

## ABSTRACT

Title of Thesis:                   DEVELOPMENT NEEDS AND CRITICAL CHALLENGES IN THE APPLICATION OF CONSTRUCTION AUTOMATION AND ROBOTICS

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Construction automation and robotics is a construction technology by which the process is conducted without or with limited human assistance, with the goal of advancing construction. With many procedures in the construction life cycle, there are plentiful applications construction automation and robotics can be applied in those steps, including excavation, framing, surveying, painting, pre-fabrication, tunneling, inspection and maintenance, etc. This study compared automation and robotics entities between 2010s and 1980s-1990s, distributed a questionnaire survey in the construction industry after which critical needs for applying the technology and influential factors in applying the technology are studied, and conducted case studies of typical companies that embraced construction automation. An international conference on this topic was held to provide professional opinions on future automation application. The results reveal development needs and critical challenges in the application of automation and robotics and provide guidance in future studies.

DEVELOPMENT NEEDS AND CRITICAL CHALLENGES IN THE  
APPLICATION OF CONSTRUCTION AUTOMATION AND ROBOTICS

by

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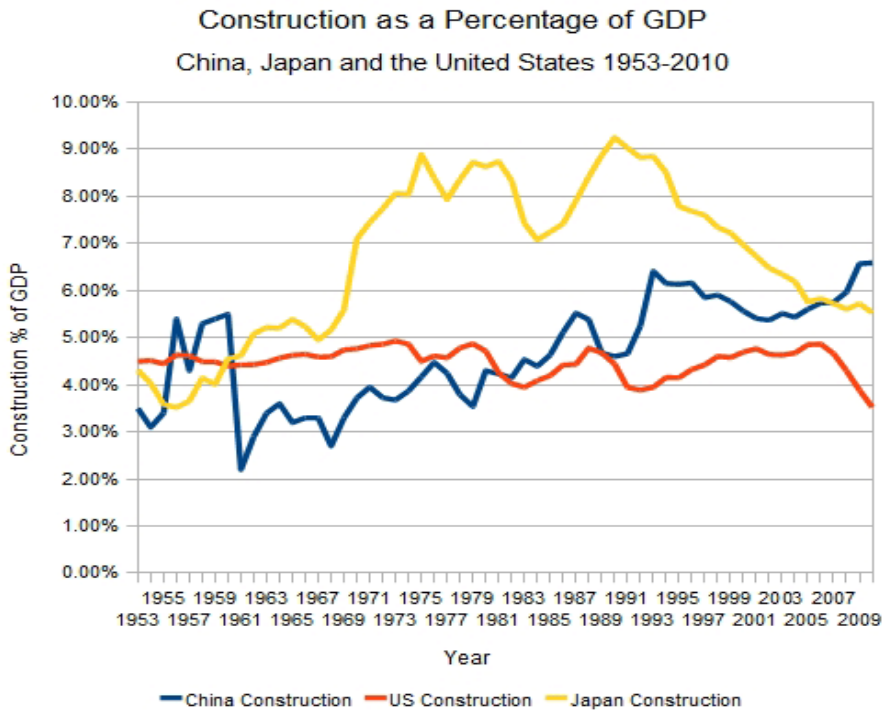
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# Chapter 1: Background Statement

The construction industry is one of the largest economic sectors in a society, and the application of construction automation and robotics are gaining increasing interest in the past several decades. The production technologies have been developed continuously throughout the history, but the construction overall process has not been much changed over years. For instance, despite the application of construction machines, visual feedback of construction, positioning error and parts of transition are still manually operated. Therefore, just like other fields like medicine, manufacturing, military and agriculture, it is reasonable to believe that there is a huge potential for construction industry to widely apply automation and robotics.



**Figure 1 Comparison of Construction as a Percentage of GDP between China, Japan and United States (Source: DQYDJ, 2013)**

Rather than a newly development term, the concept of using robotics in construction is actually a far longer history that can chase back to thousands of years, when in 210 BCE, China's first emperor, Qin Shi Huang, applied offsite construction and prefabrication technologies that later called the Terracotta Army [1].

In the 1970s and 80s, rapid development was seen in construction industry, in which Japan is an enormous one. The late 1970s and 80s saw a rich period of industry-driven development, particularly in Japan. Facing fears of a labor shortage due to an aging population and younger workers flocking into high-tech industries, a number of Japanese companies such as the Shimizu Corporation and the Takenaka Corporation invested in construction automation and robotics to great effect, developing robots and remotely-controlled devices used for all sorts of tasks, including material handling, excavation, concrete placement, concrete finishing, rebar placement, fireproofing, structural steel, interior and exterior finishing, earthworks, as well as integrated construction automation systems and prefabricated homes [2].

In past decades, many researches on construction robotics technologies, robotics feasibility in construction and construction robotics marketing were conducted. In United States, increasing interest for construction robotics is shown in research institutes, academic communities and construction firms in decades. Traditional construction brings this new robotics topic, and the new technologies are currently at the beginning and developing phase. Many disadvantages exist due to uncertainty in technical, organizational, economical and limited integration within an economic environment. For example, one of the difficulties is that the nature of work environment

is complicated. In an unstructured construction environment, automation faces a number of challenges including heavy objects transition, low level of on-site standardization, immature prefabrication technologies, and safety management.

In the 1990s, many Japanese companies and academic institutions were devoted to developing new robotic systems and in 2003, Balaguer named this period of research as “hard robotics”. By trying to automate some building processes like brick layer masonry, interior finishing, excavator controlling system and material inspection, some companies successfully made their unshakable presence in the market. With the continuous development of IT and software, some promising technologies like data acquisition and management, CPU monitoring, autonomous inventory management and worker’s operation safety management developed and influenced current construction technology market. In the 2010s, Building Information Modeling (BIM) was introduced to provide comprehensive and professional insight on architecture, engineering and construction. Besides, 3D printing technology by means of which house can be built by depositing materials layer by layer was increasingly applied. These technologies are bringing more options in construction robotics. Although many of these technologies were not adopted widely, they have effectively adapted those technologies from theoretical manufacturing into practical construction application. Today, improvements in robotics, software, and organization have allowed a new wave of automation in construction to rise, with new developments and collaborations happening across academia, government, and industry [3]. Based on those studies, a research on future trends and potential challenges of construction automation is therefore conducted.

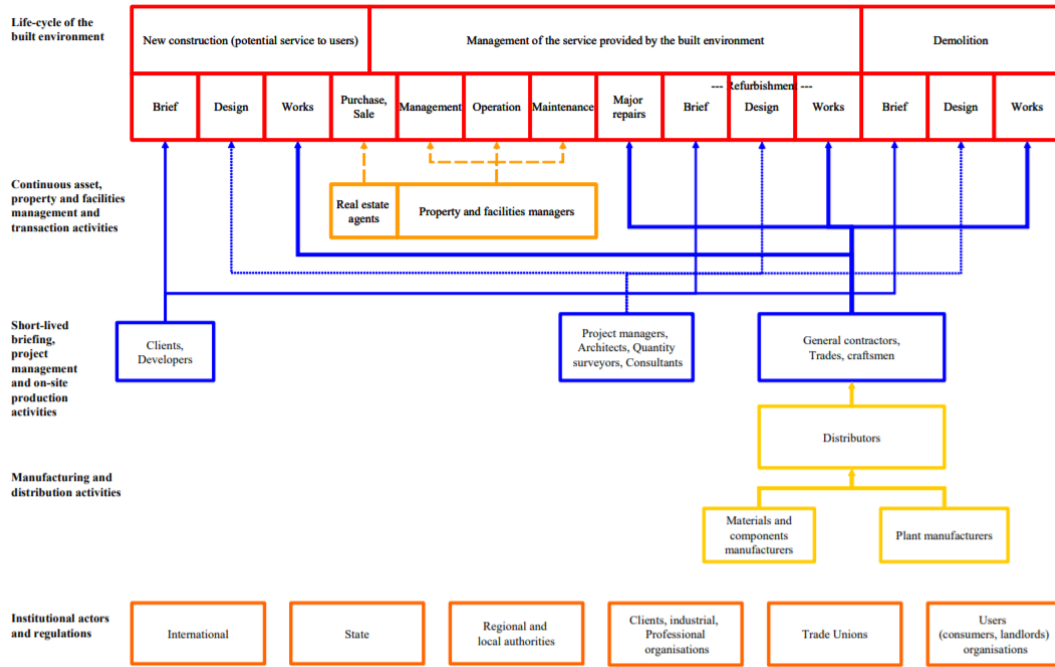
## Chapter 2: Research Questions and Methods

The explorative and descriptive methods of research are used in the study. The first phase of study is literature review. The study explored existing research on construction robotics, automation technologies and their application. A question is therefore raised: in construction automation and robotics industry, what are the differences between 20-30 years ago and now and why are the differences occurring? In the second stage, qualitative and quantitative data were gathered by distributing a questionnaire to construction companies in United States. During this stage, the respondents were asked to rate the levels of influential factors of two major questions---what are the key need of applying automation and robotics in the following construction works; what the influential challenges in are applying automation and robotics in construction industry. Meanwhile, a similar questionnaire was distributed to China's construction companies. The respondents were asked to rate from a five-point rating scale, in which 1 stands for very insignificant and 5 stands for very significant. After results were collected, the respondents' answers were compared between these two countries. It is of vital importance to raise these questions as construction industry is requiring increasing application of automation and robotics, and the reasons are listed below.

### *2.1 Scope of work in construction industry*

Scope of work, according to the Association for Project Management, scope means “the totality of outputs, outcomes and benefits and the work required to produce them” and “scope management” as “the process whereby outputs, outcomes and benefits are identified, defined and controlled”, and scope of work refers to a general description of

the work that is required from a party under a particular contract. It is typically prepared by a client or their consultants and included in tender documentation and then in the contract documentation [4].



**Figure 2 The construction sector framework (Source: Carassus, 2004)**

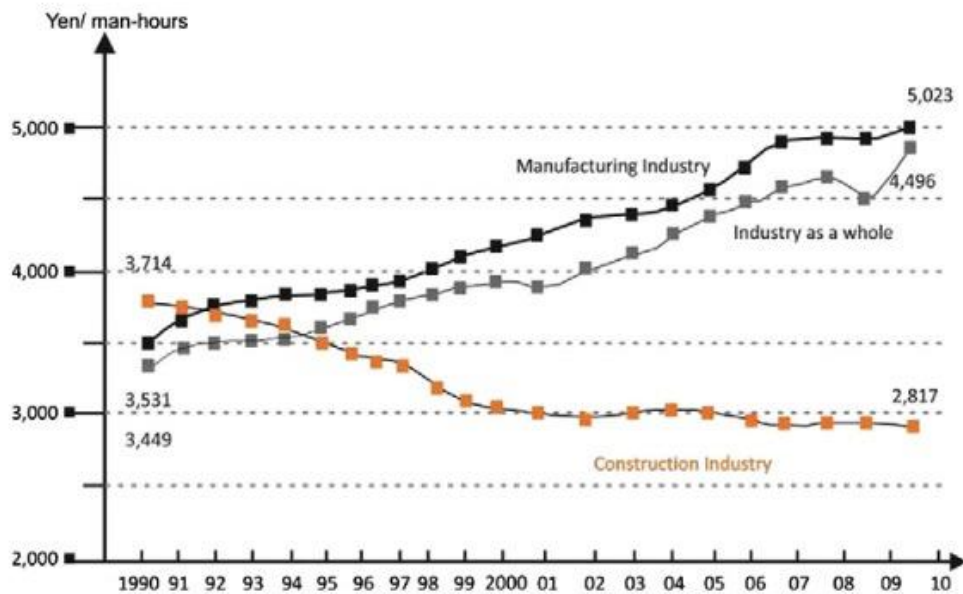
It can be seen that the scope of construction automation is wide and contains many stages, and the operation stages include positioning, excavation, construction materials production, surveying, prefabrication, actual site construction, inspection and maintenance of buildings, demolition and recycling of structures, etc.[5]. Therefore, it is important for the introduction of automation and robotics find suitable position in these complicated stages.

## 2.2 Labor shortage in construction industry

Labor shortage is deeply influencing the construction industry. According to a survey in Commercial Construction Index in 2018, the labor shortage is so acute that out of

2,700 contractors, 91 percent of the responding trade contractors, managers and are having difficulties hiring skilled labors to some degree [6].

Such situation is becoming increasingly common all over the country as the need for employment is rising. According to AGC (Associated General Contractors of America) report, during 2017-2018, 35 states have increased construction related jobs while 15 have decreased [7]. Faced with this situation, although the construction companies are capable of finding employee, many of the employee are not having sufficient construction experience and skills.



**Figure 3 Labor and manufacturing productivity yearly trends**

The construction companies in AGC have been trying to solve the problem of labor shortage in several ways [8]. Firstly, AGC reorganized the labor development plan and proposed a new plan and suggestion that the industry should take. This plan included investing twice the amount of money in career and technical education area in the upcoming five years. AGC also advocated that the immigration law allowed more

workers with sufficient construction skills into the country. Besides, AGC was willing to recruit workers in construction careers with high compensation. Secondly, AGC chose to build up a scholarship program for the teachers and principals to study the potential opportunities in the construction industry, make better plans for students and earn some school credits for two weeks in summer. Some courses cover the knowledge of fundamental construction skills, project management, and administration as well as marketing, which are supplements of site visiting. Thirdly, AGC took advantage of social media and developed a website “Build Oregon”. Aiming to attract young people to find opportunities in the construction industry, the website team advertised on different social media, and successfully got tens of thousands of hits.

Although such efforts have been made to remit labor shortage pressure, the wholistic trend still seems inevitable. According to the USG and U.S. Chamber of Commerce Commercial Construction Index, about 65% of small contractors report that they have trouble in finding skilled workers [9]. In the construction industry, the employment chance rate in 2018 was less than 0.2, which was half of the rate in 2017. These number suggested that approximately 6 applicants are interested in applying for one job in construction area. Therefore, application of construction automation and robotics is acting as an effective substitution and solution to this issue.

### 2.3 Environmental and other influence

Second, it is worth addressing that excessive construction waste is changeable with the introduction of robotics. According to US Green Building Council, building construction waste takes up to 30% of total waste across the country. Similarly, in European Union region, the estimation percentage of construction waste is 25-30%,

and globally the number may reach 40%. According to Construction & Demolition Recycling, by the year 2025, global construction waste may almost double to 2.2 billion tons as the total volume of waste is generated and increasing every year [10]. Construction waste includes materials from excavation, roadwork and demolition, as well as complex waste like plastics, metal, ceramic and cardboard [11]. Out of all construction waste generated, more than half of them are building materials including wood, shingles, asphalt, concrete and gypsum.

Besides, while increasing expectation for product quality and increasing requirement of safety regulations and decreasing project cycle time are changing the industry profoundly, there is no doubt that application of construction automation is very likely to change the current order of the industry as well.

Four cases were studied in order to explore the current implementation of construction automation and robotics. The companies mentioned in the case study were not focusing on, or simply focusing on construction robotics, however these cases reflected the latest application of robotics technologies that were widely used in the civil industry.

## Chapter 3 Literature Review

### 3.1 Building Information System Modeling Review

In the research of Becerik-Gerber and Kensek conducted in 2010, the beneath aspects were underscored in the BIM trends development: the examination of centralized data; sustainable design coordination with BIM; coordinating BIM with IPD (Integrated Project Delivery); giving instructions to teachers and students on BIM; return on investment; on-site and off-site management of project [12].

In different business purposes, the fundamental of BIM implementation includes productivity, cash flow, profit and revenue. In general life cycle, BIM is providing market share expansion, service deliver improvement, increase in productivity, decrease in project risks, reduce in waste. The goal for BIM includes increasing product quality, delivery, reliability and time cost. In recent years, numerical control (NC) and BIMAC (BIM-based automated control system) has been used to advance the automation system. As a summary, BIM practices are rapid visualization; better decision support upstream in the project development process; rapid and accurate updating of changes; reduction of man-hours required to establish reliable space programs; increased communication across the total project development team (users, designers, capital allocation decision makers, contracting entities, and contractors); increased confidence in completeness of scope [13].

In BIMAC, NC program generating system and NC program execution setup are two parts of it. Similar to BIM models, NC driving code and its execution and setup system are using same automated manufacturing components. Composition of BIMAC

initiates with importing BIM model, and after extracting parameter like shape and materials, together with importing NC program execution device parameters, NC program is generated. Those process compose the NC program generating system. In order to set up NC program execution, NC control cabinet should be controlling pumping, nozzle switch and mechanical arm [14].

BIM is also beneficial in facilities management in construction automation industry. In current implementation of BIM facilities management, even fully aware that adopting BIM technologies would decrease the errors and risks, many facility managers are still not applying them. BIM application is capable of providing updated database information that is required for analysis and further estimation (Ani et al., 2015). By enabling facility managers to adjust equipment for improved performances, facility management models can be integrated with building control system and monitor construction behaviors real-time, therefore shorten time for decision makings. Besides, adoption of BIM better documentation system and improve collaboration and work flexibility. Management personnel can reconcile and coordinate project plan with the 3D model system. By compiling comprehensive, reliable and accessible building information for stakeholders that requires action in any parts of project cycle, BIM enable increased collaboration, improved communication and commutation, lessen cycle time, therefore promote efficiencies in building automation and robotics industry.

### 3.2 3D Printing Review

Inspired by the benefits other industries---such as biomedical, aerospace, chemical and maritime have brought, 3D printing has been adopted as one of the construction methods in a variety of projects.

In construction industry, 3D printing is more combined with BIM and off-site manufacture. Currently, the scope of 3D printing is still limited by printing material and site size. However, it is positive that there are tremendous opportunities in expanding adoption scope with technological innovation and people's increasing awareness. (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012; Motamedi, Hammad, & Asen, 2014). With adoption of BIM technologies, quality of cycle life will be improved.

3D printing is beneficial in beneath aspects:

- (1) 3D printing is flexible in geometrics. Object designers are not limited by the shape and compatibility of model, which is higher than traditional models. The improvement of geometric flexibility provides possibilities of higher optimized structures.
- (2) 3D printing has higher quality and stability. As materials are filled step by step, 3D printing can improve average quality of objects.
- (3) 3D printing is time saving when preliminary setup is finished. By using machines to implement uninterrupted printing process, the labor time and cost are saved.
- (4) 3D printing is applicable in target's customization. The design of objects can be more easily changed by software compared to traditional means, so customers can change the design according to actual situation. With the same cost, designers can change and adjust the shape of structures. This advantage is likely to increase the demand for 3D printing, and therefore expand market at the same or lower cost.

- (5) 3D printing reduces risks in manufacturing. Producers are allowed to examine and verify designs before printing.

