



# **Robotics in Construction of Concrete and Masonry Structures**

BY  
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## **ABSTRACT**

This research work investigates the current state of the art of robotics in the construction industry as well as in concrete and masonry field. To fully understand the possibilities of implementation of robotics in construction industry, the basic principles of robotics are discussed at first. The general overview of robotics: definitions, brief history, robot's main parts, and recent developments in different fields are covered. The main part of the thesis is focused on the robotics application in construction industry. The main reasons for future robotization of the industry, the advantages and challenges facing the robotics application in construction industry are discussed. Few examples of robots are chosen for review to show the wide range of possible application. At last, the further developments of robotics in construction are mentioned.

***Keywords:*** robotics, building automation, construction robots, concrete structures, masonry structures

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## 1. Introduction

Technological advancements were always one of the key reasons for humanity's growth and progress as a species. The invention of animal-drawn carriages around 5500 BP has marked the beginning of Civilization Revolution. This has greatly improved the ability of humankind to produce and gather food. At the beginning of 18<sup>th</sup> century steam engines were invented and started the Industrial Revolution. However, the greatest revolution that humankind encountered was an Information Revolution, when at the beginning of 20<sup>th</sup> century modern technology was born including the invention of Internet. As some researchers believe now, in 21<sup>st</sup> century "our society is entering a 'robot society'" and we are transitioning into new revolution, Robotics.<sup>1</sup>

There is general misconception about robots, an often image that people get from the entertainment industry or science fiction books. There are countless unrealistic stories about highly intelligent evil robots that destroy human race.<sup>2</sup> Whereas, most modern day robots are produced to assist and help people in tedious or dangerous tasks. Today, the field of robotics is applied in wide range of areas like medical, construction, military, manufacturing or even in space exploration missions.

The application of robotics in construction industry is not that advanced comparing to other fields. Despite being one of the oldest and most economically important sectors, there has been little Research and Development (R&D) of robotics application in construction industry.<sup>3</sup> Nevertheless, the increasing problems with labor shortage, decrease of productivity and concerns for safety of construction workers in the past few years have pushed the researchers to develop new innovative robots for application in construction.<sup>4</sup>

The objective of this research work is to summarize the current state of the art of robotics in the construction industry. Also, this thesis aimed to identify as many as possible applications of robotics in the construction industry and how they can benefit the industry in general. Moreover, further exploring the future prospects and trends in robotics for construction field application.

The first part of this research work covers in brief the current developments in robotics in different kind of fields. Also, main parts of the robot, how they function, move and perform the given tasks will be explained.

The main part of this research is focused on application of robots in construction in general as well as in concrete and masonry field. Following with few examples of already invented robots. At last, the benefits, challenges, social aspects and future developments of robotics in construction industry are investigated.

## **2. General overview of robotics**

### **2.1 Definitions**

#### **2.1.1 Robot**

The word “robot” comes from a well-known play written by a Czech writer, Karel Čapek, R.U.R (‘Rossum’s Universal Robot’) in 1920s. The word “robot” was derived from the word “robota” which means “forced labor”, “drudgery” or simply “work” in Czech, Slovak, Russian, Polish and other Slavic languages. The word’s root “rab” means, “slave” in Slavic linguistic. This perfectly described a play where a human like machines were invented in order to serve their masters and do hard, dangerous, dirty works for them.<sup>5</sup>

Since then, the word robot was used to describe many things, humanlike machines in movies, people that expressed little or no emotion, toys for children or programmable systems controlled by humans.<sup>6</sup> However, today there is not a universally acceptable definition of what is robot and what makes them different from the machines. If a machine suddenly becomes able to do what we normally associate with people, the machine can be upgraded in classification and classified as a robot.<sup>7</sup> All robots are machines, not all machines are robots.<sup>8</sup>

According to a dictionary robot means “a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)”.<sup>9</sup> As for the purpose of this research work simpler definition will be used, the robot is “a machine that can sense, process and act.”<sup>10</sup>

#### **2.1.2 Robotics**

A famous American writer Isaac Asimov is credited for naming the whole branch of science and technology dealing with robotic inventions, Robotics.<sup>11</sup> According to Isaac, robotics is the study

of the design, manufacture, and operation of robots, i.e. machines capable of being programmed to perform mechanical tasks and to move by automation control.<sup>12</sup>

Others define robotics as “the branch of Science, Technology and Art that deals with robots”<sup>13</sup> or simply “technology dealing with the design, construction, and operation of robots in automation”.<sup>14</sup>

## **2.2 Brief history of robotics**

For many decades scientists have attempted to build machines that resembled humans or animals. The earliest robot appears in Greek mythology, a robot named Talos. The writer describes this robot as “artificial servant with the ability of thinking, speech, and locomotion for the Gods at Mt. Olympus, which was built by the blacksmith cum craftsman Hephaestus”.<sup>15</sup>

18<sup>th</sup> century: Early day machines were not that sophisticated to be called robots by modern day standards. However they are important inventions that inspired other scientists in the following years and laid the foundation for the robotics development. In 1738, Jacques de Vaucanson developed an automated duck (Figure 1) that resembled real duck quite well. His duck could flap its wings, make quacking noise, drink water, eat grains and seeds with nearly realistic gulping action.<sup>16</sup> He also invented three humanoids, one that could play mandolin, another piano and the third one could play flute.<sup>17</sup>

19<sup>th</sup>-20<sup>th</sup> century: At the beginning of 20<sup>th</sup> century two inventors made a considerable breakthrough in field of robotics, Thomas Alva Edison and Nikola Tesla. In 1877, Thomas Alva Edison invented a machine that could record and playback human sound, known as phonograph. Whereas, in 1898, Nikola Tesla created a robot-boat that could be remote controlled using a

radio signal. He demonstrated his robot-boat (Figure 2) in a water basin in Madison Square Garden during the Electrical Exhibition.<sup>18</sup>

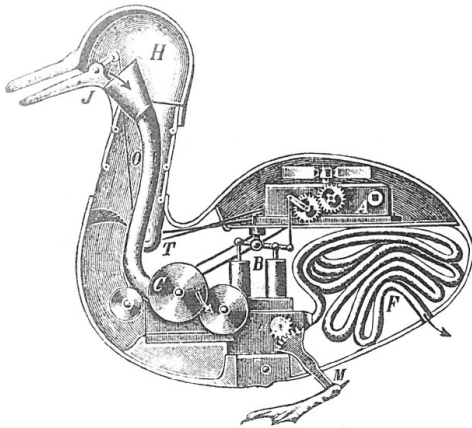


Fig.1 Jacques de Vaucanson's mechanical duck<sup>19</sup>

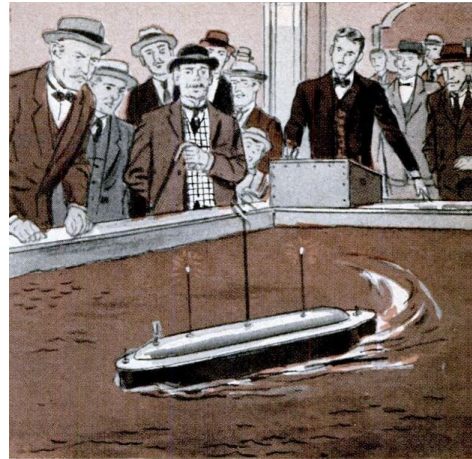


Fig.2 Testing of robot-boat by Nikola Tesla<sup>20</sup>

In the beginning of 20<sup>th</sup> century, building robots was still challenging due to the size of computational technologies that were impossible to fit into a mobile robot. However, the situation changed during 1930s and 1940s when the first digital computers were invented. In 1949, William Grey Walter built first small electronic robot that resembled a 'tortoise'. (Figure 3) It could follow a specified path, avoid obstacles and find a power supply to recharge itself when it run low on battery.<sup>21</sup>

In 1954, Joseph Engelberger and George Devol invented first industrial robotic arm Unimate, and subsequently named their company Unimation. In the following years, they sold many robots to General Motors for the usage in automobile production. Following, in 1978, the Unimation produced their famous PUMA (Programmable Universal Machine for Assembly) (Figure 4) robot and the usage of robots in industrial sector took off worldwide from there.<sup>22</sup>



First humanoid robot Wabot-1 (Figure 5) was built in 1970s in Waseda University in Japan by professor Hirokazu Kato. The robot was controlled by a computer and was equipped with tactile sensors. Also, the robot could communicate in elementary level, walk and hold objects with its hands.<sup>23</sup>

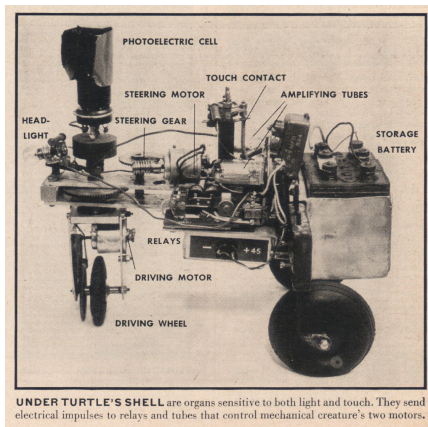


Fig.3 William Grey Walter 'tortoise' robot<sup>24</sup>



Fig.4 PUMA robotic arm from Unimation<sup>25</sup>

In 1988, MIT artificial intelligence lab produced a robot named Genghis. It was a small six-legged robot resembling an insect. It was built with 22 sensors, 4 microprocessors and 12 servomotors. Because of its design it was able to walk on difficult terrains and avoid obstacles easily.<sup>26</sup>



Fig.5 Wabot-1 humanoid robot<sup>27</sup>



Fig.6 Roomba robotic vacuum cleaner<sup>28</sup>

21<sup>st</sup> century: The last few decades saw a boom in robotics development. Currently, there are many kind of robots used in different fields. One example is the popular robotic vacuum cleaner Roomba (Figure 6) invented by iRobot, which was released for commercial use in 2002.<sup>29</sup> The robot can be programmed to turn itself on at certain times and when it encounters an obstacle it backs up and goes around it.<sup>30</sup>

### **3. Main parts of a robot**

#### **3.1 Body**

Generally a robot's body serves a function like human body. It encloses the internal parts giving it the rigid shape and protecting them from the external damage. Also the body provides a structure where other important parts like sensors can be attached.<sup>31</sup>

For economic and efficient design, robot's body should be lightweight, strong and resistant to vibrations. On the other hand, for social or humanoid robots, their structure should be familiar to people to whom it would interact with. Thus, having human like features or friendly structure would considerably increase the robot's efficiency.<sup>32</sup>

