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Role of Industrial Robotics Automation Systems

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Francis Darmont Araya   Kaan Emir

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Approved:

Prof. John Sullivan

Prof. Arthur Heinricher

Abstract

This Interdisciplinary Qualifying Project focuses on the role of robots in increasing safety, productivity and profit for four specific industries. These industries include manufacturing, medical, construction and food packaging. In the manufacturing industry, robots are used primarily in welding process, material handling systems and inspection of parts. Some of the robots used include Fanuc LR200i, Fanuc R20000iC and Motosight. The technical specifications of these robots range from an end effector payload of approximately 25-210 kg, distance reach of 717-2650 mm and power of 200-575 volts. In the medical industry, robots are used in surgical and sanitation applications. Examples of these robots include the Da Vinci and Xenex. A notable specification of the Da Vinci robot is its capability to provide seven degrees of freedom at its end effector. In the construction industry, robots are used to improve worker safety and structure of the building. Robots as the SAM 100 and the Oscar 100 provide a wide range of end effector capabilities of approximately 2,000 to 3,229 mm. In the food packaging industry, robots are used primarily for picking, packing and palletizing finished products. Some of these robotic systems include IRB 340, IRB 260 and the IRB 660, which are manufactured by ABB. Their payload capabilities are approximately 1-250 kg and they are used for wide range of packaging operations. A cost analysis shows that the incorporation of robotic systems into the four industries reduce labor and operational costs, and improve performance substantially. In many robotic system, translational, rotational and simultaneous translation and rotational motion may be required to move or orient loads. The motion planning, selecting suitable mechanical components and electrical power systems for robots with many degrees of freedom demand several design iterations. Paths, speeds and orientations of robots are controlled by motors embedded with software, hardware and electronic amplifiers. A prototype robot for welding process is designed and built. This provide the IQP team an opportunity to apply basic engineering experience to industrial robotic systems. A detailed engineering drawing of the prototype welding robot is presented. The IQP team used the robots in WPI Washburn machine shop to gain hands-on experience of pick and place robots and measurement of machined parts using robots. Recent developments in the role of robotic systems in manufacturing, medicine, construction and food packaging are also presented. The literature dealing with robotic systems show that there is a growing effort to increase robotic systems in many other industries. Robots are found to reduce accidents in the work place and the

making of defective parts. The societal impacts of this IQP are the robots improve performance, increase safety and reduce costs.

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CHAPTER 1. THE ROLE OF ROBOTS IN MANUFACTURING INDUSTRY

1. **Introduction**

There is a growing interest in using robots in various industries. This interest stems from the fact that robotics helps to increase safety in the workplace, increase productivity and reduce production costs. With robotic applications, significant amount of labor work can be done autonomously. Advanced sensors in robots allow high precision tasks that are difficult for human workers to do. Therefore, higher qualities for products and services are achieved when robots are used.

There are robots developed specifically for manufacturing industries, applications in medicine, food production, agriculture and construction industry. These robots can be used for many different tasks, such as welding process in automotive industry, painting automobile components, and inspection. Industrial robots provide better efficiency in manual labor and usually can run 24 hours per day. These benefits greatly reduce production costs for companies in the long term since they don't have to employ a group of workers to do the same job.

Many surgeries can be carried out by robots or co-operation between human doctors and robots. Medical robots in hospitals can autonomously do the initial stage of cochlear implantation surgery, which require drilling a hole in the skull with high precision. Hospitals are also interested in implementing robots that directly cooperate with doctors and act as robotic tools. Doctors can control these robots directly from a control unit and work with enhanced vision and manipulate robotic arms with high precision. Surgeries done with this method can improve recovery time in patients and minimize the damage to the body, providing a safer surgery and higher quality treatment.

Industrial robots that are mainly built for people's safety conduct communication through hand gestures between workers, so that workers can receive input from robot easily when there is distance in between and noise in the environment. These robots are expected to decrease overall cost in long term, improve safety of people and have better and more consistent quality in products and services. It is the purpose of this project to investigate robots that are used in different industries and their roles in companies.

The main goal of this project is to describe the roles of robots in various industries and analyze their social impacts. This includes how robots can carry out tasks autonomously to reduce manual labor, or how robots can be used in tasks requiring high precision to produce better and more consistent results than humans. Robots can have significant social impact by doing tasks that can be dangerous for human workers. This reduces potential employee injuries and allows employees to work on safer tasks.

The project also focuses on analyzing the costs of robot systems and the long-term benefits of such investment. Despite being used in different fields, it is determined that robots from various industries have a certain group of common aspects. This project focuses on evaluating robots in these industries under their impact on costs, quality and safety; which are the common aspects of different robots. In addition, the IQP team aims to learn more about robotic systems and the engineering behind the making of a prototype robotic arm. Therefore, the overall objective of this project is to determine the role that robots serve in different industries and learn more about their design with hands on experience and training.

In the initial phase of this IQP, a prototype robotic welding arm was created, and mathematical analysis of dynamics and kinematics was conducted. SolidWorks was used to model the components of the robotic arm and 3D printed them to physically assemble them. Arduino Mega 2560 was used as a microprocessor to control the arm. To learn more about the welding process, appropriate training from WPI Washburn labs was received by the IQP team. Armed with that knowledge, extensive research was performed on robotic systems and their roles in the manufacturing industry. A set of examples of robots from various industries have been gathered. Their impact on cost, quality and safety have been analyzed thoroughly.

The way medical robots perform and improve surgery results have been investigated. A comprehensive cost analysis for industrial robots have been made. Financial concepts such as return of investment for mid-size industrial robots and estimations of average costs for industrial robots in future have been evaluated. The IQP team has researched safety systems implemented in robots and learned about their impact on safety improvement.

In chapter 2, examples of robots from the manufacturing, medicine, construction and food packaging industry are provided to discuss their advantages and technical capabilities. In the next section, the project focuses on robots used in medical applications and robots with safety systems to minimize foreseeable injuries. The cost analysis on examples of manufacturing robots in

companies is demonstrated along with discussing the estimations of manufacturing robot market in U.S.A. In Chapter 3, the project focuses on IQP team's welding training in WPI Washburn Labs and the designing process of the prototype robotic arm followed by kinetics and kinematics equations with free body diagrams of the prototype robotic arm.

CHAPTER 2. APPLICATIONS OF ROBOTS IN FOUR INDUSTRIES

2. Introduction

The use of robots in the manufacturing, medical, construction and food packaging industry has benefited companies in increasing safety, productivity and reducing production costs. The increase in demand of such robotic systems, has allowed for robot manufacturers to increase the variety of robotic systems in the market. In addition, increased competition in the market has pressed manufacturers to provide innovative solutions that reduce costs and meet the needs of the industry. This financial benefit has incentivized companies to keep themselves informed on the latest technologies. For companies to narrow down applicable technologies, is essential to analyze and understand the specifications and benefits that each robot can provided. Although not all robot systems are explained in this chapter, this chapter intends to provide information of the variety of robots that are used in four major industries. In addition, specific specifications are provided for each robot that are considered of most importance when considering overall costs and benefits.

2.1. Application of Robots in Manufacturing Industries

Robots are widely used in the manufacturing industry for different processes and operations. Within the many processes, the most prominent areas of robot utilization include welding, material handling and inspection. The use of robots in these areas aid in mitigating risks associated with hazardous and repetitive tasks that increase the probability of employee injury. Furthermore, due to advances in technology, robot utilization in areas of inspection have provided increased capabilities that are not affected by human factors such as concentration and motivation. In addition, the ability to reduce overall production time and costs through robotic systems has become a strong force for implementing these systems.

2.1.1 Spot and Arc Welding Processes

The process of robotic welding has gained traction over the years especially in the automotive industry. The welding versatility of robots has provided applications in arc welding, tungsten inert gas welding and spot welding. Details of the seven major robot manufacturers in the industry are provided in the list below [6].

- Yaskawa: Motoman Robotics
    - Total of 15 welding robots
    - Largest diversities of robots
    - Payloads 3 kg to 15 kg.
- Fanuc Robotics
    - Robots on rails
    - "ARC Mate" designation (branding)
    - Total of 11 welding robots
- ABB Company
    - Total of 2 welding robots
    - Recognized by letters 'ID' at the end of their name
- Kuka Company
    - Robots and robotic accessories
    - Smaller collaborative to 1,300 kg payload
    - Hollow wrists, install a welding torch or feed material
- Kawasaki
    - 7 welding robots
    - 'RS' designation before their name
- Comau
    - Build automotive body welding cells
    - Spot welding background
- Panasonic, Cloos, Nachi
    - Small Arc welding robot line

The LR- Mate 200iD and ARC Mate 0 iB robots provide some of the highest capabilities in the welding industry. As shown in Figure 1 below, the robots are set up for coordinated motion to efficiently weld a range of parts and detect any discrepancies using accessory systems like IR

vision [12]. The synchronized movement of the two robot arms and the degrees of freedom specifications (DOF) allow for faster welding process. In addition, allowing for a continuous welding process to occur without having to reposition the part, provides a noticeable reduction in production time and costs. Some of the specifications of this robot are provided in Figure 1.

- DOF: 6
- Reach: 717 mm
- Weight: 25 kg
- Payload at Wrist: 7 kg
- Controller: R-30iB
- Power: 200-230 V
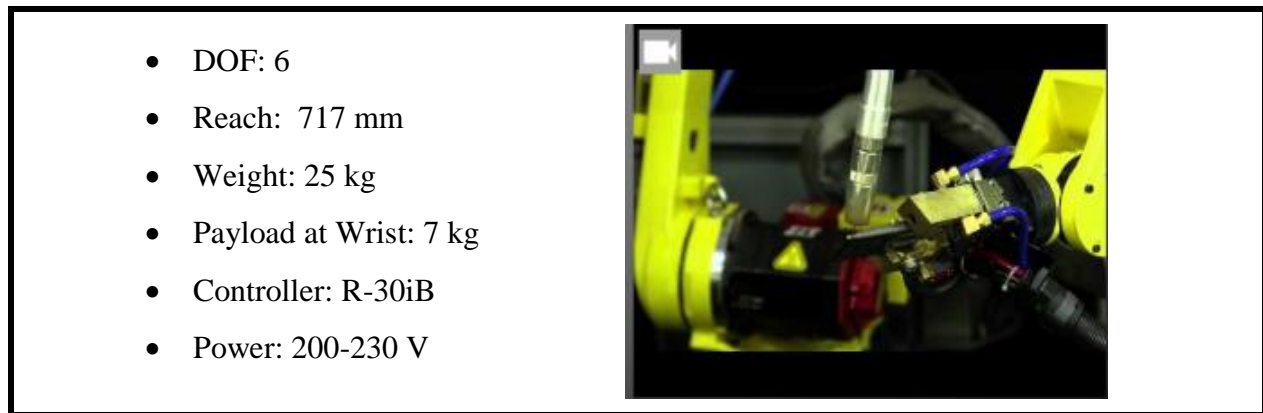
Figure 1. LR-Mate 200iD and ARC Mate

The performance capabilities of this robot are advertised by the manufacturer to increase in "optimization of energy and a reduction of cycle time by 15%" [12]. In March of 2016, Hypetherm Inc. incorporated this robotic cell into their industrial cutting equipment. Their results exceeded the manufacturer's expectations by providing an overall production output "increase of 200 percent, a 50 percent increase in operator output and reduced scrap by 50 percent" [18].

2.1.2 Material Handling in Automated Assembly Operations

The movement of components in the manufacturing industry plays a major role in supporting repetitive work roles. A robot model known as the Fanuc R20000iC (Figure 2) is widely used in industry, specifically in automated assembly operations due to its high payload capabilities [12]. Some of the additional capabilities of this robot model include transporting devices (material handling of work pieces between machines), additive- (e.g. assembly, welding, gluing, painting) and subtractive- manufacturing processes (e.g. milling, cutting, grinding, deburring, polishing) [8]. Some additional technical specifications of this robot are included in Figure 2.

