 1)

microstep resolution	number of steps per 360°
full	200
1 / 2	400
1 / 4	800
1 / 8	1600
1 / 16	3200
1 / 32	6400

Tab 1: *Microstep settings for DRV8825*

4. DISCUSION

The applicability of robotics on construction site will be definitely very difficult. In my opinion will robotization firstly affect prefabrication of construction parts in factories, where external conditions are not so difficult as on the construction site. For example, the soft robotics actuated formwork for concrete panels will be firstly industrially used. Formwork where the change of shape is enabled due to software control. The question is scale of robots as well, there is a possibility that will be more efficient to use smaller swarm organized robots rather than big and heavy machines.

5. CONCLUSION AND FUTURE WORK

Deploying the autonomous robot constructing vaults is a complicated task. The more experiments with the design of the arm is necessary. Important is as well the control system and the scripting process. Parallelly to optimal form finding is important to develop the construction members of the vault and the gripper that will be manipulating the members. The testing of variety of chassis is needed.

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