Meanwhile, the following disadvantages of 3D printing cannot be overlooked:

- (1) Under current technologies, 3D printing is likely to be more costly compared to traditional construction tools. Due to differences in project scope, material use and labor cost, this statement is not absolute. Many factors may influence the total cost---cost of optimization process, machine setup time, printing equipment itself, and energy cost, are all cost that are not largely concerned in traditional methods. Besides, although labor time may be reduced, it is still impossible to be totally labor free, and for many projects, the time to monitor and correct machines is not reduced. Therefore, it is questioned whether cost will be saved by using 3D printing technologies.
- (2) 3D printing lacks standardized regulation and operation procedures. The rate of 3D printing application is very few, and there is no agreed operation procedure in the construction industry, therefore drafting guidelines is costly in time, money and risk for commercial projects.
- (3) 3D printing technologies are not mature. Not only are printing material types limited, but the verification process is also technological challenging. Designers are hugely responsible for components to be built, and they need to be very assured of upcoming printed model structures. The current uncodified materials are making this process a challenge [15].

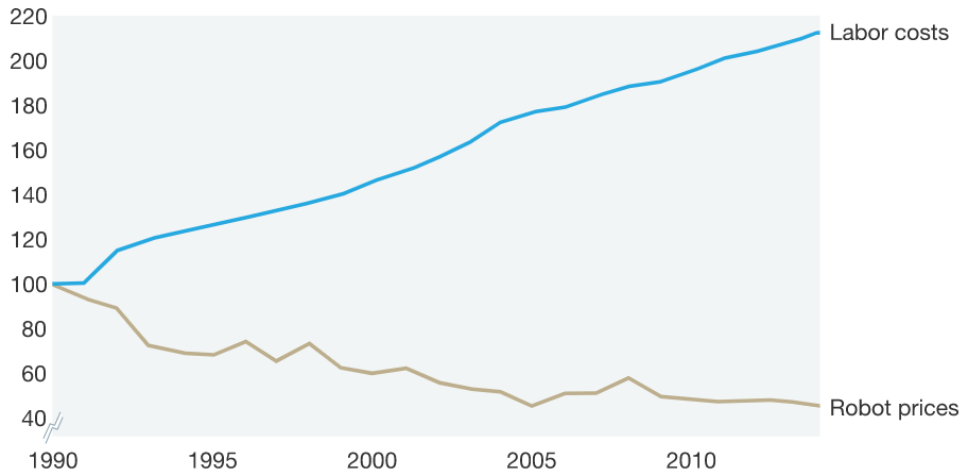
### 3.3 Economic impact of using construction automation and robotics

The increasing application of construction automation and robotics has generally

enhanced working productivity and decreased project costs. In 2016, Leopold stated that the world was undergoing the fourth industrial revolution, characterized by genetic developments, artificial intelligence (AI), robotics, autonomous consumer goods, 3D printing and biotechnology [16]. Several studies estimated the percentage of work that could be replaced by automation. In the study of Frey and Osborne in 2013, it is estimated that 47% of total jobs will be replaced within 20 years due to the introduction of intelligent machines. In 2017, PwC estimated that the percentage to be 38% by early 2030s, while McRae in 2017 provided total number of 3.4 million jobs to be replaced in 2025 in United States because of improvement machine learning, robotics, AI and 3D printing.

Since late 1990s, an increasing investment was made in the construction industry. On average, the growth rate in construction industry production was 4.3% from 1997 to 2015. Besides, the growth rate in capital in the two decades was 5.2% and labor growth rate was 3.9% yearly.

Capital share has also been hugely increased since 1997. The whole country's capital share rate for the construction industry was 31.8%, while twenty years later, the rate has increased to 37%, with a total growth rate of 5.2%.



**Figure 4 Cost of automation in United States, 1990=100% (Source: Economist Intelligence Unit; IMB; International Robot Foundation; McKinsey analysis)**

There is a huge economic potential for construction automation industry. Information about annual wages and current employment rate was looked up from OES (Occupational Employment Statistics). According to occupational employment projections, it is estimated that the growth rate of employment in construction industry is 6.5%. The table below shows current and estimated employment number and current average annual wages.

**Table 1 Employment number and annual wages**

Construction occupation	Employment, May 2018	Estimated employment, 2048	Average annual wages, 2018
Construction trade workers	5,962,640	7,202,569	\$51,220
Building Equipment Contractors	1,177,360	1,422,192	\$56,530
Foundation, Structure, and Building Exterior Contractors	703,410	849,684	\$47,750

Building Finishing Contractors	602,060	727,258	\$47,140
Residential Building Construction	480,330	580,214	\$47,360
Nonresidential Building Construction	472,280	570,490	\$55,970

The report that studies the potential economic consequences of construction automation industry, indicates that 49% of total construction tasks can be automated. Based on this number, a statistic of potential impact of construction automation was made.

**Table 2 Potential impacts of applying construction automation until 2048**

Construction occupation	Total jobs remaining	Total jobs substituted by automation	Total labor income reduction on current dollar value (billion dollars)
Construction trade workers	3,673,310	2,921,694	\$149.62b
Building Equipment Contractors	725,318	576,906	\$29.54b
Foundation, Structure, and Building Exterior Contractors	433,339	344,671	\$17.65b
Building Finishing Contractors	370,902	295,009	\$15.11b
Residential Building Construction	295,909	235,362	\$12.05b
Nonresidential Building Construction	290,950	351,453	\$18.00b

According to the table, almost three million workers will be replaced by automation and robotics in the next three decades. Considering the unavoidable fact that

automation technologies will be more advanced in the future, the quantity of actual decreased labors will be higher than three million. Equipment contractors will still be taking the most part of construction industry, but the total quantity of workers will shrink from 1.4 million to half a million. The workers for residential building construction are the least in number, decreasing from 580,000 to 240,000. Total salary loss for construction workers will be almost \$150 billion, and the equipment contractors will suffer maximum losses, amounting to \$30 billion.

The application of construction automation will decrease workers and lower income shares, which may further result in negative phenomenon. In a survey conducted by Gallup-Healthways Well-Being in 2013, nearly 20% unemployed people tend to feel depressed, compared to 5% full time employed people. Employed people tend to believe that they are making contributions to the society. As an analogy, with the introduction of future construction robotics, more people are likely to be depressed, together with financial problem and higher unemployment rate. However, on the other hand, applying construction automation is more likely to have positive effects. Other forms of job will be created, such as computer related jobs, higher-skilled construction jobs and digital technology jobs.

#### *3.4 Potential and break down capabilities of construction robotics*

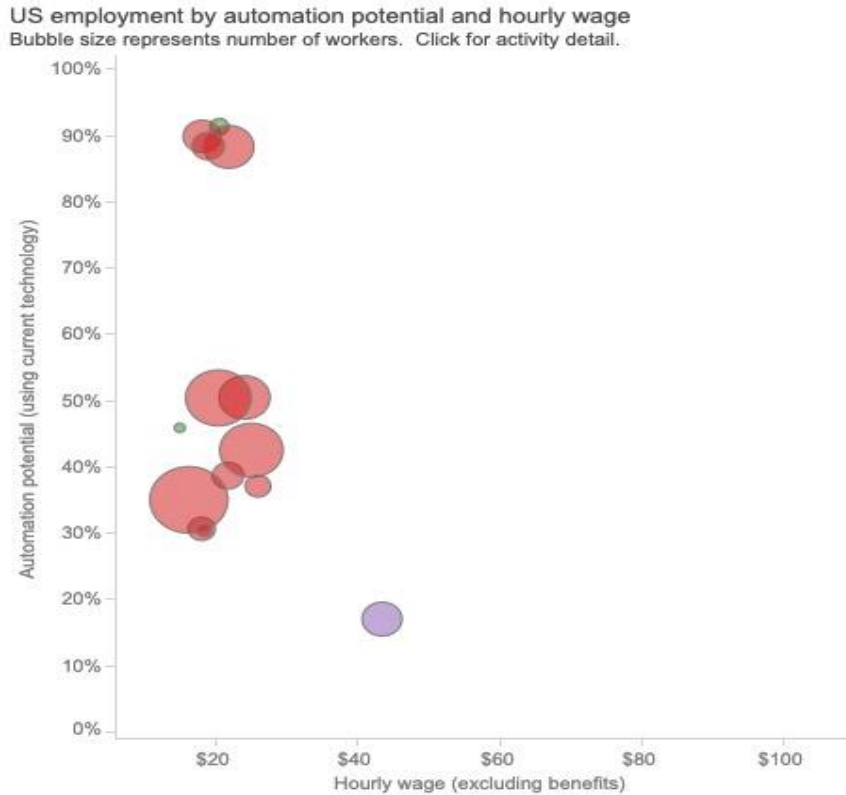
In January 2017, McKinsey Global Institute [17] conducted a research on future of automation, employment and productivity. The institute built up a system to provide technical automation potential and wages over more than 750 occupations. In order to serve research on construction automation, all occupations that may be involved in construction process are listed. Together with hourly wage and current U.S. workers, a

table is developed.

**Table 3 Construction-related works automation potential, wages and workers number**

Occupation/Construction Process	Automation potential	Hourly wage	US workers
Carpenters	50%	\$21	581,000
Cement masons and concrete finishers	88%	\$19	142,000
Construction and building inspectors	37%	\$26	88,000
Construction and related workers, all other	30%	\$19	31,000
Construction laborers	35%	\$16	825,000
Construction managers	17%	\$44	214,000
Electricians	42%	\$25	543,000
Operating engineers and other construction equipment operators	88%	\$22	341,000
Painters, construction and maintenance	90%	\$18	193,000
Painters, transportation equipment	91%	\$21	47,000
Painting, coating and decorating workers	46%	\$15	16,000
Plumbers, pipefitters and steamfitters	50%	\$24	351,000
Roofers	31%	\$18	99,000
Sheet metal workers	39%	\$22	131,000

In the construction process, the introduction of automation can replace 17% to 91% current human jobs. In order to further analyze the trends of construction automation, details of what automation and robotics can and cannot do are listed.



**Figure 5 Construction related work automation potential and hourly wage (Source: McKinsey Global Institute)**

3.5 Breakdown of jobs that can be replaced by construction automation

According to McKinsey report, we breakdown the work tasks of construction trade, and list what tasks robotics can and cannot replace [18].

For construction laborers, 35% of works can be substituted by automation. Table below lists potential replacement of construction laborers and works that cannot be replaced.

**Table 4 Automation replaceable and irreplaceable tasks---Construction Laborers**

Automation replaceable tasks	Automation irreplaceable tasks
Break up of rock or concrete	Ensure required equipment location and positioning
Implement heavy construction or installation equipment	Maintenance of construction tools and equipment

Operate pumps or compressors	Apply plumbing or piping
Indicate reference points on the on the construction materials	Location of design components
Apply protective coatings	Put aside construction forms or molds
Apply paint to surfaces	Destroy the temporary structures
Prepare dangerous waste for processing or disposal	Installation of green structural systems and components
Make ready the explosives for the denotation	Put together the temporary structures
Distribute concrete or other mixtures	Implement masonry materials
Place the materials in the specified areas	Installation of insulative equipment and structures
Mix the various substances that are required for the construction activities	Carry the construction equipment and material to where they are required
Try to test the quality of air at the work place	Complete concrete walls
Review requirements and specifications of the work	Compact materials to make level bases
-	Help the professional workers, construct trenches, loading and offloading of materials at the construction site
	Elimination of destroyed materials from the work areas, cleaning the working areas for good maintenance of the machines and other equipment
	Take measurements at the work place and implement flooring

For carpenters, the potential rate of automation is 50%.

**Table 5 Automation replaceable and irreplaceable tasks---Carpenters**

Automation replaceable tasks	Automation irreplaceable tasks
Order construction or extraction materials or equipment	Management of construction project activities
Record the environmental data	Direct construction personnel to the right places

Mark reference points on construction materials	Prepare operational reports
Apply material to fill gaps in surfaces	Apply decorative or textured finishes or coverings
Build construction forms or molds	Drill holes in construction materials
Weld metal components	Fabricate parts or components
Prepare hazardous waste for processing or disposal	Position construction forms or molds
Cut wood components for installation	Position safety or support equipment
Mix substances or compounds needed for work activities	Assemble products or production equipment
Select construction materials	Install wooden structural components
Estimate construction project costs	Install doors or windows
Measure materials or objects for installation or assembly	Install building fixtures
Review blueprints or specifications to determine work requirements	Install trim or paneling
-	Install safety or support equipment
	Assemble temporary equipment or structures
	Install carpet or flooring
	Dig holes or trenches
	Remove worn, damaged or outdated materials from work areas
	Clean work sites
	Verify alignment of structures or equipment
	Inspect work sites to determine condition or necessary repairs

It is similar for plumbers, pipefitters and steamfitters half of whose work is replaceable.

**Table 6 Automation replaceable and irreplaceable tasks---Plumbers**

Automation replaceable tasks	Automation irreplaceable tasks
Record operational or environmental data	Direct construction or extraction personnel
Operate pumps or compressors	Communicate with clients about products,

	procedures, and policies
Mark reference points on construction materials	Maintain plumbing structures or fixtures
Weld metal components	Install plumbing or piping
Cut metal components for installation	Install green plumbing or water handling systems
Cut openings in existing structures	Drill holes in construction materials
Select construction materials	Fabricate parts or components
Estimate construction project labor requirements	Install solar energy systems
Estimate construction project costs	Install gauges or controls
Measure materials or objects for installation or assembly	Remove worn, damaged or outdated materials from work areas
Inspect plumbing systems or fixtures	Clean equipment or facilities
Review blueprints or specifications to determine work requirements	Plan layout of construction, installation, or repairs
-	Create construction or installation diagrams
	Estimate materials requirements for projects
	Inspect work sites to identify potential environmental or safety hazards
	Inspect work sites to determine condition or necessary repairs
	Test green technology installations to verify performance

For electricians, less than half of the work can be replaced (42%). The breakdown is listed below.

**Table 7 Automation replaceable and irreplaceable tasks---Electricians**

Automation replaceable tasks	Automation irreplaceable tasks
Order construction or extraction materials or equipment	Direct construction or extraction personnel
Train construction or extraction personnel	Communicate with other construction or

	extraction personnel to discuss project details
Thread wire or cable through ducts or conduits	Prepare operational reports
Update job related knowledge or skills	Repair electrical equipment
Estimate construction project costs	Fabricate parts or components
Test electrical equipment or systems to ensure proper functioning	Install electrical components, equipment, or systems
Inspect electrical or electronic systems for defects	Assist skilled construction or extraction personnel
-	Dig holes or trenches
	Plan layout of construction, installation, or repairs
	Create construction or installation diagrams

Last but not least, for operating engineers, a high percentage of 88% work can be replaced by automation. Thus, focusing this aspect will be of vital significance to future application.

**Table 8 Automation replaceable and irreplaceable tasks---Operating Engineers**

Automation replaceable tasks	Automation irreplaceable tasks
Signal equipment operators to indicate proper equipment positioning	Communicate with clients about products, procedures, and policies
Record operational or environmental data	Install equipment attachments or components
Maintain construction tools or equipment	Move construction or extraction materials to locations where they are needed
Drive trucks or truck-mounted equipment	Assist skilled construction or extraction personnel
Operate equipment or vehicles to clear construction sites or move materials	Locate equipment or materials in need of repair or replacement
Operate road-surfacing equipment	-
Operate heavy-duty construction or installation equipment	
Operate pumps or compressors	

Position construction or extraction equipment	
Compact materials to create level bases	
Load or unload materials used in construction or extraction	
Remove debris or vegetation from work sites	
Update job related knowledge or skills	
Select construction equipment	
Estimate construction project costs	
Test air quality at work sites	
Monitor construction operations	
Review blueprints or specifications to determine work requirements	

### 3.6 IAARC catalogue comparison between 1998 and 2010s

In an IAARC (International Association for Automation and Robotics in Construction) proceedings published in 1998, 76 entries described a kind of robotics or automation to be used in construction industry. The 76 entries were categorized based on applications, including demolition, surveying, excavation and earthmoving, paving, tunneling, concrete transportation and distribution, concrete-slab screeding and finishing, cranes and autonomous trucks, welding and positioning of structural steel members, fire-resisting and paint spraying, inspection and maintenance and integrated building construction. Based on these categories, a list of similar entries from 2011-2019 was listed.

**Table 9 IAARC proceedings robotics and automation in 1998**


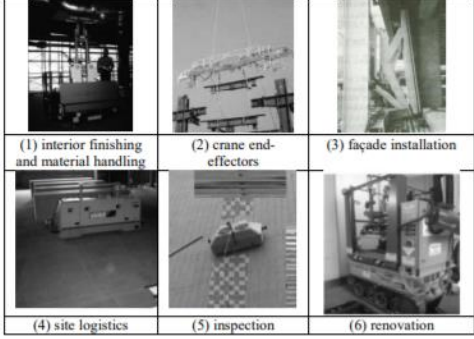
Demolition	Demolition unit mini cut
	Demolition units BROKK BM 110, BM 150
	Demolition units BROKK BM 250E, BM 330
	Concrete hydrodemolition robot

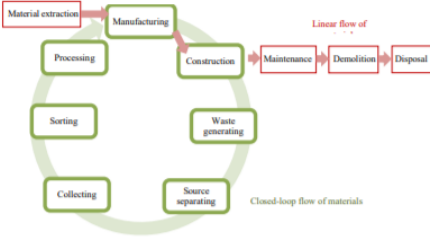


	Aqua Jet H-450 and HV-550 hydrodemolishing robots
	Conjet Jetframe system for hydrodemolition
	Conjet robot 230 for hydrodemolition
	Conjet robot 361 for hydrodemolition
	Water-jet Concrete chipping robot
Surveying	Navigation-type surveying system using real-time kinematic GPS
Excavation and earthmoving	Tele-earthwork system
	Digging work robot
	Unmanned caisson method
	ROVO Caisson method for automating excavation, soil transfer and soil discharging operations in pneumatic caisson
	Ground system for remote operation of overhead traveling excavator in pneumatic caisson
	Integrated control system for diaphragm wall excavation
	Automatic excavation for diaphragm wall excavator
	Excavation system for diaphragm wall
	High-accuracy position control system for underground diaphragm walls
Paving	SAKAI ER501F road profile cutter equipped with ACCS (Automatic Cutter Control System)
	RoadRobot - Fully automated road paver
	Bending asphalt paver
	Robot asphalt finisher
Tunneling	Automatic operation system for tunnel boring machine
	Automatic transport system intended for long tunnels, GEO-SHUTTLE laser ventilation system
	Segment automatic carrier system for shield works
	Stabilator tunnel lining repair system, Hydro-demolisher Jet Rig 2, Robot CSR
	Tunnel swift lining robot
	Segment automatic building intelligent system "SABIS"
	Multi-jointed arm erector
	Automatic shield direction control system
	Shotcrete control system