- DOF: 6
- Reach: 2655 mm
- Weight:1370 kg
- Payload: 210 kg
- Input Power: 380-575 V
- Controller: R-30iB
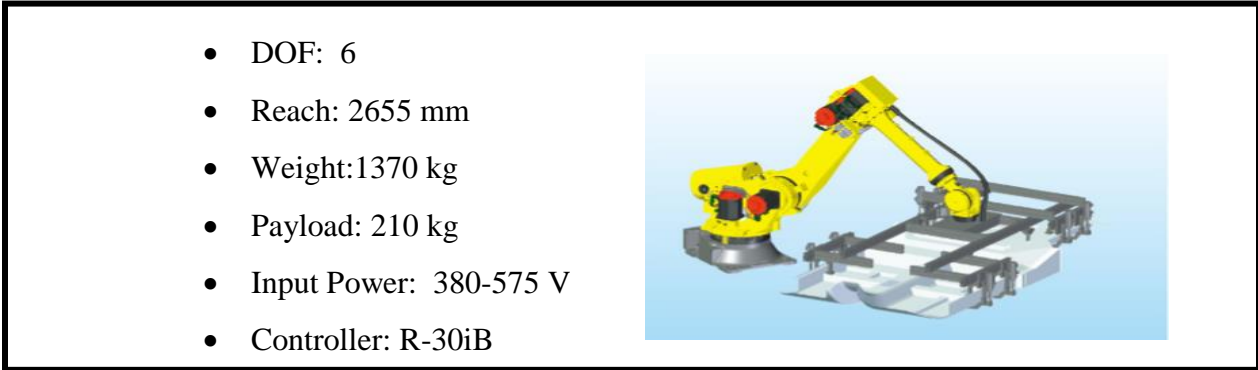
Figure 2. Fanuc R20000iC Component Robot

2.1.3 Faulty and Defective Products Inspection

Shipping faulty or defective products can have devastating effects in the success of any manufacturing business. Machine vision has a long history in part inspection, ensuring consistent and predictable quality. Whether it's gauging a part, detecting presence of a feature or error proofing, MotoSight systems have all the necessary inspection and data analysis tools for part inspection. Their inspection interface software shown in Figure 3, provides a detail view to the operator for the part being analyzed and any resulting flaws detected in the process.
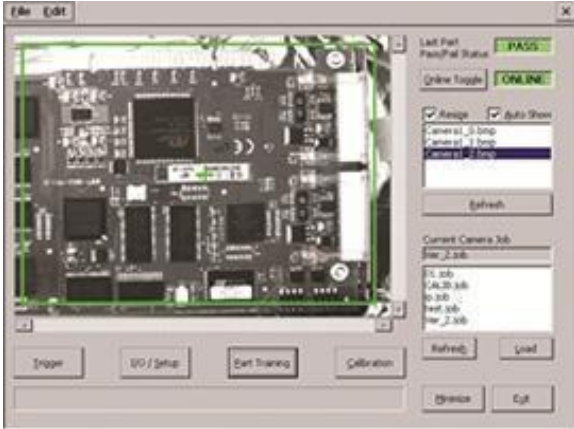
Figure 3. Visual Inspection System Depiction

A study from Institute Maupertuis compared welding quality of a Robotic Friction Stir Welding (RFSW) arm and a CNC system. Gantry-type CNC machines offer high stiffness and

they can tolerate high forces during FSW. There is an effort by companies to replace them with industrial serial robots to increase process flexibility and reduce cost investment. However, there are two limitations that should be considered. The first one is the payload capability of industrial robots which limits the welding thickness to 8 mm for aluminum materials. Second is low stiffness of robotic joint, therefore deformations that occur in FSW tools under high process forces which impact the welding quality. To compensate for the deformations, a real-time embedded controller calculates the deviations in tools and improves welding quality.

In the CNC machine experiment, good welding quality was not obtained due to high forces on the CNC system creating deviations in the welding path as shown in Figure 4 and Figure 5. In RSWF this problem is overcome by having an algorithm to compensate for the deviations in real time. The program takes a while to correct itself to the right path while still welding, however, researchers concluded that overall quality was improved in RFSW application.

a) Reference path   b) Tool Deviation   c) Tool Compensation
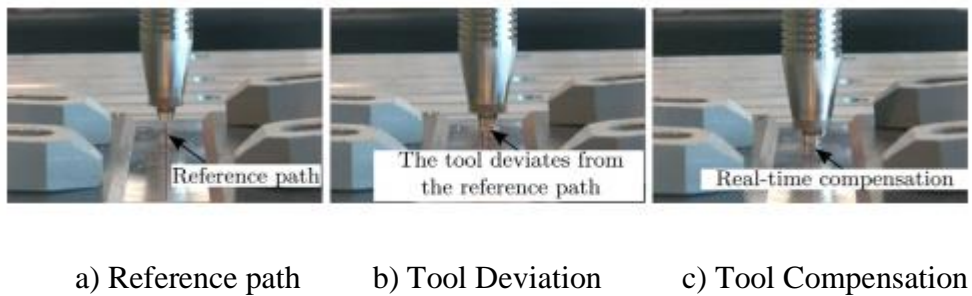
Figure 4. Real-time Compensation of the Lateral Tool Deviation

Figure 5. FANUC Weldment: Corrected Path (Blue); Real Path (Red)

2.2 Application of Robots in the Medical Industry

The medical industry has also had an increase of robotic systems implementation. Although reduction of costs is typically the driving force for such expensive implementations, improved patient recovery and reduced complications has also become of immense importance. In addition,

the increase of liability insurance and medical costs has driven hospitals to streamline their processes across all areas of medicine. The following robot assembly analyzed have been found to have a direct impact in the quality of patient care. In addition, they have provided more ergonomic postures for surgeons and increased motion precision.

Other non-surgical robotic systems have allowed for an increased sterilization of medical floors with consistent and measurable results. Systems as these can reduce human errors associated with performing strenuous repetitive tasks.

2.2.1 Non-Intrusive Surgical Procedures

The application of robotic systems in surgery has increased in the recent years. Specifically, surgery procedures such as cystectomies have greatly benefited from the advanced capabilities of these robots. A robot having beneficial and consistent results on surgical operations is known as the Da Vinci, manufactured in 2000 by Intuitive Surgical. An image of the robot is provided in Figure 6 below.
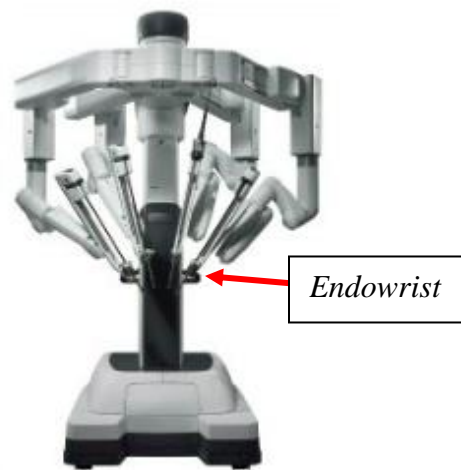
Endowrist

Figure 6. Da Vinci Robot by Intuitive Surgical

The entire system is composed of a surgeon console, a patient side car and endowrist instruments. One of the many outstanding capabilities of this robot is its 7 degrees of motion at its endowrist end effector [9]. Since its introduction into the medical field, it has had remarkable success as reported by a study conducted by the Department of Surgery in Tottori University. During this study, the objective was to investigate the usefulness of these robot assisted surgeries

by comparing its surgical technique, perioperative and oncological outcomes and learning curve with surgeries performed without assistance of a robot. The overall findings regarding perioperative outcomes provided significant statistical differences in surgery time in favor of non-assisted surgeries, blood loss in favor of assisted surgeries, transfusion in favor of assisted surgeries, in-hospital-stay in favor of assisted surgeries and with similar intraoperative complications rate. Regarding survival and recurrence, a few reports showed the five-year survival rates were similar. Furthermore, regarding the learning curve analysis, a steep learning curve was found to be necessary when utilizing a robot assisted surgery equipment. The study further showed that, surgeons who had performed fewer than 50 robot assisted surgeries, their operation time was longer [3].

2.2.2 High Precision Implantation Cochlear Implantation

Researchers in University of Bern developed a surgical robot in 2013 to be used in Cochlear Implantation [13]. This surgery is a risky process that requires high precision drilling through skull bone without damaging facial nerves and it is very hard for surgeons to perform on their own. Surgeons must drill in a 1.8 - 2.5 mm space between two facial nerves and if they damage the nerves, can cause facial paralysis in the patient. Around 30% to 55% of patients have significant hearing loss in the implanted ear after surgery. This can be ascribed to variations in surgeon-operator experience, practice, and method [13]. The robot is expected to overcome those human operator limitations with reproducible and minimally invasive cochlear access. A model of implantation after surgery and the process of drilling through bone is shown in figures below.
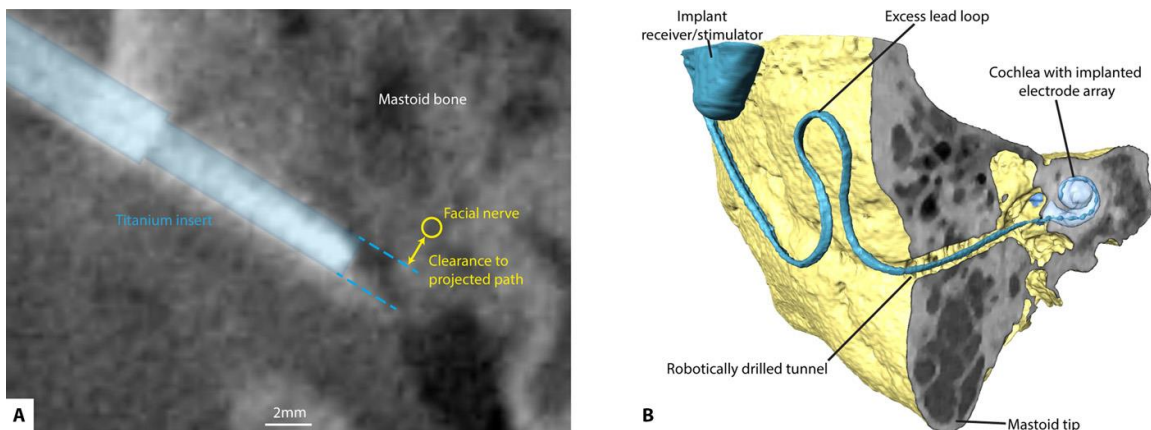
a) Intraoperative Cone Beam Computed Tomography Imaging b) Inserted Electrode Array
Figure 7. Cochlear Implantation

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(**a**) Intraoperative Cone Beam Computed Tomography imaging allows delineation of the trajectory and the facial nerve. A neuro-radiologist manually confirms sufficient distance between the trajectory and the facial nerve. (**b**) Inserted electrode array, excess lead placement, and final implant position as measured in postoperative CT imaging [13].