#### **3.2 Locomotion**

Locomotion of a robot describes how it moves from one place to another. Traditionally, there were two types of locomotion, robots that had legs and walked or robots that had wheels. However, in recent years many other types of locomotion were invented. Modern day robots can fly, swim or even crawl, allowing them to go to places that are hard to reach for human beings.<sup>33</sup>

When designing the type of locomotion the end purpose of the robot should be taken into account. Modes of locomotion all have trade-offs: one, two or four legs, wheels, and treads are all limited by the smoothness of the terrain. Also, multi-legged locomotion increases robot's complexity and requires more power than wheels or treads need to travel the same distance.<sup>34</sup>

### 3.3 Sensors

The same as humans have five sense organs; robots need to have sensors to function in real world. Sensors receive information from the environment and send electric signals to the control unit.<sup>35</sup> Robots can have simple sensors only for the purpose of moving through specified path or more complex ones. In most basic level sensors keep robots from crashing into some objects or make it possible to navigate in light and darkness.<sup>36</sup>

The basic visual sensors include cameras that transmit visual information in form of images to the control unit. It helps robot to recognize shape, color, size and distance of an objects.<sup>37</sup> Other sensors might include touch sensors or microphones for sound detection.<sup>38</sup>

More advanced sensors could be laser range finders, that work by measuring the time it takes for a laser beam to reflect from an object and come back to the source of the signal. Alternative sensors could be Global Positioning System (GPS), acoustic range finders, and motion sensors to mention few.<sup>39</sup>

### 3.4 Power supply

Every robot needs some kind of power source to function. Robots that need to move around usually use battery, while the stationary robots like manufacturing robots usually use three main types of power supplies: electric, hydraulic, and pneumatic power.<sup>40</sup>

Most robots run on electrical power supply, usually DC (Direct Current) supply of 5V up to 36V are used. Hydraulic power uses non-compressible fluid like for example oil. This kind of power source is used for works that need high amount of force and precision. On the other hand, pneumatic power uses compressible gas as a source of energy. The advantage of pneumatic power is that the exhausted air goes back into the atmosphere.<sup>41</sup>

### **3.5 Manipulator**

Depending on the purpose of the robot the manipulators can have different shapes and sizes. They serve as an arm for a robot that interacts with the physical world. For industrial robots it is usually stationary arms.<sup>42</sup>

The simplest manipulators have three Degrees of Freedom (DOF), which describes the number of axis that it can move. Robots with three DOF can move in x-axis up and down, in y-axis back and forth and in z-axis rotate. The higher DOF of a manipulator the more complex is the robot.<sup>43</sup>

### **3.6 End effectors**

End effectors are attached to manipulator arm to do specific tasks. Depending on the purpose of the robot the end effectors can be grippers like human fingers, hammers, spikes or even screwdrivers.<sup>44</sup>

### **3.7 Control system**

Control system is a 'brain' of a robot. All the information gathered through sensors transmitted to control system and processed as a data. Most industrial robots are preprogrammed, they repeat same tasks over and over again and do not require complex encodings. However, the recent developments were centered in adding Artificial Intelligence (AI) into the control system. AI would eliminate the need to preprogram robots and it would enable them to learn from its experiences and make decisions based on the received data.<sup>45</sup>

## **4. Modern day robots**

### **4.1 General**

Very first robots were developed for industrial field application especially for car manufacturing that freed workers from hard, manual and repetitive work.<sup>46</sup> However, today robots are developed in wide range of fields. In the last few decades there have been a great amount of robotic inventions in the fields like military, construction, medicine, and even for social purposes.

Well known Segway scooter is one of the few examples, it is powered by a battery and uses specific sensors to keep its balance.<sup>47</sup> Other robots include: social robot like Roomba, is helping humans to clean the house,<sup>48</sup> small tunnel-crawling robots are used for inspection of pipes that are hard to reach for workers,<sup>49</sup> simple humanoid robots are used as a museum guides.<sup>50</sup> It is not possible to list all of the robotic developments here but few important robots were mentioned in the following examples.

### **4.2 Robots in different fields**

#### **4.2.1 Robotics application in medical field**

##### ***4.2.1.1 Surgical robots***

Robots in surgical operations have been used in medical field for almost two decades now. Most robotic developments intended to augment the medical staff rather than replacing them. These robots are equipped with enhanced monitoring systems and improve the precision of the surgery. One example is Da Vinci system (Figure 7) from Intuitive Surgical. The robot consists of a 3D

camera that is placed through a small incision inside of a patient and displays the image on the monitor. The robot comes with three to four robotic arms equipped with surgical instruments and the surgeon can control them remotely from the monitor.<sup>51</sup>

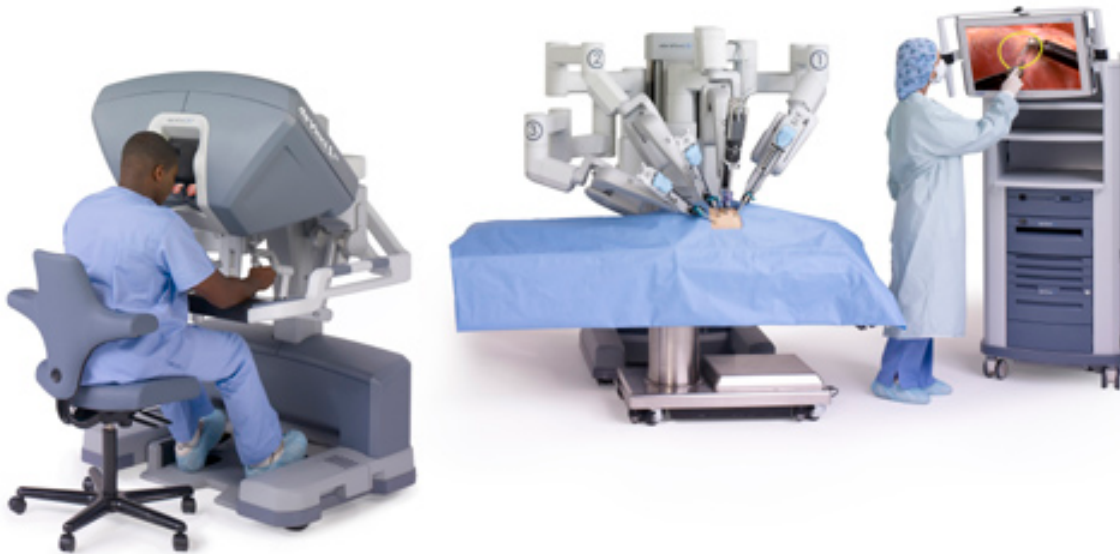


Fig. 7 Da Vinci robotic surgery assistant<sup>52</sup>

#### ***4.2.1.2 Robotic prosthetics***

Prosthesis is an artificial device used for substituting or aiding human parts such as limbs, heart valves, eyes and hearing deforms. It is estimated that around 45 million amputees exist throughout the world. Robotic prosthetics (Figure 8) is an enhanced form of limb prosthesis. It works by transmitting signals from a patient's brain nervous system to the prosthetic limb actuator through its biosensors. Thus, making it possible to control the limb by thoughts.<sup>53</sup>

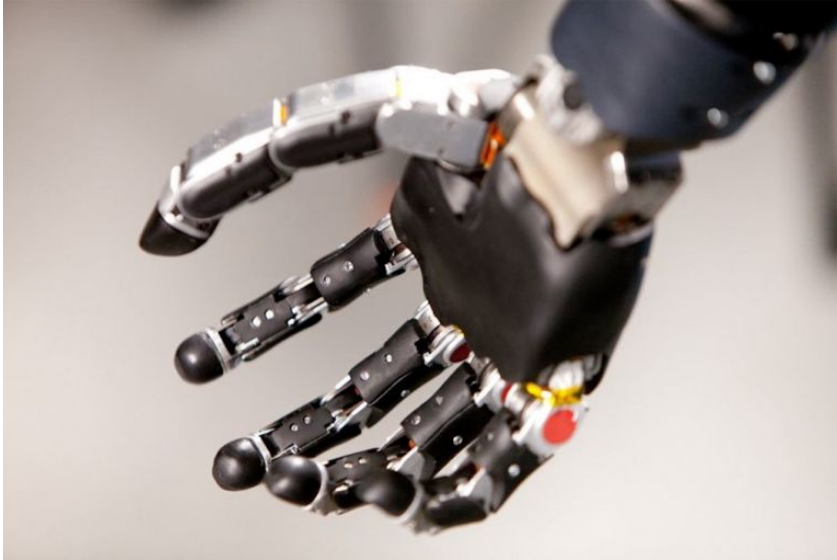


Figure 8. First robotic prosthetic arm <sup>54</sup>

## **4.2.2 Robotics application in military**

### ***4.2.2.1 Humanoids***

A lot of research and funding has been done by the United States military DAPRA (the Defense Advanced Research Projects Agency) for robotic applications in military.<sup>55</sup> The military robots are not only designed for combat purposes but also they are used for search and rescue. One example is Atlas (Figure 9), humanoid robot. It was designed to use in disastrous events like nuclear accidents or natural disasters. The Atlas can move through obstacles, resist radiation and other harmful conditions.<sup>56</sup>

### ***4.2.2.2 Unmanned Ground Vehicles***

Unmanned Ground Vehicles (UGVs) can move by wheels and tracks, or by two legs. The tracked UGVs have been used extensively in military in the last two decades, especially in



Middle East. A PackBot robot (Figure 10) from iRobot is a remotely controlled tracked UGV. It has been used to find and dispose thousands of bombs in the war zone.<sup>57</sup>

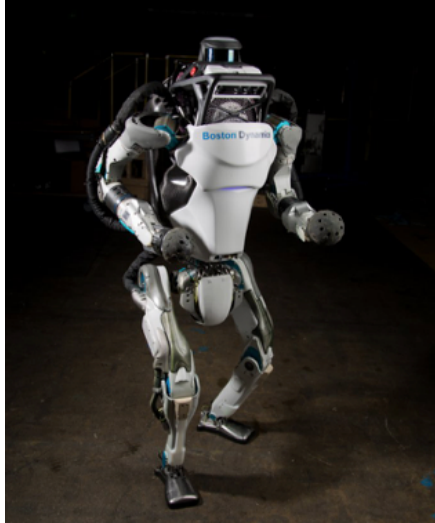


Fig. 9 Atlas humanoid robot <sup>58</sup>



Fig. 10. PackBot by UGV for military use. <sup>59</sup>

### 4.2.3 Industrial robots

Traditionally, industrial robots were designed to replace humans in repetitive, dirty and boring tasks. In addition to that, industrial robots provide more precision and accuracy, increased productivity that directly relates to decreased costs. For example, human workers can weld a car frame for 4 to 6 hours, while welding robots can finish the same amount of work in 90 minutes.<sup>60</sup>

