

Robotics in Construction

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This report is the product of an education program, and is intended to serve as partial documentation for the evaluation of academic achievement. The report should not be construed as a working document by the reader.

Abstract

This project reviews construction process and new emerging robotic technologies, all while keeping in mind the societal implications the new technologies may have. The study identifies and analyzes the benefits and limitations of a wide array of robotic applications. A roadmap and timeline are created to guide Massport on how and when to implement the various robotic applications into their construction operations. The end result of this project could be extended to the construction industry as a whole.

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1.0 Introduction

This study explores how robotics is being used, and could be used in the future, in the field of construction. Robotics as a whole is a synchronous combination of mechanical, electrical, and software engineering. It is a field that aims to better the lives of humans in tasks that are dangerous, dirty, or demanding. Construction is the process of creating or renovating a building or an infrastructure facility.

Due to the evolving field of robotics, the goal of this project is to find out how robotics can be implemented into construction tasks and to identify as many robotics technologies as possible that can have some application in construction, while also determining if any of these potential technologies can be integrated in the near future. This could potentially facilitate many construction processes to make them safer for workers, take up less time, or even to perform simple tedious tasks.

The project is sponsored by the Massachusetts Port Authority (Massport) who is exploring the potential integration of robotics to benefit their construction projects in the upcoming years.

This project reviews construction process and new emerging robotic technologies, all while keeping in mind the societal implications the new technologies may have. The study identifies and analyzes the benefits and limitations of a wide array of robotic applications. A roadmap and timeline are created to guide Massport on how and when to implement the various robotic applications into their construction operations. The end result of this project could be extended to the construction industry as a whole.

The research was conducted through an extensive review of robotics technology and through two online surveys distributed to construction workers and other individuals not directly involved in construction. A methodology was developed to assess the benefits and limitations of each technology.

2.0 Background

This chapter serves as a summary of multiple concepts necessary to fully understand the scope and underlying factors involving the projects necessity and requirements. In the following sections we describe the construction industry, the possibility of improvement in the construction industry, the role robotics may play in that improvement, and the societal implications robotics present.

2.1 Evolution of Construction

Construction has been prevalent since the dawn of mankind. From the pyramids of Egypt and the Great wall in China to the latest projects such as modern bridges and architecture. Construction has been a human endeavor for generations in all parts of the globe. These projects took extensive amounts of time to build and demanded large use of resources including labor. Some of this was slave labor, many of whom died in the course of building the project. The contemporary construction methods of the modern world have seen a vast improvement. Today there are machines and tools to assist labor in accomplishing tasks that would have taken significantly more time in ancient times. With the introduction of new materials, steel and concrete, the construction industry has also seen vast improvements. Concrete is a relatively low cost, structural material. It is strong and durable, and is widely used for virtually any type of project around the world. Steel provides needed strength for supporting the loads of large scale buildings in a more efficient way (“Construction Industry History”, 2010). In addition, there are also regulations put into place to harbor safer working

conditions, thanks in part to the Occupational Safety and Health Administration, or OSHA (“OSHA”, 2015).

2.2 Massport

Massport is “a world class organization moving people and goods - and connecting Massachusetts and New England to the world - safely and securely and with a commitment to our neighboring communities” (“Massport - Mission”, 2015). This mission statement clearly defines their intentions to become a global gate for transportation of people and goods. Their aim is to improve and modernize the facilities they have created and give them the best amenities for improved best customer service. Their projects include Boston Logan Airport, Worcester Airport, and the Port of Boston to name a few. There are also countless other construction projects involving facility creation, taxiway creation, and countless more projects. With many diverse projects being maintained and future projects, construction never ends for Massport (“Massport - Home”, 2015). Massport wants to improve and modernize their construction process through the use of technology, particularly through the advancement and transition to robotic technologies.

2.3 Development of Constructed Facilities

Whether it be modern times or ancient times, construction starts with an idea for a structure. Whether it be for a house or a skyscraper, there must be a need for a structure. Once the idea is formulated, architects are given the task of designing the structure, fleshing the idea out into specifics such as quality, functionality, and workmanship. Once specifics are

defined in terms of drawings and specifications a builder is called upon to erect the designed facility. This turns the design into a finished built product. The entire process is coordinated by a project manager in charge of securing all required resources to complete the project on-time, on budget, and according to the designer specific quality. The project manager is also in charge of finding and enlisting contractors for the construction project. Once finances and contracts are in order, construction begins. The project follows a defined timetable and finances are constantly monitored throughout the duration of the project. The construction process is sequential and many tasks are done throughout the entirety of the process from start to finish ("Construction Process", 2015).

2.4 Opportunities for Construction Improvement

The rate at which construction progresses is subject to variability. Productivity depends on many variables including the weather and worker productivity which depends on factors such as overtime, morale and attitude, fatigue, stacking of trades, mobilizing and demobilizing, general errors, reassignment of manpower, crew size inefficiency, hazardous work areas, and the list goes on ("Factors Affecting Construction Labor Productivity", 2012). A common underlying factor to this variability is natural human imperfection. Another issue seen in the construction industry is security. Security has been a rising issue at many construction sites. One primary example is thieves have been stealing copper pipes during the night. Even the workers themselves may be pilfering materials from the construction site for their own personal gain ("Why Construction Surveillance is so Important", 2015). A need for enhanced security is necessary for construction managers and industries as a whole to operate smoothly

without any hindrance or disappearing materials. Another primary issue seen at construction sites is the safety of workers. Although OSHA has helped in keeping the number of injuries and death tolls down, safety is still a large issue today in construction. Over the past summer, an ironworker working on the new Logan Airport parking garage was trying to secure a concrete panel when the panel fell from the crane and caused him to plummet 40 feet. He was sent to the General Hospital where he succumbed to his injuries (Crimaldi, 2015). Clearly safety on a construction site is most crucial, and steps should be made to further increase the safety at the job sites.

2.5 The Role of Robotics

With traditional issues surrounding the construction industry, there is always opportunity for improvement and robotics engineering plays an important role in it. “Robotics is the science of designing, building, and applying robots. Robotics is a solid discipline of study that incorporates the background, knowledge, and creativity of mechanical, electrical, computer, industrial, and manufacturing engineering” (Jackson, 2015). Robots, in general, have many advantages and benefits. Some of these benefits are an improved production quality, and an improved quality of life for workers in any industry (Jackson, 2015). For example, robots can have microscopic precision and produce quality in products otherwise not possible to achieve with traditional labor skills. Robots can also be used in areas that are hazardous to humans. Many of the emerging robotic technologies today that can be applied to construction applications are demolition robots, 3D printing robots, robotic drones, bricklaying robots, welding robots, exoskeletons, forklift robots, and roadwork robots. All of these robotic

technologies have the potential to improve many construction industry areas such as productivity, quality, security, safety, and can even stimulate the creation of more jobs. Robots also come with their own respective negative aspects. There are also many future technologies which could further enhance the construction industry including humanoids and mobile telepresence robots. All of these technologies are further discussed in this study in more detail.

2.6 Social Issues

There are many social issues to take into account when discussing robotic applications in construction. One of these concerns comes in the form of privacy, both worker and public privacy. Any surveillance technologies are examples of potential invasions of privacy when using robotic technologies. Another main issue is the fear of job loss. One big fear for the rise of robotics is that workers may lose their jobs to a machine. They do not want an automated robot to do the job they, as a human, are paid to do (Romeo, 2015). The robots make the job easier and potentially lower costs of production since they are not necessarily subject to negotiation of hourly wages. A robot is a one-time investment that will pay for itself over time. With a robot there are no unions to worry about, no healthcare costs, just maintenance costs. This job substitution could also be seen as a good thing. Instead of humans being in charge of the simpler jobs that robots can do, they could potentially be hired to perform maintenance checks on the robots instead. With the rise of robotics comes the rise of those with knowledge in robotics to work on them. Another societal issue is the concern of safety. While we do not have to worry about a science-fiction robot apocalypse scenario where robots become more intelligent than their creators, there can be a concern with their programming. For most robots,

their program is procedural. If a random event occurs, such as a worker walking in its path, the robot may not be prepared for that. In this case, safety protocols would need to be placed to protect those around the robot's work envelope ("Industrial Robots and Robot System Safety", 2015). Another societal issue is hacking of the robotic systems or hijacking them. Cybercrimes have evolved along with computer technology. Robots can be hacked either directly or indirectly. Indirectly, a hacker can infiltrate a robot similarly to hacking a website. Drones can be hacked on their Bluetooth communication network ("Burke, 2015). The fear of technology as well as change are topics that easily tie together with the fear of job loss the public has with robotics being used in the current job market. A large portion of robotics movies are also themed around the fear of change and how the world changes due to the introduction of robots into society. Most are quite negative, as that makes for more entertaining storyline, taking a movie such as, "I, Robot", as an example. The movie is about robots working with humans in society until a new version of robot comes out that gets a virus and tries to take over the world ("I, Robot", 2004). This is a fear many people experience and what they see about the future of robotics.

3.0 Methodology

The procedure to conduct this project is a multi-step process with many iterations. This chapter outlines the strategy and process followed in order to attain the project goals and to achieve the desired outcomes. It provides a guide to how the goal was met, what objectives were attained, what methods were used to complete the objectives, and finally how those objectives accomplish the project goal. Figure 1 shows, graphically, the flow and components of this process.

The research strategy is based on the posing of key questions aimed at answering the focus question of the project: “How can robotic technologies be used to benefit the construction industry of Massport and the surrounding communities?”

In order to answer the focus question, many secondary questions were formulated and answered by gaining knowledge through research along the way and collecting data as needed. Appendix B shows the various list of questions that were formulated. Each week, two or three of these questions were answered through various research methods. The secondary questions have the following distinct categories: the construction process, Massport, robotic technologies, and the workers and surrounding communities. Work between team members was divided equally and each member worked on individual research for every sub-question. Once collected, the team congregated and compiled all the gathered information.

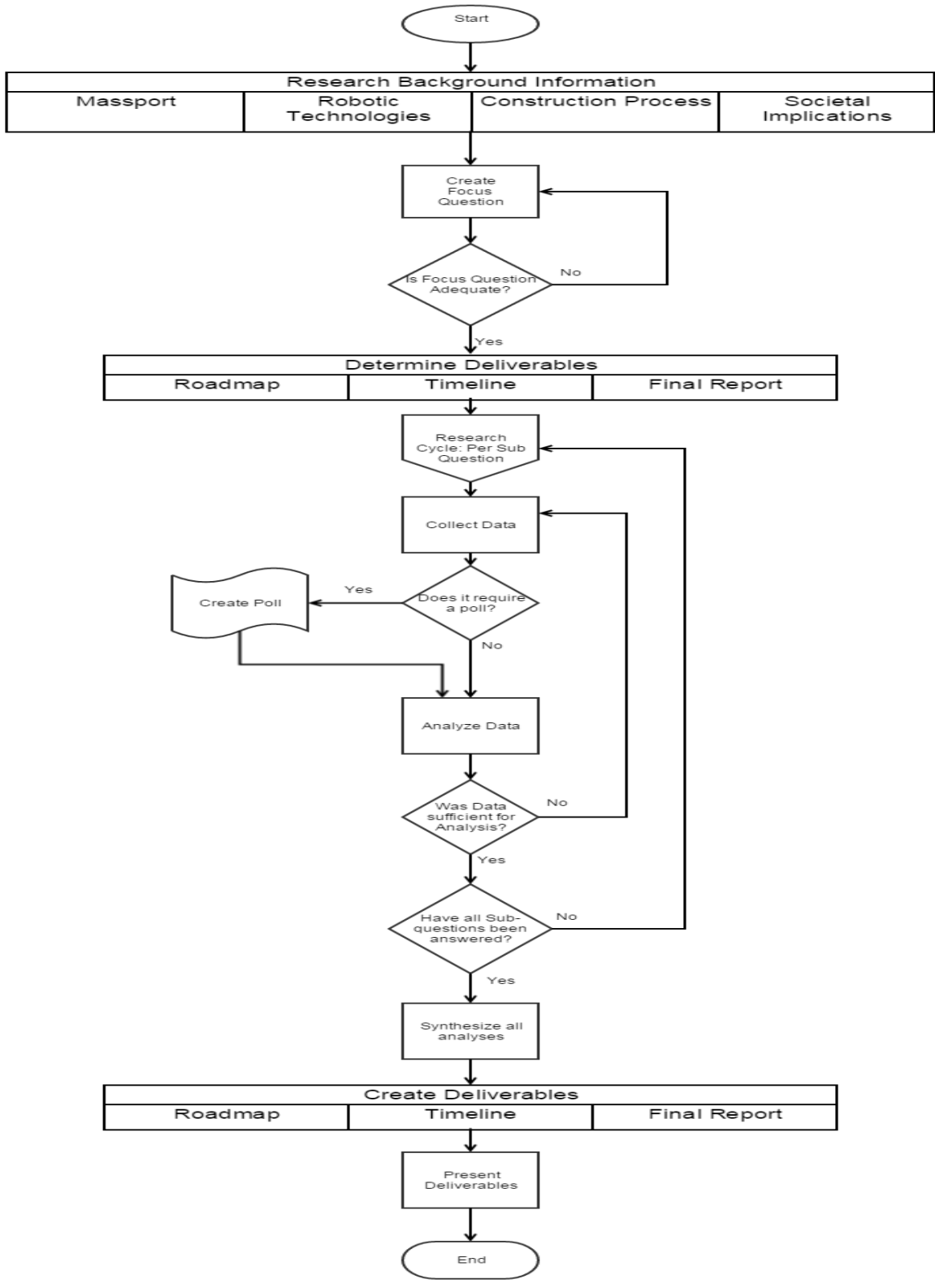


Figure 1 - Flowchart of Methodology

In order to answer the secondary questions, data was generated from methods such as online research, using polling software to poll construction workers and communities. These methods were used to collect the relevant data for opinions of workers, robotic technologies that are readily available and those to come in the future, the construction process, as well as data on past, present, and future Massport projects.