(i)   (ii)   (iii)   (iv)
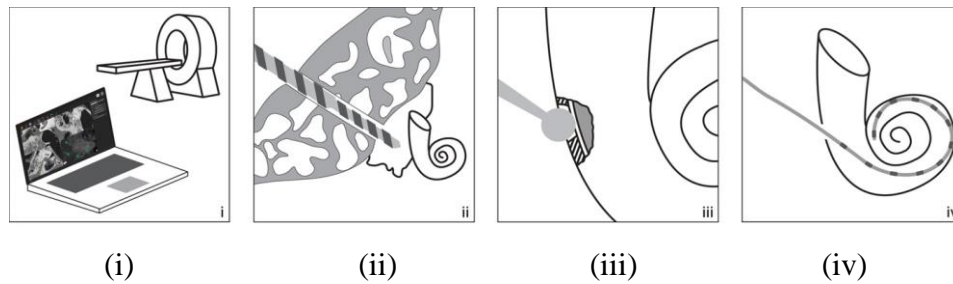
a) Elements of Robotic Cochlear Implantation

(i)   (ii)   (iii)   (iv)
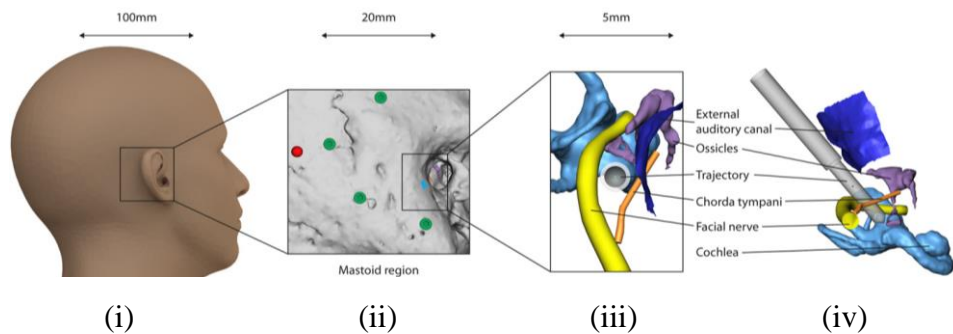
b) Scale of Robotic Cochlear Implantation

Figure 8. Cochlear Implantation Procedure

The Cochlear Implantation procedure shown in Figure 8 has two distinctive specifications which include the following: First specifications includes the Elements of Robotic Cochlear Implantation (RCI) (a): (i) computer-based patient-specific intervention planning, (ii) Robotic Middle Ear Access (RMA), (iii) Robotic Inner Ear Access (RIA), and (iv) Robotic Electrode Array Insertion. Second specification includes the Scale of RCI (b): A 1.8-mm trajectory to be planned and drilled starting from behind the ear: (i) through the mastoid bone, (ii) bypassing critical structures at <1-mm proximity and toward the inner ear. Trajectory viewed along its axis (iii) and from the side (iv) [13].

Figure 9. Surgical Robot for Cochlear Implantation

With the approval of Ethics Committee of the Canton of Bern, this robot was tested on a 51 year old female patient with bilateral deafness in 2016. The goal was to achieve high precision sensing beyond human capabilities, thus avoid two vitally important components which are facial nerve and chorda tympani. After the surgery was performed, postoperative CT scanning of patient's skull was taken and scanning's confirmed safe distances of robotically drilled tunnel to facial nerve and chorda tympani to be about 1.0 and 0.3 mm respectively. Neuromonitoring showed unchanged facial nerve function in the patient which confirmed that the integrity of the nerve was achieved during surgery. Eleven out of 12 electrodes implanted were activated by sound stimulation. Patient was tested with Freiburg monosyllabic test under 65 dB sound pressure and quiet testing. Results showed that she had 50% word recognition [13].

Because of the experimental surgery, doctors found that a robotic solution to the surgery is more effective than template guided, manually drilled approaches in terms of geometric accuracy and active safety mechanisms. The data confirms that a clinical application based on a robotic treatment model will be able to resolve challenges of precision, accuracy and safety. In this robotic application we can see that the robotic approach to a medical problem provided reproducible results with higher precision and safety than results of human surgeons. Therefore, it is an example where robots impact quality of the service provided with improved patient safety.

2.2.3 Hospital Sanitation Assistance

Another important application of robotic systems can be found in the sanitation of hospital spaces. A robot manufacturer called Xenex has taken the lead in providing a hospital robot that utilizes pulsed xenon ultraviolet light as a means of destroying "bacteria, viruses, mold and other pathogens" [16]. The ultraviolet light penetrates the cell walls of microorganisms and fuses their DNA. This prevents viruses from being able to mutate sequentially and kills them entirely. As

reported in 2016, Doctors Hospital at Renaissance, located in Edinburg, Texas, incorporated 7 Xenex robots. The current goal of the hospital is to "reduce the hospital acquired infections to zero" [16]. In retrospect, such sanitation robots provide additional benefits associated with reducing cleaning staff exposure to hazardous environments and labor scheduling issues.

2.3 Application of Robots in Construction Industry

To mitigate some of the hazards and inefficiencies within the construction industry, robots have been integrated into areas of safety and structure assembly. The decrease in the labor force and increased construction work liabilities has provided an opportunity for consistent use of robotic systems. In addition, such system can reduce the number of workers per job creating greater efficiency and reduction in project completion times. Since some of these robotic systems are manipulated through electrical control systems, they can be utilized in adverse weather while keeping the operator indoors. Another benefit can be found in the compactness and mobility of these robotic systems. This benefit allows them to be easily integrated in a construction floor and transported to a different site at a moment's notice. Although the market is not flooded with a variety of robotic systems, the robots described in this chapter inform of some of the capabilities that are currently commercially available and in circulation.

2.3.1 Worker Safety Mitigation

Another type of safety robot that has been implemented in the construction industry is known as the Robotic Safety Barrel. The focus of this implementation is to mitigate the safety risk associated with the installation of safety cones and traffic signs in busy highway roads. Mechanically, the robot as seen in Figure 10 is composed of dual 20 cm diameter wheels that are independently driven. This design allows for the ease of rotation of the robot. In addition, the robot measures 30 cm in height. The robot is powered by a 12 V battery and can operate continuously for about 20 hrs. [19]. The implementation of such robots could have a significant impact on reducing the companies costs of employee insurance and labor compensation. In addition, it could allow for staff to be utilized more efficiently in other tasks of more importance.
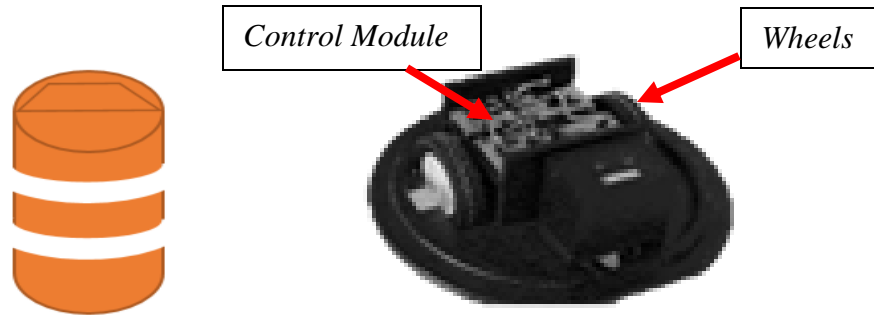
a) Traffic Cone Top Assembly   b) Traffic Cone Robotic Base

Figure 10. Robotic Safety Barrel

2.3.2 Structure Assembly Operations

The construction assembly industry is also moving in line with technology to mitigate the shortage of workers and their exposure to harsh environments. The utilization of robot systems for construction provides unique advantages that are transforming the way structures are created. Here are a few of these systems that are being implemented today and in the future.

A New York based company called Construction Robotics has developed what is known as the SAM100, the Semi Automated Mason, that is utilized to lay construction bricks. It has been widely used successfully implemented in the construction of a Middle Schools in Tennessee, New York, Maryland and Washington DC for example. It is advertised as providing an increase of productivity by a factor of 3-5 times and reducing lifting by 80 percent [14]. In addition, the robotic arm can lay in impressive 2,000 to 3,000 bricks per day [15]. Figure 11 provides a side image of the robotic arm (red) and the conveyor belt system (gray).

Figure 11. SAM100 Construction Brick Robot

A different robot application within the construction industry can be found in a robot manufactured in UK based GGR group. Oscar 100, as it is known, provides glass panels and windows installation assistance. Its dual circuit hydraulics allows for all 14 suction cups, located at its end effector, to be easily controlled through a radio remote [16]. Technical specifications and visual representation of the robot is shown below.

- DOF: 2
- Payload: 1000 kg
- Horizontal Reach: 1398 mm
- Vertical Reach: 3229 mm
- Power: 110 V
- Controller: Radio Remote

Figure 12. Oscar 100 Glazing Robot

2.3.3 Wearable Exoskeleton for Reducing Strain

A more relatable area of robot application can be found in the wearable robotics systems. These systems, sometimes known as exoskeletons, can improve the efficiency and increase personal safety of construction workers. The wearable exoskeleton provides stability and support to back muscles that are repeatedly under strain. It is estimated that such strain can be reduced by 15 kg. [17].   Although costs for such systems are currently too high to be widely implemented, the long-term benefits could outweigh the short-term costs of liability insurance, workers compensation and turnover rates.

2.4 Application of Robots in Food Packaging Industry

As the demand for package foods increases, the food packing industry has shifted towards more efficient and reliable systems. In turn, robots have been incorporated into the industry in tasks as picking, packing and palletizing. These tasks widely use in the food packing industry can have a wide range of floor formats. In addition, the number of workers needed to perform these

tasks can be considered to be of great numbers. In turn, food packaging robots have been designed to be adaptable to almost any factory configuration. This includes the ability for some of these robots to be mounted on the ceiling if necessary. Another ability implemented in the design of such robots is the ability to synchronize their motions with the motions of other sections of the factory. This allows for easy of integration and flexibility in adjusting for company and customer demands. The robots described in this chapter provide an overview of the typical robots utilized in the food packaging industry.

2.4.1 Picking Products in Conveyor Belt

Robots can be utilized to pick products as they travel through the conveyor belt of a food packaging process. Robots as the IRB340 (FlexPicker) has been claimed to be "the fastest robot in the world" [1]. It is composed of carbon fiber arms with a high strength to weight ratio. The internal gear system is in the base of structure which allows for a compact design measuring only 950 mm high and 1,050 mm across. Figure 13 provides additional technical specifications.

- DOF: 4
- Payload: 1 kg
- Reach: 1050mm
- Weight: 140 kg
- Tracking Speed: 150 mm/s
- Input Power: 50V
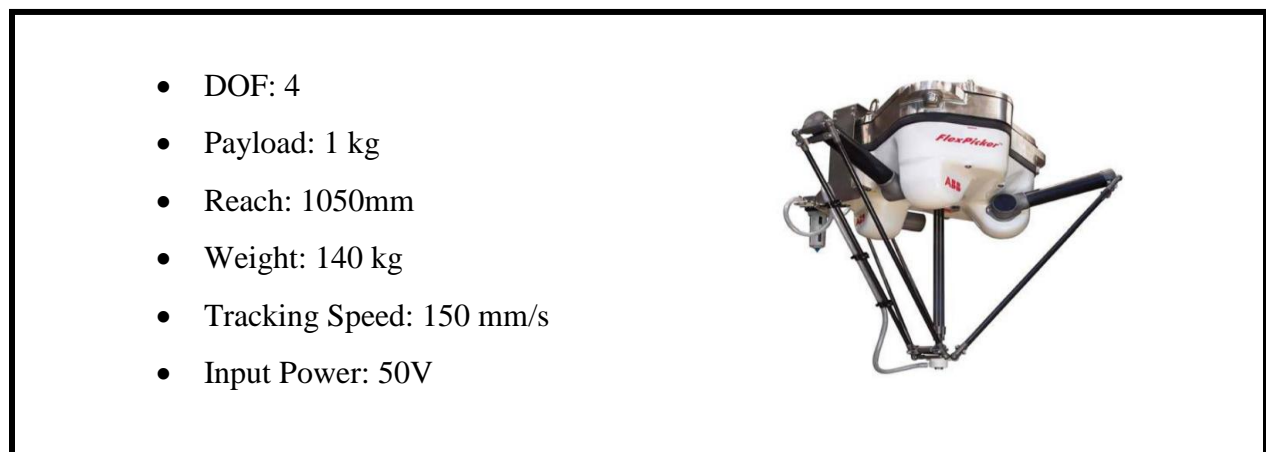
Figure 13. IRB340 FlexPicker Picking Robot

2.4.2 Packing Products in Large Quantities

Another application of a food packaging robot includes the ability to assemble packaging of final products. Robots as the IRB 260 manufactured by ABB Robotics, has the accuracy, strength and versatility to be integrated into many compact packing systems. Its application success has allowed for 12,000 installations since its introduction into the industry. The speed has

been optimized for an "800 by 800 by 800 mm working envelope" [2]. Additional specifications are provided in Figure 14.