#### 4.2.3.1 Robotic arms

Robotic arm (Figure 11) is the most common type of robot used in manufacturing. It can be classified according to its ability to move or rotate in space. Cartesian robots move in traditional x,y,z axis; while, cylindrical and spherical arms can in addition rotate. Articulated robots have

more complex abilities to move, thus they are used for more complex works like welding.<sup>61</sup>  
Today, most industrial robotic arms are used in car manufacturing factories worldwide.<sup>62</sup>



Fig. 11 Robotic arm welding a car frame.<sup>63</sup>

#### **4.2.4 Space exploration robots**

Designing robots for space exploration have been a main interest since the 1970s. Sending robots to space is much more efficient and safer than sending astronauts. Comparing to humans, robots do not need to rest, eat or comfortable conditions to function. On top of that, they can survive in inhabitable environments.<sup>64</sup>

##### ***4.2.4.1 Rovers***

Famous rovers that were used for exploration of Mars planet are Spirit (2004) and Opportunity (2004). These rovers were used for observational purposes. Following in 2012, more sophisticated rover named Curiosity (Figure 12) was send to Mars. It had ability to take a sample from the soil and even conduct geological surveying.<sup>65</sup>



Fig. 12 Curiosity rover by NASA on its mission on Mars <sup>66</sup>

#### ***4.2.4.2 Humanoids***

Valkyrie (Figure 13) is a humanoid robot invented by NASA (National Aeronautics and Space Administration). It is 190 cm tall and weighs about 136 kg, it was designed with the mission to colonize Mars planet in the far future. Valkyrie consists of high definition cameras on its head, 38 sensors on each hand, few motors that control 44 degrees of freedom.<sup>67</sup>



Fig. 13 Valkyrie humanoid robot from NASA <sup>68</sup>

## **5. Robots in construction industry**

### **5.1 General**

For most countries the construction industry accounts to be one of the biggest economical sectors. In developed countries construction industry contributes 10% to GDP (Gross Domestic Product), while in developing countries it contributes more than 25%.<sup>69</sup> Also, it is estimated that about 2.7 million enterprises in EU work in this sector.<sup>70</sup> Nevertheless, comparing to other fields there has not been much progress in robotics for the last few decades.

Robotic application in construction industry is relatively new topic. First robots for construction application were developed in late 1970s. At that time robots were merely used to improve the quality of prefabricated elements, while today the researchers are more focused on inventing new robots for the construction site application.

### **5.2 Developments in different countries**

In general, the robotics development is increasing rapidly in the past few years. One example is the manufacturing field. In manufacturing the automation has increased from 66 robot units per 10,000 workers in 2015 to 74 in 2018 worldwide. According to the International Federation of Robotics (IFR) leading countries in robotics development are South Korea, Singapore, Germany, Japan and USA. The following graph (Figure 14) compares the density of robots used in industrial application in different countries.<sup>71</sup>

As for construction robots, developments are considerably different in the Eastern and Western parts of the world. For comparison developments in Japan versus in USA are considered.

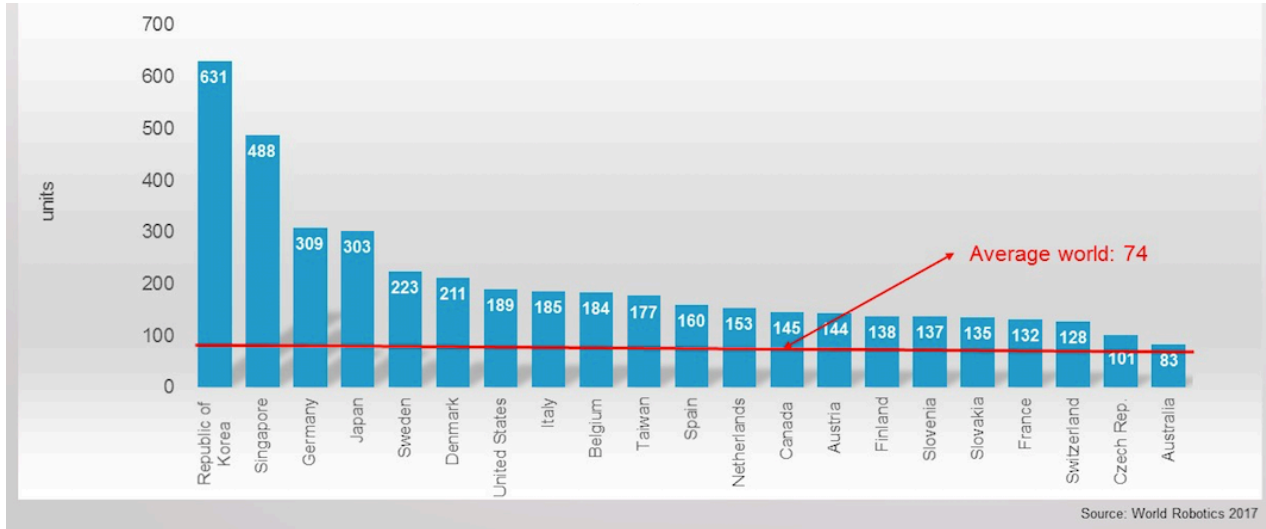


Fig.14 Graph of industrial robots per 10,000 employees in different countries.<sup>72</sup>

### 5.2.1 Robotics development in Japan

Robotics development in construction sector is highly influenced by the social demand and demographics. Japan has been a leading country in Research and Development (R&D) in robotics application for the construction industry.<sup>73</sup> This is connected with the low birth rate that is causing a steady decrease of population and labor shortage.<sup>74</sup> Also, the studies show that employment rate in Japan will drop by 70% by the year 2045.<sup>75</sup>

In Japan, the construction work is viewed to be dirty, hard and dull by the younger generation, thus making it challenging to find new workforce. Not only robots improve the productivity and efficiency in the construction work, also it would improve the image of the construction industry, consequently attracting the millennial.<sup>76</sup>

Thus far, most construction site robots were developed and tested in Japan. Over 200 prototypes of robots were tested, including robots for concreting, concrete treatment, fire protection for steel structures and spray paint finishing.<sup>77</sup>

### **5.2.2 Robotics development in USA**

Comparing to Japan, developments in USA is falling far behind. Generally, the demand for robots in USA is weak because of the cheap labor supplied by high number of immigrants. In USA most construction work owners believe that training unskilled workers is more practical than investing in expensive robots. Therefore, instead the researchers are more focused on developing different software that would benefit the construction field.<sup>78</sup>

## **5.3 Need for robots**

Construction industry is said to be lagging behind the manufacturing industry by 20 to 30 years in terms of its technological progress.<sup>79</sup> Conventionally, construction industry has not been a favorable field for robotics application. However, the various issues connected with technical, economical and social aspects of construction industry have motivated to develop robots in recent years.<sup>80</sup> Social factors may include the increasing urbanization and concerns for the safety of construction workers. Technical and economical aspects include the overall decrease of productivity in the construction industry.

### **5.3.1 Increasing urbanization**

With the increasing urbanization a need to accommodate more people in big cities has grown. According to the research done by the United Nations (UN), currently the world's 55% of

population is living in the cities and this number will increase to 68% by 2050 (Figure 15). This is estimated to be adding more than 2.5 billion people to urban inhabitants worldwide.<sup>81</sup>

### Urban and rural population projected to 2050, World

Total urban and rural population, given as estimates to 2016, and UN projections to 2050. Projections are based on the UN World Urbanization Prospects and its median fertility scenario.

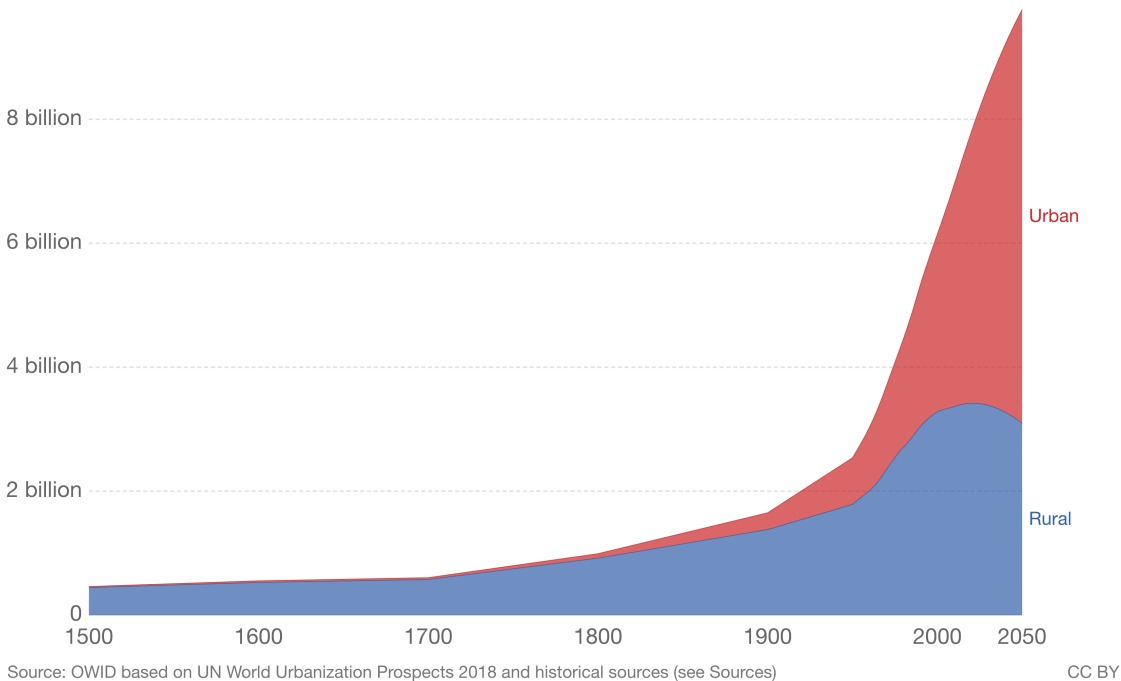


Fig. 15 A graph of increasing urbanization.<sup>82</sup>

### 5.3.2 Concerns for safety of workers

Another driving force for application of robots in construction industry has been the issue with the workers safety. Traditionally, construction work is considered to be one of the most dangerous occupations. According to the studies conducted by the Bureau of Labor Statistics (BLS) on Census of Fatal Occupational Injuries (CFOI) the construction industry is on top of four occupations of total fatal injuries per workers (Figure 16).<sup>83</sup>

