CONSTRUCTION ROBOTICS,

PRESENT IMPLEMENTATION AND PROSPECTS

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ABSTRACT

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ABSTRACT

The purpose of this Bachelor's thesis was to find out the latest development of construction robotics, its implementation and usage, to analyse the data and to conclude its prospects. The research part of the thesis includes the author's ideas on robotics, which could be used for façade renovation works, based on his work experience.

At first, in order to justify present development of construction robotics, several models from several countries were described. Available technical data, method of usage, efficiency and prices were collected from official web-sites of manufacturers. Practices of its application, as well as possible drawbacks, were highlighted from various videos which are available on the net.

The practical part is based on the author's proposal on robotics implementation for the given façade renovation project. A beneficial renovation method for the contractor was estimated by a comparative costs analysis of manual labour with robotics usage.

The third part of the thesis discusses the prospects of construction robots. It contains personal reflection based on a deductive analysis on demands of the construction industry and the results obtained from scientific literature.

The results of the thesis are justification on usage of construction robotics from an economical point of view, comparative analysis of manpower efficiency with robotics on repetitive construction tasks.

Keywords construction robots, efficiency, present and future

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1 INTRODUCTION

«The term robotics is derived from the word robot, which was first introduced by Czech writer Karel Capek in his 1920 play R.U.R. (Rossum's Universal Robots). The word robot comes from the Slavic word robota, which means labor. In Capek's play, it begins in a factory where artificial robotic people (similar to the modern idea of androids) are being built. Capek maintained that the word robot was not of his own origin, noting that actually came from his brother Josef. He explained this in a short letter in reference to an etymology in the Oxford English Dictionary. Since then, we have come to think of robots as the mechanical men or "androids" of modern science fiction. In reality, technical manuscripts from as early as 300-400 BC reveal that human beings have been trying to build automated machines or "automata" for centuries. One of the earliest descriptions of automata appears in the Lie Zi text, telling of a much earlier encounter between King Mu of Zhou (1023-957 BC) and a mechanical engineer known as Yan Shi, who allegedly presented the king with a life-size, human-shaped figure of his mechanical handiwork. Archytas of Tarentum built a wooden, steam-propelled bird in 420 BCE, which was reportedly able to fly. In 1206 AD, inventor Al-Jazari created the first early humanoid automata. The first designs for a humanoid robot surfaced in 1495, when Leonardo da Vinci created a mechanical knight.

The development of modern robotics was precipitated by the advent of steam power and electricity during the Industrial Revolution. A growing market for consumer products drove engineers to devise ways of producing automatic machines to speed up production, do tasks that humans could not do, and to replace humans in dangerous situations. In 1893 a Canadian professor George Moore produced "Steam Man," a prototype for a humanoid robot made of steel and powered by a 0.5 horse-power steam engine. Essentially, a gas boiler housed in what looked like a mechanical suit of armor, it could walk independently at a rate of 9 miles per hour (14.5 kph) and pull light loads. In 1898 inventor Nikola Tesla(1856-1943) demonstrated a model for a remotely operated submersible boat at Madison Square Garden. Tesla also wrote that he believed it possible to someday build an intelligent, autonomous humanoid robot. Tesla's ideas were not taken seriously until well into the twentieth century. In fact, the robotics industry as we know it emerged only around the mid-twentieth century. Once research and development teams began to work in earnest, however, robots were integrated into manufacturing and gradually adapted to the military, aeronautics and space, medical, and entertainment industries. Elektro, developed by Westinghouse Electric Corp., became the first humanoid robot to be exhibited to the public, shown at the 1939 and 1940 World Fairs. In 1948, Elsie Elmer and William Grey Walter developed the first robots to exhibit biological behavior. George Devol created the first commercial robot, Unimate, in 1956, which became the first installed industrial robot in 1961. ABB Robot Group introduced the world's first microcomputer-controlled electric industrial robot, called IRB 6, in 1974. The robot was delivered to a small mechanical engineering company in Sweden. That robot was patented in 1972. Victor Scheinman introduced the first programmable universal manipulation arm in 1975». (Nocks, L. (n.d.))

According to the definition of robotics in English in Oxford Dictionaries, it is an interdisciplinary branch of engineering and science that includes mechanical engineering, electronics engineering, information engineering, computer science, and others. It deals with design, construction, operation, and use of robots, as well as computer systems for their control, sensory feedback and information processing. Robotics is the most important technical basis for the development of production and sustainability.

Robots have been successfully used for decades in factories. It successfully replaces humans when performing routine, energy-intensive, dangerous operations. Robots do not get tired, they do not need pauses for rest, water and food and are not members of trade unions. Usually, industrial robots do not have artificial intelligence, various manipulators do repetitive tasks of the same movements in a rigid program. The great success has been achieved in the use of robots on the conveyors of automobile plants. There are already plans for enterprises in the automotive industry, where all the processes of assembling cars and transporting semi-finished products are carried out by robots, and people only control them. The situation is almost the same in construction element and concrete factories, where automatic modules and manipulators create construction products under the supervision of an operator.

There is no doubt that in near future robots will replace manpower. The process has been already started. New technologies such as autopilots in different types of transports, various robotic prototypes of people, animals and insects, smart tools and machines are already in common use. , ministries of employment and ministries of construction of "According to Jan Mischke, Senior Fellow at McKinsey & Company and one of the writers of the well-known McKinsey report 'Reinventing Construction: A Route to Higher Productivity'," the gap in productivity between average economy and construction is up to $1.6tn a year." This is a shocking statistic which highlights the potential that global construction has if productivity problems are overcome. The use of robotics on a large-scale repetitive site tasks(eg. demolition, painting, bricklaying, cleaning) can speed up construction projects, increase safety on site and rapidly decrease the costs. Moreover many post-industrial countries such as Japan, The USA, Australia, Germany, Finland, Sweden and other developed countries have stated a lack of manpower and even bigger shortage of skilled or highly professional labour workers (painters, plasterers, carpenters, bricklayers etc.) Construction robots which could replace employees is an actual matter to cover the issues of present construction industry. (Hyttinen, 2017)

The purpose of the thesis is to conduct a research on the implementation of the present robots. The aim is to discuss the features of usage, possible drawbacks and advantages, efficiency and costs, state the prospects. Another aim is to consider robotics application for renovation of facades made of plasters, using observation results, obtained from the author’s work placement in a small sub-contractor company Pro Rappaus Oy during summer 2018.

To achieve the above-mentioned targets the following tasks must be completed:

- To find out and examine the present construction robots in the world.
- To make a comparative analysis of manpower and robotics efficiency on same tasks.
- To state robotics implementation for the given renovation project.
- To calculate and to state payback period of replacing workers with robots for the given renovation project.
- To analyze the demands of construction industry and to make conclusion or proposal on future of construction robotics, based on the latest available scientific and public data.