- DOF: 4
- Payload: 30 kg
- Reach: 1.56 m
- Input Power: 50-250 V
- Weight: 340 kg
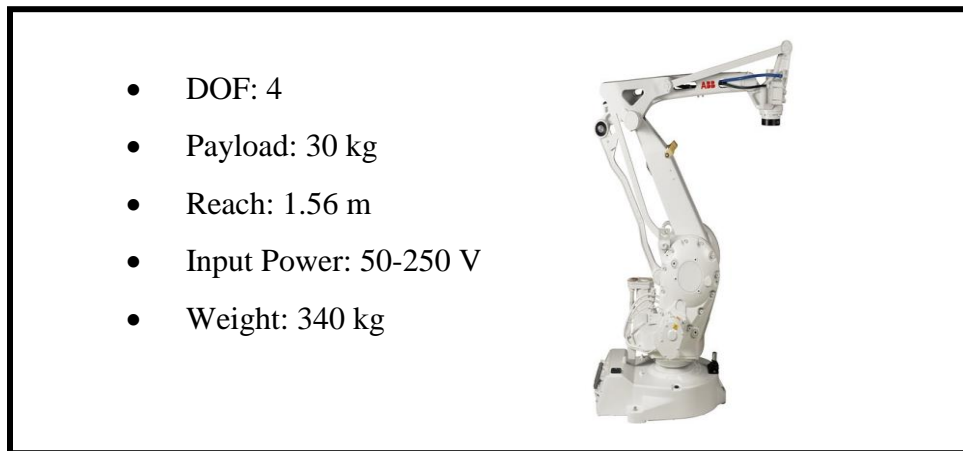
Figure 14. IRB260 Packing Robot

2.4.3 Palletizing and Relocation

A final process in the packaging industry is known as palletizing. Palletizing is the process of stacking and relocating large ready to ship items. A palletizing robot utilized in the industry is known as IRB 660. Generally designed for floor mounting, the robot is available in two versions of handling capacities [10]. Additional specifications are provided in Figure 15.

- DOF: 4
- Payload: 180-250 kg
- Reach: 3.15 m
- Input Power: 200-220 V
- Power Consumption (Max Speed): 3.08 kW

Figure 15. IRB660 Palletizing Robot

CHAPTER 3: FINANCIAL ANALYSIS OF ROBOTS IN THE INDUSTRY

3. Introduction

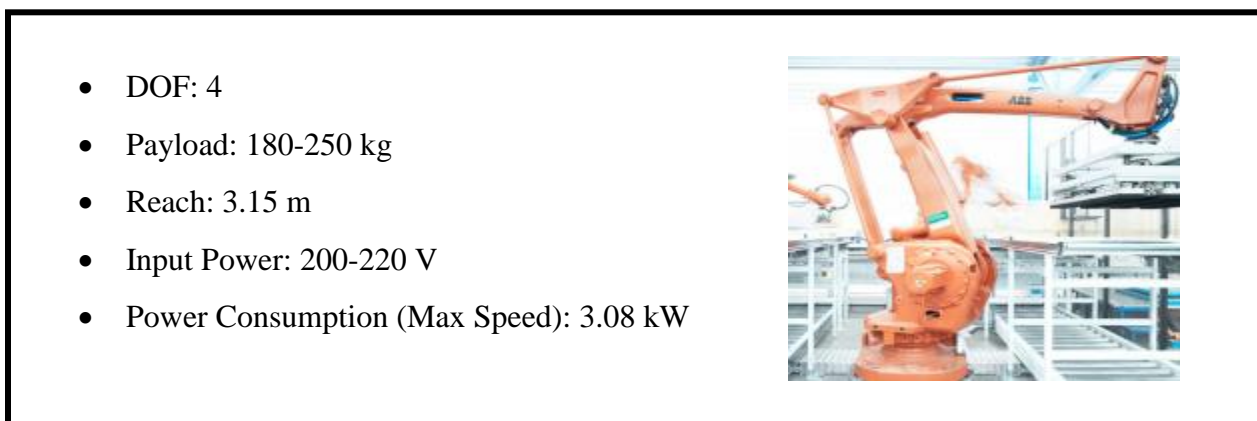   The implementation of robotic systems is an expensive investment. Costs for a single robot can range from 500 to 30,000 dollars. Due to this high price range, it is necessary for companies to analyze and quantify through research the long-term benefits of such investment. Not doing so, could easily pivot a company from succeeding in the market to becoming bankrupt. This chapter seeks to provide research documentation that supports the purchase of robotic systems through the analyzes of labor cost, robot cost and future reduction of overall costs due to increase in demand. This chapter also considers underlying costs associated with human labor that may be overlooked but can be found to be eye opening when comparing long term costs for companies.

3.1 Cost Comparison of Robots vs Humans

      A research document titled "Industrial Robot Application Trend in World's Metal Industry" presented by the University of Bihac, provided very useful information worth comparing [4]. Its research goal was focused on providing an analysis of existing data concerning installed robots worldwide and promotes the implementation of such systems. Specifically, a comparison is made between the costs of a human worker and a robot system. In summary, the cost per an 8 Hr. shift is as follows:

- Robot: $2.40
- U.S. Worker: $120
- Chinese Worker: $24

It is evident that the cost gap is large. This cost gap is associated with human worker costs which to name a few include:

- Lunch breaks
- Vacations
- Injuries
- Turnover
- Protective Gear/Supplies
- Insurance
- Pensions

- Parking space
- Unpredictable production

Although the initial cost of robots is very high and preventive maintenance to ensure consistent operation is required, they have estimated through a robot project payback analysis that the costs of robots in comparison to human labor is considerably lower. A depiction of this information is provided in Table 3 below [4].

Table 1. Cost Comparison Between Humans and Robots

Year of Use	Robot System Cost	Manual Labor Cost	Yearly Cash Flow	Cumulative
1	$200,000	$100,000	-$100,000	-$100,000
2	$500	$102,000	$101,500	$1,500
3	$500	$104,040	$103,540	$105,040
4	$500	$106,121	$105,621	$210,661
5	$5,000	$108,243	$103,243	$313,904
6	$500	$110,408	$109,908	$423,812
7	$500	$112,616	$112,116	$535,928
8	$500	$114,869	$114,369	$650,297
9	$500	$117,166	$116,666	$766,969
10	$30,000	$119,509	$989,509	$856,472

Table 2. Robotic System Cash Flow Analysis

Year	System Cost	Maintenance Costs	Operating Costs	Labor Savings	Productivity Savings
1	$250,000	$1,000	$6,000	$162,000	$43,740
2		$1,000	$6,120	$165,240	$44,615
3		$1,000	$6,242	$168,545	$45,507
4		$1,000	$6,367	$171,916	$46,417
5		$10,000	$6,495	$175,354	$47,346
6		$1,000	$6,624	$178,861	$48,292
7		$1,000	$6,757	$182,438	$49,258
8		$1,000	$6,892	$186,087	$50,244
9		$1,000	$7,030	$189,809	$51,248
10		$60,000	$7,171	$193,605	$52,273
11		$1,000	$7,314	197,477	$53,319
12		$1,000	$7,460	$201,427	$54,385
13		$1,000	$7,609	$205,455	$55,473
14		$1,000	$7,762	$209,564	$56,582
15		$1,000	$7,917	$213,756	$57,714
TOTAL		$83,000	$103,761	$2,801,534	$756,414

The table above makes a direct comparison between total costs of robots and total costs of labor work assigned for the same job. These values are based on a mid- sized robot. We can see that the robot will cost relatively a lot of money in the beginning. However just like in most robotic systems, return of investment (ROI) of robot in this example is aiming to generate positive cash flow over long term. Therefore, its benefits are getting more visible as years pass. Despite the high purchase price, robots are a lot cheaper to maintain compared to laborers by about 95% every year. From this table we can see that, ROI can be achieved after 2-3 years and it turns into profit over rest of the years.

3.2 Impact on Labor Costs of Manufacturing

Industrial robots are expected to have a very big impact on labor costs of manufacturing companies. Boston Consulting Group estimates that the average global labor-cost savings are going to be 16% by 2025 across the globe. USA is estimated to have 22% labor cost reduction and South Korea will have 33% cost reduction as the country that saves the most percentage of costs. Saving values for each country can be seen in the graph below.
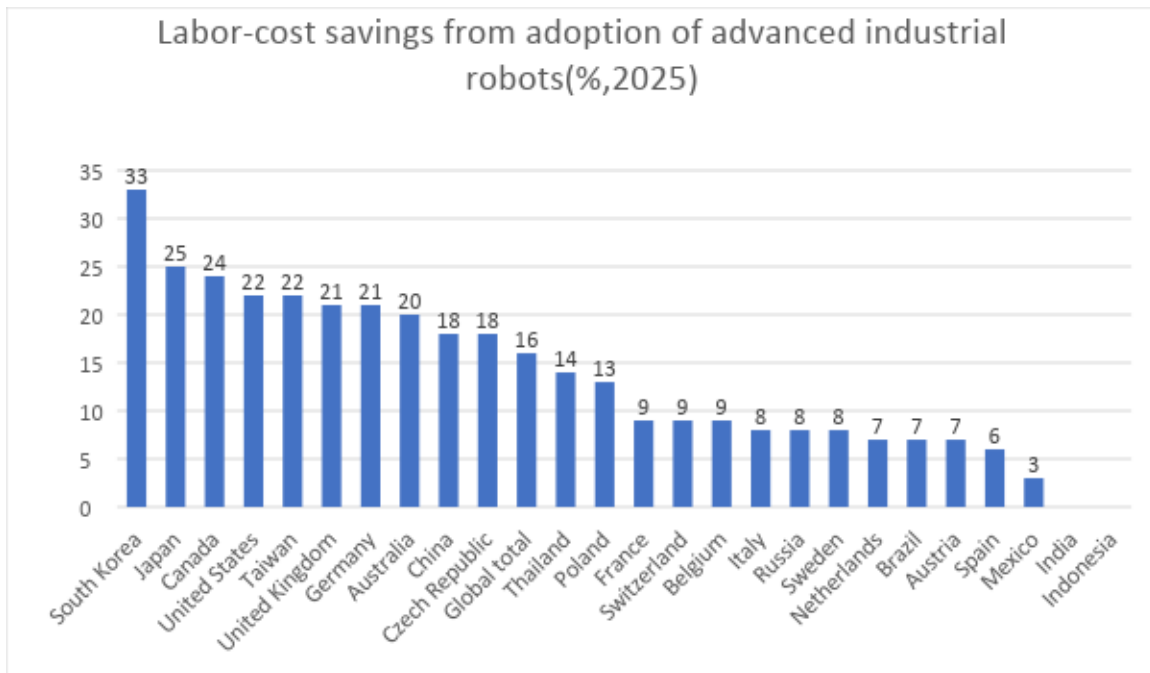