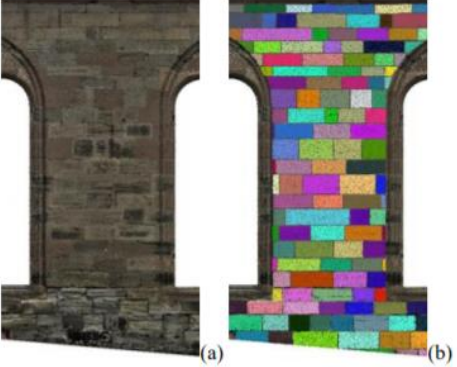

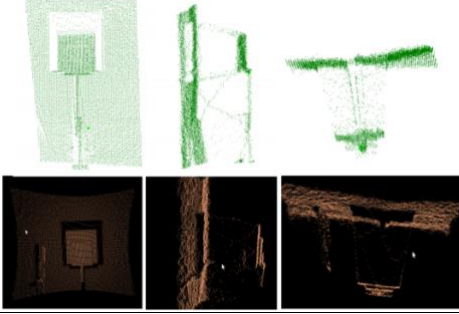
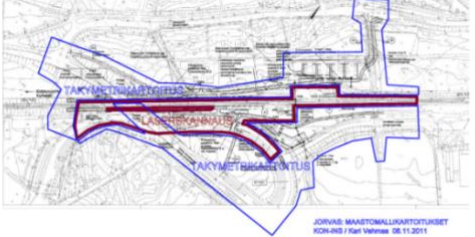
	Automatic slump adjusting system
	Front monitoring system for mountain tunnel
Concrete transportation and distribution	Computer controlled mobile concrete distributor
	Simplified distributor "DB ROBO"
	Automatic concrete distribution system with tower crane applications to super high-rise R.C. building
	Stabilator shotcreting system, robot 7500 on truck chassis or on rail car
	Stabilator shotcreting system, Trixer-Robot D5000H
	Dam concrete transport facilities INCLINE
	Grout data control system
	Konoike transfer car automatic control system
Concrete-slab screeding and finishing	Concrete floor screeding robot "SCREED ROBO"
	Concrete-slab finishing robot
	Floor troweling robot
	TAPS (Tobishima Auto Level Pantograph Slipform) method
Cranes and autonomous trucks	New mini crane from Japan Can Ride on the Van, Can Go Up and Down the Stairs "KALCATT" (LM15-1)
	Material handling system for interior finishes
	Light weight manipulator
	Autonomous truck system
Welding and positioning of structural steel members	Automatically adjusting system of plumbing structural steel column TO-Plumb NAVI
	Column welding robot
	"T-UP" building construction methods
	Remote shackle releasing system - Mighty Shackle ACE
Fire-resisting and paint spraying	Fire resisting rock wool spraying robot TN - Fukkun
	Exterior-wall painting robot
	Robot for painting exterior walls
	Vaccum-adhering and self-traveling system, polishing and painting robot
	Wall surface operation robot
Inspection and maintenance	Service robot for façade cleaning and tasks of inspection and maintenance

	Surface preparation system "BIBER" ("BEAVER")
	Exterior wall tile inspection robot
	Ultra-compact inspection robot
	Clean room inspection robot "CRIMRO"
	Climbing robot RoSy II
	Vaccum-adhering and self-traveling system, abrasive blasting robot
	Automatic cleaning system for the under carriage of construction machine "YC300W-1"
Integrated building construction	Automated construction system for reinforced concrete building
	Automated weather-unaffected buildings construction system "AKATSUKI 21"
	Computer integrated and automated construction system-SMART system-MCCS (Mast climbing construction system)
	Roof push up construction method
	Automated building construction system (AMURAD construction system)

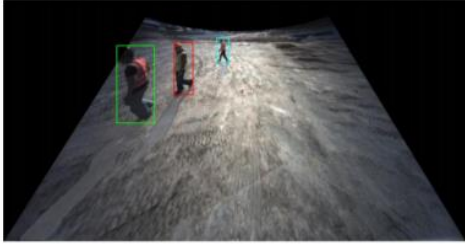


**Table 10 IAARC proceedings robotics and automation from 2011 to 2019 (2010s)**

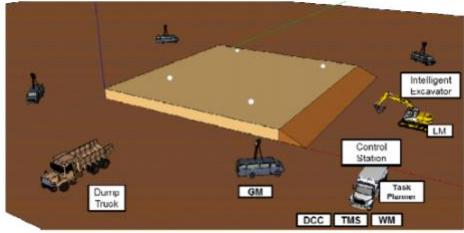
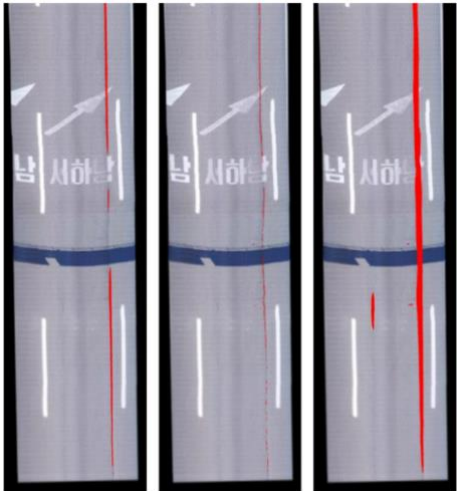
Demolition Description	Year	Image
Supporting Deconstruction Waste Management through 3D Imaging	2019	
STCR Assisted Deconstruction	2015	



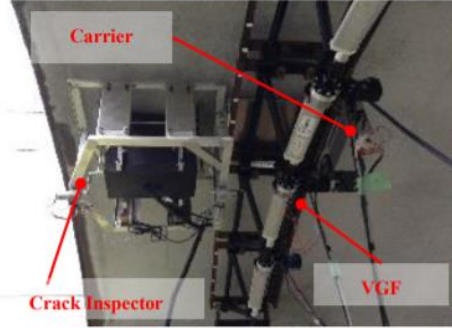
<p>Closed-loop system of Construction and Demolition Waste Recycling</p>	<p>2014</p>	
<p>Model for adoption demolition robot</p>	<p>2013</p>	<p>-</p>
<p>Double arm working machine for demolition and scrap processing</p>	<p>2011</p>	
<p>NEDO robot system for removing asbestos sprayed on beams</p>	<p>2011</p>	
<p><b>Surveying description</b></p>	<p><b>Year</b></p>	<p><b>Image</b></p>

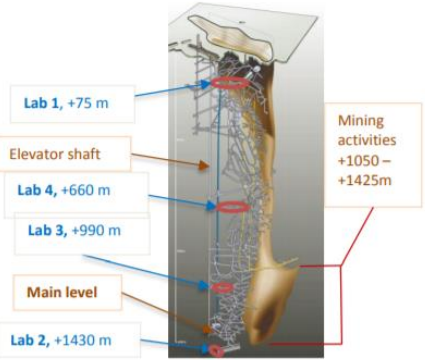


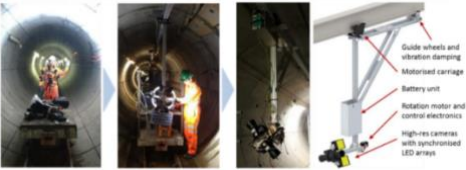
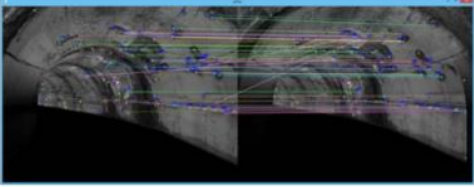
<p>BIM and machine learning based wall defect surveying</p>	<p>2018</p>	
<p>Photogrammetric Models using Oblique Aerial Imagery for Construction Site Surveying</p>	<p>2018</p>	
<p>SFM (structure from motion) photogrammetry-based automation surveying</p>	<p>2017</p>	<p>-</p>
<p>3D Time-of-flight camera for surveying remote cavities</p>	<p>2013</p>	
<p>Automated laser scanner 2D technology for underground mine surveying</p>	<p>2013</p>	<p>-</p>
<p>Multi-point concurrent tracking and surveying in construction field</p>	<p>2013</p>	<p>-</p>
<p>Unmanned aerial vehicle surveying of terrain model</p>	<p>2013</p>	

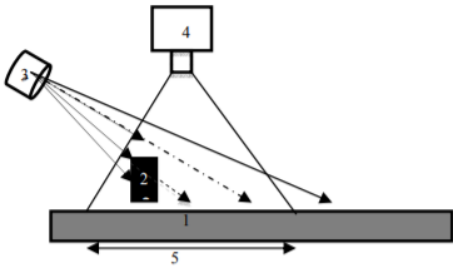
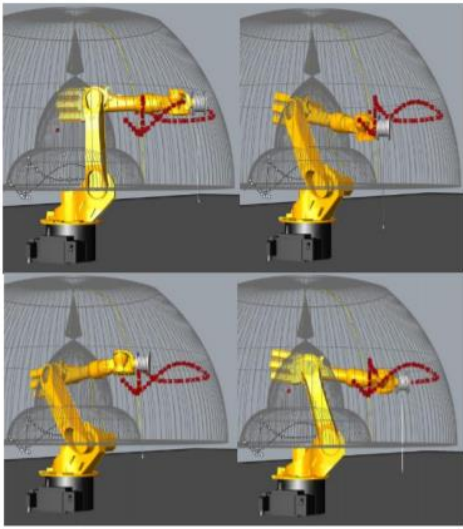
Surveying earthwork using UAV for mobile 3D mapping	2013	
Mobile LiDAR surveying road slopes	2012	-
<b>Excavation and earthmoving description</b>	<b>Year</b>	<b>Image</b>
Earthmoving Machinery Autonomous Excavator Development Platform	2019	
SEFOP (Simulation-based Earthmoving Fleet Optimization Platform) for truck or excavator	2018	-
Underwater Heavy Machine Operator	2018	
Behavior-based Architecture for Excavation Tasks	2017	-


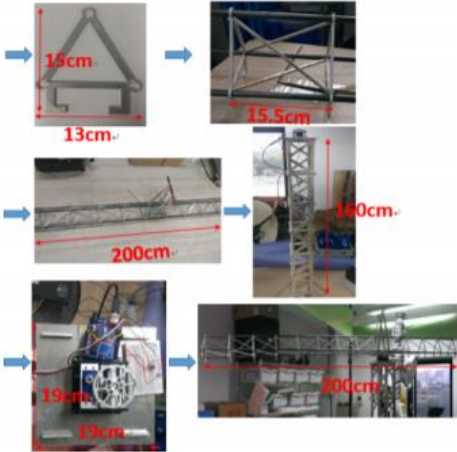
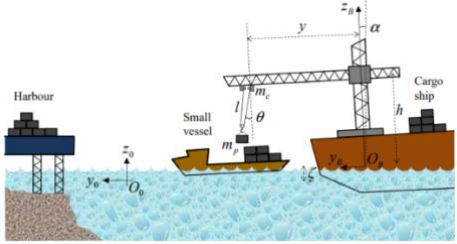
Detection of Nearby Obstacles for Earthmoving Operations	2017	
Emissions Modelling of Earthmoving Equipment	2016	-
Pile-Supported Excavation in 3D and 4D Modeling	2016	-
Smart-Dig Vision-Based Articulated Excavation Monitoring and Guidance	2016	
UAV based mesh image of excavation work	2016	
Geotechnical Monitoring for Safe Excavation of Large Rock Cavern	2015	-
Optimal Digging Range for Intelligent Excavation	2015	-
Truck excavator combination robots	2015	-
Tracking hauling trucks for cut-fill earthmoving operations	2015	-

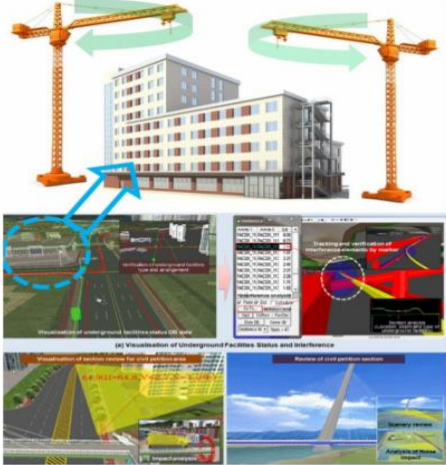
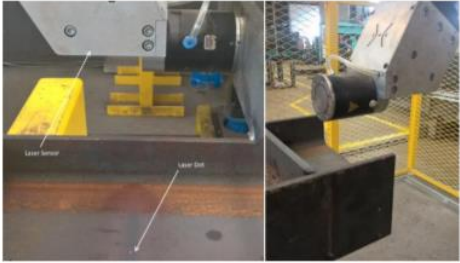
DCM (Data Communication Manager) for intelligent excavation system	2015	
Dynamic planning of earthmoving projects using system dynamics	2012	-
Kaizen GPS fleet tracking and stochastic simulation to soil excavation	2012	-
Avoidance of earth obstacles for intelligent excavator	2011	-
<b>Paving description</b>	<b>Year</b>	<b>Image</b>
Hyper Spectral Cameras autonomous inspection of road pavement defects	2019	-
Pavement Crack Mosaicking Based on Crack Detection Quality	2019	
Deeper Networks for Pavement Crack Detection	2017	-

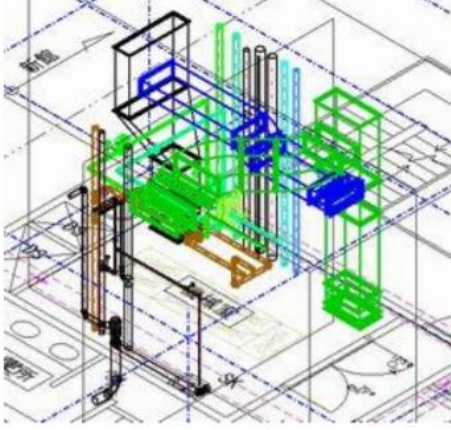
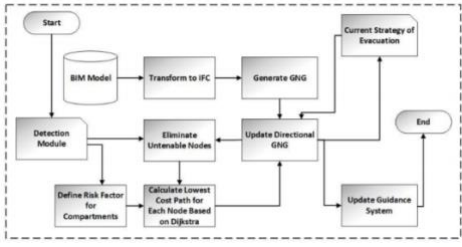
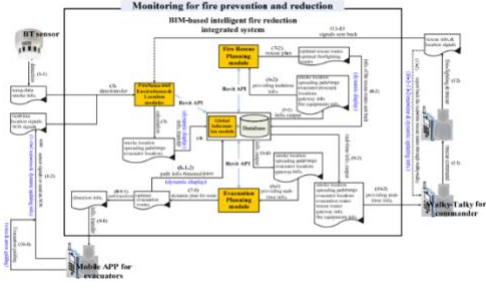
Information Modelling based Optimization for Asphalt Pavement Renovation Robot	2015	
Automation for improved safety in roadside construction	2013	-
Patch distress detection in asphalt pavement images	2013	-
Automation in resurfacing pavement operation of highways	2011	-
Tunneling description	Year	Image
Automatic traveling method for the self-propelled Tunnel Inspection System	2018	
Tunnel lining concrete inspection robot	2018	




<p>Pyhasalmi mining automation and tunnel construction robotics</p>	<p>2018</p>	
<p>ROBO-SPECT Robotic System with Tunnel Inspection Tool Positioning</p>	<p>2017</p>	
<p>Variable Guide Frame Vehicle for Tunnel Inspection</p>	<p>2017</p>	
<p>Shape Control of Variable Guide Frame for Tunnel Wall Inspection</p>	<p>2017</p>	<p>-</p>
<p>Visual Inspection of Tunnels Robot</p>	<p>2015</p>	
<p>TBS Maintenance Robotics</p>	<p>2015</p>	<p>-</p>
<p>Localization inside Tunnels Using Machine Vision</p>	<p>2014</p>	

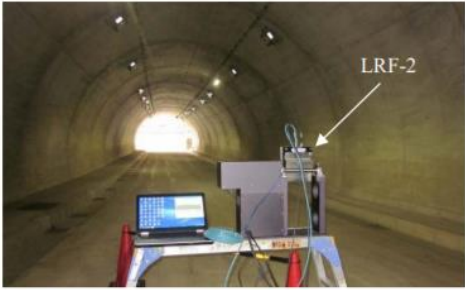

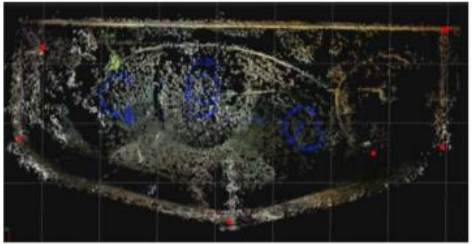
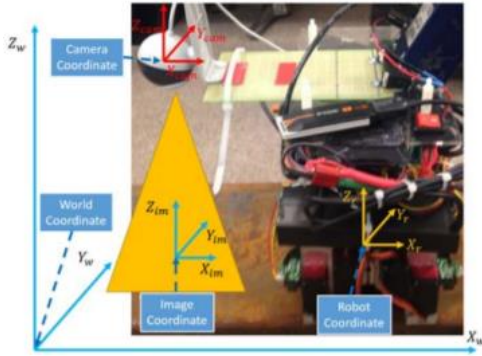
Tunnel boring machine positioning automation in tunnel construction	2012	-
Automation for extracting tunnel cross-sections	2011	-
Concrete transportation and distribution description	Year	Image
Benders Decomposition for Solving Ready Mixed Concrete Dispatching Problems	2014	-
<b>Concrete-slab screeding and finishing description</b>	<b>Year</b>	<b>Image</b>
Automated surface profiling of drywall surface	2011	
<b>Cranes and autonomous trucks description</b>	<b>Year</b>	<b>Image</b>
Simulating Extreme Points of Crane by Robot Arm in Virtual Reality	2019	
Crane safety system with monocular and controlled zoom cameras	2018	-


Measuring Operator's Situation Awareness in Smart Operation of Cranes	2017	-
Lift Virtual Prototyping (LVP) Approach for Crane Safety Planning	2016	
A Sway Reduction Controller For Construction Crane	2015	
Offshore Container Crane Systems with Robust Optimal Sliding Mode Control	2014	
Integrating Mobile Crane Lift Path Checks Automation	2013	-
Tower Crane Automation Monitoring System	2013	-
TSP-Based Model for On-site Tower Cranes	2013	-

<p>Crane Motion Planning High-Dimensional Space Search System</p>	<p>2011</p>	
<p><b>Welding and positioning of structural steel members description</b></p>	<p><b>Year</b></p>	<p><b>Image</b></p>
<p>Beam for the Steel Fabrication Industry Robotic Systems</p>	<p>2017</p>	
<p>Automatic Positioning and Alignment for Hole Navigation</p>	<p>2014</p>	<p>-</p>
<p>Geomagnetic Field based Positioning Technique with Mobile Phone to Underground Tunnels</p>	<p>2014</p>	<p>-</p>
<p>Laser scanner 2D Positioning and Orienting Automation</p>	<p>2013</p>	<p>-</p>

<p>Laser Positioning System Using RFID-tags</p>	<p>2012</p>	
<p><b>Fire-resisting and paint spraying description</b></p>	<p><b>Year</b></p>	<p><b>Image</b></p>
<p>Real-time Path-planning Model for Building Evacuations</p>	<p>2019</p>	 <pre> graph TD     Start([Start]) --&gt; BIMModel[(BIM Model)]     BIMModel --&gt; Transform[Transform to IFC]     Transform --&gt; Generate[Generate GNG]     Generate --&gt; Current[Current Strategy of Evacuation]     Current --&gt; End([End])          Detection[Detection Module] --&gt; Eliminate[Eliminate Untenable Nodes]     Eliminate --&gt; Update[Update Directional GNG]     Update --&gt; Current          Define[Define Risk Factor for Compartments] --&gt; Calculate[Calculate Lowest Cost Path for Each Node Based on Dijkstra]     Calculate --&gt; Update          Update --&gt; Guidance[Update Guidance System]     Guidance --&gt; End   </pre>
<p>Extending IFC for Fire Emergency Real-Time Management</p>	<p>2018</p>	<p>-</p>
<p>HBIM and fire prevention system</p>	<p>2016</p>	<p>-</p>
<p>BIM-based Real-time Evacuation and Rescue System for Complex Buildings</p>	<p>2016</p>	
<p>Trajectory of the painting robot</p>	<p>2016</p>	<p>-</p>

Gondola Wall Classifier Robot	2013	
Rust Surface Area Determination of Steel Bridge Robotics	2013	-
Fastening Device for the Vertical Outer Walls of High-rise Buildings	2011	-
Automatic Cleaning Tool and Robot for Façade in High-rise Building	2011	
<b>Inspection and maintenance description</b>	<b>Year</b>	<b>Image</b>
AR Supported On-site Rebar Inspection Automation	2019	
Cloud-based Inspection of Temporary Structures	2019	-

AR based Smart Facility Maintenance System	2019	-
Convolutional Neural Networks and Support Vector Machines	2018	-
Variable Guide Frame for Tunnel Wall Inspection	2018	
LiDAR-equipped UAV Platform for Structural Inspection	2018	-
RFID, Web-Based, and Artificial Intelligence Integration in Facilities Management	2017	
3DFlow Zephyr Aerial (Zephyr) Perception Sensing Inspection Robot	2016	
Visual and 3D Mapping for Steel Bridge Inspection Using a Climbing Robot	2016	

BIM-enabled Inspection Management System for Maintenance Diagnoses of Oil and Gas Plants	2016	-
Quadrotor Inspection Robot of Flyover Bridges	2015	-
Cleaning Tool System for Building Wall Maintenance Robot	2014	-
Self-growing Motion Automation for Inspection and Maintenance	2012	-
Micro-Walking Robot Using Flexible Microactuator	2011	

In 1997, Slaughter examined the automation technologies for construction industry at that time and listed 85 technologies on 20 attributes. She examined the opportunity to adopt, perceived cost and benefits, complexity of adoption and complementary changes. In this research conducted in 2019, 26 companies in United States that have embraced construction automation and robotics are listed below, based on a similar application category.