In this thesis general research methods were used such us deductive analysis, comparison, observation and survey.

2 PRESENT CONSTRUCTION ROBOTICS

This chapter illustrates three demolition robots, one multi-purpose robotic arm, one brick laying robot which are wildly available on the market. In addition, one multi-purpose humanoid robot and one plastering robot which are under testing or demo mode is described in the chapter. This is a short introduction to the use of robots, providing some evidence, that construction robotics is not any more fantasy.

2.1 Swedish demolition robot Brokk 110

Robot Brokk is one of the most versatile and one of the first created robots available on the market for demolition in confined spaces. The History of robot Brokk started in 1976. At that time two companies PE Holmgren and Rivteknik had been involved in various demolition activities for some time. The idea of designing their own demolition machine came when they were carrying out the difficult and hazardous job of demolishing a lead furnace at Boliden Rönnskärsverken smelting plant near Skellefteå, Sweden. The first machine was christened Mini-Max and later renamed PH250 to finally develop into Brokk 250. The operations grew and in 1982 the owners decided to establish a separate company for the development and production of the machines. The company’s name was Holmhed Systems AB, later changed to Brokk AB. The name has been taken from the mythical figure Brokk, who forged the god of war Thor's sword in the realm of the Norse gods. Brokk was small but very strong, just like this machine. Brokk is today a wholly owned subsidiary of the Swedish investment company Lifco Group. (Brokk, n.d.)

Today, the company offers more than 10 different models of Brokk’s robots, available from official representatives in 18 countries in each continent. In this thesis Brokk 110 is being considered, as it incorporates the best features of the previous models and all the experience gained by Brokk operators and owners and fills the gap between the smallest Brokk 50 and the biggest Brokk 800P. (Brokk, n.d.)

The Brokk 110 is one of the most versatile machines available for demolition in restricted areas. It has 360 degrees work radios. When the job has to be done in a confined space, the size really does matter. The goal is to bring as much power and flexibility as possible to the site, and the Brokk 110 achieves it. Its compact design, easy operation and powerful tools make it the perfect choice for use in a wide variety of residential, commercial and industrial environments where there are load restrictions on floors, but where a powerful, labor-saving tool is a must. The Brokk 110 folds into a compact package, transports in a small truck or trailer and goes floor to floor via an elevator or stairs. Wherever it goes, it can be plugged in and ready to work in an instant, delivering power when and where you need it. Figure 1 below shows a picture of the robot Brokk 110. (Brokk, n.d.)

Figure 1. Demolition robot Brokk 110 (Brokk, n.d.)

It can be applied in light and medium-duty demolition work in residential, commercial and industrial buildings, also perfect for jobs in the metal processing industry.

Technical Features:

Undercarriage:
Slewing speed 10 sec/360°;
Transport speed, max. 0,7 m/s;
Incline angle, max. 30°.

Hydraulic breaker SB 152.

Engine:
Electric motor Type ABB;
Output 15kW;
Current 31A.

Control system:
Portable control box;
Signal transfer Cable/Radio;

Dimensions:
width(min) 771 mm, height (min) 854 mm, length (min) 1847 mm;
Weight of basic machine excluding attachment 990 kg.

Vertical reach (incl. breaker) 4,3 m
Horizontal reach (incl. breaker) 3,7 m

Noise level (From the machine, not from the breaker):
Sound power level measured according to directive 2000/14/EC 91dB(A).
(Brokk, n.d.)

Price: 100 000 euro, delivery to Finland, according to information provided by Russian distributing company «OOO Brokk». (Tershenko, 2018)

2.2 Swedish demolition robot Husqvarna DXR

The history of Husqvarna company started in 1689 when the first Husqvarna plant was established as a weapons foundry. However, its demolition robot DXR was 23 years late to the market compared to Brokk Group, i.e. it appeared in 2009. Figure 2 below shows a picture of the robots Husqvarna DXR series. (Husqvarna Group, n.d.)

Figure 2. Husqvarna’s robotics DXR series (Husqvarna, n.d.)

The Husqvarna DXR series of remote-controlled demolition robots are the very latest in demolition machines, featuring high power, low weight and functional design. They are the obvious choice for users who want manoeuvrable yet highly powerful, stable machines with long reach. (Husqvarna, n.d.)

Duke Long, the owner of a demolition company from the USA, has five years' experience in DXR series usage. They used them for picking paved concrete, specialized on confined space, excavating schools and hospitals. He says: "It's probably the best thing, we've done now. We are growing, I bought one robot five years ago and now we are having seven of them and the future is bright." It's great to hear such positive feedback, in case the provided information is 100% honest, we might conclude that demolition robotics will conquer the whole demolition market very soon. (Husqvarna, n.d.)

Technical Features for DXR 140:

Undercarriage:
Slewing speed 8 sec/360°
Transport speed, max. 0,8 m/s;
Incline angle, max. 30°.

Hydraulic system:
Hydraulic breaker SB 152.

Engine:
Electric motor Type ABB;
Output 15kW;
Current 22A.

Control system:
Modular, digital CAN-based PLC.

Dimensions:
width(min) 771 mm, height(min) 1215 mm; length(min) 1932 mm;
weight of basic machine excluding attachment 975/985 kg;
Vertical reach (incl. breaker) 4,4 m;
Horizontal reach (incl. breaker) 3,7 m.

Noise level (From the machine, not from the breaker):
Sound power level, measured according to directive 2000/14/EC 86 dB(A).

Price: 135 000 euro, according to the price from official web-site (Husqvarna, n.d.).

2.3 Russian demolition robot Atlant 4000

Atlant 4000 is designed for different kind of demolition work in the construction, cement and process industry. The machine allows to apply all types of most demanding tools. A High productivity hydraulic system provides stable work and great performance even with strong attachments. The robot is heavier when previously described demolition robots, so that its reach is about 6 meters with a 360-degree turning radius. The combination of manoeuvrable undercarriage and the capacity to carry heavy tools makes the Atlant 4000 very efficient. Husqvarna’s and TopTec’s attachments could be installed in as well as original parts. Robot is very productive inside buildings as well as at open spaces. Atlant 4000 is equipped with an electric or diesel motor depending on work conditions(outside, inside). Atlant 4000 's remote control allows an operator working out of the danger zone. The operator remains at a safe distance, away from the negative impact of noise and vibration and falling debris. All in all, Atlant 4000 is analogue to Brokk 280, while Husqvarna does not provide such heavy demolition robots. Robot Atlant 4000 is shown below in Figure 3. (CCT Malinin Group, n.d.)