Figure 16. Labor Cost Saving Graph

There are some companies, like Rethink Robot, that offer agile factory robot for as little as $25,000. According to a study made at Stanford University, this cost is equivalent to paying a worker $4 per hour. PayScale estimates that average labor salary in manufacturing industry is between $9 - $18. Therefore, such robots save at least half of a salary given to one person. The table below shows the cash flow of an average robotic system to the company.
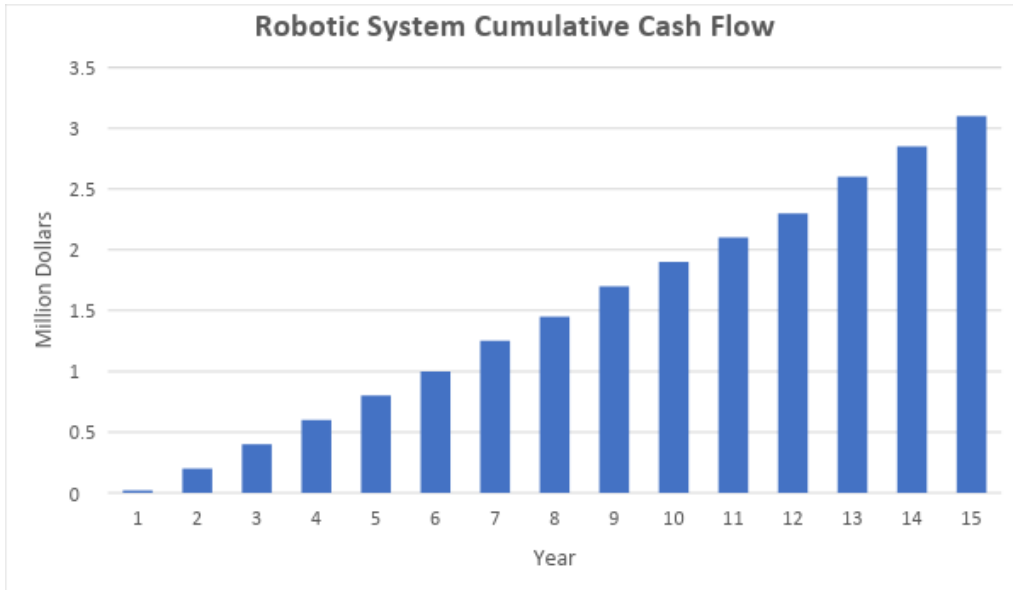
Figure 17. Robotic Systems Cumulative Cashflow Over Years

3.3 The Decline of Robot Costs

Even though robots cost less to company compared to human workers in long term, most companies are still reluctant to adopt industrial robots because it is expensive in short term. However, Boston Consulting Group found that spot welding used in industries like car manufacturing are reduced from $182,000 in 2005 to $133,000 in 2015. They estimate that decline in costs will continue by 20 percent over the next decade.

Industrial robot market is also growing rapidly as more companies adopt their products. An Investment company called ARK has made a research about unit costs of robotic systems over the years and also compared their estimates to BCG's (Boston Consulting Group) estimates.
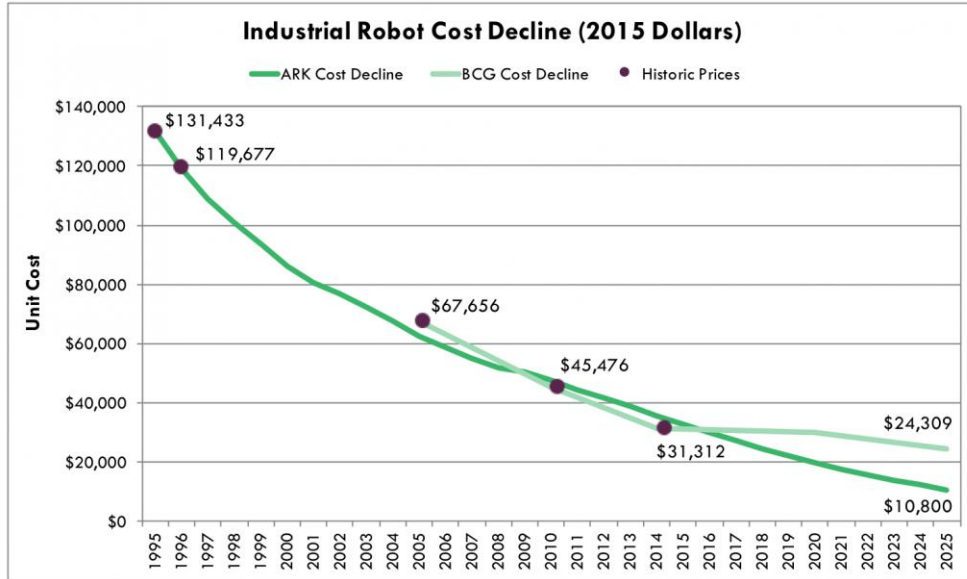
Figure 18. Industrial Robot Cost Decline

3.4 Robot Systems Demand Increase

As we can see from the graph, there is a steep decline of unit costs for industrial robots. This lures smaller manufacturing companies into buying Industrial robots more, because it is getting more affordable to smaller companies.
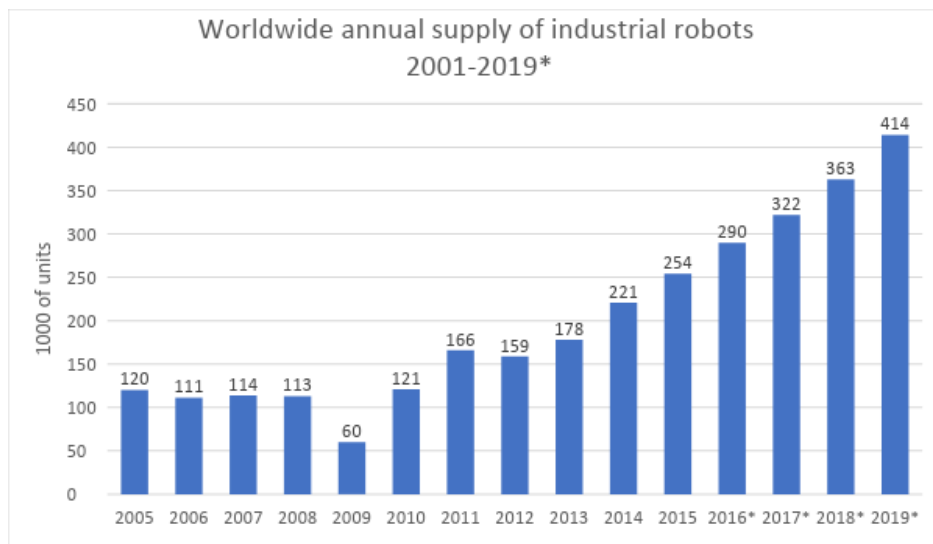

Figure 19. Worldwide Annual Supply of Industrial Robots

This table shows the increase in demand for industrial robots. This increase in supply and decrease of unit costs from previous table mutually affect their trends, since as cost decreases more companies including smaller ones are beginning to buy more industrial robots. As industrial robots are becoming more and more common, their costs are decreasing.

Ron Potter is Director of Robotics Technology for Factory Automation Systems[1] in Atlanta, Georgia. He provides an example of a robotic system and makes a cost analysis of the robot and compares it to labor costs. He uses a medium-sized robot, about 100-kg payload, as an example of a typical industrial robot. He takes power consumption into account which is 7.35kW and the average energy cost of 10 cents per kWh. He then calculates that average cost of running mid-sized robot costs 75 cents.

CHAPTER 4. DESIGNING AND BUILDING A WELDING ROBOT

4. Introduction

To begin designing a robot system, the team began to familiarize itself with available resources provided by the institution. This familiarization was a key component in providing exposure to robotic systems and understanding the complexities of their designs. To begin, this chapter provides a breakdown of some of the fundamental specifications and operations of robotic systems. Secondly, information is provided regarding TIG welding as it applies to the design of the robotic welding arm prototype. Thirdly, an analysis of the associated forces during the motion of the robotic arm is provided. Free body diagrams for each section are provided to better understand the complexity of the motions. Lastly, a detail overview of the robot design, assembly and operation is provided.

4.1 WPI Washburn Robot Systems

WPI Washburn Laboratories is composed of several types of robot and welding systems. For familiarization purposes, the team was introduced to the FANUC LR Mate Model and the Tungsten Inert Gas welding system.

4.1.1 FANUC LR Mate Model Familiarization

This robotic system model # LR MATE 200iB 5P, is composed of several key components shown in Figure 20, 21 and 22.
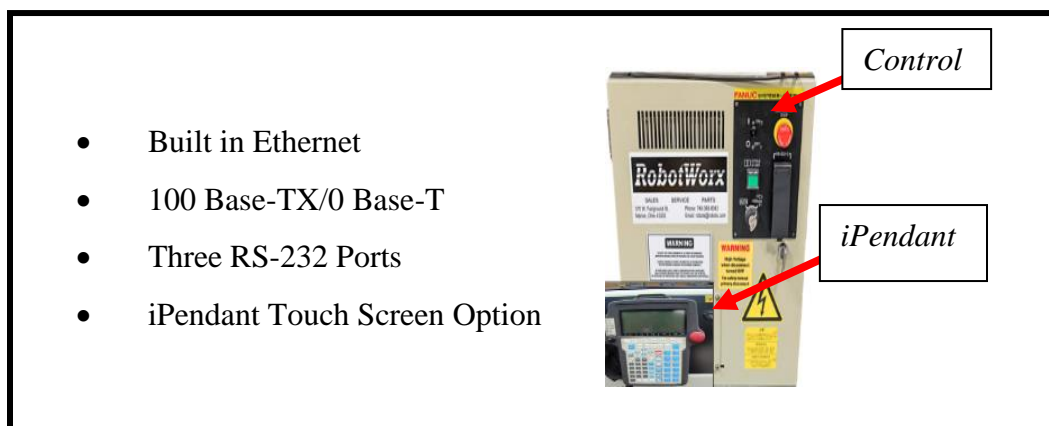

- Built in Ethernet
- 100 Base-TX/0 Base-T
- Three RS-232 Ports
- iPendant Touch Screen Option

Control

iPendant

Figure 20. FANUC System Controller R-J3iB

- DOF: 6
- Payload: 5 kg
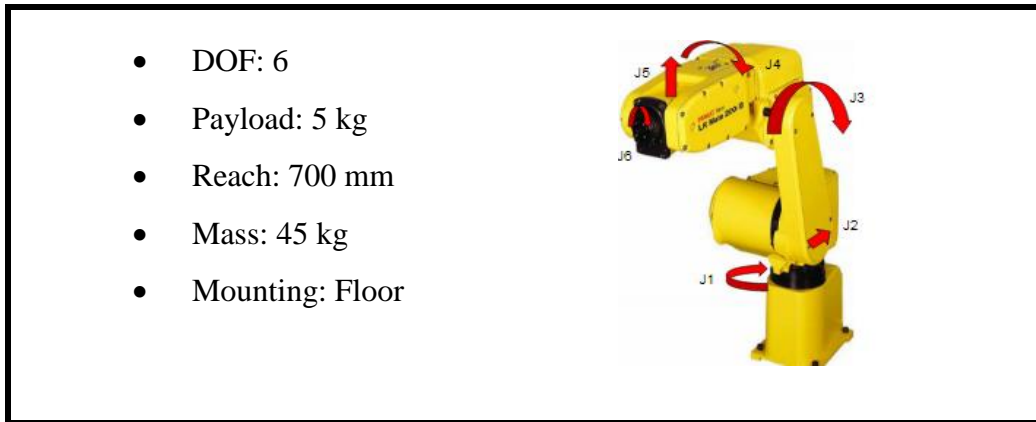- Reach: 700 mm
- Mass: 45 kg
- Mounting: Floor

Figure 21. FANUC LR MATE Robot

The Controller in Figure 20 is a system of circuits that allow for precise control of the six different motors located in each of the axis depicted by red arrows in Figure 21. Although complete familiarity of the system has yet to be achieved, operation using the Teach Pendant as seen in Figure 22, is straight forward system. The teach pendant allows for the control of each axis on command by the user. For safety purposes, the teach pendant includes two dead man switches depicted in Figure 22, that must be pressed appropriately to allow the robot to move. To distinguish between a weak and strong pressure (associated with fainting or death), the dead man switch has three positions in which the second position is considered normal. If a weak or strong hold is detected, the robot will stop all operation in the system until it is reset.
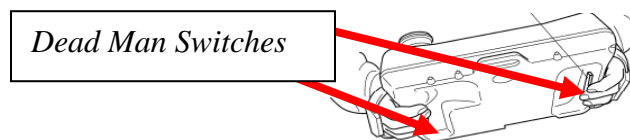

Dead Man Switches

Figure 22. Teach Pendant for FANUC Robot System

4.1.2 FANUC LR Model 200iB Specifications

There are other details about this robot that are worth noting considering that they are important when implementing in the manufacturing industry. As shown in CONTROLLER SPECIFICATIONS (APPENDIX A), the power supply necessary to operate this robot is 200-220 Volts for single phase or 380-500 VAC in three-phase. This is particularly important considering that a three-phase system has been found to be a more economical in the manufacturing industry, due to its reduction of current use. Specifically, a three-phase system provides higher power

density with approximately 43% less current (3 Phase). In addition, this controller allows for up to 40 I/O Subsystems that can be used to incorporate pneumatic actuation of different end pieces. This can provide increased adaptability. In addition, all these subsystems are routed inside the case of the robot which ensure that they are protected and that they do not conflict with the movement of the robot.