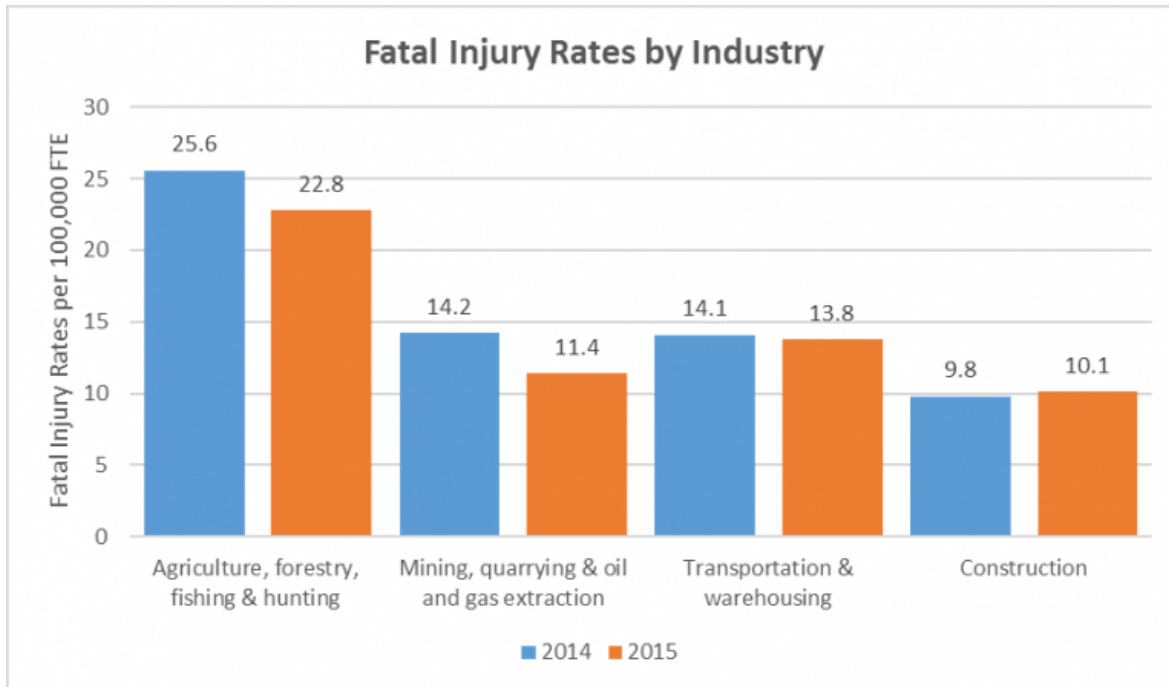


Fig. 16 Graph of fatal injury rates by industries 2014-2015 <sup>84</sup>

### 5.3.3 Decrease of productivity

The recent studies show that productivity in construction industry is decreasing throughout the world. This is connected with the low number of technological inventions and most part of the work is still done manually. For example, a study in Japan (Figure 17) shows the comparison of productivity between the manufacturing industry and the construction industry in the past two decades.<sup>85</sup>

Another factor is the average wage of construction workers has been increasing steadily for the past few years. This increase is influenced by the shortage of skilled professionals, as the old generation of workers is retiring and the younger generation is becoming less attracted to construction work.<sup>86</sup>



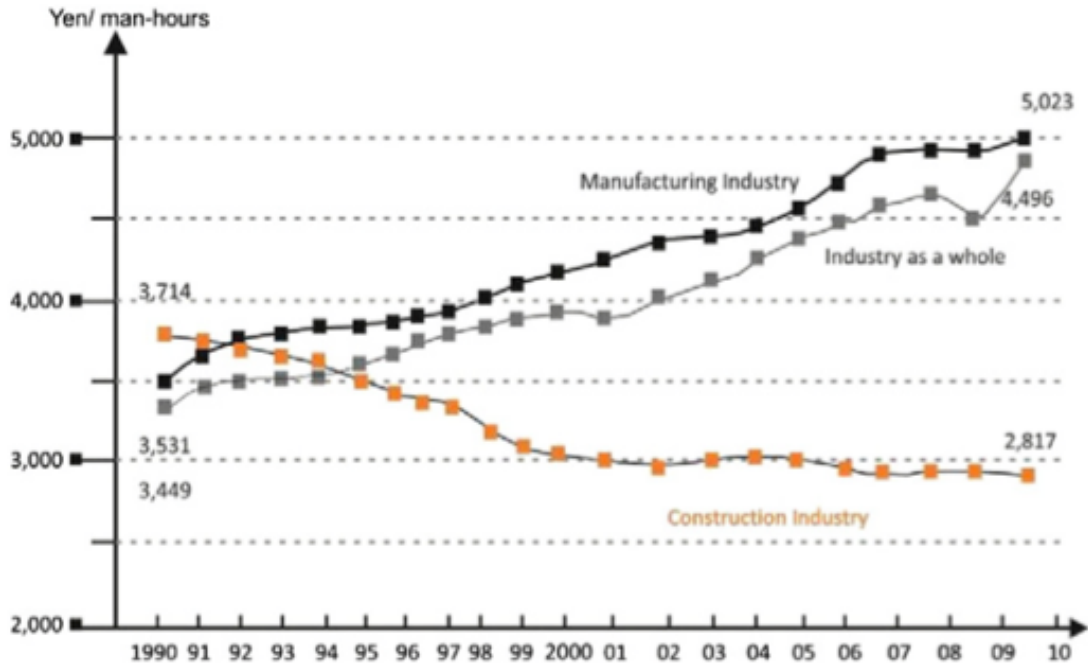


Fig. 17 Productivity report manufacturing industry vs. construction.<sup>87</sup>

## 5.4 Advantages of robots in construction

The productivity of construction processes can be increased tremendously by introducing robots in it. Robots can work almost without break, do not need to sleep, do not need health insurance or comfortable working conditions the same as human workers need.<sup>88</sup> In developed countries with high labor costs, the robotization of construction processes can reduce the expenses by more than 40%.<sup>89</sup>

Furthermore, robots can replace human workers in environments that are dangerous or unsafe for them. For example, robots can be used for building structures on former nuclear accident places, underwater or even on another planets.<sup>90</sup>

Other advantages of implementation of robots include: better quality, because of the higher accuracy of robots; increased control over construction process by easy monitoring; ecological benefits, such as producing minimum material waste.<sup>91</sup>

## **5.5 Challenges of implementation of robots in construction**

The biggest challenge in implementing robots in construction industry is the unpredictable working site conditions. In manufacturing for example, robots work in factories mostly installed in one place, whereas on the construction site robots need to have an ability to move on uneven terrain, avoid obstacles and withstand harsh weather conditions.<sup>92</sup>

Another challenge is that every construction task is unique. It requires instant adjustments and adaptability depending on the situation. Thus, it is impossible to predict all events and preprogram the robot. Unless the artificial intelligence will be utilized in the future, robots are more suitable for repetitive tasks.<sup>93</sup>

## **5.6 Examples of robotics application in construction**

There are many types of robots that are utilized for construction industry today, whether they are remote-controlled or semi-autonomous. These robots are applied for construction sites, installation and finishing works.<sup>94</sup> However, because of the unpredictable and complex nature of the construction work, it is hard to fully robotize the construction process.

Following table (Figure 18) suggest a level of tasks that could be potentially robotized. From the table it can be seen that the last three tasks are favorable for robotics application due to its repetitive nature.<sup>95</sup> In the following sections few examples of robots were selected to show a wide range of possible application of robotics in construction process.

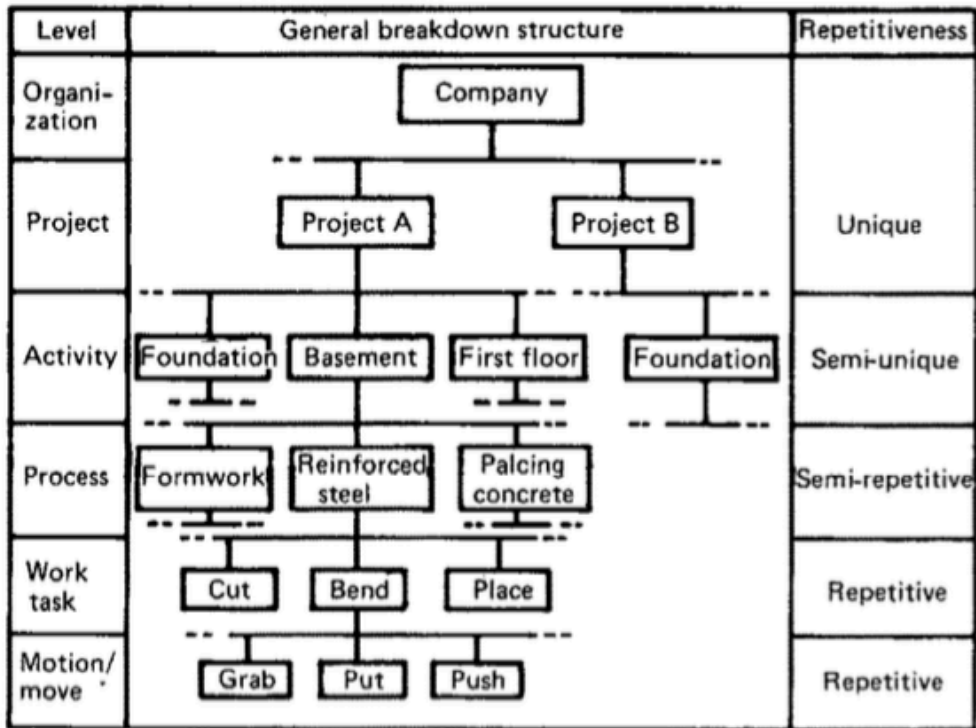


Fig. 18 Example of repetitive tasks where robotics can be applied.<sup>96</sup>

### 5.6.1 Demolition robots

Demolition robots (Figure 19) are remote-controlled robots that are used to demolish old buildings as well as for usage in renovation works. Because they are compact and easily transported they can be used in confined areas. They can be controlled and monitored from a distance, consequently protecting human worker from a potential harmful contaminants in the air.<sup>97</sup>

Demolition robots can be classified into three types: multi-tooled, hydropowered and eco-friendly. For multi-tooled demolition robot (Figure 20) the end effectors can vary depending on the task. Hydropowered demolition robot uses high-pressure water and is useful to demolish weak concrete because the water eliminates the dust coming from the process. Eco-friendly robot (Figure 21) works by removing old concrete structures with the help of high water jet system.