Once the critical data was collected, analysis was conducted. The information that was gathered from the workers opinions was analyzed using polling charts on a Likert type scale. SurveyMonkey software was used to gather these charts and needed data. This data was then organized and analyzed. It contains the opinions of the workers on various subjects regarding the integration of robotics into the workforce.

Each robotic technology was analyzed to determine how they could be used, their pros and cons, how they could be integrated into construction, and at what cost. Using a grading rubric, each potential robotic technology category was graded out of 100% and assigned a grade based upon its results on key factors that determine its success such as availability, risk analysis results, cost benefit results, responses from both the community and construction worker surveys, and lastly on the opinions of the researchers. Using this rubric, these analyses were sorted into distinct categories based on where and how they can most directly assist the construction process. These categories were formatted based off of the CSI masterformat.

Once the analysis was completed for all four categories, the next task was to synthesize all of it to create a roadmap. This roadmap served as suggestions for integration of each researched robotic technology into construction. The roadmap was a deliverable for Massport

that would assist them with decision making on how to proceed if they choose to involve robotics in their processes. Another deliverable for Massport, in conjunction with the roadmap, was a timeline that allows one to know when each individual robotic technology is estimated to be commercially available, if not already available. The timeline was a separate deliverable, but worked in conjunction with the roadmap. The timeline assisted them with planning the integration process. Once all of the previous steps (data collection, data analysis, synthesizing of analysis, deliverable creation) were accomplished, the last step, yet developed as progress was made on the project during its entirety, was to generate a final report on the outcomes of this IQP. Once this document was created, the roadmap and timeline was presented in a cumulative portfolio and Massport was given a final presentation about our entire research process, concluding the IQP, Robotics in Construction.

4.0 Research and Results: Robotic Technologies

Our research investigated three main areas: Robotic technology, construction processes and its trends, and lastly the social implications of robotic integration. This first section of our research and results focuses on the robotic technologies studied in this project. To fully research these technologies we looked at their applicability, their pros, cons and limitations, and their availability. Many of the emerging robotic technologies today that can be applied to construction applications are demolition robots, 3D printing robots, robotic drones, bricklaying robots, welding robots, exoskeletons, forklift robots, roadwork robots, and humanoids. All of these robotic technologies have the potential to solve many current issues affecting the construction industry but some still have negative aspects.

4.1 Demolition Robots

Demolition robots are primarily used for tearing down building walls and other various structures. Demolition is an important part of construction, specifically in the renovation field. In a case where a floor of a building needs to be redesigned, demolition occurs to topple existing walls in order to give room to create a new layout. The primary benefits of demolition robots are that they are much more effective than handheld equipment. They also allow the operator to stand away from the debris and contaminants, making them safer than handheld devices. A key note here is that current versions of demolition robots are primarily designed for small scale demolition, not large scale applications. Some demolition robots use hydropower to bring down materials such as weak concrete and can prevent the air from being polluted with material dust. Some of the negative aspects of demolition robots from the social point of view

is that it could require less workers for the typical demolition job, leading to job loss (“Remote Demolition”, 2015).

There are three distinct types of demolition robots that are available or being developed: multi-tooled, hydro-powered, and eco-friendly. Multi-tooled demolition robots allow for multiple types of tools to be placed at the end of a robotic arm on the demolition robot. Figure 2 shows a multi-tooled demolition robot:



Figure 2 – Multi-Tooled Demolition Robot

Hydro-powered demolition robots use high pressured water jets to disintegrate walls and beams with ease. Figure 3 shows a hydro-powered demolition robot:

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Figure 3 – Hydro-Powered Demolition Robot

Eco-friendly demolition robots aim to function similarly as hydro-powered demolition robots, but also absorb the material they remove and process it to make the material recyclable. Figure 4 shows an eco-friendly demolition robot:

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Figure 4 – Eco-Friendly Demolition Robot

One key positive aspect is that they only require one operator no matter the type of demolition robot. They all allow for the safety of demolition workers to be significantly increased by keeping only one worker at bay behind a controller. The hydro-powered demolition robots also prevent dust particles from getting into the local atmosphere. The eco-friendly demolition robots turn the waste product into recyclable aggregate. All types of demolition robots save money, as an investment, as they reduce the number of workers required which is discussed later on in this report. The major negative aspect of demolition robots is that they all require a significant power source to operate, whether it be a battery or a cord to an industrial grade outlet or generator.

4.2 3D Printing and Contour Crafting

3D printing has evolved over the past decade. From rapid prototyping to full scale working cars, 3D printing has changed the way we think about manufacturing and will continue to do so for generations to come. Figure 5 shows a 3D printing robot:

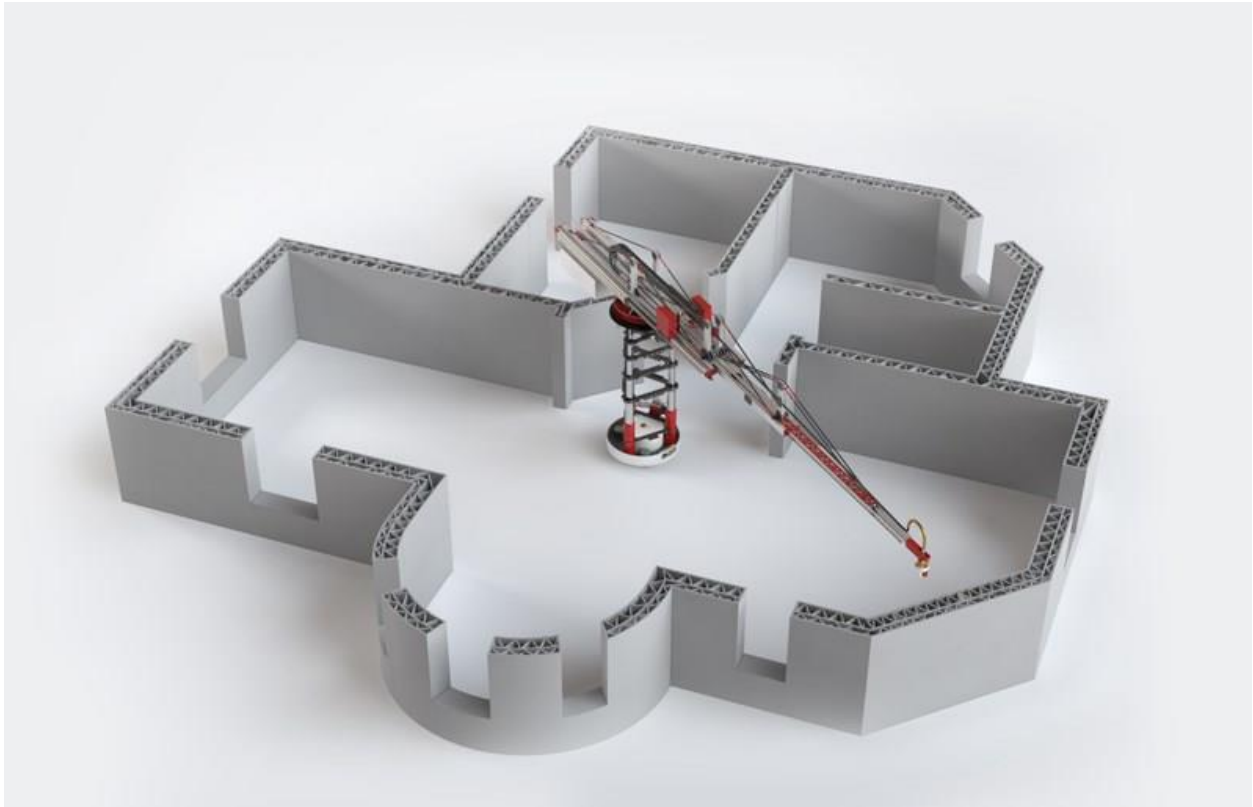


Figure 5 – 3D Printing Robot

3D printing is now coming to the construction industry. From building homes in a day, to building a block of apartments in a week, this technology can fundamentally change the way we construct buildings. Where normal construction takes a few months, construction by 3D printing robots can print a structure in a day or two. There is little to no waste created, as the robot applies the exact amount of material needed for the structure. One main downside to

this emerging technology is that this kind of robot can replace a large number of workers, as only a few would be needed to operate the robot, potentially causing job loss (Khoshnevis, 2014). 3D printing and contour crafting robots require the placement of a rig which can be very demanding. However, this is already done similarly when building tall buildings in cities where gantries are used to lift large beams. The same setup practices can be applied to the setup of a 3D printing robot. 3D printers aim to be highly mobile when setup is complete. While it may take some time to set up the apparatus, the 3D printer aims to save significant time in the build period of the structure. Many of the current 3D printing technologies are purely academic in nature or experimental, however there are companies looking to sell these machines in one to two years.

4.3 Drones

Another emerging robotic technology is that of robotic drones. Drones are unmanned robots that are controlled remotely by human interface and are used to accomplish various tasks. They are very versatile as these robots can be small or large, fast or slow. Drone technology has the ability to be applied in just about any field including construction. There are four main types of drones that are directly applicable to construction practices: Contour crafting, transportation, surveying, and monitoring.

Contour crafting drones merge drones and 3D printing technology to create a flying 3D printer. Figure 6 shows a contour crafting drone:



Figure 6 – Contour Crafting Drone

These drones are purely in an experimental stage. While the benefits are obvious, the ability to 3D print anywhere and the verticality prowess, the negatives to this technology are hefty. There are wind invariances that cause drones to become unsteady and thus the drone cannot perform outdoors. The motor vibrations from the drone also make the application of 3D printing almost impossible, at least if you want it to be precise.

Transportation drones would be used in a formation called swarm robotics. Figure 7 shows a swarm of drones and figure 8 shows a single transportation drone:

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Figure 7 – Swarm of drones



Figure 8 – Transportation Drone

Swarm drones would work as a unit to lift heavy payloads and deliver them to a high location. The benefits of this technology is that they can attain high locations very easily whereas it could take a human worker a long time to deliver materials, ones light enough to not

require a lift or crane, to the same high location. The negatives are that wind invariances can cause for the drones to not work well as a unit.

Surveying drones are used to get still images, 360 panoramas, and aerial shots of a construction site. Figure 9 shows a surveying drone:



Figure 9 – Surveying Drone

The benefits are obvious as the drones can capture multiple angles in a short amount of time and eliminates the need for multiple cameras to be rigged at multiple locations surrounding the site. When partnered with advanced imaging technology, companies can analyze the progress of a site in real time. An example of this is the application of bridge inspection. A surveying drone is capable of analyzing weaknesses in a bridge when partnered with software imaging technology (Drelich, 2015). The negatives of this technology is that the quality of the images may not be as good as a still frame due to the vibrations caused by the rotors.

Monitoring drones are used to act as security at a construction site. Figure 10 shows a monitoring drone:



Figure 10 – Monitoring Drone

They can be used as security for the construction site but also can be used to monitor the site to determine who is there and how long they have been there using facial recognition. The advantages of this technology are similar to that of the surveying drones in that they can attain high locations. The disadvantages are that some workers may feel that it violates their privacy. The counter argument that has been made about this is that security cameras already exist and that these monitoring drones would be no different.

Some of the major benefits of drones are that they are usually small, which usually means cheaper, however there are some exceptions. Ranging from simple to complex, drones are usually capable of more than just one task and a great many of them could do these tasks autonomously. Another obvious benefit is that they can attain higher elevations quickly and without much effort. The downside of using this technology is the maintenance costs, their ability to get lost, and there are many regulations against their usage in many locations (“Drones”, 2015). However, recent loopholes in the rules allow for a licensed operator to use a drone so long that it does not eliminate the need for workers. Drone use near airports is still tightly enforced as a no fly zone.

4.4 Bricklaying Robots

Robots are used to accomplish jobs deemed too tedious for humans. One such tedious task is bricklaying. Bricklaying robots are being used in the construction field to perform a task consecutively and efficiently of layering bricks for buildings, roads, walls, etc. Bricklaying robots come in a few sizes. Industrial robotics arms are able to do repetitive task efficiently. Figure 11 shows a bricklaying robot for walls:



Figure 11 – Bricklaying Robot: Walls

Many bricklaying robots utilize industrial robotics arms to do repetitive tasks including bricklaying or stacking. Other bricklaying robots can lay a masonry pathway using a conveyor belt or a coupled pattern arrangement system. Figure 12 shows a bricklaying robot for roads and pathways:



Figure 12 – Bricklaying Robot: Roads

Bricklaying robots can assemble the masonry structure of the building, while the workers operate the robot or perform support task (such as mixing the cement or bonding agent). They can also make elaborate masonry structures that could not be created with traditional methods.

The major benefit of this technology is that it can perform the task efficiently and quickly. However, this technology has the downside of a high cost which will be discussed in the cost benefit section later in this report. An investment would have to be made that would pay off in the long term goals of the construction process for the potential of this type of robot to be used ("Semi-Automated Mason", 2015).

