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Productivity And Quality Evaluation In Assembly Using Collaborative Robots

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PRODUCTIVITY AND QUALITY EVALUATION IN ASSEMBLY USING COLLABORATIVE ROBOTS

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Dedication

I would like to thank God for blessing me with the opportunity of completing this thesis work by putting the right people in my path to make this possible.

I would like to dedicate this work to my parents, Carlos & Flor, who no matter the circumstances, have been my side and kept supporting and believing in me through all the stages of this process. Thank you for never letting me down when I wanted to give up and for your unconditional love.

To my sister, Flor, and my brother-in-law, Hector, for always being supportive and never letting me down throughout this process.

To my girlfriend, Vivian, for always being by my side and being a source of support through the difficulties of this journey.

To my professor, Dr. Amit Lopes, for guiding me and mentoring me through this process, and for all his support through these couple of school years.

PRODUCTIVITY AND QUALITY EVALUATION IN ASSEMBLY USING COLLABORATIVE ROBOTS

by

CARLOS FELIPE MANZANARES VEGA, B.S. IE

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Industrial, Manufacturing, and Systems Engineering
THE UNIVERSITY OF TEXAS AT EL PASO
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Abstract

In Industry 4.0, various technologies have been applied to achieve automation for traditional manufacturing and practices. For this reason, Smart Manufacturing (SM) environments utilize collaborative robots for process optimization by integrating the Internet of Things (IoT). Cobots are equipped with sensors and/or other devices to be able to transmit data in real-time while performing their tasks. Consequently, such SM implementations improves the decision making and business development, such as supply chain and operations, by sharing real-time data from a plant operational level. The collaborative robots are also designed to safely interact and collaborate with humans to perform tasks and optimize a wide variety of tasks.

In this research, a manufacturing station equipped with a cobot, camera/gripper end-effector, pneumatic piston, inspection camera, and linear actuators, was utilized to analyze the productivity and quality aspects of a four-piece assembly process using a camera-guided setup and coordinate-guided setup. This station allowed us to demonstrate how Industry 4.0 technologies could potentially be deployed in small and medium industrial setups and maximize its applications on assembly processes. The main variable for this experiment was the robot speed setting in the assembly (50%, 75%, and 100% of the robot capacity). The effects of the experimental variable on the failure rate, including components that caused the failure, were documented. The results showed that in the conditions of the experiment the camera did not perform as accurate to determine it was the best option. There are modifications and improvements to make in the equipment, such as verifying that the equipment has the technical requirements, to make these technologies suitable for this process and maximize its benefits. In the meantime, the coordinate-guided setup proves to be an efficient way to temporarily perform the process since it was the configuration that show that highest quality and greater productivity rate.

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Chapter 1: Introduction

There has been evolution on how humans build things utilizing technologies to make processes more efficient. We have gone, as a society, through three major Industrial Revolutions that goes from steam engines all the way through automated processes [1]. In Figure 1.1, the main contributions of each industrial revolution are shown; the First Industrial Revolution introduced mechanization, the Second Industrial Revolution introduced mass production, the Third Industrial Revolution introduced automated production, and the Fourth Industrial Revolution introduced the smart factory [2]. The Fourth Industrial Revolution, or Industry 4.0, was first introduced to the world at the 2011 Hannover Messe by Bosch, among other German supporters, stating a "widespread integration of information and communication technology in industrial production" [3][4]. Industry 4.0 enable companies to implement innovative technologies to optimize their processes and systems integration in areas such as manufacturing and supply chain, to achieve a greater overall performance [5].

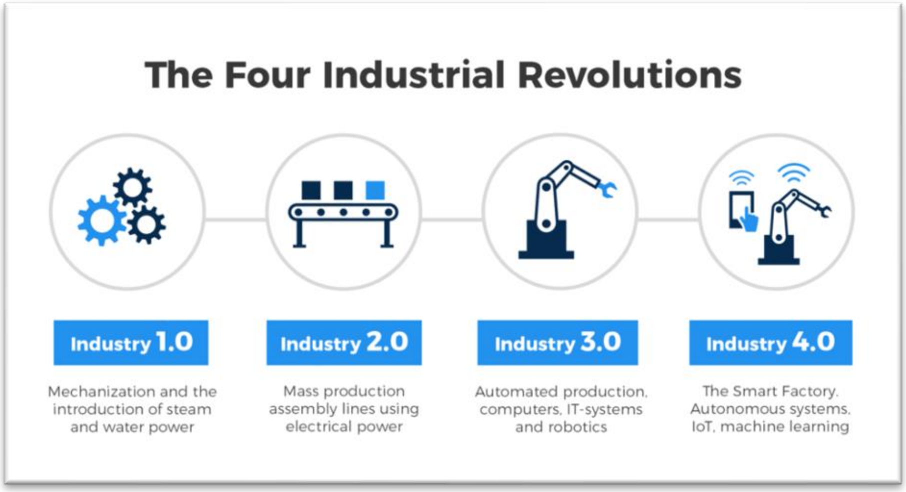


Figure 1.1: The Four Industrial Revolutions [2]