Afterwards, the removed material is directly sucked back into the robot, processed and separated into aggregate and filtered water that are later reused in construction.<sup>98</sup>



Fig. 19 Demolition process with the help of a robot.<sup>99</sup>



Fig. 20 Multi-tooled demolition robot by Husqvarna.<sup>100</sup>



Fig. 21 Eco friendly ERO robot.<sup>101</sup>

### 5.6.2 Welding robots

Welding is considered to be highly specialized work in construction. To perform precise and good quality welding the professionals usually need to have many years of experience. While, to develop welding robots only few professionals who know how to weld are needed to preprogram the robot.<sup>102</sup>

The latest developments include a steel column-welding robot by Shimizu Corporation in Japan. The Robo-Welder (Figure 22) is an improved version of already existing stationary welding robots. The robot has a manipulator with welding end effector and with the help of laser sensors it determines the contours of a column where it needs to weld. The benefit of the robot is that it is mobile and can be used on construction site.<sup>103</sup>

Other example is a welding robot (Figure 23) developed by Obayashi Corporation for welding beam-to-column connection. It was developed for their fully automated robotic construction system but also it can be used separately. This robot consists of two manipulators installed on a frame and it needs to be attached to the beam for a support.<sup>104</sup>





Fig. 22 Welding robot from Shimizu corporation.<sup>105</sup>

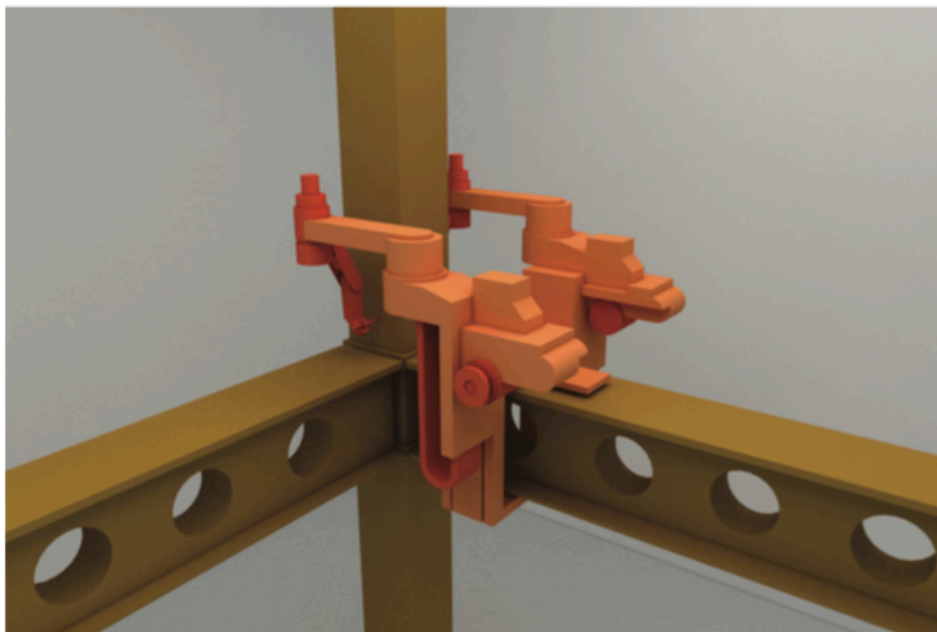


Fig. 23 Scheme of a beam-to-column welding robot.<sup>106</sup>

### 5.6.3 Drones

Drones are remotely controlled small aircrafts, also called Unmanned Aerial Vehicles (UAVs). Drones can be used in a wide range of fields because their size and shape can be customized according to their intended application. Three types of drones can be used in construction: transportation, surveying and monitoring.<sup>107</sup>

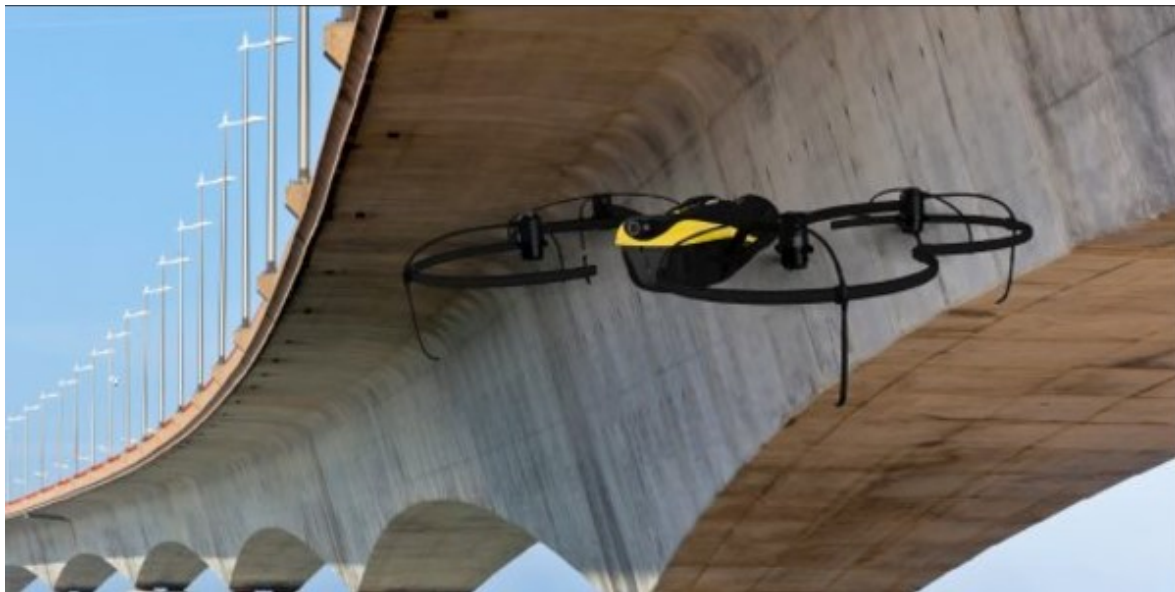


Fig. 24 Bridge inspection test with a drone in Ohio, US.<sup>108</sup>

Surveying drones can be used for high-rise buildings or bridges, in locations that are hard to reach for humans. With addition of special software, drones can also inspect defects in bridges (Figure 24). Moreover, they can be used for surveying and measuring landforms (Figure 25) by taking aerial images.<sup>109</sup>

Monitoring drones (Figure 26) can be used on construction site. They can monitor the process of site work or the degree of completion of works. Also, they are useful for monitoring the site for security reasons when workers are absent.<sup>110</sup>



Fig. 25 Land surveying with drones.<sup>111</sup>



Fig. 26 Monitoring drones.<sup>112</sup>



Drones can be efficiently used for transportation of materials to high locations. The advantage of using drones for lifting heavy materials is that many drones (Figure 27) can lift the object at the same time.<sup>113</sup>

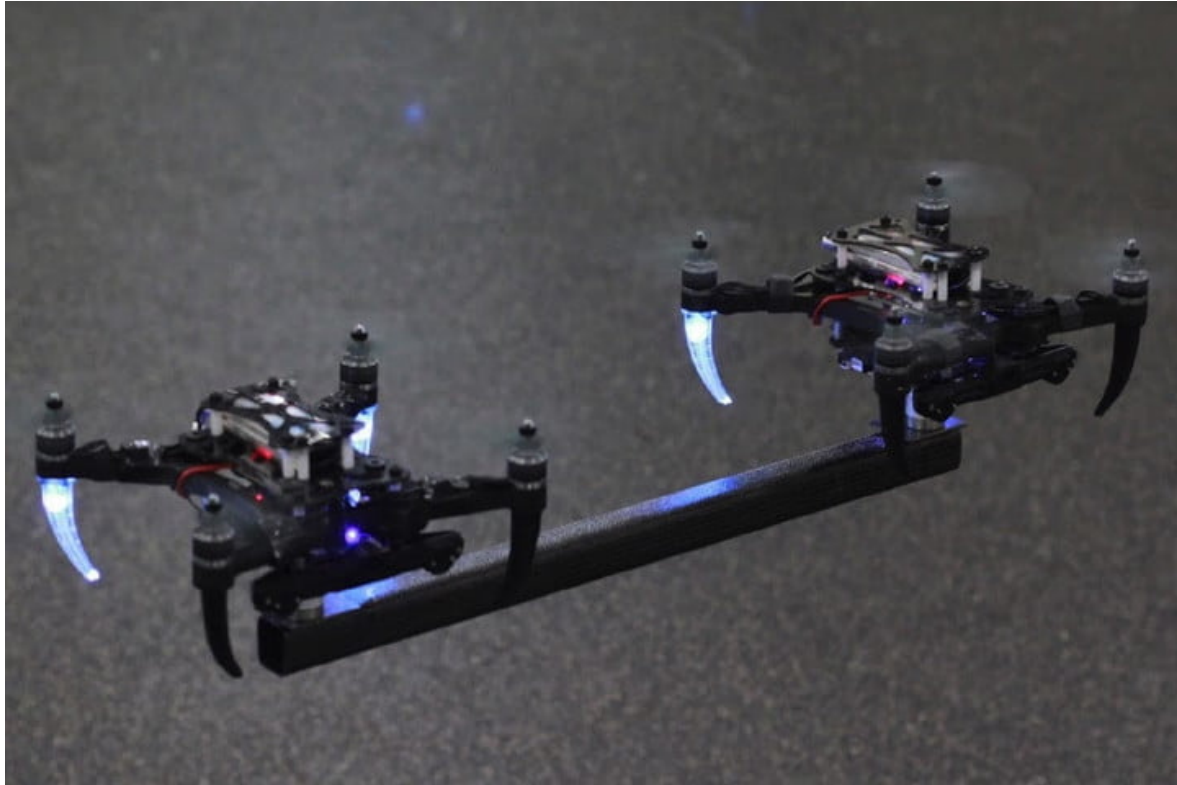


Fig.27 Test of drones for lifting an object.<sup>114</sup>

#### **5.6.4 Exoskeletons**

Exoskeleton is a wearable robotic suit that enhances physical ability of the person who is wearing it. It was mainly designed and used for military and medical fields; nevertheless, the suit has been slightly modified for the use in construction. It will greatly amplify a person's ability to handle and endure heavy loads.<sup>115</sup>

The latest development in exoskeleton is a Guardian XO Max (Figure 28) that is planned to be commercially available in 2020. It is a full-body exoskeleton and functions on batteries that

last up to eight hours. The exoskeleton decreases the lifted weight with the ratio of 20 to 1, which means 45 kg object would feel like lifting only 2,3 kg.<sup>116</sup>



Fig. 28 Guardian XO Max exoskeleton.<sup>117</sup>



Fig. 29 FORTIS exoskeleton demonstration.<sup>118</sup> [85 p. 207]

FORTIS (Figure 29) is a simpler version of exoskeleton that weights less and assists in less demanding tasks. The exoskeleton has a manipulator arm with end-effector replaced with desired tools. The exoskeleton supports and balances the worker during the welding or grinding operations. It will help workers do a repetitive work for longer period of time.<sup>119</sup>