4.5 Welding Robots

Welding robots are used for the construction of ships, and for any application to joining metal. These robots can be used on steel structures and particularly on the docking stations of ports. They are able to make precise welds and maneuver in hard to reach locations. Figure 13 shows a welding robot:



Figure 13 – Welding Robot

There are two areas where this robot can be used in, one being the construction of skyscrapers. In Japan, welding robots are used to weld steel beams together. Another use in construction are concrete slabs. Before the concrete can be poured, riggings must be placed in and welded. Because of the maze of riggings, a welder is at a large risk of getting hurt, but a welding robot could take the place of a worker and prevent injury. Unfortunately, there are very limited implementations of welding robots for onsite construction. Besides Japan, there are no other records of welding robots being used in the construction industry. The closest

implementation is in-ship building where a dozen welding robots are lowered to the hull of a ship to weld the hull together. However, this still seems impractical in a construction site setting.

The benefits of this technology is that it is safer for workers who don't have to be near sparks flying and intense heat when using these robots, making them useful for safety. The welding robots are able to attain a high quality of welding. The disadvantages are that it currently is a stationary device so a worker needs to place it and situate it. At this point in time, it may be simpler and less costly to manually weld. The only determining factor would be the quality of the robot versus that of a human (“Mini Welding Robot”, 2013).

4.6 Exoskeletons

Another emerging technology is robotic exoskeletal suits working with humans to enhance a task or ability the human body lacks. Intelligent suits are meant to increase the strength of the average user, endurance, speed, agility, etc. Figure 14 shows an exoskeleton suit:

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Figure 14 – Exoskeleton Suit

A major benefit is it allows for injured or disabled workers to work in construction. Also it allows workers to lift and transport heavier objects than ever before. Some of the disadvantages of exoskeletons are that most are quite bulky, even though they increase abilities mentioned. Some of the suits that focus on strength or endurance tend to lack speed, or the suits that specialize in speed or agility tend to lack in durability when trying to lift large payloads. The cost benefit, which is discussed later in this report, is not good and would not be practical for construction companies to invest in. Humans must also be willing to learn to use these suits, as they are a very new technology to get used to (Mane, 2014).

4.7 Forklift Robots

Forklift robots have a main goal of transporting heavy or generally large objects from one point to the next. They aim to alleviate the need for a human to carry these objects, or

have a human control a forklift to transport the goods. They are able to accomplish this through vision tracking and map localization. Figure 15 shows a forklift robot:



Figure 15 – Forklift Robot

Based off of the work done by the MIT team on forklift robots, if a robot is pre-programmed a map it can essentially traverse the path generated using algorithms in a short amount of time, all while delivering heavy payloads (Gyimah, 2015). This application can be used almost anywhere that a large or heavy objects need to be transported. In construction, it is very common for many materials and supplies to be heavy and or burdensome for workers. Having a forklift robot would alleviate this burden.

There are two main foreseen limitations of forklift robots. With the nature of a forklift robot being a forklift, the terrain needs to be relatively flat with no harsh gradients or bumps. In a construction site it may be a common case where the terrain is too harsh for such a robot to be able to perform. Another limitation, which is not too big of an issue, is that the map of the job site needs to be pre-planned into the robot.

The main advantages of this technology are or seem to be that there is a low cost of ownership and it has the ability to lift heavy payloads that humans cannot feasibly accomplish

(4000 lb by the Patriot P325 model). The current drawback of this technology is that it cannot handle intense terrain and needs to be kept in a controlled environment. Some of the robots require mapping of the terrain for them in their current state of development (Teller, 2010).

4.8 Roadwork Robots

Roadwork robots are primarily focused upon repainting and repaving roadways. The primary reason for this is to do small patch jobs to avoid the highway clutter and traffic jams.

Figure 16 shows a repaving robot while figure 17 shows a repainting robot:

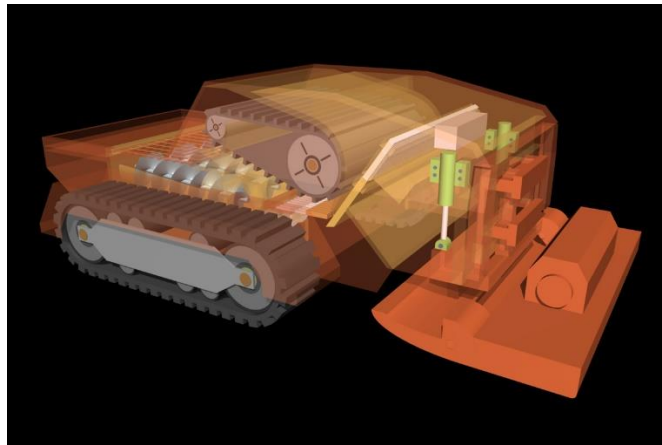


Figure 16 – Repaving Robot



Figure 17 – Repainting Robot

Currently, large machinery is required to repaint and fix small potholes and other cracks in roads. This technology is smaller in scale and is able to do smaller patch jobs on potholes and cracks. The repainting robots allow for the same type of small job scale fix jobs. Their main abilities are that they alleviate the need for a large workforce and machinery for jobs that are relatively small in nature. The only drawback is that this technology is not very precise at the moment and further technological testing needs to be made to perfect this ("Paint and Coatings Industry News", 2013).

4.9 Future Technology: Humanoids

Humanoid robots, a self-explanatory concept, is of the most complex types of robots we can try to create in today's world. Currently, the robot called Atlas is the closest robot to a humanoid and with complex abilities like balance and obstacle avoidance (Boston Dynamics, 2015). Figure 18 shows the humanoid robot, Atlas:



Figure 18 – Humanoid Robot

These robots are able to navigate through hazardous areas and accomplish tasks that humans are unable to do due to the environment. These robots could be also used to do almost

anything a human could do. This technology is very far away from being a reality at the moment and therefore it has been classified as a future technology.

The downside to these robots are that costs are high and the development time is extensive. The amount of complexity in a system that has a lot of kinematic motion and can create safety concerns (“Boston Dynamics: Atlas”, 2013).

4.10 Researcher Ranking Analysis

From the research done on all of the above robotic technologies, the three researchers analyzed their pros, cons, limitations, and other factors to determine a rating for each. The researchers assigned the nine main categories of robots along with their subcategories a score out of 20. The worst possible score was a 0 and the best possible score was a 20. The three scores from the researchers were averaged to determine the final score for this section. The total weight of this section is to count towards 20% of the final grade for each technology. The purpose of this sections weight, and the determination of it is discussed later in chapter 8. The results from this analysis are shown in table 3.

As shown in table 3, the top 3 robotic technologies are surveying drones, multi-tooled demolition robots, and hydro powered demolition robots. The researchers believed, based upon their research and findings, that these were the best three technologies that could be implemented into construction. The worst 3 robotic technologies were welding robots, 3D printing drones, and lastly humanoids. Humanoids received the worst score not only because they are a futuristic technology that is not even remotely close to becoming a reality for the

construction industry. The benefits of replacing an entire human did not seem to outweigh the negatives of taking jobs away from actual human construction workers.

TECH	Researcher 1	Researcher 2	Researcher 3	Average
Drones: Surveying	20	19	19	19.3
Demo: Multi-tooled	20	20	18	19.3
Drones: Surveillance	19	20	17	18.7
Demo: Hydro Powered	20	19	17	18.7
Demo: Eco Friendly	18	17.5	16	17.2
Bricklaying: Walls	20	14	16	16.7
Drones: Swarms	14	17	14	15
Bricklaying: Roads	15	16	14	15
Roadwork: Repainting	15	15	15	15
Drones: Transportation	15	16	13	14.7
Roadwork: Repaving	15	15	14	14.7
Forklift robots	13	17	12	14
3D Printing	15	15	5	11.7
Exoskeletons	12	12	9	11
Welding	5	1	8	4.7
Drones: 3D Printing	0	3	1	1.33
Humanoids	0	1	2	1

Table 2: Researcher Ratings

5.0 Timeline to Commercial Availability

A major factor in integrating robotics into construction is the commercial availability of the robotic technology. In order for construction companies to know when they could purchase and use the robotic technologies, a timeline was created to help estimate when the technology would be commercially available. This timeline was comprised of the 9 robotic categories as well as their subcategories. All of the data was estimated based upon research findings. The resulting timeline is shown in figure 19.

Based upon the timeline in figure 19, construction companies can establish a plan to integrate technologies over time. From this data, they also can realize there are already existing technologies ready for use such as many specific drone applications, exoskeletons, and bricklaying robots for roads and walkways. A company may also use this timeline to determine that some technologies are too far in the future to wait for such as 3D printing drones and humanoids.

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Figure 19 - Timeline to Commercial Availability

5.1 Timeline Analysis

This timeline was further used in the quantitative analysis of all the robotic technologies being researched. The score for the timeline was 10% of the final score for each robotic technology, with a max score of 10 in this section. The weight of this section will be discussed later in chapter 8. If a technology is available now, it would receive the highest score of 10, whereas if it is not available until 10 or more years it would receive the lowest score of 1. The availability rating is shown below in table 3:

Technology	Prediction to Availability	Score:
Drones: Surveillance	Now	10
Drones: 3D Printing	10+ years	1
Drones: Transportation	Now	10
Drones: Surveying	Now	10
Drones: Swarms	Now-6 months	9.5
Demo: Multi-tooled	Now	10
Demo: Hydro Powered	Now	10
Demo: Eco Friendly	7 years	4
3D Printing/Contour Crafting	2 years	7
Bricklaying: Walls	3 years	6
Bricklaying: Roads	Now	10
Welding	1 year	10
Exoskeletons	Now	10
Forklift robots	3 years	6
Roadwork: Repainting	2 years	7
Roadwork: Repaving	5 years	5
Humanoids	10+ years	1

Table 3: Availability Rating

6.0 Research and Results: Construction and Social Implications

Our research investigated three main areas: Robotic technology, construction processes and its trends, and lastly the social implications of robotic integration. This section focuses on the latter two, respectively. For the social implications of robotic technology, we analyzed how construction workers and the communities perceive the impact of robotic integration among many fields in construction. In order to do this, the ways in which construction work is classified in this industry were identified. This provided a framework to determine the best fit of robotic technologies into construction work.

6.1 Construction

The construction worker survey was assembled according to trade classifications. In order to do this, we needed to create a breakdown structure to analyze which subtask each robotic technology would be categorized under. We adopted the Construction Specifications Institute (CSI) Masterformat. Under this format we were able to categorize which robotic technologies would be able to replace, or assist, in each task in construction. This led to the inclusion of 16 distinct categories on the construction worker survey. The 16 distinct categories on the survey were general requirements, site construction, concrete, masonry, metals, woods and plastics, thermal and moisture protection, doors and windows, finishes, specialties, equipment, furnishings, special construction, conveying systems, mechanical and lastly electrical. In addition to these 16 categories, the survey allowed for the inclusion of other options for any other possible classification of jobs such as surveying, demolition, and road work.

6.2 Social Implications

One of the primary goals of this project is to determine how the general population and the construction workers perceive the integration of robotics into construction for all 9 categories of robots. More specifically, this perception was further categorized in terms of safety, privacy, and the duration of construction projects if robotics were to play a leading role. In terms of construction workers, the survey sought out their opinions on job security, productivity safety, security, and quality of work if and when robotics are introduced. In addition, the survey sought out their opinion on their willingness to learn maintenance for robots, understand how robots can assist, and gauge their interest in cooperation with robots. In order to determine all these key aspects from the general population and from the construction workers two surveys were created for each group.

6.2.1 Community Survey

The community survey analyzed timeliness, privacy, and safety of all 9 robotic technologies. 100 survey responses were collected and the data pool spanned all age, gender, and had a widespread educational level. In order to take into account varying levels of knowledge between respondents, a knowledge multiplier was created. Respondents answered from 1 to 5, 1 being no knowledge and 5 being highly knowledgeable. This response was used as a multiplier for all the individual responses for safety, privacy and timeliness. This allowed for filtered responses and a better representation of data. The weight of this section was 15% of each technologies final grade so the maximum score would be a 15. The purpose of this sections weight, and the determination of it is discussed later in chapter 8. The final results, all using the multiplier discussed above, are shown in table 4 below:

Technology	Timeliness	Privacy	Safety	Averages	Score (Score=15*Average)
3D Printing	90%	90%	90%	90%	13.5
Roadwork	88%	88%	88%	88%	13.2
Bricklaying	90%	88%	86%	88%	13.2
Welding	87%	85%	80%	84%	12.6
Forklift	83%	83%	81%	82%	12.35
Demolition	83%	81%	76%	80%	12
Exoskeleton	79%	79%	76%	78%	11.7
Drones	77%	65%	80%	74%	11.1
Humanoids	63%	60%	62%	62%	9.25

Table 4: Community Survey Results

These results reflect society's perceptions about different types of robots. In terms of timeliness 3D printing and bricklaying robots have the highest rating while drones have the lowest. These two technologies received the highest scores most likely do to the mass production nature of 3D printers and bricklaying robots. Figure 20 shows the scores of each robotic technology in terms of timeliness below:

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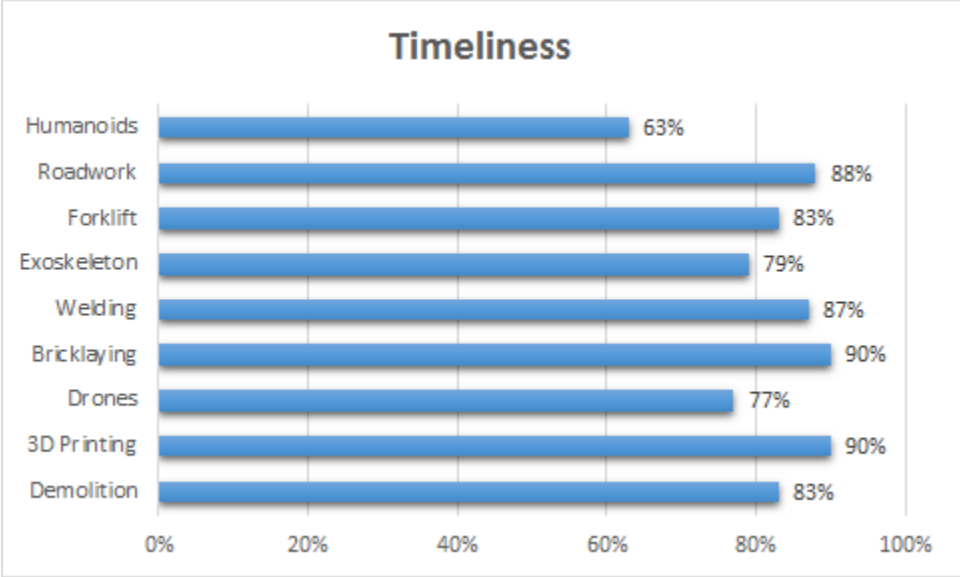


Figure 20 – Community Survey: Timeliness

In terms of privacy, 3D printing has the highest rating while drones once again have the lowest. Drones most likely had a very low rating because many people tend to feel that drones with cameras have the ability and use of spying on them. This would be seen as an invasion of privacy and can be directly attributed to the low rating it received in privacy. Figure 21 shows the scores of each robotic technology in terms of privacy below:

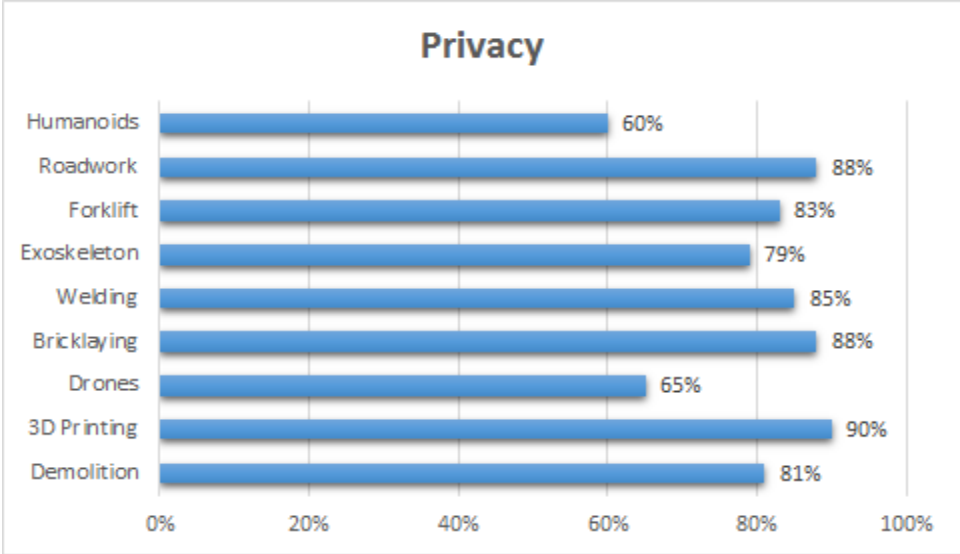


Figure 21 – Community Survey: Privacy

In terms of safety, 3D printing once again took the highest rating while demolition and exoskeleton took the lowest. This is moderately surprising due to the large moving components an industrial 3D printer has. Yet 3D printing was rated the highest among the 3 categories and drones was rated the lowest. Figure 22 shows the scores of each robotic technology in terms of safety below:

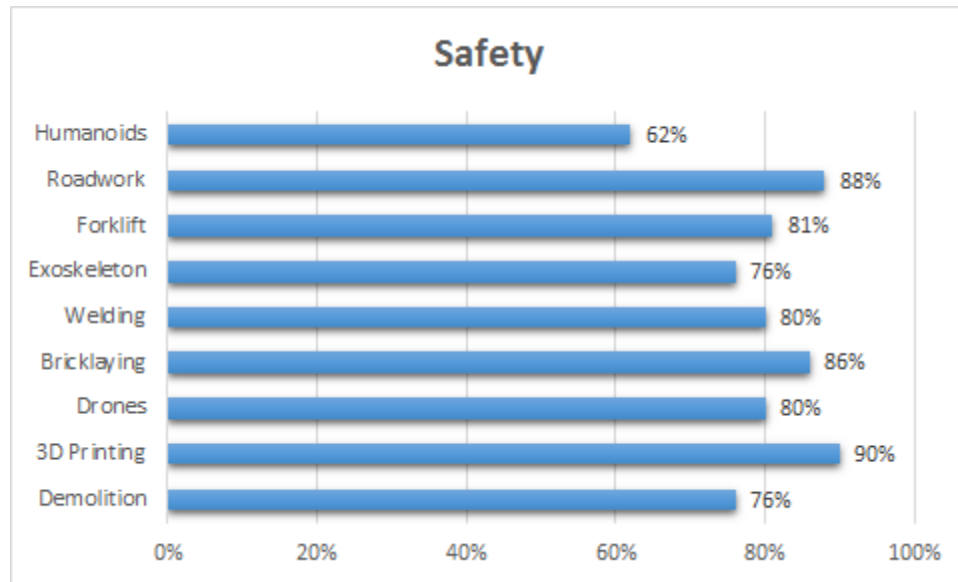


Figure 22 – Community Survey: Safety

6.2.2 Construction Worker Survey

The construction worker survey analyzed job security, productivity, safety, security, quality of robot integration as well as construction worker interest in learning maintenance and their willingness of acquiring assistance and cooperation with all 9 robotic technologies. 100 survey responses were collected for this survey. Each respondent identified with a trade of work according to the CSI classification. This allowed for the correlation of the trades with the robotic technology. In order to take into account varying levels of knowledge between respondents, a knowledge multiplier was created. Just as in the community survey,

respondents answered from 1 to 5, 1 being no knowledge and 5 being highly knowledgeable, and this response was used as a multiplier for all the individual responses. This allowed for filtered responses and a better representation of data. The weight of this section was 15% of each technologies final grade so the maximum score would be a 15. The purpose of this sections weight, and the determination of it is discussed later in this report. The final results are shown in table 5.

As shown in table 5, drones got the highest score across the categories and humanoids got the lowest score across the categories. Dissecting each of the categories, construction workers felt that 3D printing would be the least threatening to their job security, however, welding robots scored an underwhelming 36%, meaning that construction workers overall felt afraid that this robotic technology is very threatening to its corresponding trade. Figure 23 shows the scores of each robotic technology in terms of job security below:

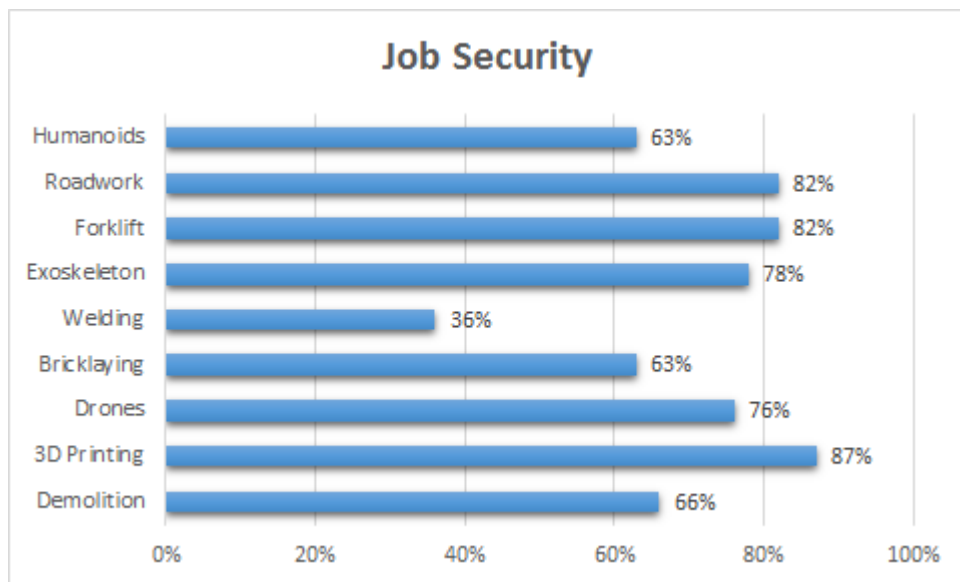


Figure 23 – Construction Worker Survey: Job Security

Technology	Job Security	Productivity	Safety	Security	Quality	Maintenance	Assistance	Cooperation	Averages	Score
Drones	76%	86%	72%	79%	90%	90%	92%	84%	84%	12.5
Bricklaying	63%	79%	87%	80%	85%	87%	91%	92%	83%	12.5
Roadwork	82%	80%	78%	79%	89%	83%	90%	77%	82%	12.3
Forklift	82%	83%	73%	72%	90%	81%	87%	81%	81%	12.2
3D Printing	87%	75%	70%	82%	83%	76%	84%	84%	80%	12
Exoskeleton	78%	82%	73%	73%	88%	80%	85%	80%	80%	12
Welding	36%	85%	89%	88%	86%	84%	84%	83%	79%	11.9
Demolition	66%	74%	82%	80%	80%	70%	79%	77%	76%	11.4
Humanoids	63%	70%	76%	77%	79%	78%	79%	76%	75%	11.2

Table 5: Construction Worker Survey Results

In terms of productivity, drones scored the highest, meaning that respondents who were surveyors or similar, felt that drones would allow them to be more productive at the job site. Humanoids scored lowest in productivity and this can be most likely attributed to the societal perceptions of humanoids as well as the general feeling that there is currently no way that a humanoid could work as productively as a human could at the current technological standpoint humanoids are in. Figure 24 shows the scores of each robotic technology in terms of productivity below:

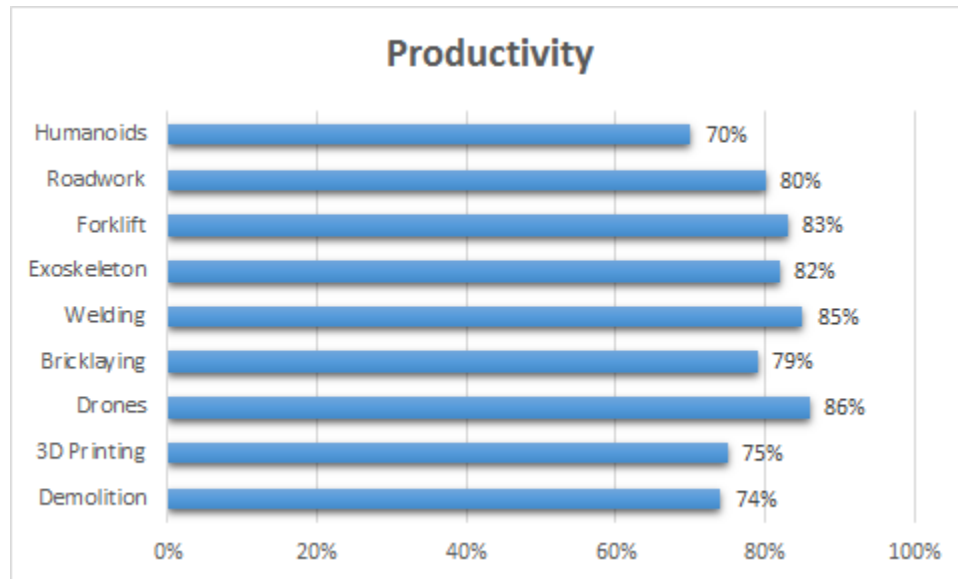


Figure 24 – Construction Worker Survey: Productivity

Welding robots scored the highest in terms of safety meaning that workers felt their integration would allow for an overall safer work environment. When analyzed with job security, one may attribute the high score in safety with the low score in job security. Workers may feel that a safer work environment created by welding robots would directly translate into the welding robots replacing human workers entirely for safety concerns. 3D printing robots scored the lowest in terms of safety, which can most likely be attributed to the mass scale of 3D

printed homes with its large scale moving components. Figure 25 shows the scores of each robotic technology in terms of safety below:

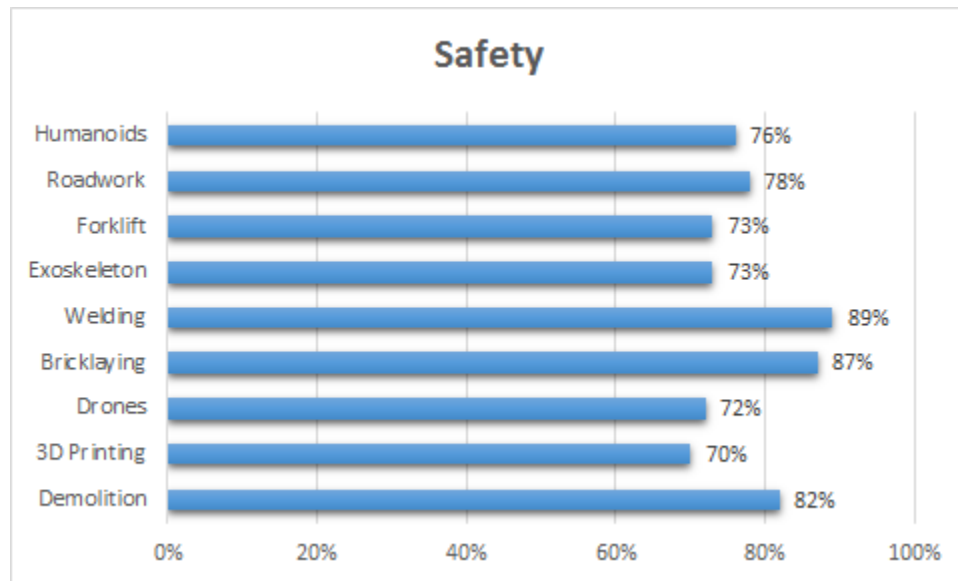


Figure 25 – Construction Worker Survey: Safety

In terms of security of the job site welding robots got the highest while forklift robots received the lowest. Unexpectedly, drones received a low score for security. Surveillance drones have the capability of ensuring there are not trespassers on the construction site or that materials are being stolen. Because of this it was expected that drones would receive a higher score, but this can be attributed to the fact that construction workers may not know the true benefit of a drone in this capacity. Figure 26 shows the scores of each robotic technology in terms of security below:

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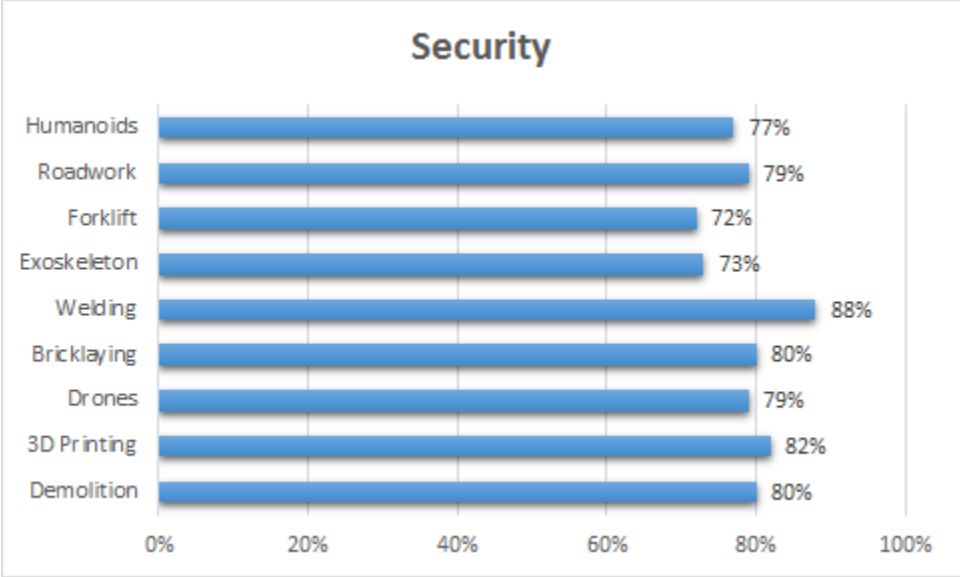


Figure 26 – Construction Worker Survey: Security

Drones and forklift robots were tied for the highest rating in terms of quality of the work. Both can be attributed to the respondent's job type and how they feel a robot would better the quality. A drone would better a surveyor's quality of work because it could get 360 panoramas faster than a human could as well as aerial topographical shots. A forklift would be able to deliver things pre-programmed from location to location without human error. Humanoids distinctly got the lowest rating in terms of quality of work most likely because, as stated before when analyzing the productivity, the level of humanoid ability is technologically not advanced enough to even match that of a human. Figure 27 shows the scores of each robotic technology in terms of quality below:

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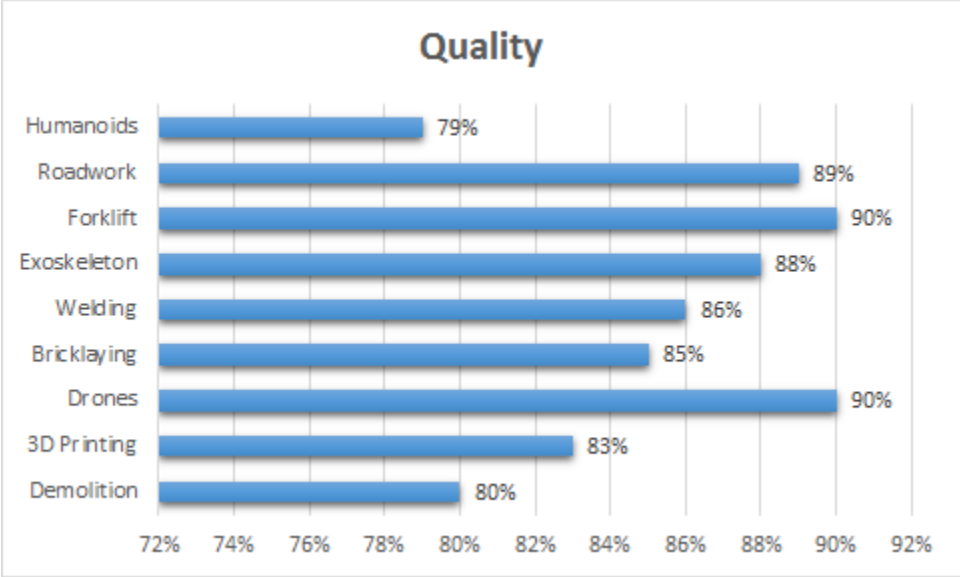


Figure 27 – Construction Worker Survey: Quality

Drones scored the highest in terms of maintenance, meaning that construction workers would be willing to learn how to maintain and repair drones if need be. Demolition robots scored the lowest in terms of maintenance, however this result is okay because most all of the demolition robot companies offer free maintenance services. Figure 28 shows the scores of each robotic technology in terms of learning maintenance below:

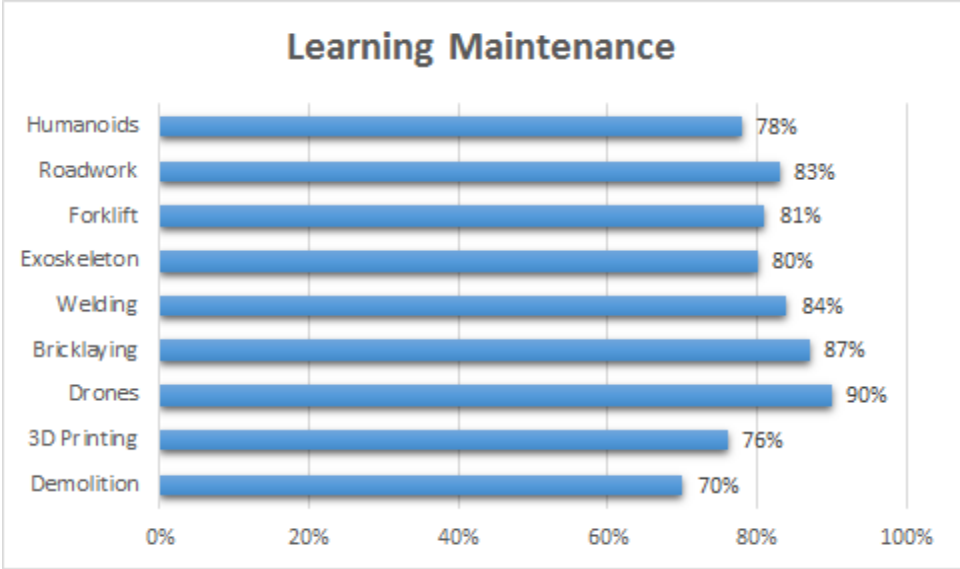


Figure 28 – Construction Worker Survey: Learning Maintenance

Drones also scored the highest in terms of assistance, meaning that construction workers who would interact with drones are willing to allow them to assist in their everyday jobs. Humanoids scored the lowest in this category, presumably because construction workers do not want to have robots assist them over that of another human. Figure 29 shows the scores of each robotic technology in terms of assistance below:

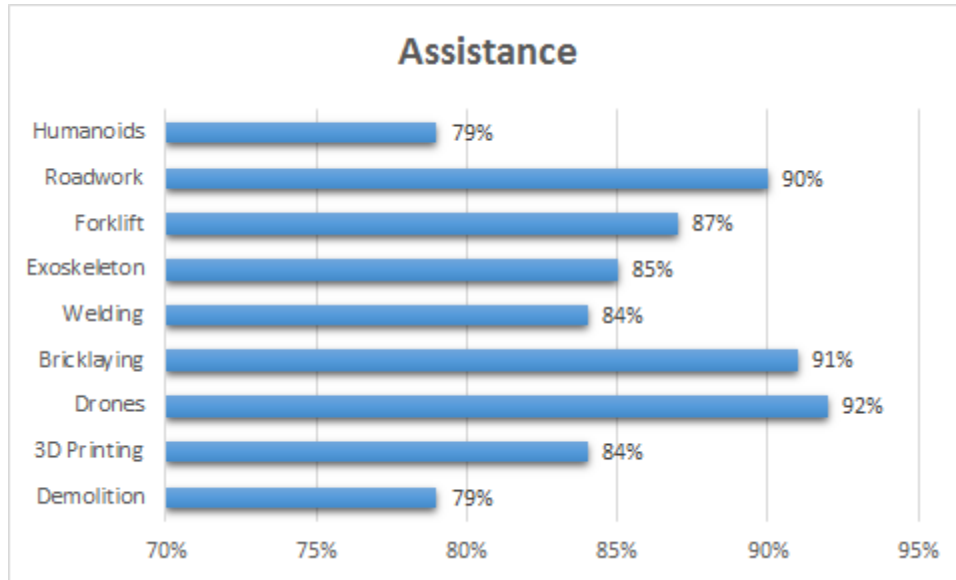


Figure 29 – Construction Worker Survey: Assistance

Bricklaying robots got the highest score for cooperation with construction workers meaning that the workers in the corresponding trades such as masonry would like a partnership with a robot to collaborate and work together on separate tasks to get a common goal done. Humanoids scored the lowest in this category, once again, most likely due to the fact that workers do not want to have to collaborate and partner with robotic versions of humans. Figure 30 shows the scores of each robotic technology in terms of cooperation below:

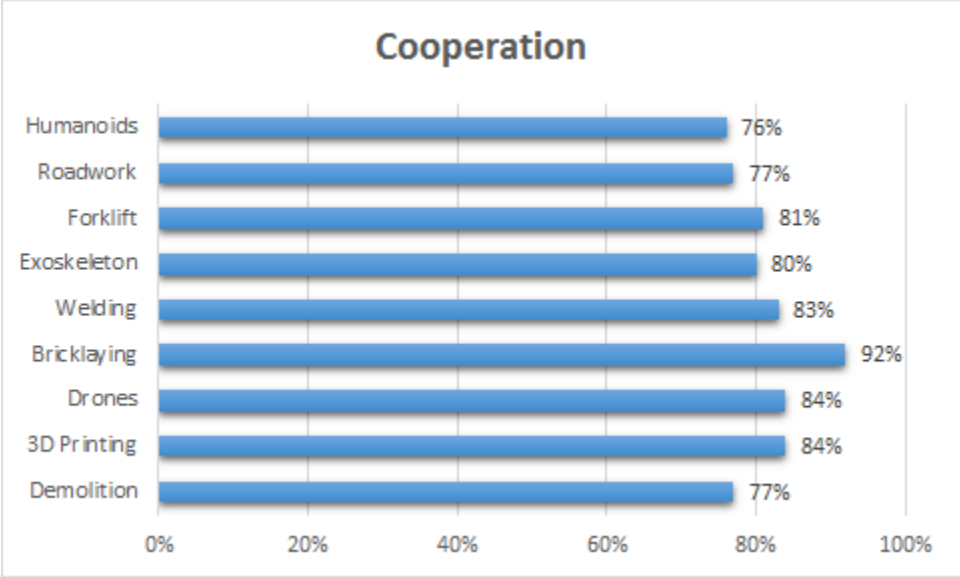


Figure 30 – Construction Worker Survey: Cooperation

In the end, construction workers highly favored drones and highly disliked humanoids. All of the assumptions and probabilistic conclusions made in the above discussions about the surveys were based upon the raw numerical results and research done on each robotic technology. The research done previous to these surveys gave meaning to the results of the survey.

7.0 Research and Results: Risk and Cost Benefit Analysis

One of the primary tasks that needed to be accomplished was the creation of the risk and cost benefit analysis. Both of these analyses were conducted in order to have a more complete evaluation of all the robotic technologies.

7.1 Risk Analysis

The risk analysis is primarily used in order to determine the safety or the risk of an accident for a construction worker performing a task. In order to evaluate the risk, workers compensation insurance rates were used as a proxy for the different tasks that the construction workers would be doing on site. In order to determine the tasks, the CSI classification system previously discussed was used and correlated to the workers compensation insurance rates for each respective task. The averages of these rates were used and entered into a spreadsheet for evaluation, as can be seen in the second column of table 6.

The data that was collected and assigned to a grading rubric. This rubric determined the score for each technology in terms of relieving the risk of the respective task(s). To determine the risk value we created an equation to translate the worker compensation insurance rate per hour into it. The equation for how the risk value was calculated is shown in the table. In the equation, a constant value of 7 was added to intentionally add a buffer to technologies with insurance rates approaching 0. The rate is multiplied by 2.25 to allow an insurance rate of \$3.5 per hour to achieve the max score of 15. The final risk analysis scores for each technology are shown below in table 6:

Tech	Worker Compensation Insurance Rate per Hour	"Risk" Value Value $\approx (7 + (\text{Rate}) * 2.25)$
Bricklaying Robots	\$3.46	15
3D Printing & Contour Crafting	\$3.28	13
Welding Robots	\$3.28	13
Roadwork Robots	\$3.10	13
Demolition Robots	\$3.01	13
Drones: Transport	\$2.04	11
Exoskeletons	\$2.03	11
Humanoids	\$2.03	11
Forklift Robots	\$1.86	10
Drones: 3D Printing, Swarm	\$1.27	9
Drones: Surveillance	\$0.59	8
Drones: Surveying	\$0.41	7

Table 6: Risk Analysis

As can be seen in the above table, bricklaying robots, 3D printing, and welding robots were the top 3 robotic technologies while surveying drones, surveillance drones, and 3D Printing drones scored lowest. These three drones most likely received the lowest scores because the jobs don't require high worker compensation rates as jobs such as surveying does not require as risky a task as say a welder. Welding robots, for example, scored highly because the worker compensation rates are high for tasks such as welding.