**Table 11 Part of companies that applied construction and robotics in 2019**

Category	Company Name	Website
Foundation	TyBot	<a href="https://www.tybotllc.com/">https://www.tybotllc.com/</a>
	Kewazo	<a href="https://www.kewazo.com/">https://www.kewazo.com/</a>
Excavation	CGR	<a href="http://www.robotloader.com/">http://www.robotloader.com/</a>

	BUILT ROBOTICS	<a href="http://www.builtrobotics.com/">http://www.builtrobotics.com/</a>
Brick	Construction Robotics	<a href="https://www.construction-robotics.com/">https://www.construction-robotics.com/</a>
	Fast Brick Robotics	<a href="https://www.fbr.com.au/">https://www.fbr.com.au/</a>
Framing	Frame Robotics	
	Williams Robotics	<a href="http://www.williamsrobotics.com/">http://www.williamsrobotics.com/</a>
Drywall	Build-r	<a href="https://build-r.com/">https://build-r.com/</a>
Drilling	nLink	<a href="https://www.nlink.no/">https://www.nlink.no/</a>
Painting	MIST	<a href="https://trymist.com/">https://trymist.com/</a>
	HOPE ROBOTICS	<a href="http://www.hope-robotics.com/">http://www.hope-robotics.com/</a>
	TRANSFORMA	<a href="https://www.transformarobotics.com/">https://www.transformarobotics.com/</a>
	ENDLESS ROBOTICS	<a href="https://endlessrobotics.com/">https://endlessrobotics.com/</a>
Prefab	RAD Urban	<a href="https://radurban.com/">https://radurban.com/</a>
	Katerra	<a href="https://www.katerra.com/">https://www.katerra.com/</a>
	Blueprint Robotics	<a href="http://www.blueprint-robotics.com/">http://www.blueprint-robotics.com/</a>
	Factory_OS	<a href="https://factoryos.com/">https://factoryos.com/</a>
Data	Doxel	<a href="https://www.doxel.ai/">https://www.doxel.ai/</a>
	Skycatch	<a href="https://www.skycatch.com/">https://www.skycatch.com/</a>
	Hangar	<a href="https://hangar.com/">https://hangar.com/</a>
	3DR	<a href="https://3dr.com/">https://3dr.com/</a>
	Versatile Natures	<a href="https://www.versatile.ai/">https://www.versatile.ai/</a>
Surveying	Civdrone	<a href="https://www.civdrone.com/">https://www.civdrone.com/</a>
	TinyMobileRobots	<a href="https://tinymobilerobots.com/">https://tinymobilerobots.com/</a>
	Mechasys	<a href="https://www.mechasys.ca/">https://www.mechasys.ca/</a>

As a comparison between the robotics development of these two periods, some examples from different time were listed in different categories and further discussed.

### 3.6.1 Robotics in road construction and maintenance work

In 1990, ASCE members Skibniewski et al. studied the development in road construction and maintenance, in which discussions about the future trend of automation and robotics were mentioned [19]. The research categorized operations in

road construction and analyzed the application potentials of automation and robotics use in these aspects.

- (1) Cut and fill: Massive transportation of earth is involved in the preliminary work in order to provide sufficient terrain before starting of any construction process. In the future work, autonomous navigation is expected for future machine, including excavators, dump trucks and front loaders.
- (2) Grading: In grading works, rocks and soil pieces are required to be broken into smaller size, no larger than maximum theoretical size. In most cases, specialized grader machine is applied to implement the process. For the future of automated equipment, dispersion of blade implementation should be improved by automated grading navigator.
- (3) Base and site preparation: Sand dumping, screeding and compaction are general procedures in preparing base. The machines used for this process are screeder and drum truck. The autonomous work scheduling software tools is expected to enhance the efficiency of the mentioned machines, which can provide comprehensive work data, including deciding working area and implementing the decision of optimum working area.
- (4) Preparation of surface material: This process includes placement of paving mix, bituminous mix, concrete mix, and vibration and screed. During the placement, better navigation and more sensitive material sensors will be used for equipment automation.
- (5) Placement of curbs and barriers: Placing permanent of temporary curbs and barriers requires curb and barriers prefabrication, transportation and placement.

Better numerically controlled equipment with higher mobility is expected in the future. Moreover, standardized procedures will be introduced in the machines.

- (6) On-site maintenance: On-site maintenance includes failed pavement management, road shoulder repairs, road painting, sign placement and cleaning, pipe installation, and debris removal. In the future, smarter machines loaded with smarter sensors that can provide dexterous manipulator end effectors and artificial vision will be used.

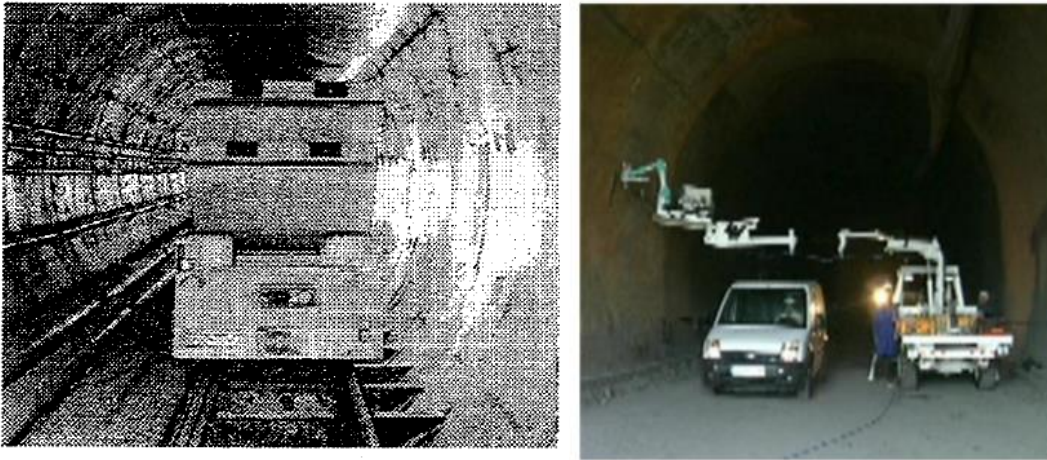
Road construction and maintenance is different from high-rise building construction and maintenance, but the theory and practice of automation is very similar. Based on ergonomic and economy of different work flows, a systematic method to develop automated equipment can be used to make optimal choices for machine implementation modes [20]. According to the research, Numerically Controlled equipment (NC) was expected to be the future direction of road construction robots that requires complicated and numerous tasks.

### 3.6.2 Tunnel inspection and surveying work using robotics

In civil infrastructure procedures, inspection, assessment and maintenance are crucial challenges. Using different NDI methods (Non-destructive inspection), engineers can check whether a functioning structure is safe or not. These methods include:

- (1) Visual methods
- (2) Strength Based methods
- (3) Sonic and ultrasonic methods
- (4) Magnetic methods
- (5) Electrical methods

- (6) Radar methods
- (7) Radiography methods
- (8) Endoscopy methods
- (9) Thermology methods



**Figure 6 Tunnel inspection robotics comparison between 1990s and 2010s**

As a disadvantage, most of the inspection methods are to some degree tele-operated. The remote operation satisfies the need for one or more human operators in the operation systems sometimes that require the workers to be in the same location as the robot, eliminating one of the benefits of the robotic inspection. [21]. Because of this, the operator is exposed to the dangerous tunnel environment, including large isolated areas, low visibility, dust, humidity or even toxic gases.

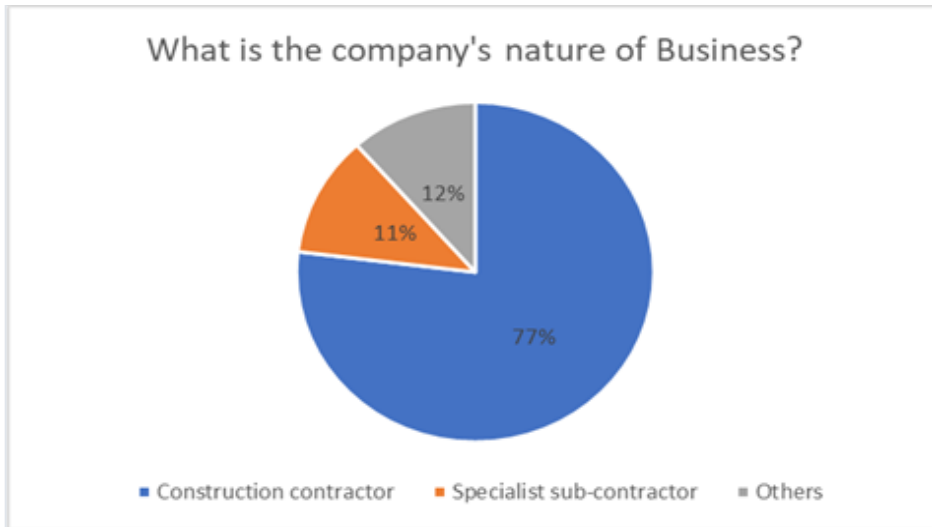
## Chapter 4: Questionnaire Survey Design

### 4.1 Questionnaire Design Method

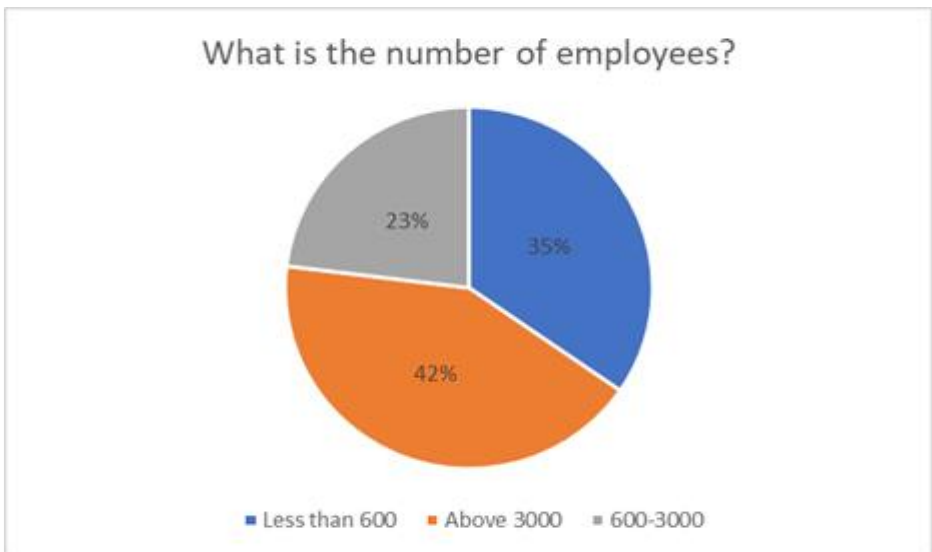
Considering that research institute and construction companies that are the two major parties applying the construction automation and robotics technologies, the survey was designed and conducted at the purpose respondents of construction contractors and other related companies. During the design phase, it is realized in the research institute side that the development priorities and key challenges are not only important to future research, but also of vital significance to the construction contractors. Therefore, the survey was distributed to AGC members, ASCE members who representing the companies to consider the detailed importance of the questions.

The questionnaire includes basic information, current application status and future application-related requirements. The same online survey was also designed in mandarin and sent to Chinese construction companies as a comparison to U.S. result. Based on the response in two countries, the identification of the research goal was then analyzed.

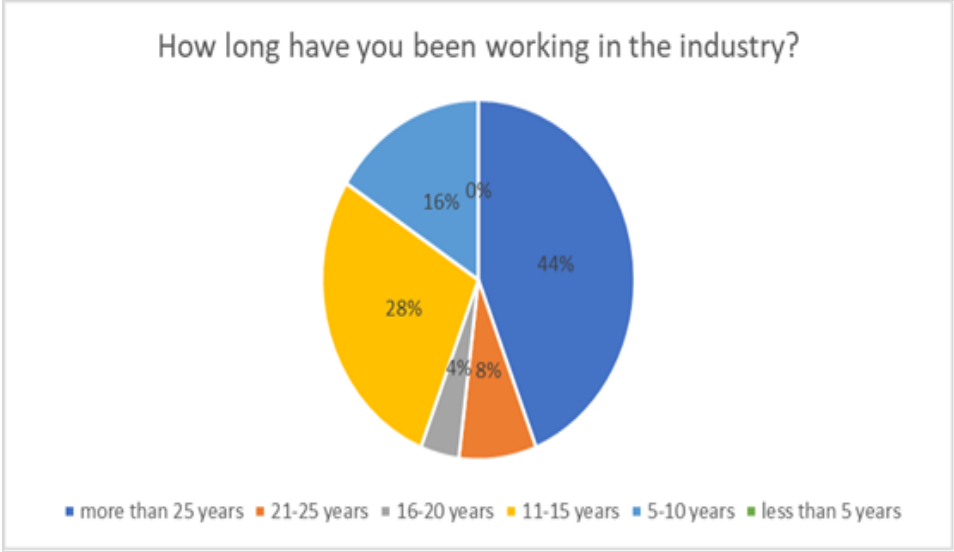
### 4.2 Survey Result



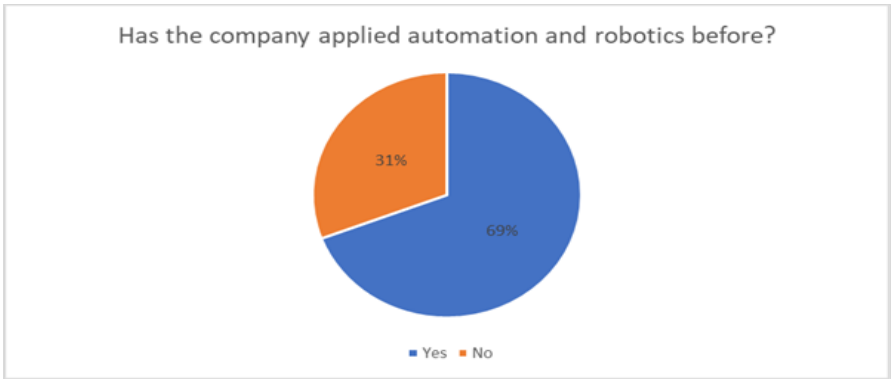
**Figure 7 Company's nature of business**



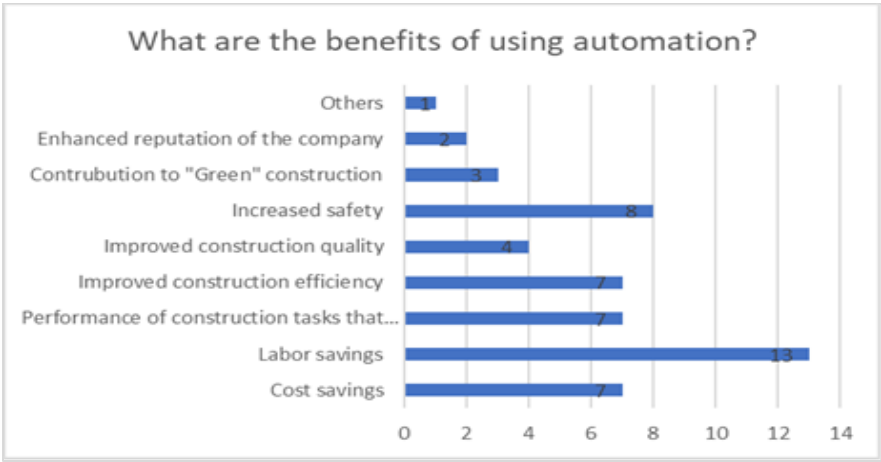
**Figure 8 Number of employees**



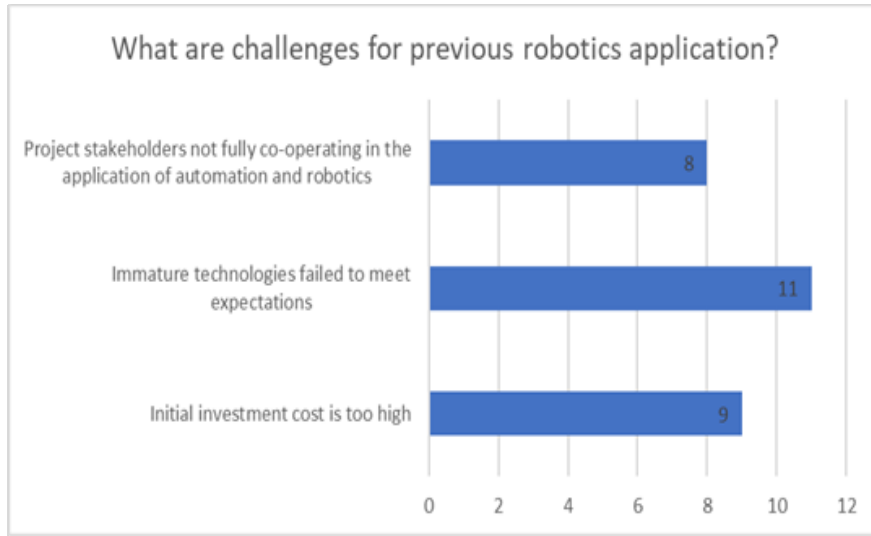
**Figure 9 Working years in the industry**