This industrial revolution requires digitalization to implement different technologies to achieve process optimization. The implementation of these technologies can achieve a specific purpose while simultaneously assisting in other areas within the enterprise. There are nine main technologies in Industry 4.0 that are transforming industrial production; Autonomous Robots, Simulation, Horizontal and Vertical Systems Integration, Big Data and Analytics, Augmented Reality, the Industrial Internet of Thing (IoT), Additive Manufacturing, Cloud Computing, and Cybersecurity, as shown in Figure 1.2[1][6][7][8][9].

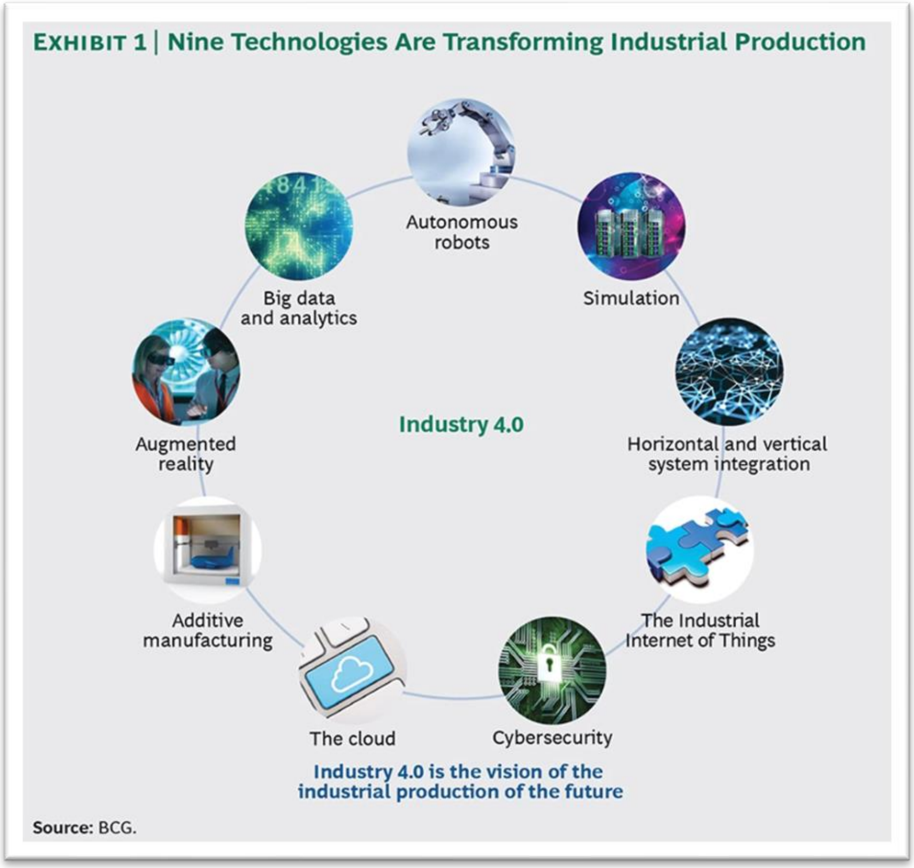


Figure 1.2: Industry 4.0 Technologies. [9]

One of the great advantages that Industry 4.0 offers, is the integration of the Industry 4.0 technologies to create smart factories. An article posted in the Materials Today Journal in 2021, describes that the foundation concept of Industry 4.0 is the Intelligent Manufacturing, or more commonly referred to as Smart Manufacturing (SM). This is a system that could potentially adapt to various changing conditions and products by having automatic and flexible adaptable production processes to meet production in changing conditions [10]. Smart factories that implement Industry 4.0 technologies improve mass production, quality, and productivity, and have an impact on important factors such as cost reduction, lead time reduction, downtime reduction, process automation, and energy savings among others [11]. Figure1.3 shows how these Smart Factories have machines that communicate with each other and are capable of tracking everything in real-time, as well as optimizing machine preventative maintenance and energy consumption [12]. Companies that have transitioned to Industry 4.0 technologies, have been implementing smart products to achieve proper communication between machines and humans. These smart products are equipped with sensors that digitalizes physical parameters and enables connectivity, monitoring, control, optimization and autonomy, resulting in proper integration of Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) [13].