The typical application that this robot can provide includes the following

- Assembly
- Clean Room
- Dispensing
- Machine Loading
- Material Handling
- Material Removal
- Part Transfer
- Spindling
- Vision.

Some of the benefits that are advertised by the manufacturer include:

- Commercial/Industrial applications
- Upright, invert or angle mounting positions
- Placement in tight surroundings
- No calibration at power up
- Brushless AC servos

Regarding robot maintenance, we were able to find significant amount of literature that supports a direct and consistent process. Appendix A provides a portion of how such maintenance intervals are distributed and organized for this robot. The literature is user friendly which allows for quick referencing of the maintenance crew.

4.1.3 Research Welding Experience

To better understand the welding procedure for design purposes, a welding training exercise was performed at WPI Washburn Lab with Senior Instructional Laboratory technician Ian Anderson. The objective of the training exercise was to expose the team to the fundamental manual

operation of Tungsten Inert Gas welding system and its general components. In addition, the team focused on gathering information pertaining to posture, mobility and surrounding environment necessary to perform the task. The details of these topics and their application to automation are as follows:

Understanding the posture of a welding technician allows us to determine how to integrate the assisted welding robot into the welding position without interfering with the movement of the filler rod. Although parts being welded vary in size and position, the selected part was placed on a table the welding technician utilized a stable metal chair to position himself. The position of the welding technician is depicted in Figure 23.

a) Front Welding Position View   b) Side Welding Position View

Figure 23. TIG Welding Technician Position

As noted in the image, the welder utilized the welding table for support as his body leaned forward to get a good view of the TIG torch contact point. Analyzing the hand motion of the welding technician allowed for a clear understanding of the limitations that we may encountered with the robot degrees of freedom. As shown in Figure 23, the TIG torch and the filler rod have their respective positions to support arms during long welding sections. This provided a clear view of not only the position of the robot figure but also the end factor position and mechanism to ensure visibility of the welding technician.

Analysis of the surrounding environment provided insight on the position of the robot relative to supporting and surrounding equipment. Better mounting and securing options for the robot base were analyzed to ensure no movement during operation. The venting system was also

considered to ensure adaptability of the robot system to different venting configurations. Lastly, the position of the TIG assembly grounding cable, TIG torch cable, and welding pedal were considered to ensure no interference or movement during the welding process.
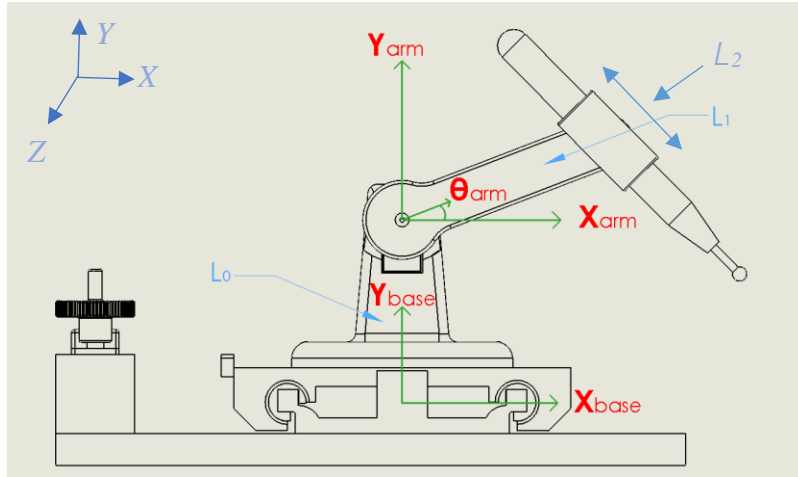
4.2 Researching Forces of Robotic Systems

Figure 24. Complete Robot Arm Representation

This figure is a rough representation of arms of our robot. In this picture "L_0" represents length of our base which has no degrees of freedom. "L_1" represents the length of first arm and "L_2" represents the length of end effector arm. "θ_1" stands for the angle of first arm's orientation with respect to "x" axis. "θ_2" stands for the angle made by end effector arm with "x" axis. Kinematics equations that represent position and velocity of the end effector of this model are shown below.

$$X = L_1 \cos \theta_{arm}$$

$$Y = L_0 + L_1 \sin \theta_{arm}$$

$$Z = \dot{Z} t$$

Where "X", "Y", "Z" stand for x, y, z position of end effector respectively. $\dot{Z}$ stands for the velocity of slider in z direction and t stands for time. If we take the derivative of each individual

equation with respect to time. We can find the velocity of end effector in x, y, z direction too. Velocity equations are shown below.

$$\dot{X} = -l_1 \sin \theta_{arm} \dot{\theta}_{arm}$$

$$\dot{Y} = l_1 \cos \theta_{arm} \dot{\theta}_{arm}$$

$$\dot{Z} = rpm_{motor} \cdot \frac{2\pi \; radians}{1 \; rev} * \frac{1 \; min}{60 \; sec} \cdot r_{gear}$$

Where $\dot{X}, \dot{Y}, \dot{Z}$ stand for x, y and z velocities of end effector, t stands for time in seconds, rpm_{motor} stands for rotation speed of motor in rotation per minute and r_{gear} stands for radius of the gear attached to the motor.

Since L_0 has no degrees of freedom we didn't have to use Denavit-Hartenberg (D-H) parameters to determine kinematics of this robot arm. However, it can be improved by giving it the ability to rotate around vertical axis. Then, D-H parameters and other necessary tools can be used to evaluate the kinematics of our robot arm.

To better design our welding robot, research was performed on the forces that the robot structure encounters during its full range of motion. Calculations were performed on the base slide, arm and end effector.

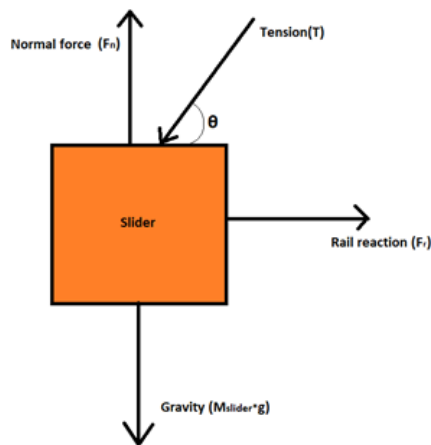4.2.1 Base Slider Calculations of Associated Forces

Figure 25. Slider Free Body Diagram

29

In Figure 25 we depicted the forces acting on the base slider where, "F_n" stands for normal force, "T" stands for tension force applied by the first arm of the robot, "F_r "stands for reaction force by the vertical ends of rail(walls of rail)."M_{slider}" stands for the mass of slider and "g" stands for gravity constant. We omitted the stand of the arm since it has no degrees of freedom and it is technically a part of slider anyway. Force equations of the slider are shown below. θ is the angle between horizontal axis and tension force.

$$F_x = -T\cos\theta + F_r = 0$$

$$F_y = N - M_{slider}\,g - T\sin\theta = 0$$
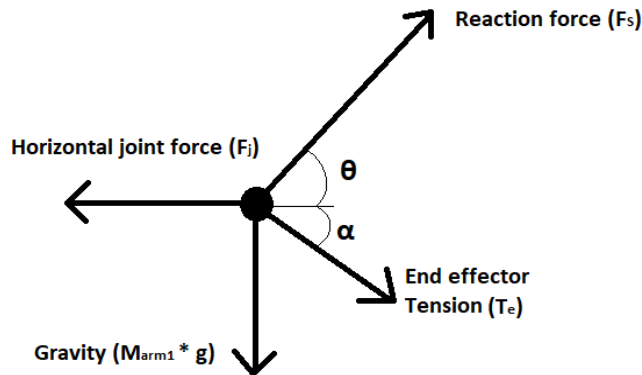
4.2.2 Robotic Arm Calculations

Figure 246. Arm 1 Free Body Diagram with Associated Forces

Figure 26 represents the free body diagram of the first arm of robot (arm 1), where motor is currently attached in our prototype. In the diagram, "F_s" stands for reaction force from slider, "T_e" stands for tension caused by end effector arm connected to end of this arm, "M_{arm1}" stands for mass of arm 1 and "F_j" stands for reaction caused by joint to the motor (as in stalling state). Force equations regarding arm 1 are shown below.

$$F_x = T_e \cos \alpha + F_s \cos \theta - F_j = 0$$

$$F_y = F_s \sin \theta - M_{arm1} \, g - T_e \sin \alpha = 0$$

Where θ stands for angle of reaction force with respect to horizontal axis and α stands for angle of end effector tension force made by horizontal axis.

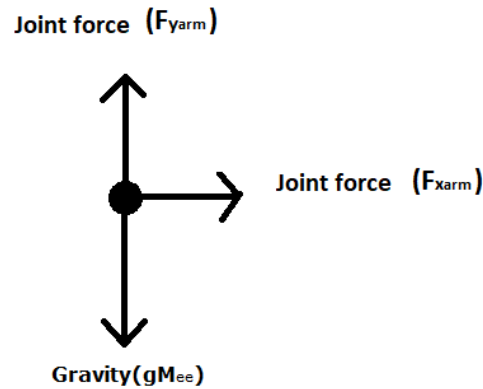4.2.2 End Effector Force Calculations

Figure 257. End Effector Free Body Diagram

This Figure 27 above represents free body diagram of end effector. In this diagram, "F_{yarm1}" stands for vertical component of reaction force from joint with arm 1, "F_{xarm1}" stands for horizontal component of joint reaction force and M_{ee} stands for mass of end effector arm.

We can see that x component of joint force must be zero because it is the only force acting on x axis. There is no motor attached to the arm yet, in this prototype. Therefore, it is only held up by the joint force on +y direction. Force equations regarding arm 2 are shown below.

$$F_x = F_{x_{arm1}} = 0$$

$$F_y = F_{y_{arm1}} - gM_{ee} = 0$$

31

Minimum force required from the motor to move the slider in z direction will depend on radius of the gear attached to the end of the motor, and it should be at least more than static friction force on the slider so that it can move. Equation regarding this limitation is shown below.

$$F_{z_{motor}} = \frac{T_{motor}}{r_{motor}} \geq F_{friction}$$

4.3 Welding Robot Prototype Design and Assembly

4.3.1 Materials Utilized on Prototype Design

The prototype consisted of many associated spare and new parts that were assembled and shaped with minimal tools. These were as follows.