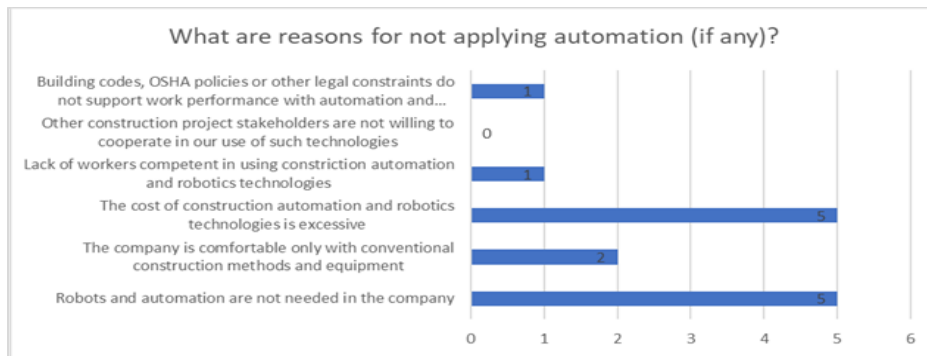
**Figure 10 Whether or not the company has applied automation before**



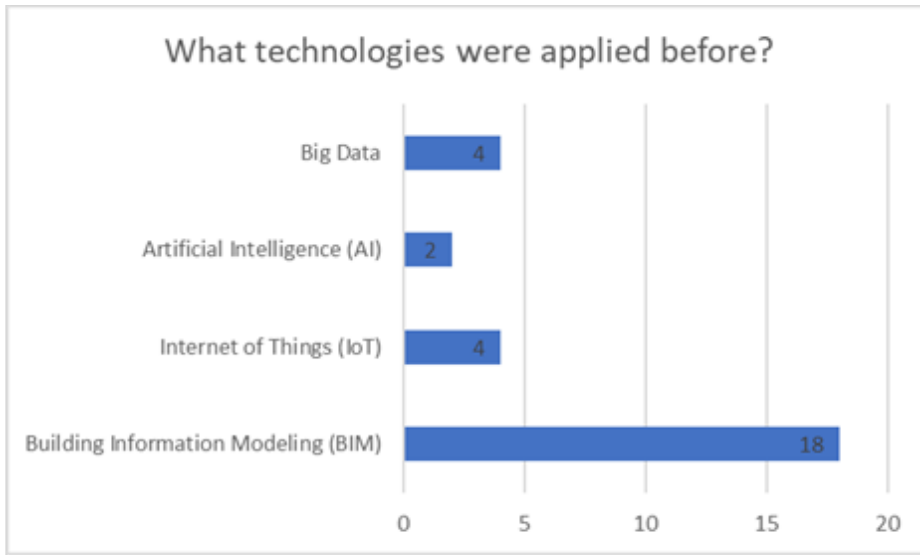
**Figure 11 Benefits of using automation**



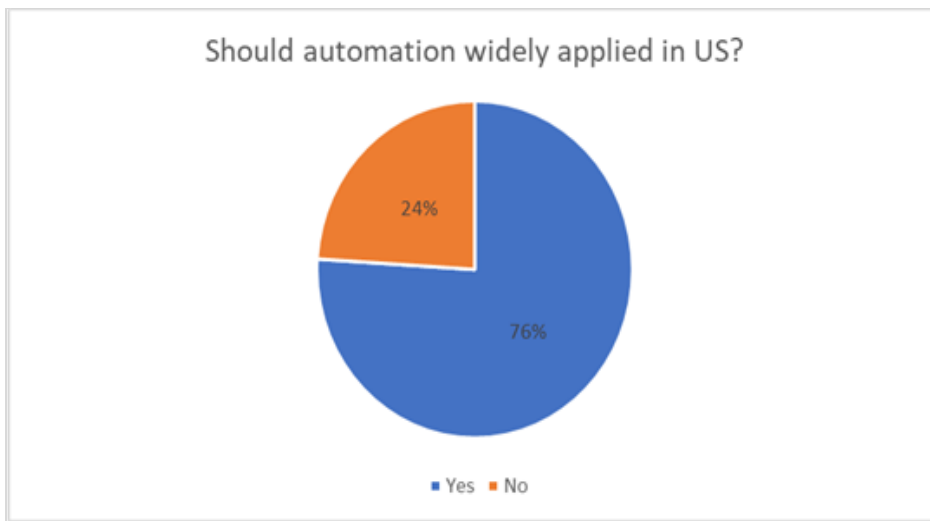
**Figure 12 Challenges for previous automation application**



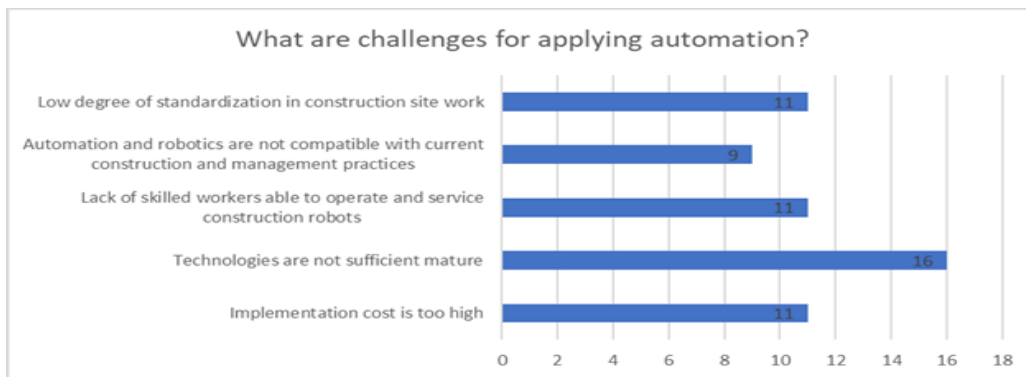
**Figure 13 Reasons for not applying automation (if any)**



**Figure 14 Previous applied technologies**



**Figure 15 Whether or not automation should be widely applied in U.S.**



**Figure 16 Challenges for applying automation**

**Table 12 Top 5 need of applying automation and robotics in high-rise building**

No	Construction Work	Average score, U.S.	Average score, China
1	Safety management of work performed overhead	4.68	3.89
2	Safety management of construction equipment	4.56	3.75
3	Construction workmanship quality inspection management	4.52	3.78
4	Steel coating	4.22	3.98
5	Steel welding	4.06	4.36

**Table 13 Top 5 influential factors of applying automation and robotics in high-rise building**

No.	Construction Work	Average score, U.S.	Average score, China
1	The ability of on-site management	4.7	3.94
2	Uncertainty of the economic benefit of automation and robotics	4.32	3.94
3	Labor cost of construction	4.31	3.82
4	Mature and proven technology to provide robust performance and ease of use	4.27	4.19
5	Initial investment cost of automation and robotics technology	4.13	4.41

4.3 Comparison between U.S. and China Result

As can be seen from the statistics, there are huge potentials in applying construction automation. More than  $\frac{3}{4}$  respondents believe that automation should be applied and 70% of the respondents actually applied before. Top benefits are labor savings and increased safety, since decreased labor in the companies reduce human cost and the

cost may be used on robots upgrading or R&D and therefore increase productivity, while increased safety provides room for innovation and renovation. Besides, before these automations are applied, immature technologies and high initial investments are challenges. Due to excessive cost and unnecessary, some companies didn't apply construction robotics. Safety issues are top concerns for future automation application. The ability of on-site management and uncertainty of economic benefit are the top influential factors of applying new technologies in the future.

#### 4.4 International Expert Workshop

In order to identify and further analysis the priorities and challenges, an international expert workshop was held in Beijing, November 2018. 16 experts were invited to the conference all around the world, including U.S., China, Japan, Germany, Canada and Germen. In addition, several representatives in the construction industry were invited to express their concern on actual production practice.



**Figure 17 International Experts Workshop, Tsinghua University, Beijing 2018**

The experts made presentations on their fields of study first in the workshop and followed by a focused group discussion was proposed afterwards. In the discussion

session, the experts were divided into two groups to separately raise top three priorities in the development priorities and challenges and list reasons for them. The information of experts in the two groups is presented in the table below.

**Table 14 International Experts Workshop Experts Description**

Group	Number of Experts	Experts description
English	5	2 university professors from the U.S.
		1 university professor from Japan
		1 university professor from Germany
		1 specialist from a software company for construction automation and robotics in China
Chinese	8	2 university professors from China
		1 university professor from Canada
		3 senior engineers from construction companies in China
		1 specialist from a software company for construction automation and robotics in China
		1 specialist from a robot developer in China

In the focused group discussion, two group proposed top three priorities, key challenges and provided reasons for them. For development priorities, English group believed safety control of work performed overhead, safety control of construction equipment, and steel works are top three important factors. For the reason concerning safety, English expert group considered the reasons are: 1) Safety issues are so important that it cannot be overstated, while high-elevation works are accident prone and need to be

protected; 2) Wearable devices, such as intelligent helmets, vests, and shoes, can be used to monitor the safety status of the workers and warn of potential dangers; 3) Fall protection systems can be designed with lifeline attachments, airbags, or other devices; 4) Many accidents happen on construction machines, such as cranes tipping over in a high wind; 5) The equipment safety can be monitored by adding sensors and controllers to the existing machines and connecting them in the cloud. For steel works (assembly, coating and welding), English group believed reasons are: 1) The work amount of steel works is large in high-rise building construction, and it is usually hard for workers to find a safe and convenient position to conduct steel works; 2) Coating and welding are conducted in poor working environment with serious pollution, which harm the health or even threaten the life of workers; 3) The quality management of steel works is a big problem now and it is possible for the robots to conduct steel works and quality inspection at the same time. For key challenges in English group, top three concerns are uncertainty of economic benefit, immature of technology, and incompatibility of existing construction pattern and robot application. For the economic reason, English group believed that economic benefit is the fundamental driver for both the robot developers to provide technologies and the construction companies to implement robots while currently, for construction companies, the return on investment (ROI) of implementing robots is too high or hard to evaluate in many cases; while the market volume is still limited for robot developers. For technological immaturity reasons, English group believed that: 1) The prototypes proposed in many studies are not verified in real construction projects; 2) The construction environment is developing rapidly and the robots should follow the latest changes; 3) Some basic technologies for

automation and robotics need to be improved, such as positioning and navigating. Last but not least, for incompatibility reasons, English group considered that: 1) The construction methods and the equipment performance need to develop together and promote each other. Currently, few studies have worked on this topic; 2) The design and construction need to be integrated to promote the application of robots because robots have advantages on standard operations and nonstandard design will limit the application range of the robots; many construction tasks can be redesigned to fit the function of robots.

As a comparison, Chinese group also raised their opinions on development priorities and key challenges. Concerning development priorities, top three of Chinese group are prefabricated component assembly; façade construction and maintenance; construction quality inspection. Reasons for prefabricated component assembly are: 1) The assembly efficiency is low because of repeated operation of survey and calibration, which are relatively easy tasks for robots; 2) The development of BIM and sensing technologies has laid the foundation of implementing automated assembly robots by providing positional information; 3) Prefabricated construction has a large potential market, especially in China, because of the promotion by the Chinese government. For façade construction and maintenance, Chinese group listed reasons as: 1) It is common but dangerous work in high-rise buildings and the maintenance work needs to be conducted frequently in a long term; 2) Robots can be implemented with pre-installed guide rail systems and in both construction and maintenance phase, which can reduce the difficulties in operation and lower the total cost. Moreover, for construction quality inspection, the reasons are: 1) It is a large amount of work with repetitive operations

dealing with numerical indicators, which are relatively easy tasks for robots; 2) Robots can avoid data falsification, which is a serious management problem now in the manual inspection; 3) Implementation of robots may change the work pattern and reduce the work amount by combining statistics and sampling methods. As for the question of key factors, Chinese group top three concerns are immature of technology, lack of data and analysis on user demand, incompatibility of existing construction pattern and robot application. For the reason on technology immaturity and incompatibility, two groups held the same reasons. For data demand, Chinese group believed that the research and development should be based on a full understanding of the users' needs, and the researchers and robot developers should first collect sufficient data and analyze it thoroughly.

## Chapter 5: Further Analysis on the Result

### 5.1 Safety management of overhead work and construction equipment

We found from the result that safety issue was the primary need of applying construction automation. According to the Bureau of Labor Statistics, 1013 deaths were experienced in construction industry in 2017, and the rate of injury and illness cases in full-time workers was 3.1% [22].

**Table 15 Work related fatalities, injury and illnesses**

Year	2014	2015	2016	2017
Number of fatalities	933	985	1034	1013

**Table 16 Rate of injury and illness cases per 100 full-time workers**

Description	Year 2017
Total recordable cases	3.1
Cases involving days away from work, job restriction, or transfer	1.8
Cases involving days away from work	1.2
Cases involving days of job transfer or restriction	0.6

Facing the issue of current safety issues in the construction industry, one of the solutions to reduce the trend is involving architects and design engineers in further consideration of construction safety process [23]. Based on reasons of construction safety failure and likelihood of the failure, this study gives suggestion to current and future design.

**Table 17 Designed suggestions for existing construction machines**

No.	Description	Probability of safety failure
-----	-------------	-------------------------------

1	Design special attachments or holes in members at elevated work areas to provide permanent and firm links for supplement, guardrails as well as scaffolding	Very high
2	Break the circuit or lower the voltage power lines on site before it starts	High
3	Make sure that the address, phone number, and the name of the utility are indicated in the drawings	High
4	Mark the location of overhead power lines and their position that is related to new design on the map	High
5	Draw columns with holes at 21 and at 42 in on the upper area of the floor to give support positions for guardrails and lifelines	Medium
6	Design a coned, rather than flat skylights that have strengthening wires	Medium
7	Position the parapet to be 42 inches high. Such a parapet that is tall and brings instant guardrail protection and do away with the urge to design a guardrail in the construction and future roofing	Medium
8	Provide long-lasting guardrails within the floor openings	Medium
9	Review the situation and integrity of the current structure and show any identifiable hazards of the contract structures	Medium
10	Draw and schedule durable stairways to be constructed within a short time in the construction stage and applied by the workers on the construction site	Low
11	Draw and schedule durable stairways to be constructed within a short time in the construction stage and applied by the workers on the construction site. Draw perimeter beams and others on the top floor openings to give support to the lifelines. Draw linking points along the beams for the lifeline. Carefully check on the number of lifelines and the positions along the beams	Low
12	Design the slope, height, width, turning radius, and the treatment of traffic surfaces by taking into account the required weight and the measurement ability of the construction equipment	Low
13	Give room for enough clearance between the power lines and the design	Low
14	Accept the pedestrian traffic to be isolated from designing the vehicular traffic	Low
15	Avoid road constructions and maintenance during peak traffic capacity moments of the day	Low
16	Keep away from the stair landings designed from the stairs	Low

17	Apply pre-fabricated stairways which can be raised as a single assembly	Low
18	Design and schedule the material and the various equipment that should be painted	Low
19	Design and schedule protected tie-ins to the current utilities	Low
20	Design the members that are of constant size and not difficult to handle	Low
21	Make a drawing of the completed floor to be at the same level	Low
22	At the time of road construction, make the traffic to be slow through closing the neighboring lanes by putting red flags on the way	Low
23	Assign police officers to keep a constant traffic check-up and patrol in the area	Low
24	Make sure that the installation of the electricity along the road adheres to the rules and regulations of the national electric code as well as the rules of the national fire protection association	Low
25	For access to doors through floors, use doors which immediately provide guarded entry around the hole perimeter when the door is opened	Low
26	For provision of access doors through the grounds, grant access to the doors that protected entry within the hole perimeters	Low
27	Align the project and rank the site in the standard way to reduce too much effort on the on the steep slopes	Low
28	Re-arrange the power lines within the project site before the construction activities starts	Low

**Table 18 Suggestions for future construction robotics**

No.	Description	Probability of safety failure
1	Design the correct and lasting fall protection systems for public roofs that are used for maintenance. Consider permanent anchorage points, lifeline attachments, and/or holes in perimeter for guardrail attachment	High
2	Design the correct and lasting fall protection systems for public roofs that are used for maintenance. Consider permanent anchorage points, lifeline attachments, and/or perimeter holes for guardrail attachment	High
3	For the use by all contractors, when design features, such as ventilation systems, trash chutes, chimneys, elevators, etc. ensure that cause floor	Medium

	openings are available during construction, and provide a warning in the plans and specifications for construction, and design in permanent guardrail systems and sequence them in early in the construction process	
4	In case of long building structures such as towers, come up with a cable-type lifeline mechanism that enables the workers to stick to the structures and give room for upward and downward movement in the structure	Medium
5	When workers are planning to demolish a building that is not worth for human safety, there should be a detailed survey carried out to ensure that there will be no unplanned collapsing of the house that will cause injuries and loss of lives. The probability of the building that is ready for the procedural demolishing should be greatly considered	Medium
6	Design and locate the of the tie-off points into the outside walls to allow renovations to take place	Medium
7	Before demolishing and renovating any structure, a survey should be conducted to determine the prevailing safety conditions during the demolition process	Medium
8	In the construction sites where the spaces are not enough, more priority should be given to the adjacent work schedules.to give room for crane installation	Low
9	Make sure that in the case of roofing activities that may involve sharp materials that resemble the ground are distinguishable from the ground to avoid injuries	Low
10	When coming up with a drawing of an atrium in the building, design safety mechanisms that are channeled early to enable them to be applied by construction workers	Low
11	Make clear of the necessity for a permit-required confined space program when using flammable materials inside tanks	Low
12	Clarify warning about project plans and specifications when electrical systems create openings of floor	Low
13	When one plans to make a structural drawing about of commercial buildings, single out the correct and recommended sheet metal gauge	Low
14	For projects that occur on or near steep slopes, provide clear warning and information including conditions of site and specifications documents	Low

15	In the process of roadwork, when there is a conflict between the work zone of the trucks and the work zone of the flaggers, build an alternate solution to the work zone, such as closing extra lanes of the highway	Low
16	Do not allow to design elevated exterior structures or equipment next to roof edges	Low

### 5.2 Construction workmanship quality inspection management

Construction quality is closely linked to project safety, cost and marketing; therefore, it is anticipated that the respondents rank this factor high in the survey. Although there are different standards in different societies, the core principle of quality inspection management is that after primary construction process, the contractors should self-examine the project before supervisors and owners should double check the project.