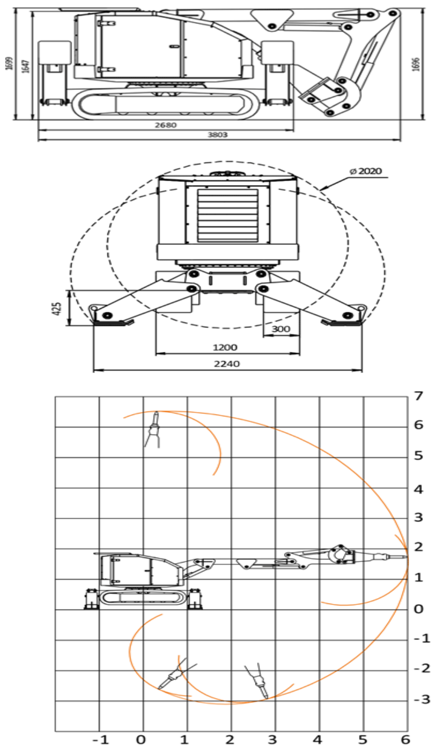

Figure 3. Robot Atlant 4000 (CCT Malinin Group, n.d.)

Attachments:

breakers, concrete crushers, drilling equipment, tunnel and miming equipment, clamshells buckets, side angling device, cut off saw, metal shears, multipurpose grapples, sorting and demolition grapples, planers.

Applications:
Demolition
- demolition of concrete structures: foundations, raft foundations, etc.;
- demolition of jet-grouting pile heads;
- demolition work in areas with chemical, toxic lesion;
- demolition of dilapidated structures.

Underground construction:
- dismantling resistant walls and punching;
- sinking shafts;
- disassembly of rocks.

Nuclear industry
- work in radioactive contamination areas.
- Cement and steel industry:
- cleaning and debricking of furnaces and melting units.

Technical Features of Atlant 4000:

Undercarriage:
Slewing speed - 20 sec/360°;
Transport speed max. – 0,8 m/s;
Incline angle max. - 23°;

Engine:
Electric/diesel engine power - 30 kW

Control system:
Portable remote control;
Transfer - Radio or cable;
Range, radio - 200 м.

Dimensions:
Width(min) 1300mm, length(min) 3803mm, height(min) 1696mm;
Weight of basic machine excluding attachment - 4100 kg;

Vertical reach (incl. breaker) 7 m;
Horizontal reach (incl. breaker) 6 m.

Noise level (From the machine, not from the breaker): 95 dB
Sound power level, measured according to directive 2000/14/EC

Price: 202 000 euro. (Neyman, 2018)

2.4 German robot Kuka KR 125/2

KUKA Roboter is a German company, a manufacturer of industrial robots, headquartered in Augsburg. The company claims to be one of the three leading suppliers of industrial robots for the automotive industry in the world and the leading supplier in the European market. KUKA has 25 subsidiaries in the United States, Mexico, Brazil, Japan, China, Korea, Taiwan, India and almost all European countries, mainly sales and service subsidiaries. The KUKA company name is short for Keller und Knappich Augsburg, as well as a registered trademark of industrial robots and other company products. The robot Kuka KR 125/2 I shown in Figure 4.
(Kuka, n.d.)

Figure 4. Robot Kuka KR 125/2 (University of Stuttgart. Institute for Computational Design and Construction, n.d.)

The faculty of architecture's Robotic Manufacturing Laboratory features a 6-axis KUKA KR 120 industrial robot and a vertical turntable as the 7th external axis. With its 8kW spindle it is equipped for the (pre-)fabrication of building elements and parts, as well as molds for lamination of fibre composites, and mock-ups for furniture, car or industrial design.

Robots are gaining traction when it comes to the highly precise construction of geometrically complex assemblies. Initially, architects employed them to fabricate small-scale, prototypical installations. But as the technology continues to develop, architects are using machines to create larger, permanent structures. In April 2014, Stuttgart University's Institute for Computational Design completed the construction of the Landesgartenschau Exhibition Hall, a 400 square meters, 6-meters-tall pavilion created for the purpose of demonstrating innovative building methods. Its prefabricated lightweight timber shell, which has a surface area of 2,640 square feet, is the first structure to be made entirely of robot-fabricated plates, according to the project team. The researchers selected beech plywood for its lightness, strength, local availability, and alignment with resource-sensitive forestry practices in Central Europe. After studying the microscopic plate joints in sand dollars, they devised a series of 50-millimeter-thick (2-inch-thick) plates with perimeter finger joints for panel-to-panel connections. Figure 5 below shows a picture of Landesgartenschau Exhibition Hall.

Figure 5. Landesgartenschau Exhibition Hall (University of Stuttgart. Institute for Computational Design and Construction, n.d.)

The unique shapes of the five-, six-, and seven-sided panels, ranging between 1 and 2 meters in length, were generated through custom designed tools in Rhino and based on biological principles, the planar approximation of freeform surfaces, the plywood's material properties, stock availability, the robotic fabrication technique, and workspace. "Due to the computational design process, all panels have different geometries," says research associate Oliver David Krieg. "Introducing different sided polygons is a natural behaviour of the design and simulation process." Sofistik was used conduct the structural analysis. "It is important to point out that the beech plywood is not used as some sort of interior cladding," Krieg says. "It is used as the primary load-bearing structure." The computational design and robotic fabrication workflow were developed over the course of nine months. First, a CNC machine cut each panel from a stock piece of beech plywood to its approximate final shape. Two small holes were drilled into each panel for attachment and orientation on the turntable of a seven-axis industrial robot. The robot then used a milling bit to refine the panel edges, finger joints, and screw pockets. Each of the 243 interior panels required about 1 minute of programming and 20 minutes of fabrication time. Nearly all off-cuts were reused as parquet flooring.

On-site construction also took four weeks. Through conventional manual labour, the panels were attached mechanically with crossing screws. On the foundation, a steel angle connects the panels to a wood sill plate on the concrete slab.

Designed for a five-year lifespan, the exhibition hall demonstrates that robot-driven fabrication is a legitimate method for building construction, particularly when designers want to create formal complexity with heterogeneous components and optimize material resources. This effort also bridges the gap between product and building: As plywood is transformed into interlocking panels, the unique construction system becomes inseparable from the final product. (Menges, Schwinn, Krieg, 2015)

Technical data:

Maximum reach 2698 mm;

Number of axes 6;

Footprint 830mm x 830 mm;

Weight approx.. 1104 kg.

Operating conditions:

Ambient temperature during operation 10 C to 55 C (283 K to 328 K).

(Kuka, n.d.)

The price of this series depends on the equipped options (mounting base, energy supply, CNC software, fieldbus etc). “Generally, around 50 000€ would be the price with some options” – according to Kimmo Kymäläinen, Kuka Country Manager in Finland. (Kymäläinen, 2018)

2.5 **Robot OKIBO**

Robot OKIBO is an automotive machine for plastering, putting and painting, which is still under developing stage. It is planned to have a mobile, six-wheel, platform with two Kuka arms attached with a nozzle, rendering and paint tool. Artificial intelligence of robot can detect the dimensions, obstacles and shape of the building using integrated laser measurement system. Figure 6 below shows a picture of Robot Okibo.