1. Electrical assembly box: was composed of four plexiglass parts that were glued in order to create a rectangle shape box.
2. The step motor shafts were drilled in order to accommodate for fasteners to secure that arm and gear system of each motor. Hot glue was also used as a backup reinforcement on these components.
3. The sliding track mechanism.
4. The second step motor gear rack was glued to the sliding mechanism as a temporary measure of the prototype.

4.3.2 Assembly Instructions of Prototype Design

The assembly of the robot prototype was assembled as follows:

1. Install the sliding rail system on to the grate with fastening bolt and nuts. Be sure to utilize bolts that will allow for the top assembly to clear as it slides through the rail system.
2. Next position the L stops at each end of the rail system to prevent disengagement during operation.
3. Install the step motor onto the base of the robot with fastening screws. ensure that the cable is routed carefully at the top of the bracket system.
4. Secure base to top sliding rail mechanism.

5. Install the robot arm on the motor and secure to motor shaft with a screw fastener.

6. Install the end factor on the arm of the robot and secure with screw fastener.

7. Secure second step motor to mounting bracket with screws. Ensure wiring is routed after of the bracket to prevent interaction with moving arm.

8. Secure second step motor bracket to the base with fasteners and nuts.

9. Install arm pivoting controller and second step motor controller on the far right and aft of the step motor. Route the wires through the grate into the electrical assembly box.

10. Once all the components have been secured, begin to wire all the cables inside the electrical assembly box. Ensure that no tension is placed on the wires to prevent damage or from being disconnected.
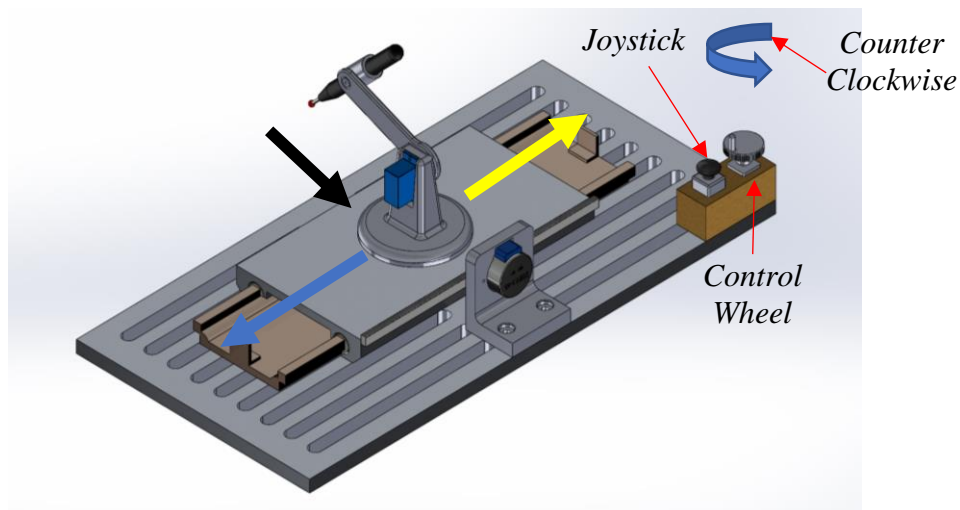

Figure 26. Isometric View of Prototype Robotic Arm

4.3.3 Operational Instructions of Prototype Design

-Control wheel:

Use the control wheel to move the base back and forward:

- Clockwise for right orientation (yellow arrow)

- Counterclockwise for left orientation (blue arrow)

- Press the control wheel down to automatically move the base back to midpoint (black arrow)

-Joystick:

- Push the joystick back/forward to control the arm from 0 to 45 degrees. (orange arrow)
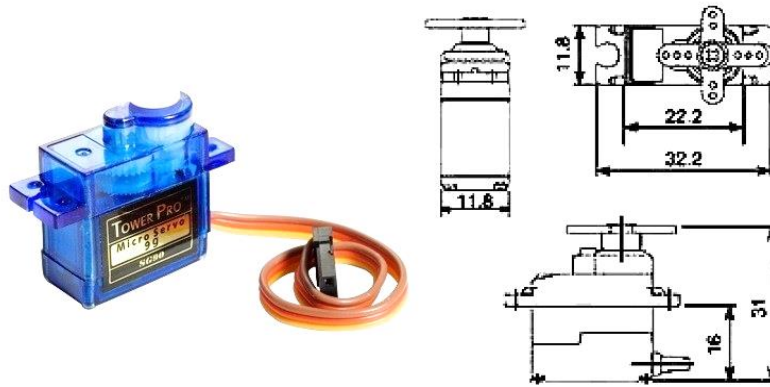
-Main Components:

Figure 27. Micro Servo Hardware Dimensions

The micro servo in Figure 29 measure 31 mm in length and has a high output power. The servo can rotate approximately 180 degrees (90 in each direction). You can use any servo code, hardware or library to control these servos. Good for beginners who want to make stuff move without building a motor controller with feedback & gear box, especially since it will fit in small places. It comes with a 3 horns (arms) and hardware.

CHAPTER 5. CONCLUSIONS AND DISCUSSION

The team enjoyed this interdisciplinary qualifying project especially during the exposure to robots located in Washburn Labs and learning how to weld using Tungsten Inner Gas. In addition, the detailed breakdown of the report structure has exposed the team to the professional format utilized in the research industry. In general, the focus of this project allowed the team to evaluate the roles of robots in various industries including manufacturing, medicine, construction and food packaging. We have collected examples of robots from those industries and evaluated the roles they serve. Our findings show that implementing robotic systems has a high initial cost but a high long-term benefit. These benefits include reduced labor costs, increase safety and increase production. Contributing factors to these benefits include the robot's dependability and effectiveness in performing the desired tasks. In addition, we found that robotic systems can be very beneficial in reducing employee exposure to hazardous environments or repetitive motions.

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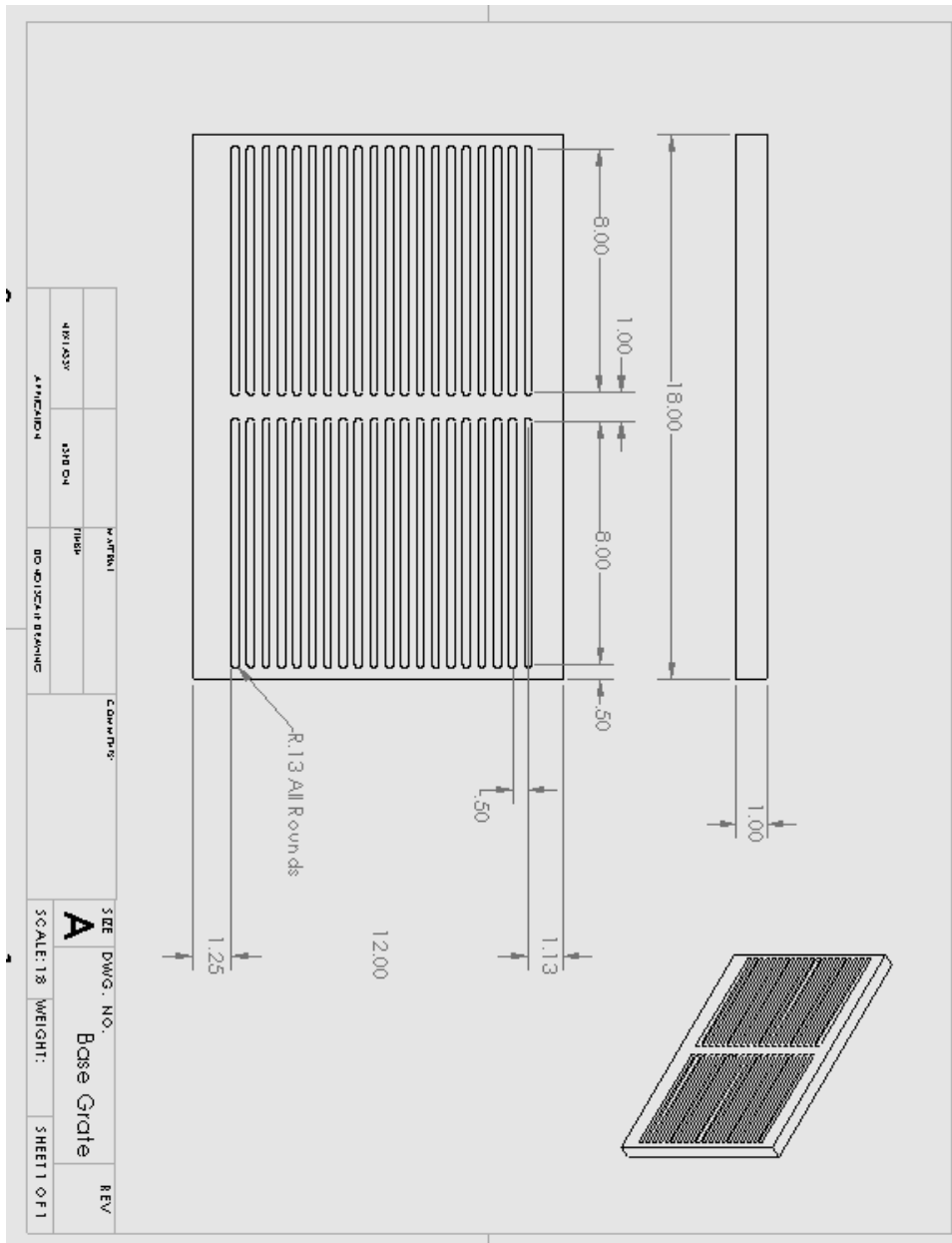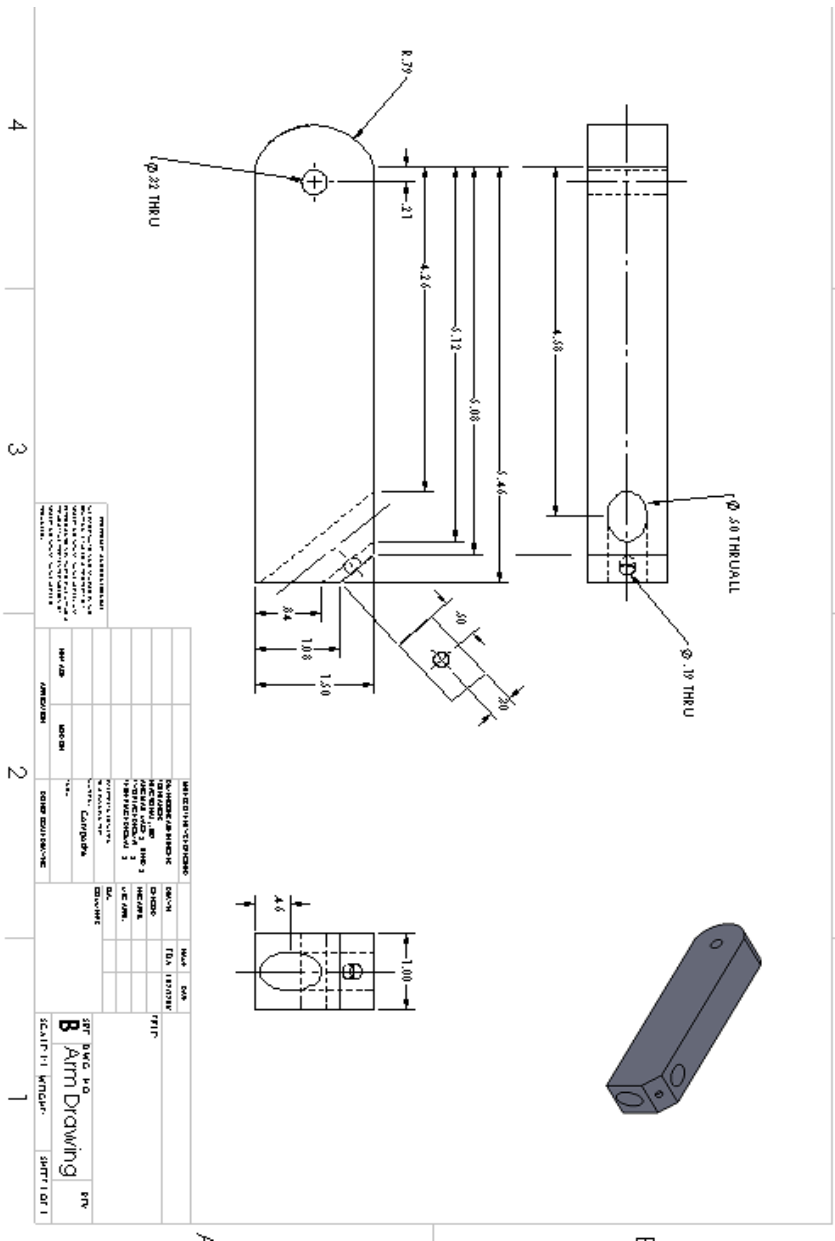
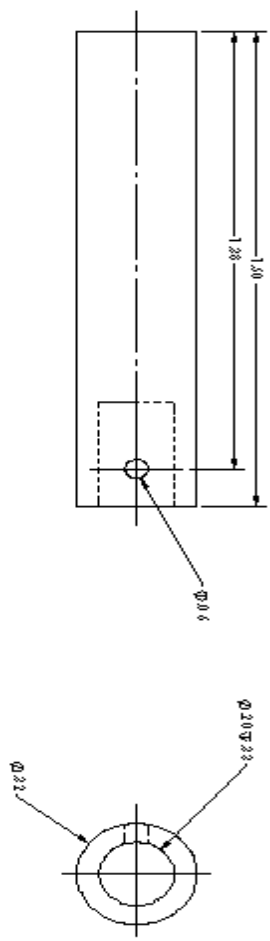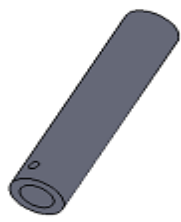**APPENDICES**