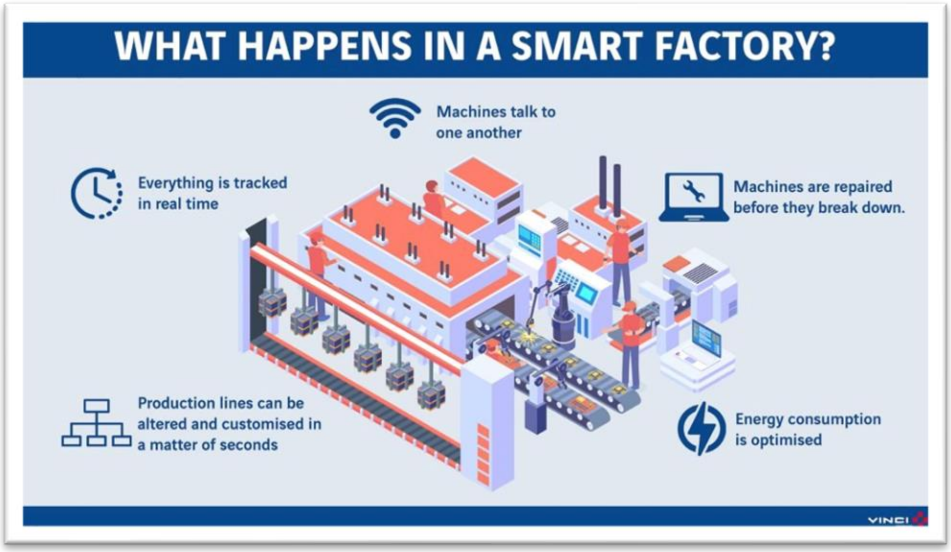


Figure 1.3: Benefits and attributes of Smart Factories [12]

Even though the technologies that Industry 4.0 has to offer are intended to optimize processes and potentially increase overall efficiency, not all can be implemented for all businesses. In the article previously mentioned, it was stated that these technologies and innovations are mostly established by large companies, but it is yet to be known how the implementation of these technologies can be adopted by manufacturing and production companies at different smaller scales today. As referred from the previous statement, the focus of the article was primarily on how companies can be organized to adopt the trends and configurations that Industry 4.0 technologies have to offer [10]. For smaller enterprises, one of the biggest constraints and challenges most companies face are the high initial investment costs associated with the technologies of Industry 4.0 needed to transition to a smart factory, as well as the cost associated to properly train operators and staff to successfully handle these new technologies [11]. Besides the size of the companies, sub-developed countries may take longer to implement Industry 4.0 because of the stage of maturity in which they currently are in industrialization [14][15]. Also, there is currently a gap in research on Industry 4.0 technologies compared to systems that are currently being used in manufacturing as standard technologies, and by people in charge manufacturing companies. However, a multi-layered framework to assist in the understanding of what is needed to accomplish what Industry 4.0 demands is proposed to assist those that are still far from reaching the industrial maturity needed [16].

1.1 Smart Manufacturing

There are several benefits that technologies of Industry 4.0 have to offer to enterprises that come in a wide range. One important Industry 4.0 concept is the Industrial Intern of Things (IIoT) that was first introduced by General Electric (GE) in 2012; GE suggested in that concept that by implementing smart equipment, smart production systems, and smart decision-making would be the future of manufacturing [17]. These benefits include the automation of processes utilizing collaborative robots that come with a variety of sensors, safety functions that allow operators, and robots to collaborate simultaneously in the same environment to perform a wide variety of activities [18]. The reason why collaborative robots can interact with humans is because there are different types of safety features that prevent the robot from injuring or harming the human operator [19].

Simulation is another important technology in Smart Manufacturing settings because it allows us to explore different real-life scenarios and their consequences before implementing them. This technology allows companies to simulate complex networks while simultaneously mitigating adversity resulting from complexity. A survey assessing the complexity of the planning process and the potential areas that could benefit from utilization was analyzed and the benefits assessed were cost reduction, shorter time of commissioning, optimal resource allocation, stability, performance, and planning support [20].

The Internet of Things (IoT), another technology implemented in Industry 4.0, consists of objects or “things,” natural or manufactured, that are equipped with built-in sensors that can be assigned an Internet Protocol (IP) address that has the capability of processing information and sending information in real-time to the network, as shown in Figure 1.4 [21][22]. One of the benefits of the Internet of Things is the amount of data generated by these sensors integrated in the “Things” that provide real-time data and sent to a cloud computing database that enables Big Data Analytics. Big Data Analytics assists in a more data-driven methodology for decision making and digitalization strategies while optimizing processes based on the data collected [23].