When developing construction robotics for inspection, several approaches that have been developed can be used on the robots, such as BIM, AR mobile computing, and RFID (Radio Frequency Identification Identification) technology [24]. When BIM system is carried on a smart robot, it can provide a series of comprehensive data and manage quality information as a tool. An AR-based system can be established and carried on a BIM models on an authentic structure. As an example of construction inspection process, laser scanning and depth sensing camera are two feasible tools for segment displacement inspection. Laser scanning has been conducted in multiple terrestrial measurement projects, but when the requirement needs to be more precise, laser scanning can be time consuming. Meanwhile, depth sensing camera is capable of measuring 3D size of a target. Currently, two major depth cameras---Kinect and Binocular Camera, are applied in real projects. Kinect uses a large amount of

calculation; therefore, a computer is needed to work together with Kinect; Binocular Camera in the meantime grasps various points to recognize the objects, therefore when the mono-color is not suitable for learning the objects, binocular camera is not a good option for segment inspection.

As an effective method to capture image of project site, AR system can be used on-site together with BIM in the following situations:

- (1) Based on construction quality standards, site managers and quality inspectors will make a systematic inspection plan;
- (2) BIM models will be collected by site managers and quality inspectors in order to store the acquired data into AR system;
- (3) BIM models to be inspected will be regarded as baseline models;
- (4) The baseline models will be linked and generated into a marker generator program;
- (5) The markers will be attached to designated places;
- (6) Using AR devices, BIM models will be augmented in actual work sites, and the inspection can be also implemented by on-site workers for self-inspection instead of merely site managers and quality inspectors;
- (7) Baseline models and actual inspection results will be compared in the system;
- (8) According to the comparison result, the quality inspectors will make decisions on whether the construction process is qualified [25];

### 5.3 Improving the ability of on-site management

It is commonly known that a wide range of stakeholders exist in a construction project. As is shown in the questionnaire result, the ability of management is a priority in future

robotics application. And while the stakeholders have major influence on construction project schedule, budget and scope, it is of great significance to study the stakeholders management in the project.

In 2003, Chapman and Ward raised a theory of SHAMPU process, meaning to shape, harness and manage project uncertainty [26]. In order to further understand this concept, the phases of SHAMPU process and their purposes are introduced.

- (1) Define the project: Integrate known information and potential risks of the project into a holistic strategy and make sure that the consolidation process should be consistent.
- (2) Focus on the process: In an operational level, plan the scope and strategic plan for risk management process.
- (3) Identify the issues: Identify the strengths, weakness, opportunities and threats of the project and clarify the risks of uncertainty and list of responses to the uncertainty.
- (4) Structure the issues: Complete the project structural plan for early stages. Test and list the assumptions for early stages.
- (5) Clarify ownership: Clarify financial and managerial ownership of the projects and clarify the responsibility ranges of different parties.
- (6) Estimate variability: Quantify the size of uncertainty and adjust the previous estimation of project assumptions.
- (7) Evaluate implications: Evaluate statistical dependence and compare the results with early phase estimation. Besides, analyze the results from all process and

make decisions of the responses and plans for future phase based on the analysis.

(8) Harness the plans: obtain approval for plans raised in evaluation implications and develop plans for action. These are base plans (incorporating preventative responses) and contingency plans (incorporating reactive responses with trigger points) ready for implementation within the action horizons defined by appropriate lead times [27].

(9) Manage implementation: Manage the designed work and prepare plans for unanticipated issues or other possible failures.

In order to improve construction management ability, it is also important to improve the efficiency and effectiveness of construction process. In the focus phase of Chapman and Ward, two important factors should be specifically noticed---scoping and planning the process. In order to comprehensively clarify the complete focus phase, all relevant personnel should be involved. For uncertainty faced by project management team, four groups of participants should be elaborated: senior managers, other managers, technical experts and risk analysis experts. Senior managers are involved to assure that the holistic requirements are distributed to the whole team, monitor the construction process and make critical decisions. Other managers are involved to guarantee that the analysis to be conducted serves the whole context management process. Technical experts are involved to assure that all technical works go smoothly and communications in all levels are in appropriate manner. Risk analysis expert are involved to analyze potential risks, and provide modeling, designing, and facilitation skills.

Effectiveness should be measured in managerial level. Measuring effectiveness has

been explored in many literatures and is studied from many perspectives. For example, the opinions of Boyatzis and Winterton are controversial over terminology. Nevertheless, these ideas of effectiveness are appropriate for designing programs that lead to portable qualifications rather than systems to measure performance. In 2001, Kagioglou brought up an explanation of effectiveness that was available for designing performance measurement [28]. This concept is used when the individual's ability, work's requirement and organizational environment are covered among each other. In this mode, the more efficient worker is the one who has sufficient skills and successfully completed work tasks. The most significant issue in this measurement is to determine the level of tasks accomplishment, together with illustrating work requirements as measurable break-down activities. Individual skill measurement and characteristics are beneficial to the prediction of future performance, though they are not the critical elements in the effectiveness measurement.

## Chapter 6: Case Studies

In order to be understand more about actual construction robotics application, three companies were studied---Tybot LLC, Construction Robotics, Redzone Robotics LLC.

### 6.1 Tybot LLC

Located in Pittsburgh, Pennsylvania and owned by Advanced Construction Robotics Inc (ACR), Tybot LLC is a commercial company which provides solid and flexible solutions in the field of rebar installation work. Tybot coordinates current bridge operations by continuously tying the intersections and flawlessly using self-directed rebar tying robot that can reduce necessary labor in bridge construction process. By combining with current construction technologies, Tybot aims to use provide innovative solutions to improve project overall productivity, profit and safety, and decrease risks during the construction process by means of reliable, safe and competent technologies.

#### 6.1.1 Timeline of Tybot LLC.

**Table 19 Timeline of Tybot LLC**

2015.09	Future of Robotics conference held in Carnegie Mellon University
2016.04	Concept of Tybot initilized
2016.11	Advanced Construction Robotics, Inc. (ACR) was founded
2016.11	Concept of Tybot substantiated
2017.08	Tybot, LLC was established
2017.10	First product was deployed on the PennDOT Freedom Road bridge project
2017.11	Tybot was recognized in the Engineering News-Record magazine
2017.12	Tybot closed a \$4 million note round led by Grouse Ridge Capital, LLC
2018.01	TyBot was awarded as semi-finalist in the Associated General Contractors of America's Innovation Award

2018.03	Tybot was in the finalist for the 2018 Innovation Award
2018.05	ACR was selected to participate in the program for innovative start-ups in the construction industry
2018.10	TyBot won the Associated General Contractors of America Autodesk Innovation Award

### 6.1.2 Tybot Rebar-tying robot



**Figure 18 Rebar-tying robot**

Tybot has developed a robot that works independently to tie the steel rebar in the construction process. The robotic arm works above every rebar intersection to tie them together before the concrete pour, and the robot can extend up to 140 feet far across a bridge. From the technical side, Tybot operations is autonomous, which means that no preliminary mapping of the site is needed; Tybot is capable of continuously navigating and identifying the bridge deck and tying the rebar self-driving regardless of weather and temperature.

Tybot reduces labor hours cut and enhances safety. Only one technician is needed to

operate and monitor the machine, compared to a whole rebar tying team previously. It is estimated that the total labor hours can be decreased by 50% and that the risk of working injuries can be reduced. According to a study report of International Journal of Occupational Safety and Ergonomics, 880 out of 1000 construction ironworkers had suffered MSD (Musculoskeletal Disorders) during the career<sup>[17]</sup>. As a highly repetitive and accident-prone activity, rebar tying robot is a solution to decrease the safety risks, as the co-founder Jeremy Searock described, “This is a very boring robot that has great application and profitability [29].”

Tybot robot was first deployed in Pennsylvania Department of Transportation Freedom Road project. The project is to replace the current bridge over Snake Run Stream (123 feet long, three-lane), Romigh Road (80 feet long, two-lane) and Park Quarry Road. The project was experiencing labor shortage, and the team decided to replace labor with automation and robotics as much as possible, therefore Tybot was selected as the company’s first actual project.

The use of Tybot on this project proved to be a success. With a conservative expectation, the integration partner saved 35% money together with a higher work efficiency and less injuries.

#### 6.1.3 Limitation of the rebar-tying robot

The advantages of Tybot make the company and its product promising. However, there are still some disadvantages that may prevent the company from further expansion.

Firstly, Tybot can only be set up for gantry type. Therefore, the robot is only suitable for rectangular construction sites. When the shape of the working site is diversified, the robot currently may be unable to perform normally. Besides, the cost of the machine is

unknown to the public, and the price may be high for the customers. Moreover, since the machine is large, it takes much time to set up the machine. With substitution by much smaller handheld rebar-tying machine on the market, the necessity of Tybot robot may be questioned.

MEDIUM BRIDGE PROJECT Cost & Schedule Savings ~43 ft Wide x 1250 ft Long ~53,000 Square Feet ~535k LBS of Rebar		Option A: Labor Augmentation			Option B: Labor Reduction			IMPACT: ↓ Manhours ↓ Days on Site ↑ \$\$
		Crew	Crew + TyBot™	% ↑↓	Crew	Crew + TyBot™	% ↑↓	
Value Creation:	Crew	10	10	0.0%	10	7	(30.0%)	IMPACT: ↓ Manhours ↓ Days on Site ↑ \$\$
DECK REBAR	Manhours	3,818	2,291	(40.0%)	3,818	2,291	(40.0%)	
	Days on Site	70	40	(42.9%)	70	59	(15.7%)	
	Cost Savings		\$46,419			\$26,335		
Value Creation:	Days on Site Reduction		30			11		IMPACT: ↑ Bidding Advantage
TOTAL PROJECT	...x LDs / Bonus per Day		\$6,060			\$6,060		
	LD \$ Risk Reduction / Bonus Capture		\$181,800			\$66,660		
	...x Site Overhead \$ per Day		\$2,250			\$2,250		
	Site Overhead \$ Reduction		\$67,500			\$24,750		
	...x Deck Support Equip. \$ per Day		\$900			\$900		
	Site Overhead \$ Reduction		\$27,000			\$9,900		
	...x Home Office Overhead \$ per Day		?			?		
			\$276,300			\$101,310		
Value Creation: GRAND TOTAL			\$322,719			\$127,645		

Figure 19 Robotics cost for a typical medium bridge project

6.1.4 SWOT matrix of Tybot LLC

In order to learn the strengths and weaknesses of Tybot more deeply, a SWOT analysis is applied. The sources for identifying the strengths, weaknesses, opportunities and threats of the SWOT matrix came from the case studies and analysis on the factors that may be influential to Tybot’s future performance.

Table 20 SWOT Matrix of Tybot

	Strength(S)	Weakness(W)
	S1: Labor hour is reduced by the machine	W1: The company has no competitive advantage on bidding prices

	S2: Safety is increased compared to traditional rebar-tying methods	W2: Lack of professional technician
	S3: The company's executive board members are experienced in the industry	W3: There is no standardized procedures for robotics rebar-tying
Opportunity(O)	S/O	W/O
O1: There is high vacancy for construction robotics market	SO1: The company expand the business in the market	WO1: Develop standardized protocol for the industry
O2: The desire for rebar-tying market is huge	SO2: Invest more money to design new robotics	WO2: Be consistent on current technical advantages and make the best use of them
O3: The investment of the robots is increasing		
Threats(T)	S/T	W/T
T1: Competitiveness in construction market is very extreme	ST1: Advertise more positive aspects about the company	WT1: Cautiously evaluate every projects and customers, and avoid overwhelming budget
T2: There is a huge concern that robotics will take over human's job		

## 6.2 Construction Robotics Company

Construction Robotics (CR) was founded in 2007 with the objective of improving the construction process by means of construction automation and robotics technologies at an affordable price and leading-edge robotics. The two main robots of CR are MULE (Material Unit Lift Enhancement) and SAM100 (Semi-Automated Mason), and these robots have been applied to a number of construction projects.

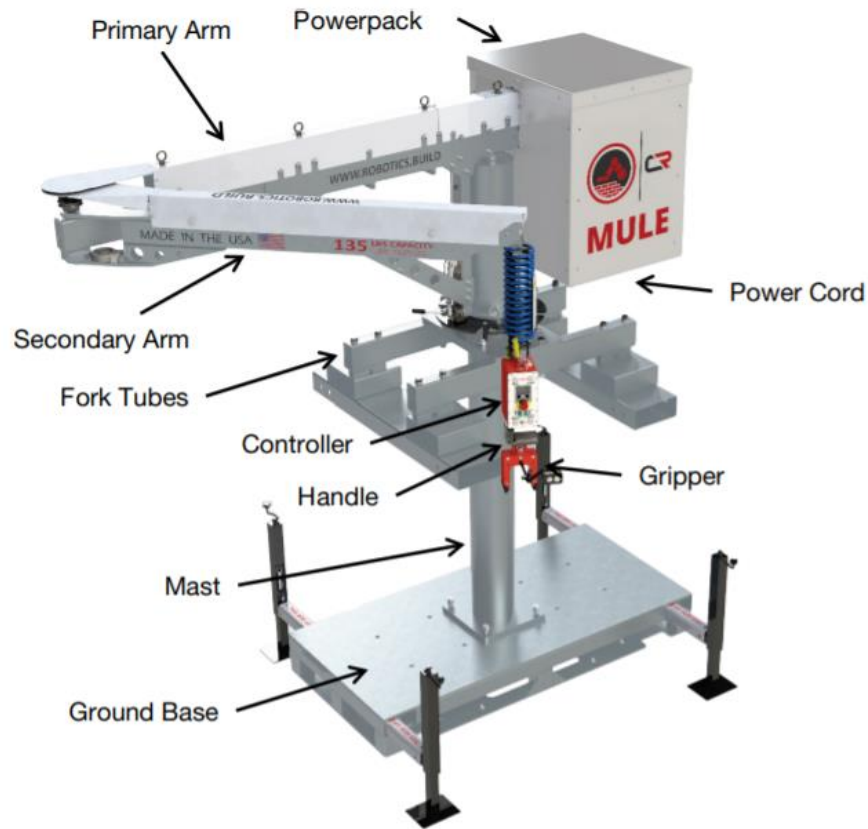
6.2.1 CR Project Portfolio

**Table 21 CR projects overview**

Project Name	Location	SAM Bricks	Brick Type	Time
UMHHC Brighton Health Center South	Brighton,MI	17,000+	Utility	July 2017
Erlanger Medical Office Building	Chattanooga, TN	25,000+	Utility	May 2018
POFF Federal Building	Roanoke, VA	250,000+	Modular	July 2018
Shenandoah University – Athletics & Events Center	Winchester, VA	80,000+	Modular	June 2017
Ford Driving Dynamics Lab	Wayne, MI	15,000+	Modular	April 2017
Purdue University, Flex Lab Facility	West Lafayette, IN 47906	60391	Modular	2017
Towneplace Suites – Cranberry Springs, PA	Cranberry Twp, PA	9043	Utility	August 2016
Aldi – Pulaski, NY	Pulaski, NY 13142	3340	Belden Modular	
Delbert Day – Rolla, KS	Rolla, MO 65401	24950	Modular	June 2016
Middle School – Goodlettsville, TN	Goodlettsville, TN 37072	13803	Utility	February 2016
Columbus McKinnon – Amherst, NY	Getzville, NY 14068	15000	Utility	November 2015
Potomac Valley Brick Showroom – Frederick MD	Frederick, MD 21704	3846	Belden Utility	September 2015
The Lab School – Washington, DC	Washington, DC 20007	10695	Norman & Closure	August 2015
Laramie High School – Laramie, WY	Laramie, WY 82070	7000	Utility	June 2015

## 6.2.2 CR MULE 135 key features and specifications

### 6.2.2.1 MULE 135 Features



**Figure 20 MULE 135 robot**

- (1) MULE 135 can carry the materials that weight less than 135 pounds
- (2) A substitution for worker's physical repetitive lifting
- (3) Convenient to control and operation and easy to set up
- (4) Improve productivity
- (5) Flexible to deploy

### 6.2.2.2 MULE 135 specifications

**Table 22 Key specifications of MULE 135**

MULE Model	135
Voltage	120V

Amperage		20A
Operating Capacity		62kg
Maximum standing height		8534mm
Maximum mast height		12497mm
Maximum arm reach from axis		3658mm
Arm and Powerpack	Weight	395kg
	Height	1270mm
	Length	4445mm
	Arm swing angle	360°
Fork Tubes	Weight	132kg
	Height	368mm
	Length	1219mm
	Width	1219mm
Ground Base	Weight	431kg
	Height	216mm
	Length	1854mm
	Width	876mm
Mule Mast	1' tower	50kg
	2' tower	62kg
	3' tower	71kg
	4' tower	82kg
	5' tower	91kg
	6' tower	103kg
Mast adapter	Weight	93kg

### 6.2.3 Advantages of MULE 135

MULE 135 is designed for brick laying worker and retaining wall contractor, aiming to eliminate the weight of Concrete Masonry Unit (CMU). CMU is widely used throughout the construction process, including foundation and structure. Due to the limitation of ergonomic, a common 8\*8\*16 CMU weighs 30-35 lbs. By using MULE 135, the daily workload of mason can be reduced from 4,000-10,000 lbs. to around 150lbs.

The robot is quite flexible. With a variety of base design and gripper attachments, MULE is suitable for operations in different environments, such as scaffold, mast climbing work platforms, or ground. MULE designed by CR is widely used for accurate control when it comes to lifting in construction process, and MULE 135 is a demonstration of this idea, by interacting onsite products and changing the way people work.

To summarize,

- (1) MULE 135 is an ergonomically friendly and innovative equipment that relieves the pressure of physical injuries
- (2) MULE 135 increases the construction working productivity.
- (3) MULE 135 offers a way to work more consistently
- (4) MULE provides more flexibility compared to traditional lifting equipment.
- (5) MULE 135 is a cost saving machine. Typically, the cycle for Return of Investment (ROI) is less than six months.

#### 6.2.4 CR SAM 100

The design of SAM 100 was initialized in 2007, when the current operation manager, Zak Podkaiminer started a series of trials of laying brick and putting mortar on it by using an automated SAM. In two years, SAM was basically able to extrude mortar on bricks, but the robot still had obvious flaws in locating the brick accurately and repeatedly. With the help of CAD, more complicated designs were available in addition to basic one-on-two placement [30]. In February 2015, SAM 100 was launched at the World of Concrete, Las Vegas.