Appendix 1. FANUC Controller Specifications

R-J3*i*B Mate Controller Specifications

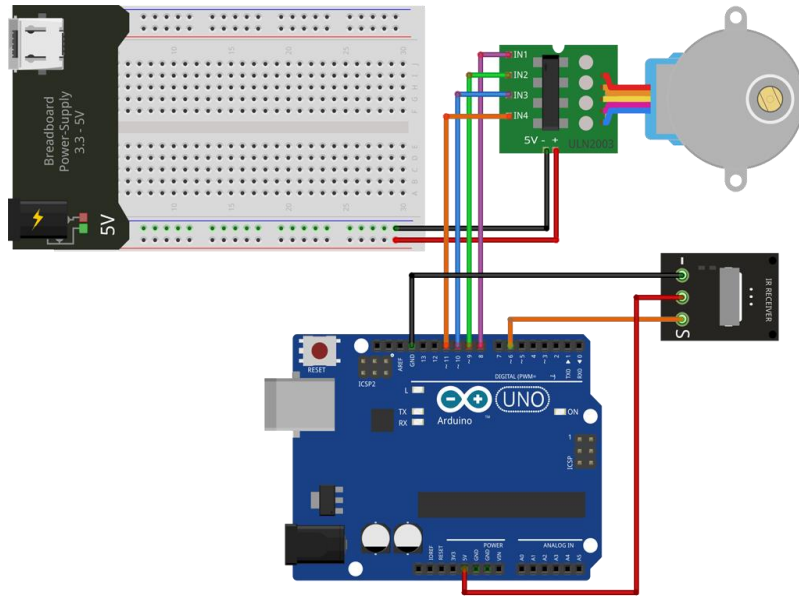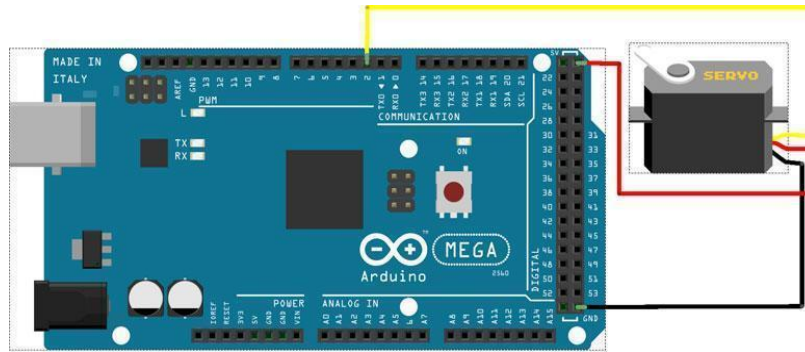| Items	
A-size cabinet	See drawing for dimensions
Operating environment	Ambient temperature: -0 to 45°C Humidity: 75% RH or less Non-condensing (95% max) Vibration: 4.9 m/s² (0.5G) or less
Power Supply	Single-phase 200-220 VAC opt. +10%, -15%, 50/60Hz +/- 1 Hz Three-phase 380-500 VAC std.
Power Consumption	0.4-0.5 kW (average) 1 kVa-1.2 kVa (maximum)
CPU	Multi-processor architecture based on R-J3iB (separate motion and communication) with real time clock-calendar
Controlled axes	5 (LR Mate 100iB) 6 (LR Mate 200iB, iB/3L) 8 (including robot axes) using 8 axis control card Additional axes available using mini-slot on CPU
I/O sub-systems	Built-in digital I/O (20 input/20 output) Built-in FANUC I/O Link Built-in Serial RS-232 Model A opt. (modular rack mounted 5 or 10 slots – user must supply enclosure)
I/O types	DI/DO: 512 point maximum each Digital AC or DC input modules Digital AC or DC output modules 12-bit Analog input or output modules
Remote I/O sub-systems	Options: Ethernet, Profibus, Devicenet
Miscellaneous Options	Supports line-tracking, vision and Karel
Memory card slot	Built-in PCMCIA type 2 interface to ATA flash disc cards
Teach pendant	Back-lit LCD, multi-function
Controller weight	35 kg

Appendix 2. Welding Robot Prototype Engineering Drawings

R.79

Ø.22 THRU

Ø.50 THRU ALL

Ø.19 THRU

.21

4.26

5.12

5.08

5.46

4.68

.84

1.08

1.60

.50

.30

.46

1.00

B
Arm Drawing

SCALE 1:1

SHEET 1 OF 1

ArmShaft Drawing

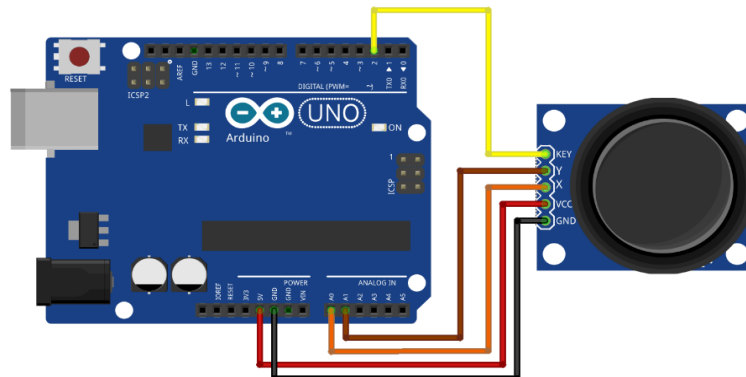Ø 0.6

Ø 20 ▽ .22

Ø .22

1.80

1.28

B

Appendix 3. Stepper Motor Hardware
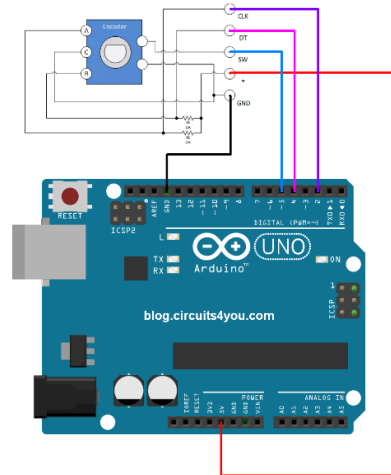

Servo Motor:

Joystick:

Control Wheel:

Appendix 4. Welding Robot Prototype Operational Code

```
#include <Stepper.h>
#include <Servo.h>
Servo tilt, pan;
int joyX = A1; //  X - axis of Joystick
int joyY = A0; // y - axis of Joystick
int x, y;
const int stepsPerRevolution = 200;  // change this to fit the number of steps per revolution
// initialize the stepper library on pins 8 through 11:
Stepper myStepper(stepsPerRevolution, 8, 9, 10, 11);
int stepCount = 0;  // number of steps the motor has taken
#define STEPS  32   // Number of steps for one revolution of Internal shaft
            // 2048 steps for one revolution of External shaft
volatile boolean TurnDetected;  // need volatile for Interrupts
volatile boolean rotationdirection;  // CW or CCW rotation
const int PinCLK=2;   // Generating interrupts using CLK signal
const int PinDT=3;    // Reading DT signal
const int PinSW=4;    // Reading Push Button switch
int RotaryPosition=0;    // To store Stepper Motor Position
int PrevPosition;     // Previous Rotary position Value to check accuracy
int StepsToTake;      // How much to move Stepper
// Setup of proper sequencing for Motor Driver Pins
// In1, In2, In3, In4 in the sequence 1-3-2-4
Stepper small_stepper(STEPS, 8, 10, 9, 11);
// Interrupt routine runs if CLK goes from HIGH to LOW
void isr ()  {
  delay(4);  // delay for Debouncing
  if (digitalRead(PinCLK))
    rotationdirection= digitalRead(PinDT);
```

```
  else
    rotationdirection= !digitalRead(PinDT);
  TurnDetected = true;
}
void setup ()  {
tilt.attach(23); // TILT on PIN 23
pinMode(PinCLK,INPUT);
pinMode(PinDT,INPUT);
pinMode(PinSW,INPUT);
digitalWrite(PinSW, HIGH); // Pull-Up resistor for switch
attachInterrupt (0,isr,FALLING); // interrupt 0 always connected to pin 2 on Arduino UNO
}
void loop ()  {
 x = joyX;    // X value btwn 0 and 1023)
 x = map(analogRead(joyX), 0, 1023, 900, 1800);
 tilt.write(x);
 // read the sensor value:
 small_stepper.setSpeed(600); //Max seems to be 700
 if (!(digitalRead(PinSW))) {   // check if button is pressed
  if (RotaryPosition == 0) {  // check if button was already pressed
  } else {        small_stepper.step(-(RotaryPosition*50));
     RotaryPosition=0; // Reset position to ZERO
   }
  }
 // Runs if rotation was detected
 if (TurnDetected)  {
  PrevPosition = RotaryPosition; // Save previous position in variable
  if (rotationdirection) {
   RotaryPosition=RotaryPosition-1;} // decrase Position by 1
  else {
   RotaryPosition=RotaryPosition+1;} // increase Position by 1
  TurnDetected = false;  // do NOT repeat IF loop until new rotation detected
  // Which direction to move Stepper motor
  if ((PrevPosition + 1) == RotaryPosition) { // Move motor CW
   StepsToTake=50;
   small_stepper.step(StepsToTake);
  }
  if ((RotaryPosition + 1) == PrevPosition) { // Move motor CCW
   StepsToTake=-50;
   small_stepper.step(StepsToTake);
```