Figure 6. Robot Okibo (German, 2018)

OKIBO is a startup company, located in Israel. The main partners of the company are GG Robotics and S-Pool. CEO of OKIBO Company Guy German says: “Our robot uses wall plastering machine to spray material on the wall and scrapers to flatten the wall. We are planning to perform many other tasks within the construction site in the future and we can theoretically use concrete as our material and print "concrete walls" but this is not our intention because concrete printing, in our opinion, is not yet prime for actual house building, as there are many industry standards that "layered" printed concrete does not comply to.“ However, who knows, what the next five years will bring to the industry. At the present moment, OKIBO doesn’t plan to sell robots, but rather offer services that replace human labor on construction sites, at competitive prices compared to human workers. (German, 2019)

Since plastering robot OKIBO is still a prototype the main technical features and robot’s price are not available at the moment. However, we could easily highlight its advantages and drawbacks from the basic design concept. (Okibo, n.d.)

The main drawbacks might become small value of mixture vessel, since for 400 m2 façade area about 3200 liters of mixture is needed to perform 2 cm thick plaster layer. For big construction projects it seems to be more appropriate to use separate silos or mixture unit like the mobile concrete factories, where dry mix combines with water.

Okibo's advantages are mobility and high accessibility. Its arm has 7 degrees of freedom, which easily allows to reach external and internal angles, long span of lifting platform is well suited for the height of common residential buildings.

Anyway, Okibo is still just a prototype, which really makes sense in robotization of plastering. However, time will show whether it will replace plasterers or not.

2.6 **Robot Sam**

«SAM, short for Semi-Automated Mason, is a brick laying robot designed and engineered by an American company Construction Robotics. SAM 100 is the first commercially available bricklaying robot for onsite masonry construction. The unit, which has a retail price of $500,000, works alongside a human tradesperson. Together, they can lay up to four times the number of bricks than a single man could lay. Figure 7 below shows a picture of Robot Sam 100.

Figure 7. Robot Sam 100 (Quirke,2015)

SAM works best on long stretches of wall and can create complex patterns using different brick types. SAM is controlled and operated wirelessly and uses a laser sensor that corrects any movements that may knock her off course. The robot has been in development for eight years and has been trialled at multiple construction sites in the US.

Construction Manager, quoted Zachary Podkaminer, operations manager at Construction Robotics, as saying: "Of course, SAM will continue to be improved, but we are finally at a stage where she is working very effectively and efficiently". Although, SAM would not yet replace bricklayers: “Your mason monitors wall quality, while SAM does the heavy lifting. Masons that haven’t worked with SAM are hesitant at first, but once they learn and work with the robot and realise it won’t take their job, they are very open to it.” Podkaminer predicts that there will be a demand for robots like SAM, as there is a lack of skilled bricklayers in the global construction industry.» (Quirke, 2015)

So far, SAM has worked at Brighton Health Centre in 2017, Erlanger Medical Office building in 2018, POFF Federal Building in 2018 and laid more than 292 000 bricks all together. (Construction Robotics, n.d.)

Drawbacks of SAM 100 is an absence of bricks storage and transport smart system, now four or five bricks installed manually to the robot. Another disadvantage of the robot is the necessity of manual removal of extra concrete mixture from brick wall after masonry placement. In addition, the robot has a small concrete mixture vessel, which, unfortunately, is filled manually.

We could highlight the robot’s precision in bricklaying as its main advantage. The company promotes that SAM 100 works four times more effective than as single man. However, the company doesn’t provide such tests which could clearly prove it. Since for a successful robotics usage, an operator, a bricks transporter, an extra mixture remover – three people in total is needed. Probably, two high professional bricklayers with one helper will be more effective. It must be tested.

Finally, Robotic SAM 100 is a quite good semi-automated machine, which has been implemented on several sites, but still can be improved.

2.7 **Robot HRP - 5P**

«The National Institute of Advanced Industrial Science and Technology (AIST), one of the largest public research organizations in Japan, focuses on the creation and practical realization of technologies useful to the Japanese industry and society, and on “bridging” the gap between innovative technological seeds and commercialization. For this, AIST is organized into five departments and two centres that bring together core technologies to exert its comprehensive strength. AIST, as a core and pioneering existence of the national innovation system, has about 2000 researchers conducting research and development at 10 research bases across the country, based on the national strategies formulated with the changing environment involving innovation in mind. Figure 8 below shows a picture of AIST Humanoid robot prototype – 5P.

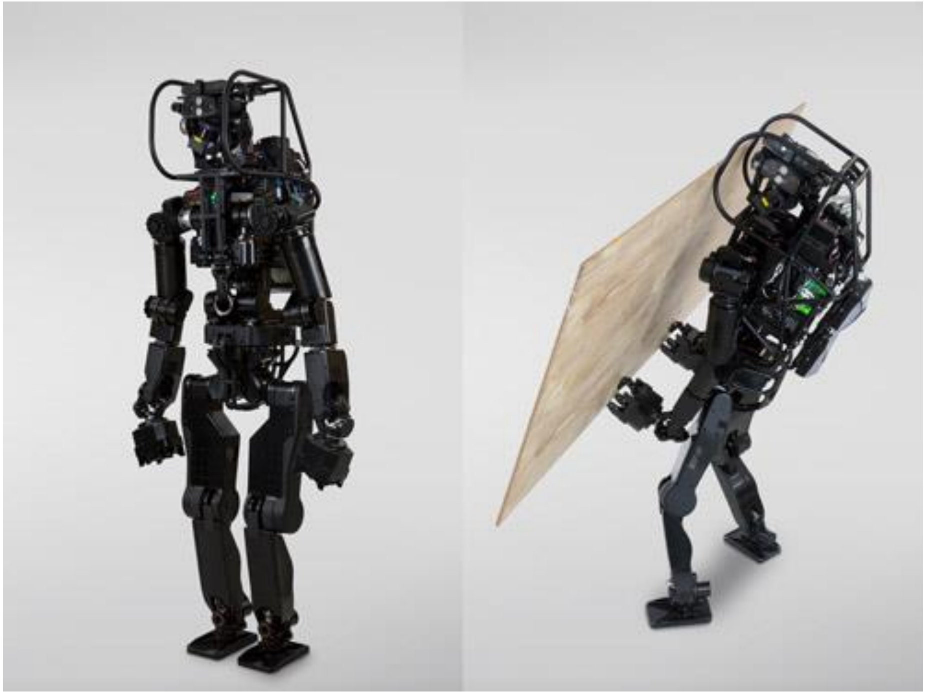

Figure 8. AIST Humanoid robot prototype – 5P (AIST, 2018)