7.2 Cost Benefit Analysis

The cost benefit analysis is one of the most pivotal aspects in determining the importance and weight of each robotic technology. The first step was to understand all of the potential aspects that influence cost benefit calculations. Of all the factors for each technology, the cost benefit analysis is the most important with a weight of 25% of the total grade. The significance of the weight of this section is described later in chapter 8. One of the main reasons a company invests in robots is to get a positive return on that investment, or ROI for short. Based upon the total savings a piecewise equation was created in order to translate the savings into a score out of 25 possible points as shown below in figure 31:

$$Score = \begin{cases} 25 - \frac{100 - (\% Savings)}{10}, & 50 \leq (\% savings) \leq 100 \\ 20 - \frac{50 - (\% Savings)}{2.5}, & 25 \leq (\% savings) < 50 \\ 10 - \frac{25 - (\% Savings)}{2}, & 0 \leq (\% savings) < 25 \end{cases}$$

Figure 31 – Cost Benefit Equation

The final results, in terms of percentage of savings and the resulting score can be seen in table 7:

Technology	Savings	Score	Source
Bricklaying Robots	50.00%	20	(SAM100, 2015)
3D Printing/Contour Crafting	60.00%	21	("FAQ", 2015)
Drones	90.00%	24	("Advanced Drone Inspection", 2015)
Humanoids	0.00%	0	("DARPA", 2015)
Exoskeleton	5.00%	1	(Farivar, 2015)
Forklift Robots	60.00%	21	(Davich, 2010)
Roadwork Robots	40.00%	16	(Skibniewski, 2015)
Welding Robots	80.00%	23	(Stapon, 2015)
Demolition Robots	60.00%	21	(Tripp, 2000)

Table 7: Cost Benefit Results

In order to obtain this data the ROI for each and all the robotic technologies was determined. As a starting approach, the book RS Means was used as a guide to get research on the various prices a contractor will offer for a job to get done on the construction site. The jobs chosen to be recorded were jobs a robot could potentially perform either autonomously or teleoperated (RS Means, 2011). In order to calculate the cost benefit, we used a ROI Analysis (See Appendix A for the ROI used for all the robotic technologies). Unfortunately, there is not enough data available to fill out a ROI for each technology. The savings were calculated from articles that stated the total cost of a job with and without the robot technology implemented or used a company's claim on how much their robot technology would save. For those that weren't calculated from articles (as cited above in table 7), the cost savings were derived from this ROI sheet and calculated over a 5 year span. This was calculated by finding the difference of paying equitable salaries of 5 years from the cost of a single robot that would do the job divided by the equitable salaries of 5 years. This was then multiplied by 100% to find the percentages of cost savings.

There were two special cases to this. The first was humanoid robotic technology. Although Boston Dynamic's new humanoid robot demonstrated many advances to the field, this technology received a zero percent on cost benefit. The reasoning for this comes from DARPA Robotics' challenge last summer. IEEE Spectrum uploaded an online video showing a collaboration of competing humanoid robots falling down. Judging by the video, this was a common occurrence with many participating robots. Also, to win the competition, the humanoid robot only had to complete the course once. This does not factor in doing a set of tasks repeatedly or adaptability to new job tasks. Even for the Boston Dynamics humanoid

demonstration video, they selectively edited their video to exclude clips of their robot failing. Due to the reliability concern, humanoids have a score of zero for cost benefit.

The second special case is exoskeleton technology. Through research, we have found the cost of exoskeleton to be dramatically different from other robot technologies. While most robots are in the \$100K+ range, we have found exoskeletons being sold anywhere from \$2K to \$20K. However, they have been given a low score for cost benefit. This is because the savings are much less than that of another robot technology. For other robot technology, you can cut labor force down and potentially cost materials down, depending on the type of technology. Exoskeletons do not cut the labor force down, but cut some of the co pay down by having workers who use them have much less chance of back injury and other injuries associated to picking and placing materials. For these reason, their benefit can be seen similar to the benefit of updated equipment, it makes task more productive but has a small savings over the bigger picture. This is not to say that this is a bad thing, as more of the benefits are accrued by the worker's health than increased revenue. In terms of productivity, exoskeletons can certainly increase the amount of weight a worker can lift and can even enable crippled or handicapped workers. In terms of accident reduction, exoskeletons have actually seen an increase in accidents because users of the exoskeletons experience illusions of invulnerability and attempt to lift beyond the suits capabilities which can lead to bodily harm.

8.0 Research and Results: Final Rubric Grades

In order to quantitatively determine which of these technologies are best, we created an overall grading rubric. This grading rubric accounted for all the factors previously analyzed including the time to commercial availability, risk analysis, community survey results, construction worker survey results, cost benefit analysis, and personal researcher opinions based upon all of the data collected. The final grades for each robotic category and its respective subcategories were calculated a raw score which then in turn represented an overall letter grade. The weights for each section were distributed as follows: 25% cost benefit, 20% researcher ratings, 15% community survey results, 15% construction worker results, 15% risk analysis, and lastly 10% commercial availability. The reason for the difference in weighting was because not every section was believed to be of equal importance. Cost benefit, for example, was given the highest weight as companies value return on investment. This is shown in table 8:

Grading Rubric:	
Cumulative Raw Score	Letter Grade
90-100	A+
85-89.9	A
80-84.9	B+
75-79.9	B
70-74.9	C+
65-69.9	C
60-64.9	D
0-59	F

Table 8 - Final Grade Rubric

This rubric was used in conjunction with the robotic grading sheet to determine the cumulative raw scores and final letter grade for each robotic technology and respective subcategories. This can be seen in figure 32. The raw scores and the final letter grade for each item can be seen below in table 9:

FINAL GRADES:		
Technology	Cumulative Raw Scores:	Letter Grade
Demo: Multi-Tooled	86.7	A
Demo: Hydro Powered	86.1	A
Demo: Env-Friendly	78.6	B
Drone: Surveillance	84.3	B+
Drone: 3D Print	59.0	F
Drone: Transport	83.3	B+
Drone: Surveying	83.9	B+
Drone: Swarm	81.1	B+
3D Printing	78.2	B
Bricklaying: Walls	83.4	B+
Bricklaying: Roads	85.7	A
Welding	74.2	C+
Exoskeletons	56.7	F
Forklift Robots	75.5	B
Roadwork: Repainting	76.5	B
Roadwork: Repaving	74.2	C+
Humanoids	33.5	F

Table 9: Final Robot Grades

Final Grading Schematic																									
Tech	Community Survey					15% Availability					Construction Worker Survey					15% Score					Cost Benefit Analysis: 25%				
	Timeliness	Privacy	Safety	Averages	Score	Job Security	Productivity	Safety	Worker Comp Cost	"Danger" Value	Rating	Rubric	Tech	Raw Scores:	Grade	Assistance	Cooperation	Averages	Score	Cost Benefit Rating					
Demolition	83%	81%	76%	80%	12	66%	74%	82%	\$1.27	9	90-100	A+	Tech			79%	77%	76%	11.4	21					
3D Printing	90%	90%	80%	90%	13.5	87%	75%	70%	\$0.59	8	85-89.9	A	Drones			84%	84%	80%	12.0	21					
Drones	77%	65%	80%	74%	11.1	76%	86%	72%	\$0.41	7	80-84.9	B+	Surveillance			92%	84%	84%	12.5	24					
Bricklaying	90%	88%	86%	88%	13.2	63%	79%	87%	\$2.04	11	75-79.9	B	Surveying			84%	92%	83%	12.5	20					
Welding	87%	85%	80%	84%	12.6	36%	85%	89%	\$3.01	13	70-74.9	C+	Transport			84%	83%	79%	11.9	23					
Exoskeleton	79%	79%	76%	78%	11.7	78%	82%	73%	\$3.28	13	65-69.9	C	Demo			85%	80%	80%	12.0	1					
Forklift	83%	83%	81%	82%	12.35	82%	83%	73%	\$3.46	15	60-64.9	D	3D Print			87%	81%	81%	12.2	21					
Roadwork	88%	88%	88%	88%	13.2	82%	80%	78%	\$2.03	11	0-59	F	Bricklaying			90%	77%	82%	12.3	16					
Humanoids	63%	60%	62%	62%	9.25	63%	70%	76%	\$1.86	10			Evo			79%	76%	75%	11.2	0					
RESEARCHER RATINGS: 20%															RISK					15%					
TECH	R-1	R-2	R-3	Average	Prediction to Availability	Score:	Tech	Worker Comp Cost	"Danger" Value	Rating	Rubric	Final Grades:													
Drones - Surveillance	19	20	17	18.7	Now	10	Drones	\$1.27	9	90-100	A+	Tech													
Drones - 3d print	0	3	1	1.33	10+ year	1	Surveillance	\$0.59	8	85-89.9	A	Demo: Multi-Tooled													
Drones - Transport	15	16	13	14.7	Now	10	Surveying	\$0.41	7	80-84.9	B+	Demo: HydroPower													
Drones - Surveying	20	19	19	19.3	Now	10	Transport	\$2.04	11	75-79.9	B	Demo: Eco-Friendly													
Drones - Swarm	14	17	14	15	6m	9.5	Demo	\$3.01	13	70-74.9	C+	Drone: Surveillance													
Demo - Multi-tooled	20	20	18	19.3	Now	10	3D Print	\$3.28	13	65-69.9	C	Drone: 3D Print													
Demo - Hydro Power	20	19	17	18.7	Now	10	Bricklaying	\$3.46	15	60-64.9	D	Drone: Transport													
Demo - Eco Friendly	18	17.5	16	17.2	7 year	4	Evo	\$2.03	11	0-59	F	Drone: Surveying													
3d print/Contour Crafting	15	15	5	11.7	2 year	7	Welding	\$3.28	13			Drone: Swarm													
Bricklaying - Walls	20	14	16	16.7	3 year	6	Roadwork	\$3.10	13			3D Printing													
Bricklaying - Roads	15	16	14	15	Now	10	Humanoids	\$2.03	11			Bricklaying - Walls													
Welding	5	1	8	4.7	1 year	9	Forklift	\$1.86	10			Bricklaying - Roads													
Evo	12	12	9	11	Now	10						Welding													
Fordiffit robots	13	17	12	14	3 year	6						Evo													
Roadwork - Repainting	15	15	15	15	2 year	7						Forklift													
Roadwork - Repairing	15	15	14	14.7	5 year	5						Roadwork - Repainti													
Humanoids	0	1	2	1	10+	1						Roadwork - Repairing													
												Humanoids													

Figure 32 - Robotic Grading Sheet

The results from these final grades allow us to quantitatively state which robotic technologies are best suited for integration into the field of construction. By using these obtained values in table 9 we were able to make a ranked list from best to worst technology. This ranked list can be seen below in figures 33 and 34:



Figure 33 - Robot Ranks Part 1



Figure 34 - Robot Ranks Part 2

As can be seen in figures 33 and 34, there were some very successful robots and some that failed to meet expectations for integration into construction. The top 3 technologies were: multi-tooled demolition robots, hydro-powered demolition robots, and road bricklaying robots, all receiving grades of “A”. By receiving an “A” the project team intends the denotation to

signify that these 3 technologies are the best, or at least better, options for construction companies that want to integrate robotic solutions into their practices. The worst 3 technologies were: humanoids, exoskeletons, and 3D printing drones, all receiving grades of “F”. Receiving a grade of “F” signifies that these 3 technologies are not yet ready to become integrated into construction practices, and if they are they will not be beneficial. Moving forward this ranking can help construction companies understand which technologies are their best bet to enhance their business. Below in figure 35 is an example of the final grading system and the components that it comprised of in a successful robotic technology as shown in the portfolio (see Appendix C for the entire Portfolio):

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DEMOLITION ROBOTS: MULTI-TOOLED



Multi-tooled demolition robots are primarily used for the destruction of concrete walls and other various structures. They allow the operator to stand away from the debris and contaminants in the air, allowing for a safer environment. These robots are mobile and allow for you to attach various destructive tools to the end of the robotic arm.