By using the robotic arm, concrete pump and conveyor belt, SAM 100 can lay around

150 bricks per hour and 1,300 bricks per day, which reduces the lifting by 80%. Compared to human worker who can lay 400 to 600 bricks per day, SAM is an innovative technology with much higher efficiency and safety. In the project of Shenandoah University, a world record was made - SAM laid 3,270 bricks in eight hours; if operated by SAM and human workers, a total number of 375,000 bricks were laid on the new center.

**Table 23 Bricklaying robotics mechanical design framework**

Category	Description
General	Holistic system design
Material	Input material into the robot
Mechanical	Structural design
	Robot dynamic
	Stock processing
	Handling system
Dynamic	Onset system design
	Lowering system design
	Brick-laying system
Economic analysis	Construction time analysis
	Construction cost analysis

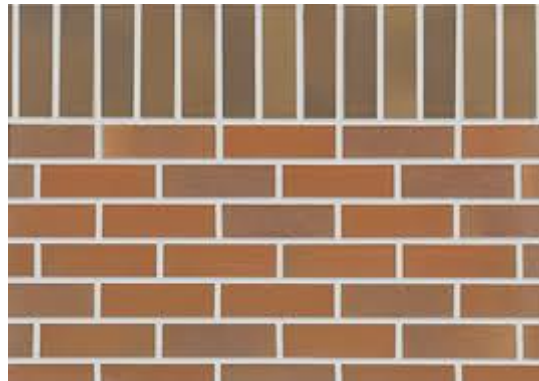
6.2.5 CR SAM 100 OS2.0



**Figure 21 SAM 100**

SAM 100 OS2.0 is an updated version of SAM 100 released in 2017. As an enhanced version, it can lay around 350 bricks per hour and 3,000 bricks per day. In addition, OS2.0 can lay soldier-course bricks to allow bricks to stand vertically. OS2.0 is also less in weight, from originally 4,500 lbs. to 3,300 lbs. Safety sensor was placed in the machine to prevent SAM from being dropped from scaffold or stroke on workers.

The automation application of SAM doesn't mean that no labor is needed. Instead, SAM requires at least three operators alongside when it's working-a mason to operate the machine, a tender to load mortar and another mason to adjust the location and fasten wall ties.



**Figure 22 Soldier graph brick**

#### 6.2.6 Disadvantages of SAM 100

The cost of SAM 100 is around \$500,000; therefore, the high building and maintenance fee would be a concern. Meanwhile, the process of setting up the machine is different from traditional bricklaying procedure, thus a challenge for the onsite manager to adjust regulations and redefine working tasks.

### 6.2.7 SWOT analysis of Construction Robotics LLC

**Table 24 SWOT Matrix of Construction Robotics LLC**

		Strengths(S)	Weakness(W)
		S1: By applying to many projects, CR robotics are experienced	W1: CR robots are big and heavy
		S2: CR robotics are ergonomically friendly	W2: Setting up of the machines takes too long
		S3: Productivity and safety of construction bricklaying are improved	W3: Initial cost of robots like SAM 100 is very high
Opportunity(O)	O1: There are not many competitors on the market currently	SO1: Make the best use of current market bonus	WO1: Invest on alternative robots with similar functions but in smaller size
	O2: A huge number of projects need bricklaying automation	SO2: Move aggressively and expand market over a short period of time	WO2: Scheduling projects more efficiently and diminish wasted time
Threat(T)	T1: Necessity for the robots may decrease as time goes by	ST1: Grasp the leading position of the market and build brand reputation	WT1: Formulate project feasibility report for every project
	T2: Innovative robots for bricklaying may appear and replace CR robots		

### 6.3 Redzone Robotics Inc.

Founded in 1987 and based in Pittsburgh, Pennsylvania, Redzone Robotics Inc.

develops wastewater inspection and asset management solution for wastewater pipeline system owners, operators, municipalities, consultants and engineers, and contractors by using robots and software tools [31]. From the company’s insight, wastewater asset management is highly related to technological application and data management. Redzone assists engineers and owners in getting access to necessary and intact information by using ownership data to access robots and software, which saves money and improves the environment.

### 6.3.1 Redzone Solo

Solo is designed to be the first unmanned sewer inspection robot in the industry to gather high quality inspection data in the highly needed daily quantity in various types of pipes, including 8”, 10” and 12” (200mm to 300mm). Solo is a small and light robot that can access deep manholes which traditional CCTV platform cannot reach. As an autonomous and battery- driven machine, Solo is less costly than other platforms, and can work day and night regardless of weather conditions. Based on general assignment of pipe condition grades (below table), Solo evaluates the target pipe, and sends comprehensive data for workers’ further operations.

**Table 25 General assignment of pipe condition grades**

Grades	Description
Grade 5	Collapsed or collapse imminent
Grade 4	Collapse likely in foreseeable future
Grade 3	Collapse unlikely in the near future
Grade 2	Minimal collapse risk
Grade 1	Acceptable structural condition
Grade 0	An observation only

In 2018, Solo was widely applied in the Winter Garden city sanitary sewer pipeline

inspection project, with a total length of 62,500 feet. Solo used laser, camera, radar, sonar and hydrogen sulfide gas sensors to evaluate the pipe detailed condition [32]. Workers first examined the objective pipes manually, and then the electrical machines were used. Dropped into a manhole, the Solo robots therefore collected data and deliver to a special team to create complete database.

### 6.3.2 Advantages of Solo

**Speed:** With the assistance of Solo, PWSA (Pittsburgh Water and Sewer Authority) can complete inspection of 100,000 feet pipe in 7-10 weeks, which is far quicker than the process without the robot

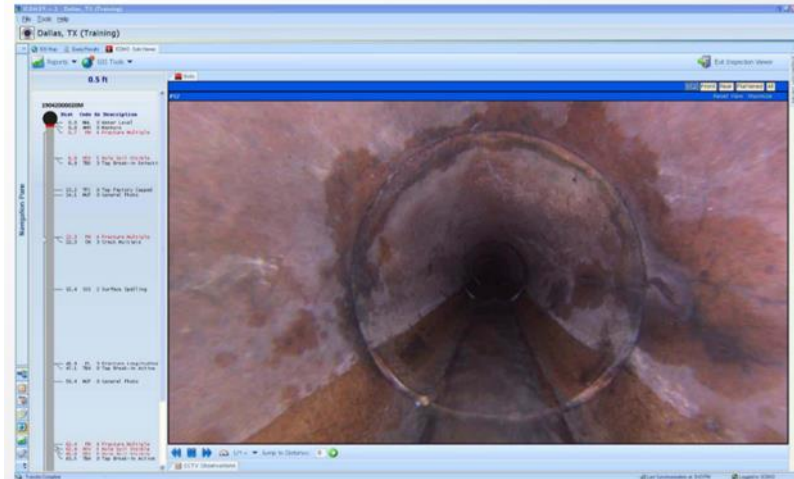
**Convenience:** Solo covers 100% of pipe and transform data in digital format; Solo is not affected by weather conditions

**Savings:** Since no manned truck is required, the cost of inspection is \$1.5 per foot

**Safety:** Solo provides overwhelmingly safety compared to manned deep inspection, meanwhile the interference to traffic is minimized



**Figure 23 Redzone Solo**



**Figure 24 Solo Viewer**

### 6.3.3 MD Sub

MD Sub is supportive underwater assessment equipment, which allows inspections for surcharged pipelines that are hard to reach by using carried computer and batteries package to provide strong transportation mobility. MD Sub uses cableless elements, including modular recording unit, compared to traditional sonar platforms that need a cable attached to the surface to operate the machine. The underwater assessment machine utilizes Multi-Sensor Inspection (MSI) information and transfers it with a long- distance sonar platform.



**Figure 25 MD Sub**

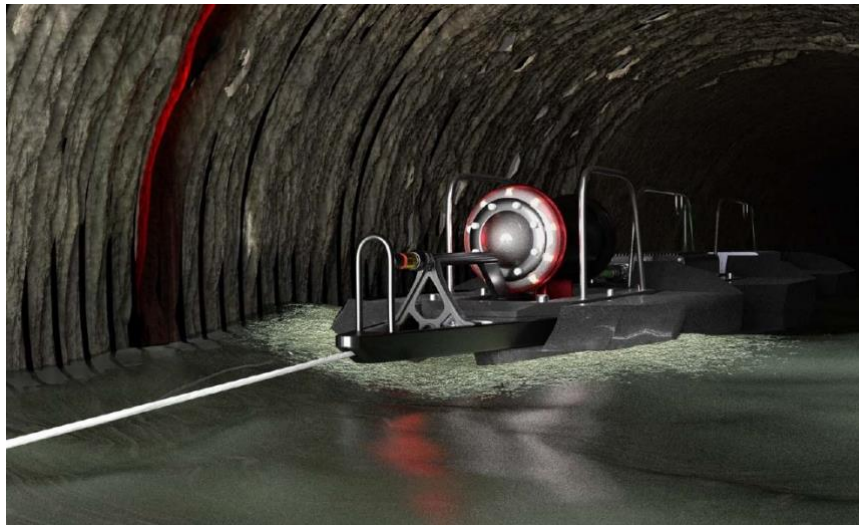
The data recorded by MD Sub helps monitor real-time underwater condition and identify failure, debris location and volume as well as water level. Besides, the data is beneficial for decision makers to identify the best plans for maintenance and rehabilitation of pipelines. Furthermore, identifying failure area within surcharged line can be helpful for planning cost-effective maintenance. The table below shows the features of MD Sub.

**Table 26 MD Sub key features**

Category	Description
Transportation	Neutrally buoyant platform
Pipe size	500mm-2200mm
Minimum flow	350mm
Minimum air gap	0mm, when fully surcharged
Battery life	6 hours
Accuracy	0.40%
Reports	Debris, flow height and pipe size

#### 6.3.4 MD Profiler

MD Profiler is another evaluation equipment that assess quantitative data for line inspection. Using standard battery and onboard computer system, this robot can be working continuously for three hours and inspect a total length of 2,000m. In some middle diameter pipelines, precise assessment of corrosion severity, levels of deformation and debris is very much needed, since visual inspection is not sufficient for decision. MD Profiler solves this problem by utilizing a combination of MSI and traditional central television, which provides 360-degree vision of pipeline.



**Figure 26 MD Profiler**

The features of MD Profiler are shown in the table below.

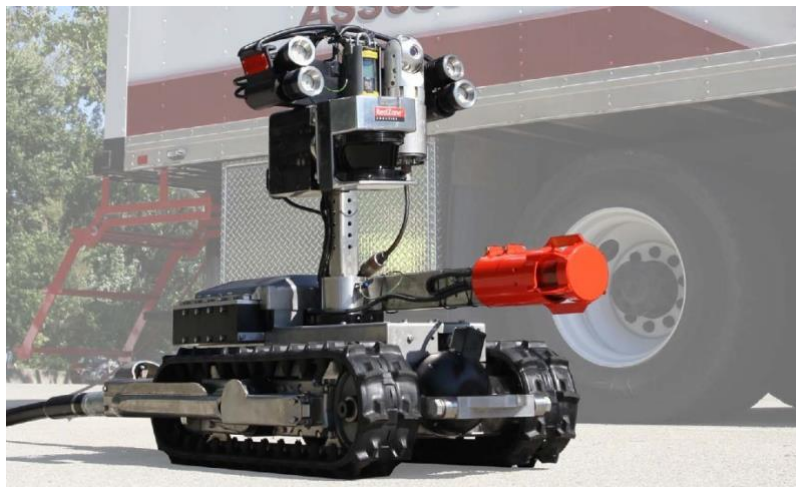
**Table 27 Key features of MD Profiler**

Category	Description
Sensors	Lasor, sonar and CCTV
Transportation	Floating and wheeled platform
Pipe size	400mm-915mm
Minimum flow	0 (Both floating and wheeled)
Minimum air gap	200mm
Battery duration	3 hours

Accuracy	0.1%
Telecommunication	Dependent on pipeline conditions
Reports	Corrosion, debris, flow height, pipe size, ovality

### 6.3.5 Redzone Responder

In contrast with MD Profiler which focuses on middle diameter pipelines, Redzone Responder is designed for inspecting large diameter pipes and tunnels - more than 36 inches in diameter and more than 8,000 feet in length. Similar to other robots, Responder is capable of collecting critical information about those large pipelines and providing solid knowledge for decision-makers by operating remotely with elements of 3D scanning lidar, air and temperature sensors, sonar and high-resolution CCTV, Responder units are flexible and can pass through assets while traditional machines cannot.



**Figure 27 Responder**

The table below shows key features of Responder.

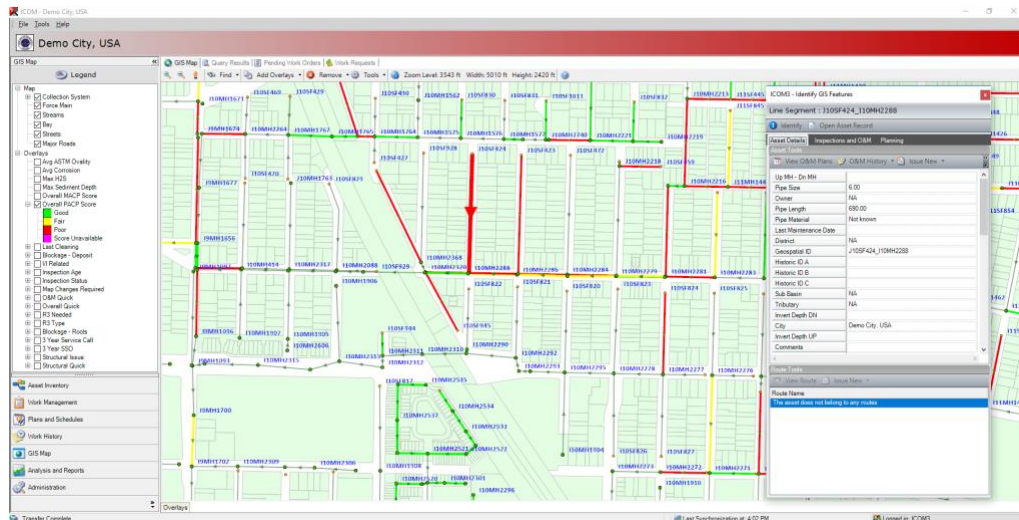
**Table 28 Key features of Responder**

Category	Description
----------	-------------

Sensors	3D Lidar, sonar, CCTV, air and temperature sensors
Transportation	Hydraulic tracked crawler
Pipe size	915mm-6,000mm
Minimum flow	0
Minimum air gap	0
Weight	300kg
Control	Real-time control and feedback
Reports	3D reports on corrosion, debris, flow height, pipe size, ovality, virtual mandrel, gas and temperature

### 6.3.6 Redzone ICOM

Redzone ICOM is a solution providing system that focuses on pipeline integration inspection, maintenance and asset program management. ICOM uses various tools to learn comprehensive condition of pipeline systems, including image and video inspection, physical feature inspections, risks measurement, hydraulic inspection and maintenance information.



**Figure 28 ICOM system interface**

There are several advantages of ICOM. As a project management software, ICOM uses

web-based system and is capable of working in disconnected mode meanwhile supporting historical CCTV data and previous work history. Core modules of ICOM comprehensive asset management programs include inspection management, work management and asset management, therefore ICOM provides automation regulatory preparation reports based on asset and activity.

6.4 Blueprint Robotics

6.4.1 Blueprint Robotics overview

Blueprint is a construction automation company that produces prefabricated customized wooden elements for construction industry. Blueprint uses innovative approaches to construct wall, floor and roof elements that are more precise compared to traditional methods by applying robotics. The products of Blueprint vary in a wide category, including window, exterior doors, exterior sheathing, wall plumbing, fire protection, and accommodation for HVAC. Most products are made in wood and are shipped by Blueprint trucks to construction sites by using standard-sized over-the-road trailer and reducing the need for oversized transportation requirements.

6.4.2 Blueprint Robotics past projects

Below table and pictures below show part of Blueprint projects and their location.

**Table 29 Part of Blueprint Robotics Past Projects**

No.	Project	Location
1	Attached town homes	Philadelphia, PA
2	Attached single family town homes	Baltimore, MD
3	Town homes and commercial space	Annapolis, MD
4	Tow attached single family homes	Baltimore, MD

5	Six attached carriage houses	Annapolis, MD
6	Single family home	Nantucket, MA



**Figure 29 Blueprint Projects (in table 25 order from 1 to 6)**

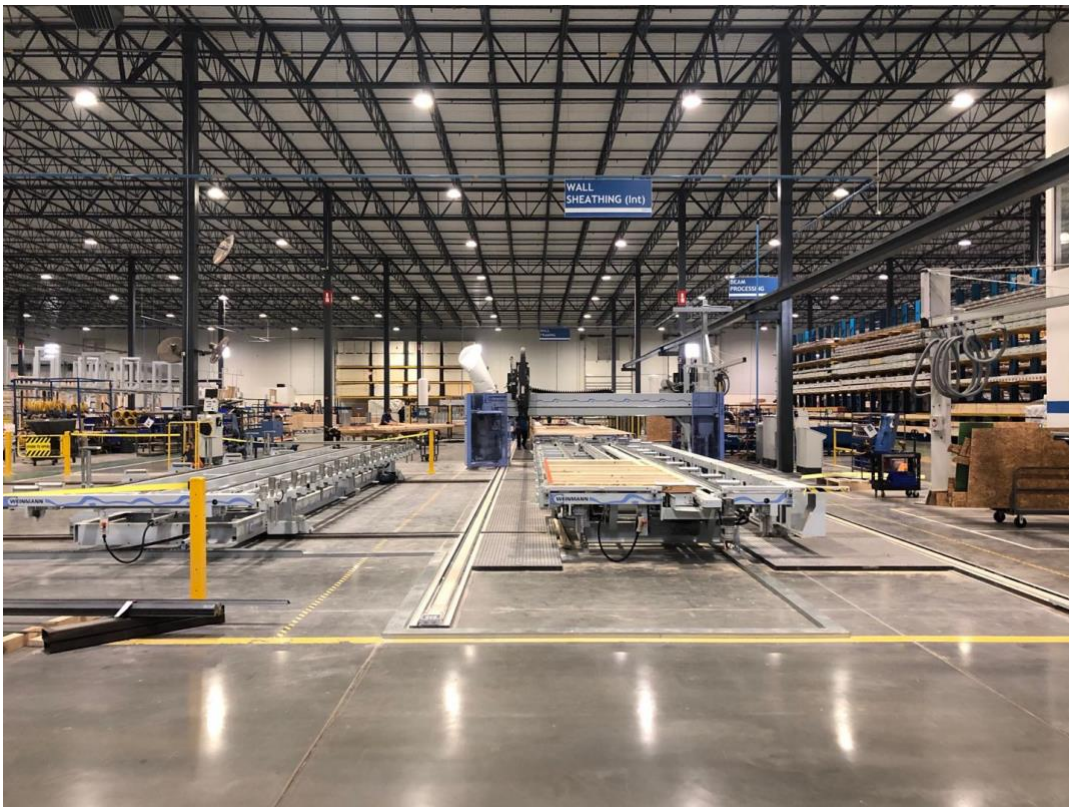
#### 6.4.3 Blueprint work mode

Currently, there are about 70 workers in Blueprint, in which 30 workers are in the production side and the rest are composed of PMs, executive staff, architects, PEs and CAD engineers. Blueprint also has an engineering office in Munich, Germany. As a start-up, there were many lessons to learn, and one of the lessons was timber engineers who could model 3D that are hard to find or impossible to find in U.S. by using Blueprint's software Dietrichs, and there is a long learning curve to train for

even the best CAD operator or architects to operate Blueprint's system because the company needs a true timber engineer where he or she needs to understand the structure and has the ability to work within the software. Blueprint coordinates all the projects in Revit and takes it as a platform to communicate with the customers about both the structure as well as full MEP. Blueprint pulls the trade permits and covers the scopes exclusively, so the GC will not need to hire another electrician or framework.