The humanoid robot prototype HRP-5P was developed with a robust body and advanced intelligence to work autonomously and provide an alternative source of heavy labour. At a height of 182 cm and weight of 101 kg, HRP-5P has a body with a total of 37 degrees of freedom: two in its neck, three in its waist, eight in its arms, six in its legs, and two in its hands. Except for the hands, this represents the most freedom of movement in the HRP series to date. Compared to the revised version of HRP-2, adding one degree of freedom to the waist and one to the base of the arms has enabled operations more closely resembling human motion. Accordingly, using both arms, HRP-5P can handle large objects such as gypsum boards (1820 × 910 × 10 mm, approx. 11 kg) or plywood panels (1800 × 900 × 12 mm, approx. 13 kg). To emulate human motion by the robot without as many degrees of freedom as people, the researchers ensured a wider movable range of joints in the hip and waist areas, where multiple joints are concentrated. For example, hip joints that flex and extend the legs have a range of motion of 140° in humans and 202° in HRP-5P, and waist joints that turn the upper body have a range of motion of 80° in humans and 300° in HRP-5P. This enables work by the robot in a variety of postures, such as when deeply crouched with the upper body twisted. Joint torque and speed were approximately doubled on average relative to the revised HRP-2, by employing high-output motors, adding cooling to the drive mechanism, and adopting a joint drive system with certain joints featuring multiple motors. As a result, the robot can do work involving heavy loads, such as lifting a gypsum board from a stack. (Each arm of HRP-5P, extended horizontally, can bear a weight of 2.9 kg, compared to 1.3 kg for the revised version of HRP-2 and 0.9 kg for HRP-4.) Using head-mounted sensors, the robot constantly acquires 3D measurements of the surrounding environment (at a frequency of 0.3 Hz). Even if the field of view is blocked by objects used in work, stored and updated measurement results enable execution of the walking plan while carrying a panel or correction of walking when the feet slip. Learning involves a convolutional neural network using a newly constructed image database of work objects. The robot can detect ten types of 2D object regions at a high precision of 90 % or more even against low-contrast backgrounds or under dim lighting.

It was possible to build a highly reliable robot system and maintain the quality of large-scale software (with approx. 250,000 lines of code) by arranging a virtual test environment for the robot intelligence in the Choreonoid(open-source integrated GUI software for robots) robot simulator and monitoring software regression for 24 hours. The integration of these technologies has enabled autonomous gypsum board installation in which HRP-5P handles and carries large, heavy objects at a simulated residential construction site independently. Specifically, this work involves the following series of operations:

① Generate a 3D map of the surrounding environment, detect objects, and approach the workbench.

② Lean against the workbench, slide one of the stacked gypsum boards to separate it, and then lift it.

③ While recognizing the surrounding environment, carry the gypsum board to the wall.

④ Lower the gypsum board and stand it against the wall.

⑤ Using high-precision AR markers, recognize and pick up a tool.

⑥ Holding a furring strip to keep HRP-5P itself steady, screw the gypsum board into the wall.

Figure 9 below shows a picture of Testing HRP-5P.

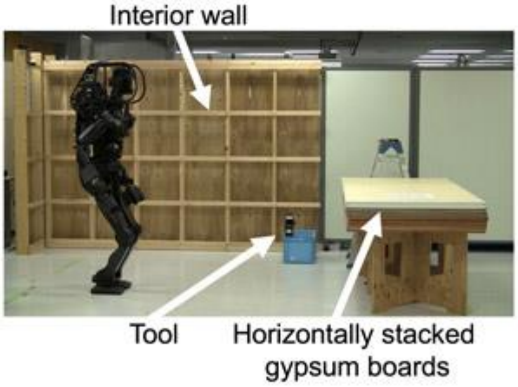

Figure 9. Testing HRP – 5P (AIST, 2018))

The promotion of the collaborative use of HRP-5P will be continued, as a R&D platform for practical application of humanoid robots, by industry and academia. R&D on robot intelligence will be promoted using this platform, targeting an alternative source of autonomous manual labour at residential or office building sites, and in assembly of large structures such as aircraft and ships. This will compensate for labour shortages, free people from heavy labour, and help them focus on more high-value-added work». (AIST,2018)

3 ROBOTICS IMPLOMENTATION PROPOSAL FOR REAL CONSTRUCTION PROJECT

3.1 Project Preface

During summer 2018, the author was working at a small construction company, which mainly specialized in building facades. The main labor works are demolition of old façade layers, plastering, puttying and painting.

In this thesis, facade renovation of «Valteri - Centre for Learning and Consluting», is considered. It was completed by Etelä-Suomen Julkisivupalvelu Oy. The building is located at Tehnolantie 15, Helsinki. The idea of comparative research is to solve whether it is more worthily to use manual labor or to implement robotics for given construction project. The basic contactors costs on manual labor are compared to the costs of robotic implementation, as well as the payback period of robotics. The total façade area of the building is 3000 square meters. Structure of façade is a brick wall, 2 cm layer of plaster, 2 layers of putty and print layer. It is a five-story building.

It must be mentioned that such an analysis is done at an ideal case, meaning that robotics ensures 100% completion of planned construction tasks, without facing any troubles. Furthermore, approximate market prices and approximate building area were used in calculations since, real data wasn’t available by the needed date.

The following works were completed in order to renovate the façade:
1) Installing scaffolding – total cost
2) Demolition of old plaster – total cost
3) Plastering, puttying and printing – total cost

These works were completed by manual labour. It took around 6 months to complete renovation of façade. There were mainly 3 sub-contractors working, scaffolding company (2-4 workers), demolition company (6 workers), plastering and printing company (6 workers). Thus, in total there were around 16 construction workers who finished actual work. There were some people who removed construction wastes, from the ground to truck and then it transported to recycle point. Author does not consider the construction wastes transportation in this research, since the transportation cost mainly remains same, whether it does robots or human.

All the jobs mentioned above are really physically demanding, and require from workers professional skills, good shape, power and stamina. It’s obvious that at the end of the day or in the middle of week workers’ efficiency decreases, since the human body needs a rest after a certain amount of stress. For instance, the scaffolding team (2 people) could lift and install 1000 – 2500 kg of metal parts in eight hours shift, the demolition worker take away 100-250 m2 of old façade using a hammer-drilling tool, the plastering team (3 people) does 200-300 m2 of plaster per eight hours and spends 5000-6000 kg of mixture. Since the work is done outside, the weather plays are huge role in efficiency. Due to high outdoor temperature, workers are thirsty and become tired faster, so that the progress of completing the tasks slows down. These factors must be taken into account when considering robotics implementation for the same type of work.