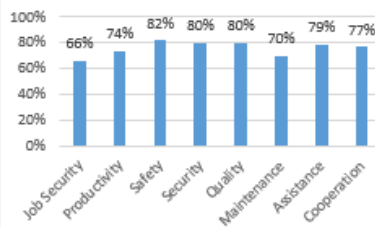
Pros:

- Safer for construction worker
- Mobile and ease of use
- Many attachable tools to the robotic arm

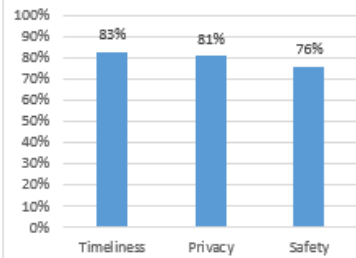
Cons:

- Initial cost
- Currently must be teleoperated by human
- Still scatters dust particles into air

Construction Worker Survey:
11.4/15



Community Survey: 12/15



Cost Benefit Rating	21/25
Risk Rating	13/15
Availability Rating	10/10
Researcher Rating:	19.3/20

Final Grade: A

Figure 35 – Portfolio Example

9.0 Conclusion

The Robotics in Construction Interactive Qualifying Project sought out to answer the leading focus question: “How can robotic technologies be used to benefit the construction industry of Massport and the surrounding communities?” By the end of this project, this focus question was answered within the context of the study and produced a detailed evaluation of all studied technologies in terms of their applicability to the construction industry. It also produced a roadmap for the integration of technology as well as a timeline to allow construction companies to determine when each technology is estimated to be available for purchase and use. Appendix C shows all 17 robotic subcategories spanning their 9 major categories: demolition robots, 3D printing & contour crafting robots, drones, roadwork robots, bricklaying robots, welding robots, exoskeletons, humanoids, and forklift robots.

In determining which technologies were the best, 6 distinct weighted categories were created to quantitatively answer our focus question. These categories consisted of a community survey, a construction worker survey, a risk analysis, a cost benefit analysis, an availability analysis, and lastly researcher opinions. The accumulation of the results in all of these categories allowed for a robotic technology to be graded on a scale of 0-100. Using this scale the robots were able to be ranked based off of their grades in order to determine which technologies were best suited to benefit the construction industry.

The research done in this project reflects the current moment in time. Technology advancements are unpredictable and innovations surge and seize at random moments in time. The results of this project reflect the current data as well as both current and foreseeable robotic technologies that can be applicable to construction. However, this project provides

framework for future analysis of the subject. The results could be very different. We hope that our format for finding the current best solution to integrating robotics can be used as a template if it were to be assessed again in the future.

The results of the proposed grading system were used to quantitatively determine that multi-tooled demolition robots, hydro-powered demolition robots, and road bricklaying robots were the best three robotic technologies at the current moment in time. This study addressed the focus question and in doing so provides Massport with a useful tool in assessing both current and future robotic technologies.

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Appendix A: Return on Investment

	Baselines	Demolition Robot	Blog Post Example	Investment	Your Application	Blog Post Example	Potential Scenario	Your Application	Blog Post Example	Time of Reimbursement [Years]; Time of Reimbursement [Months]; Robot Cell Hourly Rate (\$/hr);	Return on Investment
	Employee on a Shift [Unit]	4	1	Robot (\$)	118,372 \$	35,000 \$	Employee on a Shift [Unit]	2	0.5	0.63	(Return on Investment)
	Hours per Shift [Unit]	40	40	Gripper (\$)	- \$	4,800 \$	Shifts per day [Unit]	1	2	7.50	(Return on Investment)
	Shifts per day [Unit]	1	2	Part Presentation Fixture (\$)	- \$	1,000 \$	Employee Yearly Salary (\$)	94,640 \$	50,000 \$	\$11.12	(Total robotic cell cost / total robot working time)
	Employee Yearly Salary and Benefits (\$)	94,640 \$	50,000 \$	Vision System (\$)	- \$	- \$	Downtime Cost	- \$	1,000 \$	\$1,109,351.28	(Cumulative savings after 5 years)
	Downtime Cost	- \$	7,500 \$	Monitoring System (\$)	- \$	- \$	Scrap Part Cost	- \$	2,000 \$	Total Savings (%):	58.61%
	Scrap Part Cost	- \$	10,000 \$	Other Peripherals (\$)	- \$	- \$	Jig and Process Enhancement Cost (\$)	- \$	10,000 \$		
	Jig and Process Enhancement Cost (\$)	- \$	7,500 \$	Cleaning System (\$)	- \$	800 \$	Weeks Worked per Year [Unit]	50	50		
				Physical Barriers (\$)	- \$	500 \$					
				Robot to Machine Interface (\$)	- \$	1,000 \$	Potential Scenario	189,280 \$	63,000 \$		
	Yearly Cost	378,500 \$	125,000 \$	Integration	- \$	2,000 \$					
				Taxes, Transportation Fees ... (\$)		4,000 \$	Cost of a Robotic Cell	Your Application	Blog Post Example		
							Estimated Yearly Maintenance Cost	20,800 \$	300 \$		
				Starting Investment	118,372 \$	49,100 \$					

Appendix B: List of Research Questions

List of Questions

Massport:

What are the construction trends seen at Massport?

Which communities could/have been affected by Massport Construction?

Societal Implications:

How do construction workers feel about robots/new tech in construction?

How do the surrounding communities feel about robot/new tech?

Construction Process:

What is the construction process?

Where in the construction process can robots play the largest role?

Drones:

What are the applications of drones?

How can drones be used in construction?

What are the limitations of drones?

What are the pros/cons of drones?

When could drones be used to assist in construction?

Demolition Robots:

What are the applications of demolition robots?

How can demolition robots be used in construction?

What are the limitations of demolition robots?

What are the pros/cons of demolition robots?

When could demolition robots be used in construction?

3D Printing:

What are the applications of 3D printing?

How can 3D printing be used in construction?

What are the limitations of 3D printing?

What are the pros/cons of 3D printing?

When could 3D printing be used in construction?

Bricklaying Robots:

What are the applications of bricklaying robots?

How could bricklaying robots be used in construction?

What are the limitations of bricklaying robots?

What are the pros/cons of bricklaying robots?

When could bricklaying robots be used in construction?

Welding Robots:

What are the applications of welding robots?

How can welding robots be used in construction?

What are the limitations of welding robots?

What are the pros/cons of welding robots?

When can welding robots be used in construction?

Exoskeletons:

What are the applications of exoskeletons?

How could exoskeletons be used in construction?

What are the limitations of exoskeletons?

What are the pros/cons of exoskeletons?

When could exoskeletons be used in construction?

Forklift Robots:

What are the applications of forklift robots?

How could forklift robots be used in construction?

What are the limitations of forklift robots?

What are the pros/cons of forklift robots?

When could forklift robots be used in construction?

Roadwork Robots:

What are the applications of roadwork robots?

How can roadwork robots be used in construction?

What are the limitations of roadwork robots?

What are the pros/cons of roadwork robots?

When can roadwork robots be used in construction?

Humanoids:

What are the applications of humanoid robots?

How could humanoid robots be used in construction?

What are the limitations of humanoid robots?

What are the pros/cons of humanoid robots?

When could humanoid robots be used in construction?

Table 1 - List of Secondary Questions

Appendix C: Portfolio

Robotics in Construction: Roadmap to Integration and Commercial Availability

An Interactive Qualifying Project

Sponsored by: Massport

March 3, 2016

By Alex Ruggiero, Sebastiano Salvo, and Chase St. Laurent



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INTRODUCTION

This portfolio is an accumulation of the research and results of a project conducted on robotics in construction at Worcester Polytechnic Institute from August 2015 - March 2016. This portfolio reports on the current robotic technology and how it applies to and can benefit the construction industry. This document presents several robotic technologies by providing their applications, pros, cons, and a variety of survey, research, and analysis results which culminates in a final grade for each technology. It concludes with a timeline of commercial availability estimates and a summary of the results. Below is a list of terminologies and explanations to better understand the significance of each item:

Construction Worker Survey: This survey was given to 100 construction workers over various fields and of diverse background. It questioned their opinions, feelings, and beliefs about job security, productivity, safety, security, quality, maintenance, assistance, and cooperation if the robotic technology in question were integrated into their field of work. The results from this survey reveal each robot's societal impact and opinionated benefits in the field of construction. The total weight of this section was 15% of the final grade.

Community Survey: This survey was given to 100 respondents of various demographic background who are not directly involved in construction. It questioned their opinions on the time to accomplish nearby construction, their privacy, and safety if the robotic technology in question were integrated into a construction site near them. The results from this survey reveal each robot's societal impact and opinionated benefits in the global community. The total weight of this section was 15% of the final grade.

Cost Benefit Rating: This section analyzed the Return on Investment (ROI) of each robotic technology. The results from this analysis reflect the percent savings a company might expect when investing in the particular technology. The total weight of this section was 25% of the final grade.

Risk Rating: This section analyzed the risk presented when a human does his or her hired job by directly correlating it to the workers compensation cost for their job. The results from this analysis represent the alleviation of risk when a robot replaces a human. The total weight of this section was 15% of the final grade.

Availability Rating: This section analyzed the estimated timeline for when each robotic technology is available for purchase and use by a construction company. The results of this analysis reveal which technologies are most available to use now and which are potential future applications. The total weight of this section was 10% of the final grade.

Researcher Rating: This rating is an average of the three independent researcher ratings which were based off of the research done on each robotic technology. The rating focused on each researchers informed opinion on which technologies had the most potential to benefit the construction industry. The total weight of this section was 20% of the final grade.

Final Grade: This is the letter grade denomination based upon the 100% total of the construction worker survey results, the community survey results, the cost benefit rating, the risk rating, the availability rating, and the researcher rating. This letter grade is intended to denote the collective data for potential success or failure of each robotic technology.

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ROBOTIC DRONES: SURVEILLANCE

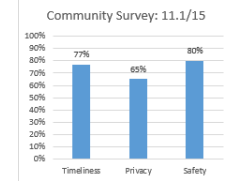
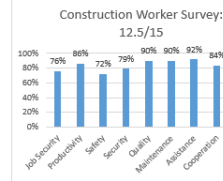


Surveillance drones are used to act as security at a construction site. They can be used to monitor the construction site's progress when partnered with enhanced imaging software. Surveillance drones can also be used to determine worker participation as well as the duration each worker has been present at work using facial recognition.

- Pros:**
- Limitless verticality
 - Swift and Agile
 - Many software capabilities

- Cons:**
- Maintenance costs
 - Easily can be lost
 - Regulations against usage*

*Licensed operators can still use drones in many places, however use near Airports is tightly restricted.



Cost Benefit Rating	24/25
Risk Rating	8/15
Availability Rating	10/10
Researcher Rating:	18.7/20

Final Grade: B+

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ROBOTIC DRONES: CONTOUR CRAFTING & 3-D PRINTING

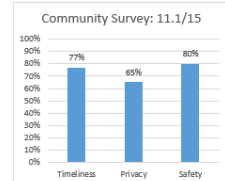
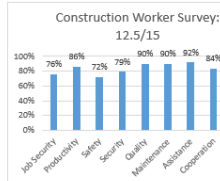


Contour crafting drones are used to act as highly mobile and aerial 3-D printers at a construction site. They can be used to print the construction site's necessary building materials and components. This type of drone is in the experimental stage currently and has yet to have a successful version.

- Pros:**
- Limitless verticality
 - Good for fillings
 - Ability to print materials on site

- Cons:**
- Inability to print many objects in one run
 - Highly inaccurate
 - Regulations against usage*

*Licensed operators can still use drones in many places, however use near Airports is tightly restricted.



Cost Benefit Rating	24/25
Risk Rating	9/15
Availability Rating	1/10
Researcher Rating:	1.33/20

Final Grade: F

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ROBOTIC DRONES: TRANSPORTATION

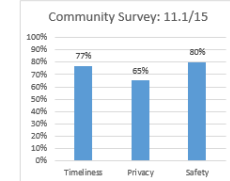
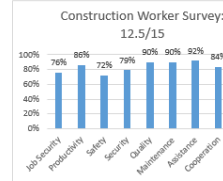


Transportation drones are used to act as flying delivery devices at a construction site. They can be used to transport items such as tools, construction materials, and other lightweight objects. These drones use sensors and GPS in order to reach their destinations inputted by the user.

- Pros:**
- Limitless verticality
 - Relatively fast
 - Ease of delivery and transportation

- Cons:**
- Maintenance costs
 - Unable to carry significantly heavy objects
 - Regulations against usage*

*Licensed operators can still use drones in many places, however use near Airports is tightly restricted.



Cost Benefit Rating	24/25
Risk Rating	11/15
Availability Rating	10/10
Researcher Rating:	14.7/20

Final Grade: B+

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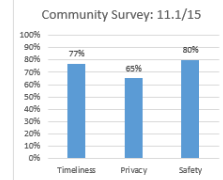
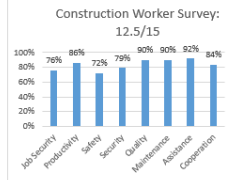
ROBOTIC DRONES: SURVEYING



Surveying drones are used to act as the surveyors at a construction site. They can be used to capture 360 degree images of the construction site. Surveying drones can also be used capture aerial shots and many other angles of the site than was ever possible before.

Pros:	Cons:
<ul style="list-style-type: none"> • Limitless verticality • Eliminates need for multiple cameras • Many software capabilities 	<ul style="list-style-type: none"> • Maintenance costs • Picture quality not as sharp due to rotor vibrations • Regulations against usage*

*Licensed operators can still use drones in many places, however use near Airports is tightly restricted.



Cost Benefit Rating	24/25
Risk Rating	7/15
Availability Rating	10/10
Researcher Rating:	19.3/20

Final Grade: B+

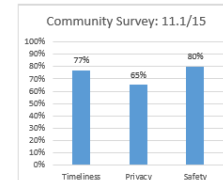
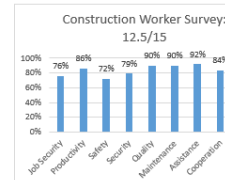
ROBOTIC DRONES: SWARMS



Swarms of drones can be used for multiple applications at a construction site. They can be used to surveillance, surveying, transportation, and any other application required in mass. Swarm drones are used for tasks that require multiple drones to be used in unison. A swarm of drones also works in collaboration using software that creates communication between the other drones.