### 5.6.5 Earthwork robots

Earthwork is on of the most demanding works in construction. The Unmanned Ground Vehicles (UGVs) whether remotely-controlled or preprogrammed can be used for works like excavation.<sup>120</sup>

The Built Robotics developed an Autonomous Track Loader (ATL) (Figure 30) that is used for digging and loading a soil. It is equipped with a LIDAR laser mapping technology and machine control sensors that allow it to operate autonomously without a driver.<sup>121</sup>



Fig. 30 Autonomous Track Loader from The Built Robotics.<sup>122</sup>

### 5.6.6 Inspection robots

Unmanned rovers were developed for the inspection of completed construction works on site. Doxel (Figure 31) is the latest development in inspection robots. It scans and measures (Figure 32) the quality of the construction work with the help of Lidar 2D scanning technology and 3D schematic deep learning algorithm. It can navigate through rough terrain and even climb stairs.<sup>123</sup>



Fig. 31 Doxel inspection robot.<sup>124</sup>

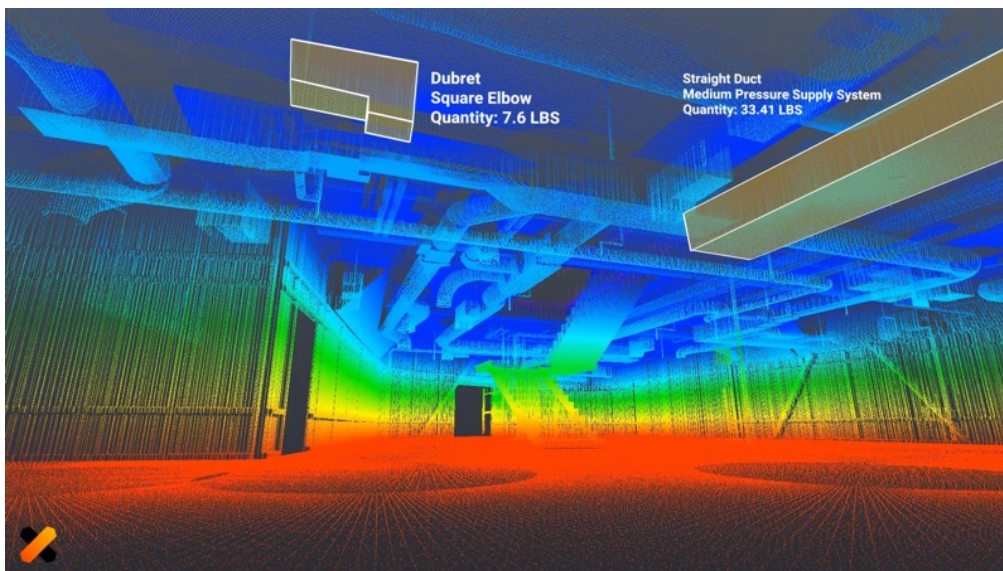


Fig. 32 Scanned construction site by Doxel robot.<sup>125</sup>



For inspection of building facades C-Bot robot (Figure 33) was developed. This robot looks like insect and has multiple legs that help it to crawl on the surface of a building. With the help of its ultrasonic sensors it can easily detect any cracks or damages in concrete and sings of corrosion in steel. The end-effectors are made of special pads that have tiny hair particles on microscopic level. They allow the robot to fully adhere to the surface without any external support.<sup>126</sup>



Fig. 33 C-bot wall inspection robot.<sup>127</sup>

### 5.6.7 Painting robots

Exterior wall finishing works are not only time consuming but also require accurate and even application of paint. Also, manual painting of walls of high-rise buildings might be difficult and unsafe for workers. Painting robots can paint in high accuracy thanks to multiple spray nozzles, controlled speed and pressure. These robots are usually used for areas larger than 2000 m<sup>2</sup> considering the costs for acquiring them.<sup>128</sup>

The SB Multi-Coater robot (Figure 34) developed by Shimizu Corporation is designed to spray paint facade of a medium to high-rise buildings. The robot has two manipulators, sensors

and control unit installed on a main body that moves up and down along the facade of a building. The SB Multi-Coater can paint about 400 m<sup>2</sup> of area per day comparing to human workers that can paint maximum 80 m<sup>2</sup>.<sup>129</sup>

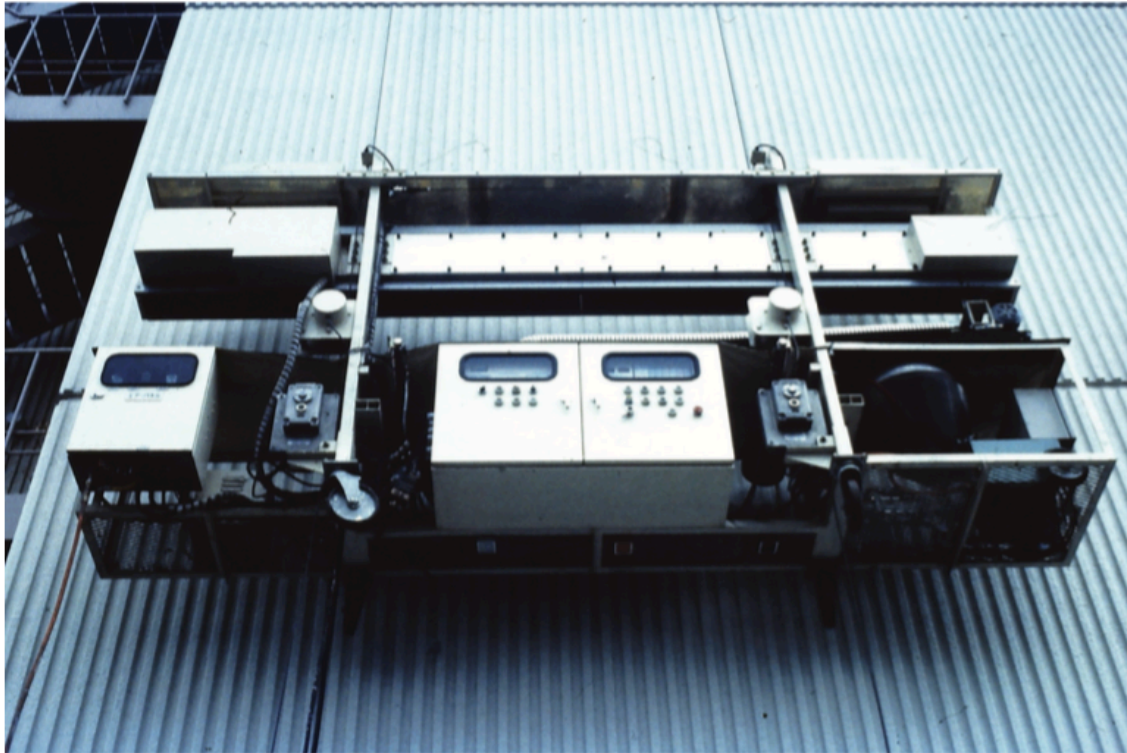


Fig. 34 front view of SB Multi-Coater robot.<sup>130</sup>

### 5.6.8 Automated construction systems

Because of the dusty and dirty nature of construction site it is difficult to fully robotize the construction process. To solve this problem few research and developments were focused on developing a full factory like robot system.

One of the first systems was developed in Japan, the Shimizu Manufacturing system by Advanced Robotics Technology (SMART) (Figure 35). The SMART system was tested for the first time in 1991 for a construction of twenty-story building and the entire system weighed

about 1200 tons. It consisted of a fully robotized weatherproof warehouse facility on top of the building. Including a jack-up frame on which different kinds of robots were installed: like welding, material handling and inspection. As the work progressed and one floor finished the whole frame system moved up to work on the next floor. The whole robot system is designed to do about 30-70% of the construction work on each floor.<sup>131</sup>



Fig 35. Visualization of a robotic system.<sup>132</sup>

Recently this technology was improved by a Robot-based Construction Automation (RCA) research center in Korea. They developed a similar system (Figure 36) that weighted 200 tons and focused on steel beam assembly work.<sup>133</sup>

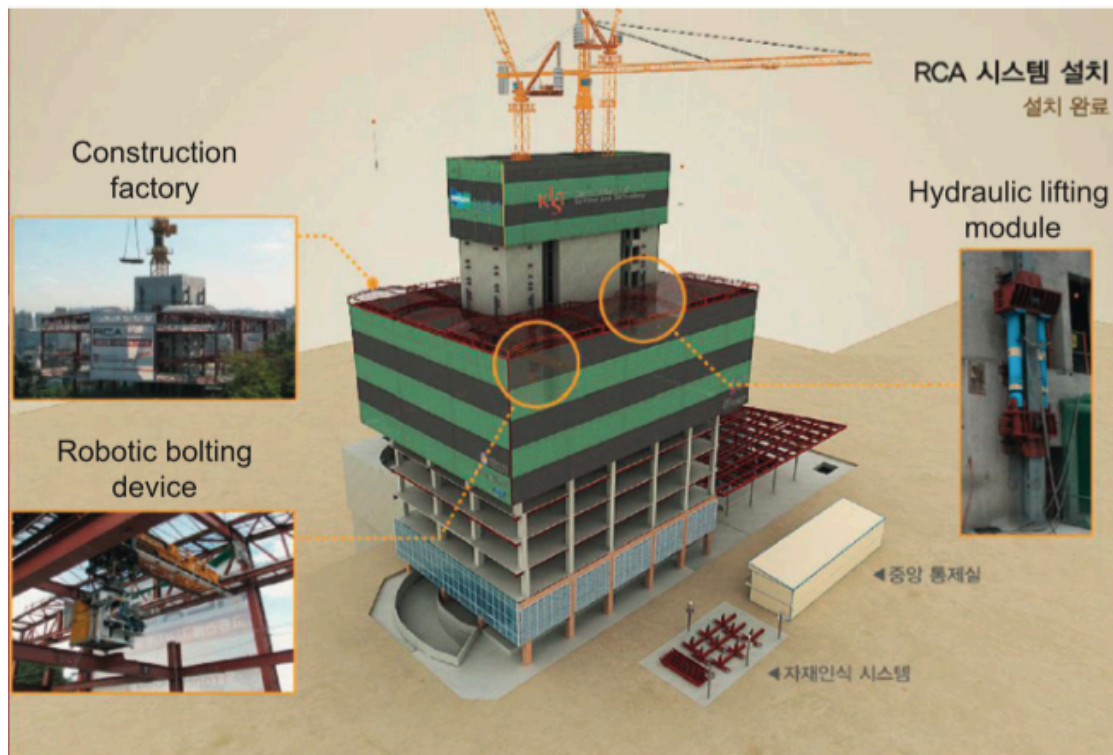


Fig 36. Steel beam assembly fully robotized system.<sup>134</sup>



## 6. Robots in concrete and masonry field

### 6.1 Examples of robots

#### 6.1.1 3D printing robots

One of the recent inventions, three-dimensional (3D) printing might completely change how structures are built in the future. Initial installation of the robot might take some time but once it is installed it can tremendously increase productivity of construction work. 3D printing will minimize waste of materials, decrease time consumption and will be able to easily create complicated shapes.<sup>135</sup>

3D printing works by reducing 3D model of an object into 2D sequence of layers in a computer program. Afterwards, a robotic arm (Figure 37) prints the model in layers, adding each layer on top of another one.<sup>136</sup> Wide range of materials can be used for 3D printing like plastic resins, metals, wood and carbon fibers or concrete.<sup>137</sup>



Fig. 37 An example of 3D printing robotic arm.<sup>138</sup>

The future prospects show that by 3D printing, a structure can be built in a matter of one to two days that conventionally took months.<sup>139</sup> For example, a Shanghai building company built 10 small family houses in a day, for a total cost of less than \$5,000.<sup>140</sup> Also, recently in Shanghai a world's largest 3D printed bridge was built (Figure 38a). It is 26.3 meters long and 3.6 m wide and was printed using two robotic arms in 450 hours.