3.2 Robotics implementation

First, in case of robotics implementation for the mentioned construction project, the contractor won’t need to install scaffolding. It would be enough to rent a mast climber, self-propelled boom lifts or scissor lifts just for the demolition semi-automated robot placement (Husqvarna DXR 140 or Brokk 110). The demolition robot with an operator will ensure at least 300 square meters up to 400 square meters plaster removal for eight hours shift, which is almost 50% more effective than manual labor.

Secondly, we are considering robot OKIBO for plastering, putting and painting the wall.

3.3 Cost Analysis

Cost analysis was simply done by comparing the sum of all contractor’s defined costs for the given project to the costs of robotics implementation.

Since the contractor didn’t provide real costs for this thesis, it was decided to use market prices for the calculation purposes.

Renting for 6 months, construction, deconstruction, and the maintenance of scaffolding of 3000 square meters was 30 000 euro.

Demolition of old façade layers without rubbish transportation costs amounted 30 000 euro.

Plastering (2 cm layer), putting (2 layers), painting 3000 square meters cost 125 000 euro (including material cost).

In total: 30000 + 30000 + 125 000 = 185 000 euro, estimated cost of manual labor.

Next, the cost of robotics implementation will be considered. In this case, the contractor must buy robot.

Husqvarna DXR 140 cost 140 000 euro
Robot IKIBO might cost 300 000 euro (since the model is in development stage)

In addition, the contractor will need to rent a lifting platform for demolition robots for 11 days, since the total area of façade is 3000 square meters divided by 350 square meters per day estimated demolished area by one robot and operator), equal 8,5 (3 days extra) – 12 000 euro.

The Salary of robot operator might be 17 euro/hour. A demolition operator will work 11 days, and plastering robot's operator will work 2 months (15 days of plastering, 15 days of putting, 10 days of painting).Furthermore, we should add to basic hours salary of the operator company's expenses on social security payments and additional taxes (30%), holiday pays and special percentage for construction workers (26,2%), thus one hour of the operator's work will cost 27 euro for the company.

The cost of the demolition operator work per 11 days for 88 hours multiplied by 27 euros which equals 2376 euro.

The cost of the plastering operator work per two months for 320 hours multiplied by 27 euros equals 8 640 euro.

Material costs: mixture for the plaster, mixture for putty, paint amount to 15 000 euro.

In total the cost of robotic implementation is the following:
140 000 + 300 000 + 12 000 + 2376 + 8640 + 15 000 = 478 016 euro.
478 016 – 440 000(robotics price) = 38 016 euro.

When comparing two costs, manual labor 185 000 and robotics 38 016 euro (excluding the costs of the machines), we can conclude that the contractor profit equals 146 984 euro. It is huge difference in company's profit, which plays the main reason in decision making, which method should be implemented. Based on obtained figures, we could define that from third similar project contractor will fully covered the robotics costs. Payback period of robotics implementation approximately equals nine months, since one project requires at least 3 months to be completed.

440 000: 146 984 = 2,99

The obtained results clearly show the profit of robotics implementation for the detected construction project. Therefore, it shows prospects for lab experiments to fully approve the effectiveness of robotics for such projects.
Moreover, the following disadvantages of manual labor compared to robotics were obtained through the conducted research:

- weather conditions, worker's physical shapes, health level, tiredness, duration of the shifts negatively influence labor's productivity;
- necessity of scaffolding installation;
- lower workers productivity in demolition, plastering and puttying;
- high company's expenses on additional taxes and social security payments for workers.

In addition, it must be mentioned that this proposal was only done for the given construction project during spring, summer, autumn time. For winter time, authors proposal of robotics implementation should be modified due to necessity of protection against rain, snow. Moreover, plastering, putting and painting works perform in positive temperature, this have to be taken into account as well.

4 Prospects

As we could see from the date above, construction robotics is not anymore future, it is already reality. However, nowadays robots are still limited in usage, as they are mainly implemented in specific tasks such as demolition and manufacturing. An ideal iron builder does not existing yet, but construction industries of many countries already need it. At the same time everyone knows the reality of economy: « where there is demand, there is supply». Therefore, the creation of universal construction robots, which will build houses autonomously is just a matter of time.

Moreover, the present construction industry is a highly mechanized industry. Nevertheless, it still has a high percentage of manual labor due to the limited possibilities for the further mechanization of many types of construction work. Therefore, the greatest prospects to increase the speed of construction and improve the quality of work lie in the field of automation and robotization of construction. Such trends can be seen now. In recent years, significant progress has been made in the field of computer technology, electric drives, control systems, and other fields of science and technology that are important for robotics. Examples of this are constant increasing of computing power, the creation of the Internet, development of mobile devices, creation of drones, automotive vehicles, blockchain technology and artificial neural networks, which can learn. These have opened broad prospects for the use of robots and robotic systems.

Many different classes of robots, intended for diverse use in the construction industry, exist or are at an advanced stage of development. While some of them seek to automate conventional construction methods, others, such as robots for the printing of concrete, support new construction concepts. Their use can bring significant economic, operational, environmental and other benefits, and many technologically advanced companies such as Google, Microsoft, Sony, Apple, Shimizu, Kuka Roboter, Husqvarna, Brokk AB widely use these opportunities. Traditionally, the industry has been in no hurry to introduce new technologies, but now robots have a real impact and will inevitably play a vital and growing role in the future.

The construction industry is ready for change. Compared to other industries, automation hasn't yet had much impact on it. However, this is rapidly changing as robots currently perform various construction tasks, committing new working ways in the industry.

Brick laying robots, street laying robots, drones, autonomous vehicles and robots for large-scale 3D printing - they all leave their mark on construction processes. They overcome the traditional problems of automation and provide many different operational advantages.

Reducing costs and expanding the capabilities of robotic systems allows us to consider the possibility of their use and implementation at a practical level. In addition to increasing the speed and quality of work, which are main purposes of robots, other positive effects from their implementation are primarily related to the people's safety improvement. Replacing a person with machines in hazardous jobs, using robots in difficult climatic and natural conditions — and increasing the overall construction robotization will reduce the proportion of human labour at the construction site, as it is itself an object of heightened danger. In addition, it can increase the environmental safety of the construction process by better optimizing the work and reducing emissions. At the same time, it is obvious that the use of automated construction machines has many peculiarities related to the specific requirements for robots.

It seems that we could classify construction robots according to the type of work performed: ground works, installation and erection, finishing and ancillary works. Special new designs are not required for ground works robotics, since it will be enough to upgrade existing machines and their structures to fully automated control system that does not require human operation. Within erection and installation, several works can be distinguished -welding, lifting and placing, concreting with specific requirements. In general, these areas of the construction process have great potential for robotization. As can be seen in previous chapter some robots for finishing and ancillary works have already been developed but have not found wide application yet. They perform various types of working areas: demolition, plastering, as well as sealing joints and seams of the building structures. Since the amount of manual labour is very large and wide in the construction industry, robotization will bring a very significant economic effect.