Pros:	Cons:
<ul style="list-style-type: none"> • Verticality and agility • Faster task completion time • Versatility 	<ul style="list-style-type: none"> • Maintenance costs • Hard to use in windy environments • Regulations against usage*

*Licensed operators can still use drones in many places, however use near Airports is tightly restricted.



Cost Benefit Rating	24/25
Risk Rating	9/15
Availability Rating	9.5/10
Researcher Rating:	15/20

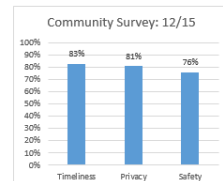
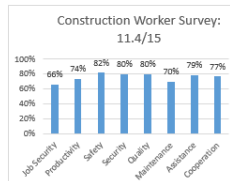
Final Grade: B+

DEMOLITION ROBOTS: MULTI-TOOLED



Multi-tooled demolition robots are primarily used for the destruction of concrete walls and other various structures. They allow the operator to stand away from the debris and contaminants in the air, allowing for a safer environment. These robots are mobile and allow for you to attach various destructive tools to the end of the robotic arm.

Pros:	Cons:
<ul style="list-style-type: none"> • Safer for construction worker • Mobile and ease of use • Many attachable tools to the robotic arm 	<ul style="list-style-type: none"> • Initial cost • Currently must be teleoperated by human • Still scatters dust particles into air



Cost Benefit Rating	21/25
Risk Rating	13/15
Availability Rating	10/10
Researcher Rating:	19.3/20

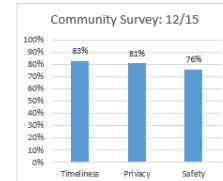
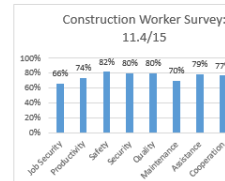
Final Grade: A

DEMOLITION ROBOTS: HYDRO POWERED



Hydro powered demolition robots are used to demolish concrete walls or similar structures at a construction site. They allow the operator to stand away from the debris and contaminants in the air, allowing for a safer environment. These demolition robots use high pressure water jets to demolish walls and they prevent debris from entering the local atmosphere.

Pros:	Cons:
<ul style="list-style-type: none"> • Prevent dust in the atmosphere • Precise demolition • Mobility and ease of use 	<ul style="list-style-type: none"> • Initial cost • Currently must be teleoperated by humans • Requires steady stream of water



Cost Benefit Rating	21/25
Risk Rating	13/15
Availability Rating	10/10
Researcher Rating:	18.7/20

Final Grade: A

DEMOLITION ROBOTS: ENVIRONMENTALLY FRIENDLY



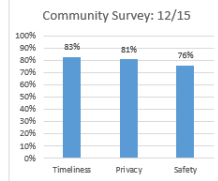
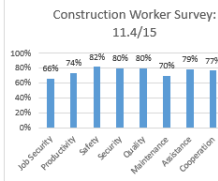
Environmentally friendly demolition robots operate similar to hydro demolition robots with the distinction that they also process the waste into aggregate. As concrete walls are destroyed, this robot sucks in the wall and processes it into a bag for export. This robot not only demolishes walls but it eliminates excess waste. Currently this robot is a design concept and has yet to be physically built.

Pros:

- Environmentally Friendly
- Precise demolition
- Eliminates need for clean up after demolishing

Cons:

- In conceptual stage only
- Requires steady stream of water
- Initial cost



Cost Benefit Rating	21/25
Risk Rating	13/15
Availability Rating	4/10
Researcher Rating:	17.2/20

Final Grade: B

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3D PRINTING/CONTOUR CRAFTING ROBOTS



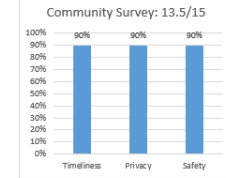
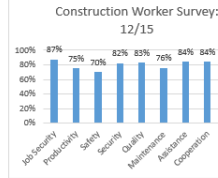
3D printing and contour crafting robots can be used in the construction industry for building structures such as walls and even entire buildings. This technology can build a home sized project in as short as a day and does so with little to no waste product. Many of these devices are still in the testing phase, yet many companies plan to sell these machines in one or two years.

Pros:

- Fast at building structures
- Little to no waste product
- Eliminates need for many workers

Cons:

- Initial cost
- Very large, difficult to transport
- Still in testing phase



Cost Benefit Rating	21/25
Risk Rating	13/15
Availability Rating	7/10
Researcher Rating:	11.7/20

Final Grade: B

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BRICKLAYING ROBOTS: WALL-LAYING ROBOTS



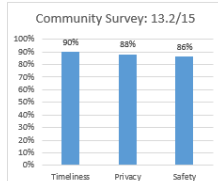
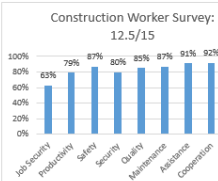
Bricklaying robots are being used in construction for tasks such as creating walls for buildings. Some make use of a robotic arm while others use a conveyor belt system to distribute the bricks. This robot is very fast and precise.

Pros:

- Precision
- Extremely fast
- Mobile in most cases

Cons:

- Initial cost
- Some require humans to lay cement sill
- Bulky size limits capabilities



Cost Benefit Rating	20/25
Risk Rating	15/15
Availability Rating	6/10
Researcher Rating:	16.7/20

Final Grade: B+

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BRICKLAYING ROBOTS: ROADS & WALKWAYS



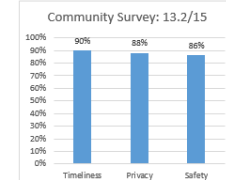
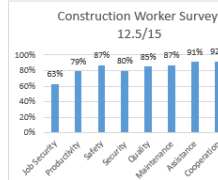
Road and walkway bricklaying robots are primarily used in construction to create seamless walkways, roads, and floors in a fast paced and precise manner. These machines allows operators to easily dump multiple bricks into the machine where it does all the sorting and placement.

Pros:

- Ease of use
- Fast and precise placement
- Great for long stretches of brick

Cons:

- Initial cost
- Requires significant human cooperation
- Requires significant setup



Cost Benefit Rating	20/25
Risk Rating	15/15
Availability Rating	10/10
Researcher Rating:	15/20

Final Grade: A

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WELDING ROBOTS



Welding robots are used for the construction of ships, and for any application to joining metal. These robots can be used on steel structures and particularly on the docking stations of ports. They are able to make precise welds and can maneuver hard to reach locations. They replace the unsafe conditions of a human welder near the intense heat and sparks created during welding.

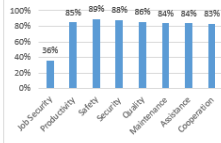
Pros:

- Safer for the worker
- Increased quality of the weld
- Precision welding

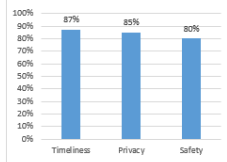
Cons:

- Currently a stationary device
- Initial cost
- Takes time to do a single weld

Construction Worker Survey:
11.9/15



Community Survey: 12.6/15



Cost Benefit Rating	23/25
Risk Rating	13/15
Availability Rating	9/10
Researcher Rating:	4.7/20

Final Grade: C+

EXOSKELETONS



Exoskeletons are suits that enable and enhance humans to do certain tasks that the human body is incapable of doing without assistance such as lifting extremely heavy objects. Exoskeletons can also be used by handicapped individuals to allow them to do tasks that they may have been unable to do because of an impairment.

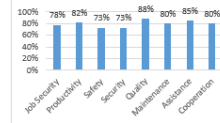
Pros:

- Ability to lift heavy objects
- Mobility returned to the impaired
- Reduces fatigue and strain on humans

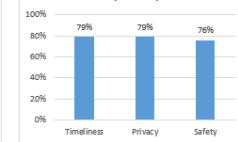
Cons:

- Cost
- Battery life is not very long
- Injuries due to lifting more than capable with the suit

Construction Worker Survey:
12/15



Community Survey: 11.7/15



Cost Benefit Rating	1/25
Risk Rating	11/15
Availability Rating	10/10
Researcher Rating:	11/20

Final Grade: F

FORKLIFT ROBOTS



Forklift robots are used to transport heavy or generally large objects from one point to another. They aim to alleviate the need for a human to carry these objects or have a human control a forklift to transport the goods. They use advanced vision tracking and map localization to reach their goals.

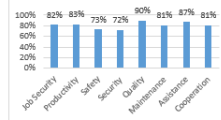
Pros:

- Little to no human involvement required
- Ability to receive voice commands
- Heavy lifting capabilities

Cons:

- Unable to traverse steep gradients
- Need a pre-programmed map of environment
- Harsh terrains are not ideal for this robot

Construction Worker Survey:
12.2/15



Community Survey: 12.4/15



Cost Benefit Rating	21/25
Risk Rating	10/15
Availability Rating	6/10
Researcher Rating:	14/20

Final Grade: B

ROADWORK ROBOTS: REPAINTING



Repainting robots are used to repaint faded or missing lines on roadways. The primary reason for this robot is to do small patch jobs in order to avoid bringing out heavy equipment that cause highway clutter and traffic jams. This alleviates the need for a crew of workers and the time required to accomplish the job.

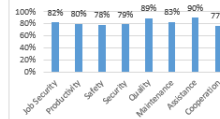
Pros:

- Great for small repainting jobs
- Prevents traffic jams
- Eliminates need for an entire crew

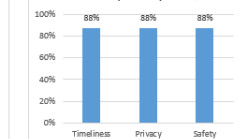
Cons:

- Only 90% accurate
- Still in the development and testing phase

Construction Worker Survey:
12.3/15



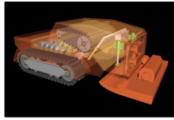
Community Survey: 13.2/15



Cost Benefit Rating	16/25
Risk Rating	13/15
Availability Rating	7/10
Researcher Rating:	15/20

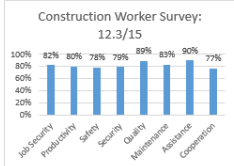
Final Grade: B

ROADWORK ROBOTS: REPAVING



Repaving robots are used to repave potholes or small patches on roadways. The primary reason for this robot is to do small patch jobs in order to avoid bringing out heavy equipment that cause highway clutter and traffic jams. This alleviates the need for a crew of workers and the time required to accomplish the job.

Pros:	Cons:
<ul style="list-style-type: none"> Great for small repaving jobs Prevents traffic jams Eliminates the need for an entire crew 	<ul style="list-style-type: none"> Maintenance costs Still in the design phase



Cost Benefit Rating	16/25
Risk Rating	13/15
Availability Rating	5/10
Researcher Rating:	14.7/20

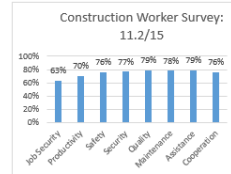
Final Grade: C+

HUMANOIDS



Humanoids are able to navigate through hazardous areas and accomplish tasks that humans are unable to do due to the environment. These robots could also be used to do anything a human could do. This technology is very far away from being a reality at the moment so we have classified it as a future technology.

Pros:	Cons:
<ul style="list-style-type: none"> Able to work in hazardous environments Ability to do most all human tasks Ability to lift heavy objects 	<ul style="list-style-type: none"> High cost Still in testing phase Incapable of doing tasks proficiently



Cost Benefit Rating	0/25
Risk Rating	11/15
Availability Rating	1/10
Researcher Rating:	1/20

Final Grade: F

TIMELINE OF COMMERCIAL AVAILABILITY

Present	<ul style="list-style-type: none"> Drones: Surveillance, Surveying, Transportation Demolition: Multi-Tooled, Hydro Powered Exoskeletons Bricklaying: Roads
6 months	<ul style="list-style-type: none"> Drones: Swarms
1 year	<ul style="list-style-type: none"> Welding Robots
2 years	<ul style="list-style-type: none"> 3D Printing/Contour Crafting Roadwork: Repainting
3 years	<ul style="list-style-type: none"> Bricklaying: Walls Forklift Robots
5 years	<ul style="list-style-type: none"> Roadwork: Repaving
7 years	<ul style="list-style-type: none"> Demolition: Environmentally Friendly
10+ years	<ul style="list-style-type: none"> Drones: 3D Printing Humanoids

FINAL GRADES

	Demolition Robots: Multi-Tooled • Rank: 1st • Grade: A (86.7)
	Demolition Robots: Hydro Powered • Rank: 2nd • Grade: A (86.1)
	Bricklaying Robots: Roads • Rank: 3rd • Grade: A (85.7)
	Drones: Surveillance • Rank: 4th • Grade: B+ (84.3)
	Drones: Surveying • Rank: 5th • Grade: B+ (83.9)
	Bricklaying Robots: Walls • Rank: 6th • Grade: B+ (83.4)
	Drones: Transportation • Rank: 7th • Grade: B+ (83.3)
	Drones: Swarms • Rank: 8th • Grade: B+ (81.1)



Demolition Robots: Environmentally Friendly

- Rank: 9th
- Grade: B (78.6)



3D Printing & Contour Crafting

- Rank: 10th
- Grade: B (78.2)



Roadwork Robots: Repainting

- Rank: 11th
- Grade: B (76.5)



Forklift Robots

- Rank: 12th
- Grade: B (75.5)



Roadwork Robots: Repaving

- Rank: 13th
- Grade: C+ (74.2)



Welding Robots

- Rank: 14th
- Grade: C+ (74.2)



Drones: 3D Printing

- Rank: 15th
- Grade: F (59.0)



Exoskeletons

- Rank: 16th
- Grade: F (56.7)



Humanoids

- Rank: 17th
- Grade: F (33.5)