Researchers still did not come up with a single way to incorporate steel reinforcement for 3D printed structures. The bridge was designed as an arch structure so that the whole cross-section would be in compression, eliminating a need for a steel bar reinforcement. The pavement of the bridge was made of plain concrete and printed in hollow shapes and filled with white pebbles (Figure 38b).<sup>141</sup>



Fig. 38a 3D printed bridge in Shanghai.<sup>142</sup>





Fig. 38b The process of building the bridge pavement.<sup>142</sup>

### 6.1.2 Steel reinforcement placing robots

Manually placing reinforcing steel bars can be time consuming. Also, over time it can cause severe health problems for workers from lifting heavy bars. Especially, reinforcing bars used for

large works like foundation are longer and heavier. The Kajima Corporation developed a reinforcement-placing robot (Figure 39) that can be used on construction site. This robot moves on a track and has steel bar handling end effector connected to the manipulator. It can carry around twenty bars at once and place them one by one at the specified distances.<sup>143</sup>



Fig. 39 Reinforcement positioning robot.<sup>144</sup>

### 6.1.3 Concrete laying robots

Concrete laying robots can lay concrete more evenly and faster than human workers. One example is a robot (Figure 40) from Takenaka Corporation. Due to its compact size it can be used for in-situ concrete slab works. The manipulator can extend up to 20 meters in radius and it can be fixed to a column or any other vertical stand for a support. The robot can work



automatically according to the preprogrammed specifications or manually by a worker who can adjust the speed and direction of concrete pouring where it is needed. Although, the robot was only tested and not commercialized yet, the tests showed that by using this robot the amount of manual work done by construction workers was decreased by 30%.<sup>145</sup>



Fig. 40 Scheme of a concrete laying robot.<sup>146</sup>

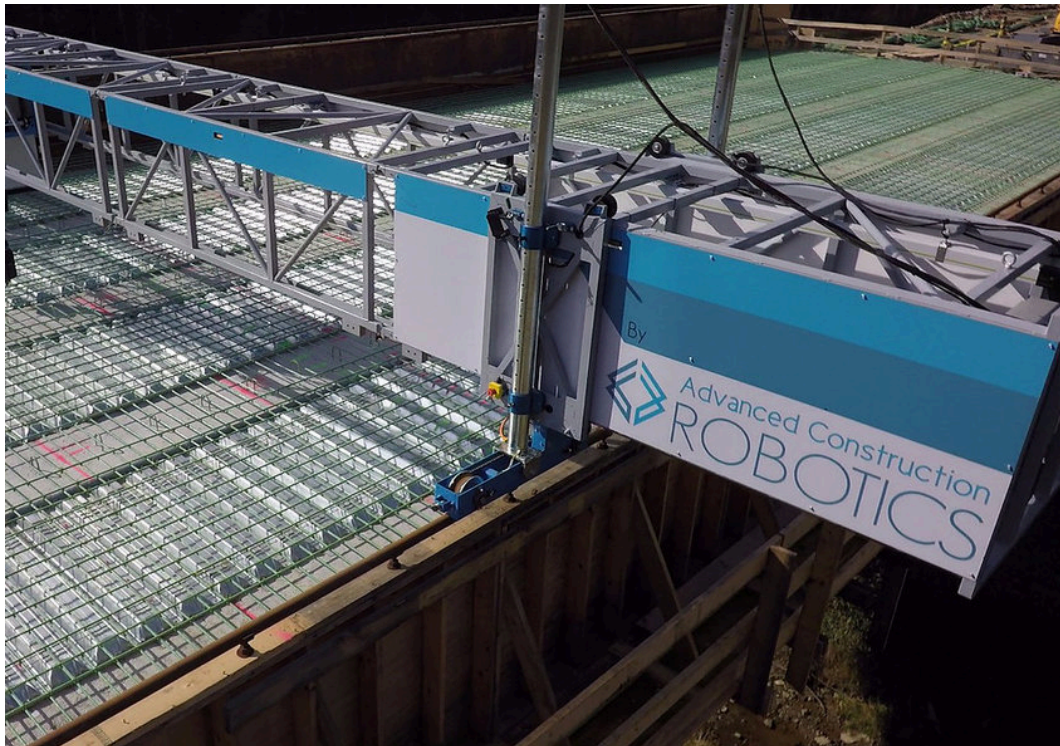


Fig.41 TyBot robot on the construction site.<sup>147</sup>

#### 6.1.4 Steel reinforcement tying robots

Recently Advanced Construction Robotics (ACR) developed a reinforcement tying TyBot (Figure 41) robot in US. Traditionally, the work has been done manually and took many hours to complete. It is useful robot for large works like bridge construction. It consists of a robotic arm moving on a crane and with the help of sensors the robot identifies the junctions where it needs to put the ties.<sup>148</sup>

#### 6.1.5 Concrete floor finishing robots

At the final stage of floor concreting workers usually spend many hours in bend position to manually smooth the surface by trowelling. Few companies invented trowelling robots to increase the time and quality of completion of this process. One example is a Surf Robo robot (Figure 42) from Takenaka Corporation. The robot is equipped with eight trowels connected to two end effectors and can be preprogrammed or remotely controlled. The required speed and amount of pressure to be applied can be adjusted according to the desired finish.<sup>149</sup>



Fig. 42 Surf Robo concrete finishing robot.<sup>150</sup>

## 6.2 Detailed review of bricklaying robots

### 6.2.1 General overview

There are many building materials that are simpler to construct on the site like precast concrete or timber elements. Nonetheless, brick materials are still widely used for construction today. In addition, bricks are produced in wide range of shapes and types. In the past there have been many attempts to robotize bricklaying process but recently two companies were successful to commercialize their bricklaying robots: Fastbrick Robotics and Construction Robotics.<sup>151</sup>



Fig. 43 Hadrian X robot.<sup>152</sup>

## 6.2.2 Hadrian X robot by Fastbrick Robotics

### 6.2.2.1 How robot works

Hadrian X (Figure 43) is a robot developed by an Australian company, Fastbrick Robotics. The robot consists of a large manipulator arm and the base is attached to a truck to easily transport it to the construction site. Depending on the site conditions, additionally, the robot can be installed on a boat or a crane (Figure 44). The body of a robot is made of steel, aluminium and carbon fibre composites. The robot's arm can extend up to 30 meters long (Figure 45) and Dynamic Stabilization Technology (DST) balances the effects of wind and vibration. With the help of this technology robot can calculate any deviations from its course and balance itself against external influences.<sup>153</sup>

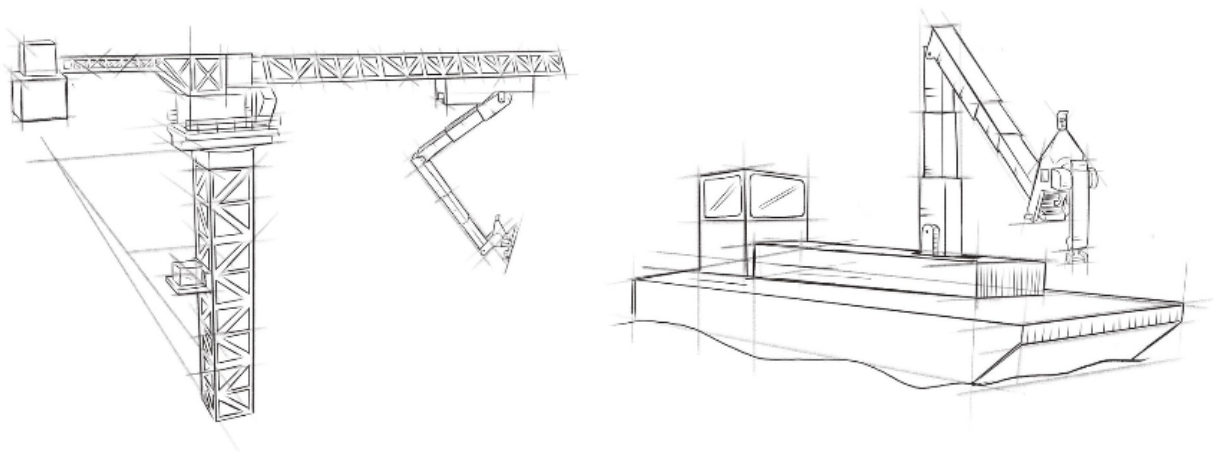


Fig. 44 Scheme of possible base application.<sup>154</sup>

The house plan is converted into 3D model in software and inputted into robot's control system and afterwards the robot "prints" the model brick by brick. The robot was designed to



work with wide range of brick sizes up to 500x250x250 mm. The bricks are stored in the robot's truck and the robot does all the necessary work including loading, cutting, applying adhesive and placing bricks according to the plan of the building. A laser tracker helps the robot to lay the bricks in precise position. The robot uses special kind of adhesive that dries in 45 minutes. Comparing to mortar binding, the use of adhesive significantly decreases the waiting time for drying. The used special adhesive also increases the strength of the structure significantly comparing to the conventional mortar. The thermal and acoustic properties are also increased by 70%.<sup>155</sup>



Fig. 45 Range of the robotic arm.<sup>156</sup>

#### **6.2.2.2 Productivity**

Hadrian X can lay about 1000 blocks per hour, while manual workers can lay up to 400 a day. On top of that, the robot can work extended hours without break and even in bad weather conditions. Thus, the robot will be able to build standard size houses in two to three days.<sup>157</sup>

### 6.2.2.3 Market price

The Hadrian X robot costs around AUD \$2 million (around 31,7 million CZK) per unit.<sup>158</sup>

### 6.2.2.4 Application

The real testing of Hadrian 105, the previous version of a robot, has started in 2015. The first outdoors house project Build1 (Figure 46) consisted of three bedrooms and two bathrooms. The house area was 180m<sup>2</sup> and it was completed in less than three days including the nights. The structure was verified to meet all the necessary building standards. After successful tests Fastbrick Robotics made an agreement with Saudi Arabia to build 50.000 houses by 2022.<sup>159</sup>



Fig. 46 Build1 project.<sup>160</sup>

### 6.2.3 SAM100 robot by Construction Robotics

#### 6.2.3.1 How robot works

SAM100 short for Semi-Automated Mason (Figure 47) is a robot designed by American company Construction Robotics.