However, mechanization is only the first step towards complete robotization of the construction process. In the future, the creation of a highly specialized form of artificial intelligence for controlling machines on construction sites seems to be the most likely development option.

The main difficulty in creating classical automated control systems for various machines and mechanisms on the site lies in the fact that, unlike a laboratory and even a production workshop, construction is an environment with unpredictably changing conditions. The standard automated control system cannot solve such complex tasks or does it rather badly, in contrast of robots equipped with artificial intelligence, which are able to do more. The recognition of image and sound, the ability to navigate in an ever-changing space will allow robots to work at a construction site without danger to themselves and others. AI can work with non-specialized universal tools. AI will be able to safely and effectively interact with people. Creating a self-learning module for such an agent would be much easier than creating a hard-coded automated control system.

Moreover, robots with artificial intelligence could replace humans at work with high risks. For instance, disassembling rubble, eliminating the effects of disasters, such as accidents at nuclear power plants or chemical plants. The conditions are extremely dangerous for people and the work of remote-controlled robots is ineffective in these areas. Another promising area of application of robots with AI is construction work that is carried out in serve weather or specific environment — high mountains, Arctic and far north, where it is impossible to use conventional robots.

Over time, the self-study module of AI, in theory, will allow robots to do their work more efficiently with the accumulation of information and learning. The creation of network between agents will allow them to learn together, speeding up the process of self-improvement. This self-study module could lead the development of heuristic properties, which will allow robots with AI to figure out non-trivial and appropriate solutions for construction purposes.

In the future, advanced information technologies will be more closely integrated with construction equipment, ensuring sophisticated robotic construction systems with greater efficiency, productivity and safety.

Several promising areas simultaneously leading to the robotization of construction work must be considered. Firstly, the development and implementation of automated control systems and remote-control systems, which will improve operation of existing construction machines with minimal costs. It seems to be more likely practically implemented in the near future, even if we cannot name it as complete robotization, since an operator is still needed. However, it is important that all the necessary technologies already exist and are sufficiently developed, so that its greatly simplifies and cheapens the implementation of such systems. Furthermore, new control systems can be installed on existing machines without radical redesign.

Secondly, small construction robots could be created for automated finishing works. Since some of them already exist, new models could be completed without special technical complexity, using a well-established structure of industrial robots. Widespread use of such small robots, or at least similar semi-automatic machines, is currently quite expensive, but it could provide high-quality of finishing and other works of the final cycle.

Thirdly, the formation of network interaction between the machines at construction sites will allow distantly monitor and adjust everything happening on the site during the construction process. The rapid development of network technologies and the so-called "Internet of Things" in the near future will drastically increase coordination levels between employees. Automatic or semi-automatic constant monitoring on site with the exchange of data between individual workstations and machines will dramatically reduce risks and accidents.

Finally, it is development of specialized artificial intelligence, which will unite all above-mentioned technologies and in fact will eliminate humans manual labour from the construction industry, leaving for them only a controlling and observative role. Although, current prospects of specific construction AIs are very far, it seems to be most effective way to achieve full integration of individual machines and robotics into a single system with a minimum amount of human labour, and with flexible adjustment of work processes on constructions sites.

5 Conclusion

Construction robotics has been developing through the centuries as we could see from its history. Present time is becoming a revolution for construction robotics, since robots are becoming available on the market and are implemented for diverse construction projects all around the world. Demolition of old structure, construction of masonry buildings, plastering, puttying, painting, welding, lifting, cutting are only some fields of present robotics implementation, which were considered in this thesis. No doubt their usage is much more widely but it’s already more than bachelor topic, since the main aim of the thesis was to show that construction robotics is not a future, highlight their advantages and drawbacks, conduct comparative costs research on robotics implementation with manpower on repetitive façade renovation tasks and, finally, indicate prospects.

Robotics usage increase efficiency, productivity and quality of work on sites, as a result profits of construction industry are increasing. In addition,
robot’s implementation improves safety on sites, which is another important and necessary goal of the industry.

Several construction robotics models from different companies were described in the thesis, in order to show its market availability and present implementation. Technical characteristics, drawbacks and advantages, costs, its applications and operation features were stated. Such data has proven extensive construction robotics usage. Moreover, it will continue to evolve. However, for the effective deployment of robots into construction process, its initial characteristics and operation specifics must be firstly considered.

Comparative costs analysis on robotics implementation with manpower on the given construction project was conducted according to thesis targets. The main idea of research was to obtain an answer to the following question: Whether it is more worthily to use manual labor or to implement robotics for façade renovation project of “Valtari Center”. The basic contactor’s costs on manual labor were compared to the costs of robotic implementation, as well as the payback period of robots. The total façade area of the building was 3000 square meters. Structure of the façade was brick wall, 2 cm layer of plaster, 2 layers of putty and print layer. It was a five-story building.

It must be mentioned that, such an analysis was done in an ideal case, meaning that robotics ensures 100% completion of planned construction tasks, without facing any troubles. Furthermore, approximate market prices and approximate building area were used in calculation, real data wasn't available by the needed date. Nevertheless, the results obtained clearly show the profit of robotics implementation for a given construction project. Therefore, it shows prospects for lab experiments for the full confirmation of the effectiveness of robotics.

Moreover, the following disadvantages of manual labor compared to robotics were obtained through the conducted research:

- weather conditions, worker's physical shapes, health level, tiredness, duration of the shifts negatively influence labor's productivity;
- necessity of scaffolding installation;
- lower productivity in demolition, plastering and puttying;
- high company's expenses on additional taxes and social security payments for workers.

The main argument of robotics usage for the given project turned out to be financial benefit. Cost analysis was simply done by comparing the sum of all contractor's defined costs for the project to the costs of robotics implementation. As a result, the estimated cost of manual labor totaled 185,000 euro, the cost of robotic utilization amounted 476 936 euro, where 440,000 euro was the price of robotics.

Compared two costs, manual labor 185 000 and robotics 36 936 euro (excluding the costs of the machines), it was concluded that the contractor profit equals 148 064 euro. It is huge difference in company's profit, which plays the main reason in decision making, which method should be implemented. Based on obtained figures, it was defined that from third similar project contractor could fully cover the robotics costs. Payback period of robotics implementation approximately equals nine months.

Despite the fact that construction robots are no longer the future, but already reality, its usage is still limited, since it only applies in specific and limited tasks. The prospects of construction robotics are important and open question. Nowadays, there is a demand for universal construction robotics, which will independently build houses. It means that construction robotics will be needed more than ever.