Blueprint schedules its automation production in a comprehensive way. Since the setup is entirely driven by the needs of particular projects, utilization rate is a significant issue. When Blueprint shifted that paradigm to exclusive multifamily, there certainly has been some lags between production and customers who weren't ready for it, Blueprint had to slow down a little bit, and within approximately three weeks the company will be ready to crank up again. By the summer of 2019, Blueprint will be in a second shift, and the multi-unit from August 2018 will be going exclusively, so the company has to sell the multi-unit jobs and get them under contract which last for four or five months. Utilization is quite flexible, and Blueprint is capable of running multiple jobs in the factory at a time. With a lot of internal coordination, the manufacturing is set to be completed in a timely manner. Instead of building a store or an entire building, storing it and waiting the foundation to finish, Blueprint aims to build a five-storey wood building in time. Blueprint might build the first two floors fabricated and packed out as the foundation is being completed and show up on site to assemble the vertical parts and fabricate the rest of the structure. Currently, Blueprint is doing one shift and preparing to do two shifts. There won't be

a third shift unless it is used for a certain period of time. On one shift frequency, the capacity is about 700,000 to 800,000 square feet a year, and Blueprint is aiming one and a half million utilization capacity per year. In the back-parking lot of Blueprint in Baltimore, lots of products are ready to be shipped because customers were not ready, and some products were produced based on old contracts several years ago. This cost of money on company's site storage and shipping products to the work site. Blueprint now has safety nets in the contracts and also makes better decisions on when it will put products to the factory so that the company does not have to wait for a certain customer. With the ultimate goal to be just in time, there will be less storage, which might be sitting on a trailer in the rear yard for no more than a week or two.





**Figure 30 Internal assembly line of Blueprint Robotics**



**Figure 31 Back-parking lot storage of Blueprint Robotics**

Ideally, the staff should pick up the panels directly off the trailer but in an urban environment, it is not always convenient to do that. Therefore, the staff will unload the pallet from the walls or floors and then place them on the site. Blueprint is cooperating with a logistics partner called J.B. Hunt, a national firm who manages all of Blueprint's trucks, trailers and drivers. With a logistics manager of J.B.Hunt sitting in Blueprint building full time and managing all that for Blueprint, there will be two trucks at maximum on site. Aiming at being environmentally friendly, Blueprint tries

to take as much waste as possible and reuse parts of it like window protector, to ensure that zero waste goes to landfill on site.

Blueprint is planning to get involved with the project for maximum efficiency at around schematic design or early design development. Basically, the step should be taken right before the architect or owner would engage the MEP engineer because the company want to be the MEP and in charge of record. Blueprint will do the 2D Design to get them to permit and at the same time the engineers will be modeling the 3D design for the company's own purposes for coordination and then ultimately our Dietrichs engineer will construct that building.

The applied system is advantageous in avoiding or eliminating conflicts frequently experienced in traditional building methods. In traditional methods, a fully integrated and coordinated building information model is not available for most wood frame buildings. Blueprint is picking up all the clashes that occur not only within the MEP system itself but also as the MEP system coordinates with the structure. By using the 3D model, it's all virtually constructed both the structure as well as the mechanical electrical and plumbing. The model is coordinated in Revit while Dietrichs is fully clash-effective, so the engineers are not able to build any model on screen until there are zero clashes. Blueprint will not fabricate until that model is clash-free and gets approved that any modeling clash is avoided.

In table 28, the inspection specification standard is listed. It includes the item and purpose for inspecting specific items, and the detailed specification. Detailed standards guarantee the accurate execution of production and avoid misunderstandings.

**Table 30 Blueprint robotics Items inspection specification standard**

	Item	Inspect for	Specification
	Before start: Sort out material - after that, measure quantity of bad wood		
1	Top and bottom plate	All processes in file have been made	Location per drawing; all tolerances<1mm; sharp edges; square corners; position of notches, electrical holes, plumbing, and rigging openings
2	Module components	Correct quantities; check notches and specifications	All processes on file have been made; location for drawing; all tolerances<1mm; sharp edges; square corners; all notches (standard details) are in file
	Module Framing		
1	Assembled module	Opening size, direction	+/-2 mm width and height
2	Assembled module	Quantity and location and dimension	Fasteners and specifications per detail dwg
	Wall panel framing station		
1	Components	Top/bottom plate modules studs	All in
2	Studs	Studs drilled for PL/EL per plan	1" through
	Frame inspection		
1	Framing components	Component location	Location per dwg.
2	Frame	Squareness	Diagonal, height and length at: +/- 1.5mm
3	Nail plate	Properly placed on top/bottom plate	2" above/below plate
4	PL/EL holes	Correct amount	Amount per drawing
	Interior sheathing: OSB (Oriented strand board)		
1	OSB	Spacing per supplier specification	1-3mm between sheets

2	OSB Fasteners	Location agree with drawing	All fastened according to detail drawing and in stud
Interior sheathing: Gypsum			
1	Advantech subfloor adhesive	Bead size/quantity per specification	Min. 1/4" bead
2	Type X Gyosum	All cuts are right and present	Location X-ends openings
3	Fastener	Fasteners per specification	All fastened according to detail drawing and in stud
4	Gypsum fasteners	Locations agree with drawing	All fastened according to detail drawing and in stud
Wall panel electrical			
1	Wiring	Material per specifications	Per design
2	Wiring	Secured to framing	Per code
3	Electrical devices	Material and location per drawing	Per design specifications
4	Electrical devices	Proper connection of wiring to devices	Per code
Wall panel plumbing			
1	Supply lines	Secured to framing	Per code
2	Plumbing rough-in	Material and location per drawing	Per design specifications
3	Plumbing rough-in	Proper connection of wiring to devices	Per code
4	Drain lines	Material per specifications	Per design
5	Drain lines	Secured to framing	Per code
6	HVAC chase	Located per drawing	Mounting height per drawing
7	Fasteners	Proper fastening	Fasteners are in studs
Wall panel insulation			
1	CelluloseAuto Insulation	Full density	55kg/cubic meter; No visible gaps in wall cavities
2	5/8"*1" T-Nut	Location and positioning	All are in and nut side out

3	Cotton armor insulation	Fill locations	In spaces where bridge cannot reach with no gaps cavities
4	Top and bottom plate	Top/bottom plate have been fire sealed	Per code
5	Wall penetration	Sealing of wall penetration	Airtight
Exterior sheathing: Gypsum			
1	5/8"*1 T-Nut	Location and positioning	All are in and nut side out
2	Advantech adhesive	Bead size/quantity per specification	Min. 1/4" bead
3	Gypsum fasteners	Material per specifications	5/8" Type X
4	5/8" Type X gypsum	All cuts are right and present	Location X-ends openings
5	Fasteners	Fasteners per specification	Fire rated: #6*1 7/8 screw
6	Fasteners	Depth per specification	Screw head at or below surface; no paper tears
7	Fasteners	Location agree with drawing	All are in regarding detail drawing: "OSB fastening"; They are in studs
Exterior sheathing			
1	5/8"*6" lifting eyebolt	Eye-bolt installation per specification	Installed and fully seated
2	17/16" Zip sheathing	All cuts are right and present	Location X-ends openings
3	Zip R	Spacing per supplier specification	No space between foam
4	Fasteners	Fasteners per specification	2*131 Ring shank: Zip
5	Fasteners	Locations agree with drawing	All are in regarding detail drawing: "Zip R fastening"
6	Cotton armour	Fill volume	Insulation fully filling cavity
Window/door installation			
1	Window/Door unit	Correct window per dwg	Part No.

2	Opening	Level sill plate	Parallel to bottom plate
3	Flashing tape	Application per specification	Applied fully across sill plate window with no gaps
4	Silicone	Application per specification	Consistent 1/4" bead inside holes on nailing flange
5	Shims	Location per specification	Placed 1/4 the width of the opening from either side of sill pan
6	Installation	Unit squareness	Square and parallel to bottom plate
7	Fasteners	Material per specification	Per spec.
8	Soudafoam	Application per specification	Applied fully around frame with no visible gaps
	Wall panel load out		
1	Wall elements	Visible damage	No damage to surfaces, corners, or windows/doors
2	Wall	Numbering to drawing and sequence	
3	Weather protection	Watertight installation	Fully protected from rain; no gaps, seams or tears
4	Weather protection	Damage of wear	No tears or wear allowing water penetration
5	Transport protection	Damage of wear	Window and drywall protected

#### 6.4.4 Future plan of Blueprint

Blueprint is expecting to expand its business scope. Over the next 10 to 15 years, Blueprint intends to build another 10 to 15 factories across the United States. Ultimately, some of the expanded factories will have the ability to fabricate mass timber and cross laminated timber and incorporate those into standard structures. In the future, Blueprint will be eventually getting involved in mass timber and added scopes of work.

At the same time, as a startup company, Blueprint wants to make sure that the company is feeling comfortable with the scope of work that has decided on and the markets that has been serving. Therefore, before the founders of the company, the private equity money, and the rest of the executive team start considering other options, execution has been at the top so that's been what's been told to the staff by the executive team. Before the company thinks about new scopes or works on new products or new types of doing things, they have to execute this model, and that goes for factory number two or more factories, nothing will occur until Blueprint executes in Baltimore site firstly.

## Chapter 7: Conclusions

In the past several decades, there has been high expectations on the potential application construction automation and robotics in the construction industry, in which many research and theories have turned into real practice. With the comparison between 2010s versus 1980-90s, changes and differences about the prospects for construction robotics implementation are noticed.

First, some concepts and terms have changed or emerged over time. The word “machine” is frequently used in the 20<sup>th</sup> century, and this concept to some degree has shifted into “robot” in the 21<sup>st</sup> century. A machine is considered as a physical tool that is controlled by users or external automation, and a machine is a mechanical or electrical device that performs or assists in the performance of human tasks that has to be operated, monitored or controlled by others. Meanwhile, a robot is not widely used until recent 15 years and the concept acts independently of external controls and can be guided by an external control device or may convey a sense of intelligence or thought of its own [33]. Concepts like 3D printing, Green construction, Augment Reality and drones emerged and developed throughout decades.

Second, the development of software and digital computation has changed construction robotics industry profoundly by providing simplified, accurate, safety and cost-saving construction activities. The technology facilitates plans and plan changes, communication between different stakeholders in a project, and is capable of coordinating between developers, builders and municipalities, streamlining the permitting and inspection processes. Throughout the software, the use of BIM changed construction industry profoundly. BIM reduces errors throughout project lifecycle

allows prediction on construction process with the change of different factors, which Blueprint Robotics has practiced for years. There are higher requirements and expectation for BIM across construction industry in the future since it can be applied more widely as an innovative tool. While labor shortage is becoming an increasing issue, BIM and other software technologies can appeal to a new generation of younger workers and fill the current skills gap.

Third, construction hardware and equipment have development in the past decades. Advanced technology has been playing vital part in design and development of autonomous construction equipment and its impact on future generation of construction equipment. Forthcoming trends in autonomous construction equipment market and growth prospects for leading construction equipment manufacturers. In 2017, it is estimated that the global construction equipment market size was \$76.87 billion and it is expected to expand at a compound annual growth rate (CAGR) of 4.8% from 2018 to 2025 [34]. Rapid development of rental market for the machineries in Asia and North America is expected to expand their market.

Fourth, construction safety standard and safety equipment have improved significantly. With continuous efforts and improvement by OSHA, as well as companies that recognize health and safety standards improve working conditions and worker efficiency, has led to a whole new attitude about safety regulations on the site [35]. Besides, with the application of wearable technology, it is increasingly common for construction managers and more experienced workers to monitor and train new employees on the job [36].

A survey was distributed to participants from construction companies to learn the primary needs for applying automation and the influential factors to apply construction robotics. In development needs for current construction companies, safety management of work performed overhead and equipment operations are most concerned; for challenges in developing these technologies, the ability of on-site management and solving the uncertainty of economic benefits are priorities.

The redesign of construction process brought by introducing robotics should also be noted. It includes accelerate acceptance of innovative technologies, change of paradigm, create environment to facilitate systematical solutions and industrialize redesigned process.

In the case study, four companies that contains prefabrication (Blueprint Robotics), on-site construction process (Tybot and Construction Robotics), together with inspection and maintenance (Redzone Robotics) are introduced. Analyzing the company's advantages and disadvantages provides opinions on future implementation of robotics in a larger scope of companies.

# Appendix

## Questionnaire survey on construction automation and robotics summary

### Part 1 Basic Information

1. In which state is your company head office located?

2. What is the nature of your company's business?

Construction contractor

Specialist sub-contractor

Others \_\_\_\_\_

3. What specialties does your company possess?

4. How many full-time employees are there in your entire company?

Less than 600

600-3000

Above 3000

5. What is the geographic location of your company's major construction projects? (Multiple choice)

New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont)

Mid Atlantic (New Jersey, New York, and Pennsylvania)

East North Central (Illinois, Indiana, Michigan, Ohio, and Wisconsin)

West North Central (Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota)

South Atlantic (Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, District of Columbia, and West Virginia)

East South Central (Alabama, Kentucky, Mississippi, and Tennessee)

West South Central (Arkansas, Louisiana, Oklahoma, and Texas)

Mountain (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming)

Pacific (Alaska, California, Hawaii, Oregon, and Washington)

6. For how long have you personally been professionally active in the high-rise building industry?

Less than 5 years

5-10 years

11-15 years

16-20 years

21-25 years

More than 25 years

7. What is your current position within your company?

General manager

Chief engineer

Technology leader

Others \_\_\_\_\_ -

8. What is your company's name and address?

Part 2 Current application of construction automation and robotics

9. Has your company previously applied construction automation and robotics technologies? (Yes, go to question 10; No, go to question 13)

Yes

No

10. In which kind of high-rise building has your company used construction automation and robotics technology? (Multiple choice)

High-rise residential building (Reinforced concrete structure)

High-rise residential building (Steel structure)

High-rise residential building (Mixed concrete/steel structure)

High-rise public building (Reinforced concrete structure)

High-rise public building (Steel structure)

High-rise public building (Mixed concrete/steel structure)

11. In your company's construction last project utilizing automation or robotics technologies, what benefits have been generated by these technologies? (Multiple Choice)

Cost savings

Labor savings

Performance of construction tasks that are difficult or impossible for human workers

Improved construction efficiency

Improved construction quality

Increased safety

Contribution to "Green" construction

Enhanced reputation of the company

Others \_\_\_\_\_

12. In your company's last project utilizing automation and robotics, what challenges were encountered? (Multiple choice)

Initial investment cost is too high

Immature technologies failed to meet expectations

Project stakeholders not fully co-operating in the application of automation and robotics

Others \_\_\_\_\_

13. Why do you think your company has not applied construction automation and robotics technologies? (Multiple choice)

Robots and automation are not needed in the company

The company is comfortable only with conventional construction methods and equipment

The cost of construction automation and robotics technologies is excessive

Lack of workers competent in using construction automation and robotics technologies

Other construction project stakeholders are not willing to cooperate in our use of such technologies

Building codes, OSHA policies or other legal constraints do not support work performance with automation and robotics

Others \_\_\_\_\_

14. Has your company previously utilized any of the following technologies? (Multiple choice)

Building Information Modeling (BIM)

Internet of Things (IoT)

Artificial Intelligence (AI)

Big Data

Others \_\_\_\_\_

Part 3 Application-related requirements of construction automation and robotics

15. Based on your knowledge, should construction automation and robotics technology be widely applied in US high-rise building industry?

Yes

No

16. Why do you think it's not necessary to widely apply construction automation and robotics technologies? (Please select three most important reasons)

Implementation cost is too high

Technologies are not sufficient mature

Lack of skilled workers able to operate and service construction robots

Automation and robotics are not compatible with current construction and management practices

Low degree of standardization in construction site work

Others \_\_\_\_\_

17. Does your company have specific plans for utilizing construction automation or robotics on new projects in the future? (If yes, please specify on what kind of projects)

Yes \_\_\_\_\_

Not sure

[ ] No

18. Please rate the need of applying automation and robotics in the following construction works (1=very insignificant, 2=insignificant, 3=neutral, 4=significant, 5=very significant)

	Construction work	Significance (1=very insignificant, 5=very significant)				
		1	2	3	4	5
Earth and foundation work	Earth moving					
Superstructure	Horizontal site logistics of the materials and equipment					
	Vertical site logistics of the materials and equipment					
	Steel welding					
	Steel assembly					
	Steel coating					
	Monitoring of the deformation and internal force of the steel structure					
	Prefabricated component assembly					
Decoration	Façade installation					
	Façade tile installation					
	External wall painting					
	Floor tiling					
	Concrete finishing					
	Ceiling installation					
	Partition wall installation					
	Door and window installation					

Construction management	Material quality inspection					
	Construction workmanship equality inspection					
	Safety management of construction equipment					
	Safety management of work performed overhead					

19. Are there any other influential factors (other than above factors) in the application of construction automation and robotics?

20. Please rate the significance of these influential factors of applying automation and robotics in high-rise building construction (1=very insignificant, 2=insignificant, 3=neutral, 4=significant, 5=very significant)

Aspect	Influential factor	Significance (1=very insignificant, 5=very significant)				
		1	2	3	4	5
Economic	Labor cost of construction					
	Initial investment cost of automation and robotics technology					
	Uncertainty of the economic benefit of automation and robotics					
Technological	Mature and proven technology to provide robust performance and ease of use					
	Mature skill training to acquire new					

	technologies					
	Adaption to the traditional construction method					
	Attention to new technologies in the industry					
	R&D capability of the construction companies					
	The application of information technologies (BIM, IoT, etc.)					
Political	Government labor policy					
	Government policy on time limit for the projects					
	Government policy on environmental impacts of construction					
	Globalization in construction (new technologies, foreign labor, etc.)					
	Governmental support on academic research of construction automation and robotics					
	Governmental support on automation and robotics application in construction					
Socio-cultural	Culture of innovation					
	Public awareness of environmental protection					
	Social attention to occupational safety & health					
	Education of the workforce					
	Age structure of the workforce					
Others	The scale of prefabrication					
	The ability of on-site management					

21. Are there any other influential factors (other than above factors) in the application of construction automation and robotics?

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