Fig. 47 SAM100 robot.<sup>161</sup>

Unlike Hadrian X, SAM100 is not fully automated robot. The robot takes the loaded bricks, applies the mortar and lays them in precise preprogrammed position (Figure 48). The robot uses laser sensors for precise placement. At least two trained workers need to work alongside the robot. Workers need to finish the wall by cleaning the excess mortar in joints and put bricks into the robot's conveyor belt. Depending on the size of the brick the robot can lay one brick every 12-14 seconds.<sup>162</sup>

### 6.2.3.2 Productivity

A professional mason can lay about 300 to 350 heavy bricks and 400 to 600 lighter bricks in one-day shift. Whereas, SAM100 robot can lay up to 3000 bricks in one day during its eight hour shift.<sup>164</sup>



Fig. 48 SAM100 in process.<sup>163</sup>

The robot increases the productivity three to five times and reduces the heavy lifting by human workers up to 80%. Companies that already used SAM100 have reported that the productivity of their bricklaying work have been increased by 400%.<sup>165</sup>

### ***6.2.3.3 Market price***

SAM100 is sold for \$500,000 each (around 11,5 million CZK). Also, according to the company it can be rented for a \$3,300 per month (around 76,000 CZK).<sup>166</sup>

An economic benefit for acquiring the robot is illustrated in the following example. For example in the United States the minimum hourly wage for construction workers is \$15. Considering that a human worker can lay maximum 400-500 bricks in one-day shift, a cost for laying one brick becomes approximately 27 cents. On the other hand, if robot lays around 3,000 bricks per day a cost for one brick is 4.5 cents. Thus, the robot cuts the costs of laying bricks up to 7 times.<sup>167</sup>

The same calculation can be done if the robot will be used in Czech Republic. If the hourly wage for brick laying worker is 100 CZK and 400-500 bricks will be laid in one-day shift, then the cost for laying one brick will be around 2 CZK. Comparing to the robot that will cost 1 CZK (4.5 cents) for laying one brick. Still the robot will decrease the costs by 50%.

### ***6.2.3.4 Application***

The SAM robot has been already used for several building projects throughout the US. One example is a construction of hospital and health center in Michigan, US (Figure 49). The robot was used to lay more than 17,000 bricks for this building.<sup>168</sup>





Fig. 49 SAM100 utilized for construction of a building.<sup>169</sup>

## **7. Future of robotics**

### **7.1 General**

Generally usage and advancement of robotics has increased rapidly in the past few years. Future prospects promise even more increase of robots in coming years. Experts in the field believe that robotics development is following the same path as computers did in nineties. At first, computers were developed and used by a small number of experts for specific purposes. However, with the invention of World Wide Web personal computers became widespread. Similarly, soon robots will be used in every aspect of our daily lives.<sup>170</sup>

More and more countries are approaching and accepting the robotics revolution with an open-mind. South Korean government plans to have robots in every household by 2020, while Japanese predict that robotics field will generate about \$65 billion by 2025.<sup>171</sup>

The following mentioned developments and trends in robotics development are likely to influence every type of field. In fact, the general advancements in robotics are highly intertwined with the developments of robots for the construction industry. Also, the social acceptance and how people will interact and coexist with robots are highly important for future developments. Thus, few social aspects are also discussed.

### **7.2 Social implications**

#### **7.2.1 General acceptance of robots**

The general acceptance of robots into human societies varies considerably in different societies. From the research it has been found that Eastern cultures favor more robotics development than

Western societies. Interestingly, in both cultures the general public acceptance of robots was mostly influenced by the religious beliefs of these societies.

For example in Japan the main two religious beliefs are Shinto and Buddhism.<sup>172</sup> Based on their religion “scientists do not reject animistic beliefs prevalent within Japanese culture and are perfectly comfortable with the idea of robots as living entities endowed with a vital force that can be employed to facilitate wellbeing”.<sup>173</sup> Also, the Japanese have a long history of anime where robots were always been portrayed in positive way: being friendly, heroic and virtues beings.<sup>174</sup>

In opposite, for westerners with their Judeo-Christian creation story, the possibility of creating an artificial being was seen as a taboo. Furthermore, the books and entertainment industries in western cultures mostly depict robots being evil and dangerous creatures. Thus, they tend to view robotics inventions with more skepticism. It might be for these reasons most robots for military application were developed in the United States thus far.<sup>175</sup>

### **7.2.2 Labor displacement**

Future developments in many industries promise to replace human workers with robots. No wonder many people fear of losing their jobs and increase the unemployment rate. Soon, in medical field robots will be able to perform surgery on their own. In financial field, there is prediction that in ten years robots equipped with advanced computer software will replace almost one half of Wall Street workers.<sup>176</sup>

The construction industry is no exception. Some researchers believe that by 2050 the construction site will be human-free. Robots will build the structures and drones and rovers will be used for monitoring and inspection of the final products.<sup>177</sup>



On the contrary, some researchers believe that people should not fear the displacement of human workforce in the future. As robots will replace humans in repetitive and dull works, more high skilled workers will be needed in other types of job. Robots will need professionals to program, to run and to fix them, thus creating many other job opportunities. The same as during the Industrial revolution most people changed from manual works to less labor-intensive jobs, robotics development could follow those steps.<sup>178</sup>

### **7.2.3 Social issues**

Future prospects show a need for developing certain laws associated with the usage of robots. When robots will become widespread and more commercialized various social issues would arise concerning the laws for human privacy and safety. There could be immense problems with human privacy invasion, as the robots will be equipped with cameras and sensors that would collect data and easily be misused.<sup>179</sup>

Other issues will be the safety of human beings. With the increase of robots in the future, the accidents connected with robots might increase as well. Also, there is possibility of hacking robots the same as hacking computers and use them for harmful purposes.<sup>180</sup>

In 1950s, Isaac Asimov, a famous science fiction writer, introduced four laws concerning human safety, insisting that the future robots should be designed with these laws in mind:

0. A robot may not harm humanity, or, by inaction, allow humanity to come to harm.
1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human being except where such orders would conflict with the First Law.

3. A robot must protect its own existence as long as such protection does not conflict with the First and Second Law.<sup>181</sup>

### **7.3 Cyborgs**

Cyborg is a person whose physiological functioning is aided by or dependent upon mechanical or electronic devices.<sup>182</sup> In modern world, there are estimated that tens of thousands of people have artificial cochleas surgically implanted into their ears. These devices help people to hear by transmitting electronic signals from the device to human nervous systems. Other devices include heart pacemakers that help stimulate heart muscle and robotic prosthetic limbs.<sup>183</sup>

Robotic enhancements expected to be developed in near future. Researchers are trying to develop retinal implants for visually impaired people as well as to be used as an enhancement for normal people. The same as cosmetic surgery is highly used nowadays; in future people will have robotic technology implanted in them.<sup>184</sup> Humans will greatly benefit from the silicon and steel enhancements into their bodies. The robotic enhancements will improve human sensory organs and also their physical abilities. In future humans will be able to see clearly at night, handle heavy loads with ease or even breathe underwater.<sup>185</sup>

### **7.4 Artificial Intelligence**

Since the first developments in the field of robotics, scientists have attempted to come up with a way to invent a robot that would have a human like intelligence. At the same time, there has been an ongoing debate whether the robots should have a conscious mind. Should they understand what they are doing and make their own decisions?<sup>186</sup>

In the past few years a new field of robot cognition have emerged that studies the possibilities of modeling cognition for robots. Currently, there are five approaches for modeling

cognition for robots: the computational approach, the artificial neural networks approach, the dynamical system approach, the quantum and the cognitive approaches. In the computational approach computer would generate human like intelligence, this cognition modeling approach is also known as Artificial Intelligence (AI).<sup>187</sup>

According to the definition: “AI is the intelligence exhibited by machines or software to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making and translation between languages.”<sup>188</sup>

Autonomous research is focused on building robots that do not need to be preprogrammed and function independently. The final goal for robotics field would be to make a machine that could think, make decisions and learn from its experiences. The future robots with AI will greatly benefit construction industry as well. They will be able to completely replace humans for construction in dangerous and hard to reach location.<sup>189</sup>

## 8. Conclusion

From science fiction to reality, robots have already found many applications in different areas of human life. The same as all new technological inventions in human history took a long time to be commercialized and accepted into everyday life; robotics field slowly shows a progress.

Similarly, the robotics development in the construction industry has been increasing rapidly for the past few years. This research work tried to identify how robotics can potentially influence the construction industry and be implemented in the future. With the overall decrease of productivity and professional workforce in construction industry, future usage of robots can highly benefit the industry. From the detailed review of the current robotic technologies that are already been commercialized or that are in the research phase, it can be concluded that most robots are designed for repetitive tasks. Nevertheless, there is an immense possibility for future improvements.

Construction robotization can bring a lot of advantages and replace human workers in dangerous, hazardous and unpleasant works. Along with great potentials many challenges are facing to fully robotize the construction site. This includes the unpredictable site job conditions and safety of workers that would work alongside the robot. However, the future developments promise to come up with a way to enhance robots with AI. It might solve the aforementioned problems and completely revolutionize the construction industry.

Furthermore, from the research it can be seen that robots are accepted differently in different societies. There are few social issues connected with the implementation of robots as well. Many people have misconception about robots and fear of losing their jobs to them. As many researchers believe, humans should receive robotic revolution with an open-mind and understand that their usage will greatly improve human life. As most robots will be doing the

dull and hard work human kind should focus in other areas and do more creative and innovative works.

For me personally, writing this research work has been a long and very interesting journey. I have learned many new things and I believe that the future prospect to fully robotize the construction site is not an imagination of few researchers but an achievable goal. Most importantly, this research work has sparked an interest in me to learn more about this topic in the future and possibly continue my further academic studies in robotics field.

\*Chicago style of citation has been used:

-Notes are used to reference pieces of work in the text. Each number in the text citation corresponds to a note.

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-Bibliography includes all sources cited within the work arranged in alphabetical order.

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