In this thesis, it was investigated that the greatest prospects to increase the speed of construction and improve the quality of work lie in automation and robotization. In recent years, significant progress has been made in the field of computer technology, electric drives, control

systems, and other fields of science and technology that are important for robotics.
Many different classes of robots, intended for diverse use in the construction industry, exist or are at an advanced stage of development. Their use can bring significant economic, operational, environmental and other benefits, and many technologically advanced companies widely use these opportunities.

Thesis results indicate that construction industry is ready for change. Compared to other industries, automation hasn't yet had much impact on it. However, this is rapidly changing as robots currently perform various construction tasks, committing new ways in the industry. Robotics overcame the traditional problems of automation and provide operational advantages. In the thesis, construction robots were classified according to the type of work performed: ground works, installation and erection, finishing and ancillary works. These areas of the construction process have great potential for robotization. Since the amount of manual labour is very large and wide in the construction industry, robotization will bring a very significant economic effect.

It was also concluded that mechanization is only the first step towards complete robotization of the construction process. In the future, the creation of a highly specialized form of artificial intelligence for controlling machines on construction sites seems to be the most likely development option. Such machines will eliminate human labour from site, leaving for them only controlling and observative role. Although current prospects of specific construction AIs are very far, it seems to be most effective way to achieve full integration of individual machines and robotics into a single system with a minimum amount of human labour, and with flexible adjustment of work processes on constructions sites.

In conclusion, construction robotics is a promising area, since there is a great demand for it. Robot utilization is cost-effective, it makes the construction process more qualitative, environmentally friendly, and safer. At the same time, there is a huge potential in this field, which has not been realized yet. According to that, further research could be done on the backgrounds of this thesis, providing a basis for Master or Doctoral thesis.

References

AIST. (2018). Development of a Humanoid Robot Prototype, HRP-5P, Capable of Heavy Labor. Retrieved September 10, 2018 from https://www.aist.go.jp/aist_e/list/latest_research/2018/20181116/en20181116.html

Atlant Demolition Robot. (n.d.). Retrieved September 2, 2018 from http://www.robotatlant.com/

Brokk. (n.d.). History for decades of successful innovation and counting… Retrieved August 22, 2018 from https://www.brokk.com/about-brokk/history/

Brokk. (n.d.). Brokk 110. Retrieved August 22, 2018 from https://www.brokk.com/product/brokk-110/

Brokk 90 Demolition Robot. (2012). Retrieved August 22, 2018 from https://www.youtube.com/watch?v=-ru6YOh7nAQ

Case story with Duke Long on the DXR demolition robots. (2012). Retrieved August 20, 2018 from https://www.youtube.com/watch?v=XhidKjlyNQo

CCT Malinin Group. (n.d.). Atlant 4000. Retrieved September 2, 2018 from http://www.cct-drill.ru/demolition-robot-atlant/

Construction Robotics. (n.d.). Sam 100. Retrieved August 23, 2018 from https://www.construction-robotics.com/sam100/

Construction Robotics. (n.d.). Introduction to Construction Robotics and the bricklaying robot SAM. Retrieved August 23, 2018 from http://www.construction-robotics.com/video/

Construction Robotics. (n.d.). Portfolio. Retrieved August 23, 2018 from https://www.construction-robotics.com/recent-works/

Construction Robotics. (n.d.). POFF Federal Building. Retrieved 27 January 2019 from https://www.construction-robotics.com/portfolio-items/poff-federal-building/

Construction Robotics. (n.d.). Erlanger Medical Office Building. Retrieved 27 January 2019 from https://www.construction-robotics.com/portfolio-items/erlanger-medical-office-building/

Eurocodes. (n.d.). Retrieved January 24, 2019 from https://eurocodes.jrc.ec.europa.eu/showpage.php?id=13

German, G. (2019). Plastering robot Okibo. Email to author January 23, 2019.

German, G. (2018). Okibo – Wall rendering robot. Retrieved January 23, 2019 from https://www.youtube.com/watch?v=Q9tC1bwX6EM

Husqvarna. (n.d.). Husqvarna DXR remote demolition robots. Retrieved August 20, 2018 from https://www.husqvarnacp.com/au/machines/demolition-robots/

Husqvarna Group. (n.d.). More than 325 years of innovation. Retrieved August 19, 2018 from https://www.construction-robotics.com/portfolio-items/umhhc-brighton-health-center-south/

Hyttinen, R. (2017). Construction Management. Open lecture on 9 December, 2017, Hame University of Applied Sciences.

Jonathan, R. (2018). Human-level intelligence to be matched by AI by the year 2029. Retrieved December 2, 2018 from http://robots.news/2018-11-21-human-level-intelligence-to-be-matched-by-ai-by-2029.html

Koutsogiannis, An. (2018). German Construction 2018: What's next for the industry? Retrieved September 1, 2018 from https://geniebelt.com/blog/german-construction-2018

Kuka. (n.d.). The history of Kuka. Retrieved August 25, 2018 from https://www.kuka.com/en-se/about-kuka/history

Kymäläinen, K. (2019). Contact [Kuka]. Email to author January 25, 2019.

Menges, A., Schwinn, T. Krieg, O. (2015). Landesgartenschau Exhibition Hall. Retrieved August 28, 2018 from https://www.researchgate.net/publication/293826957_Landesgartenschau_Exhibition_Hall

Meet SAM, the bricklaying robot. (2016). Retrieved January 27, 2019 from https://www.youtube.com/watch?v=MVWayhNpHr0

Neyman, A.(2018). Robot Atlant 4000. Email to author November 22, 2018.

Nocks, L. (n.d.) A Brief History of Robotics Since 1950. Retrieved August 27, 2018 from https://www.encyclopedia.com/science/encyclopedias-almanacs-transcripts-and-maps/brief-history-robotics-1950

Okibo. (n.d.) Retrieved January 23, 2019 from https://okibo.com/

Purkuroboti Brokk 90 ja Brokk 160 2012.wmv. (2012). Retrieved August 22, 2018 from https://www.youtube.com/watch?v=w2sIj9DuCd8

Quirke, J. (2015). SAM the bricklaying robot could be yours for $500,000. Retrieved August 23, 2018 from http://www.globalconstructionreview.com/news/sam-bricklaying-r7o7b7ot-could-be-yours-500000/

RedOrbit. (2013). History of robotics. Retrieved July 20, 2018 from https://www.redorbit.com/reference/the-history-of-robotics/

Tereshenko, A. (2018). Price for new Robot Brokk 90. Email to author 15 November 2018

The Husqvarna DXR 140 demolition robot will go to the VW Transporter. (2018). Retrieved August 20, 2018 from https://www.youtube.com/watch?v=L7ErEL1wsR0

University of Stuttgart. Institute for Computational Design and Construction. (n.d.). Landesgartenschau Exhibition Hall. Retrieved August 25, 2018 from https://icd.uni-stuttgart.de/?p=11173