Figure 1.1.4: Industrial Internet of Things connecting machines and data managements. [22]

However, the amount of data that is collected in real time is worthless without properly sorting and cleaning the data to solely focus on the primary purpose of the data request. For Big Data to be effective and to optimize its value, it is important to record the data, extract the data from the data base for cleaning and annotation, integrate and represent the data, model and analyze the data, and then interpretate said data [24]. These benefits can be challenging to some extent. For starters, leadership needs to have clear understanding of the Key Performance Indicators (KPIs) and the goals to optimize the value of that data. Another challenge is talent acquisition; with Big Data being rapidly implemented, there is an increase in need for talent and professionals, such as data scientists or other talent with the right skills, to handle the requirements. The next challenge is the need for technology that is able to process and clean the data: this challenge could be potentially solved by software that allows data scientist to perform the analysis and additionally have enough storage to hold all the data acquired. The decision making is important as well; data must be sent to the right leaders to mitigate error. Finally, having a company culture that is data driven for the right decision making should also be a priority for proper implementation [25].

As previously stated, one of the main contributors to Smart Manufacturing are collaborative robots. These robots have the potential to relieve workers from complex repetitive tasks, while improving safety and optimizing productivity.

1.2 Collaborative Robots

Collaborative robots, unlike fully automated industrial robots, are automated robots that have been designed to safely collaborate with humans in industrial setups to optimize processes and increase productivity and quality. The collaborative robots from Universal Robots, a collaborative robot company based in Denmark, are equipped with 17 safety functions in compliance with the ISO 13849-1, safety of machinery. Figure 1.3.1 demonstrates how these robots come with a control box equipped with connectors for inputs and outputs. These outputs may consist of sensors to increase safety features or to connect other equipment with the robot. They also include a teach pendant with an intuitive, easy to use human-machine interface (HMI) for easy programming of the robot [26].

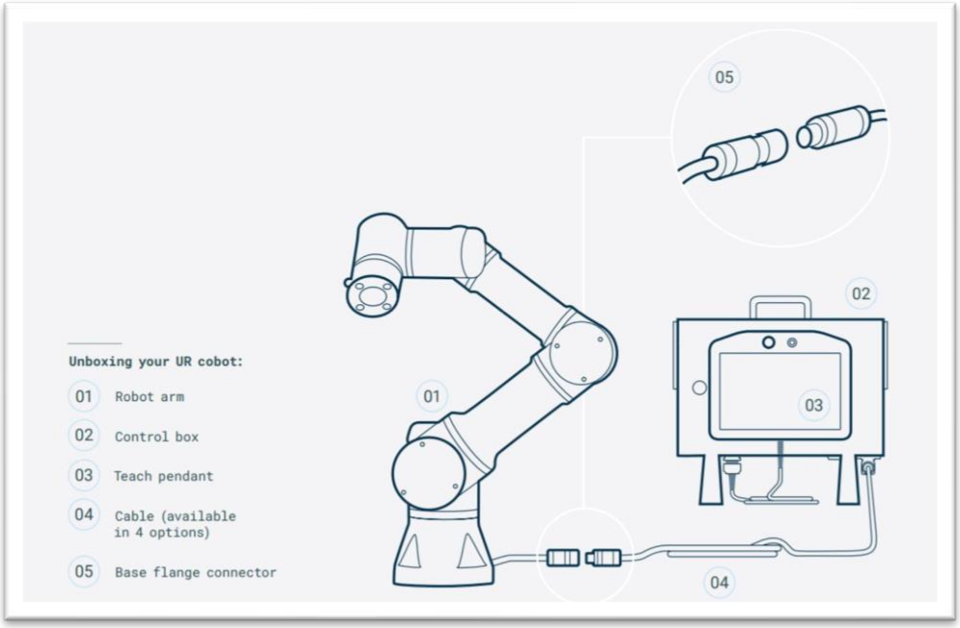


Figure 1.2.1: Universal Robot kit – Unboxing [26]

Collaborative robots have been used across many different industries and processes, allowing potential for future growth. For the several tasks and applications that these collaborative robots can perform, it is necessary to attach an end-effector to the end of the robot. End-effectors are tool tips that are attached to the robot arm end and are designed and programmed to perform one or multiple specific tasks such as grippers to handle material. An example of this are grippers, which allow easy material handling [28]. Figure 1.3.2 shows an example of the universal robot brand. This figure displays some of the applications that are advertised for their product, which is listed below:

- Assembly
- Dispensing
- Finishing
- Machine tending
- Material handling
- Material removal

- Quality inspection
- Welding

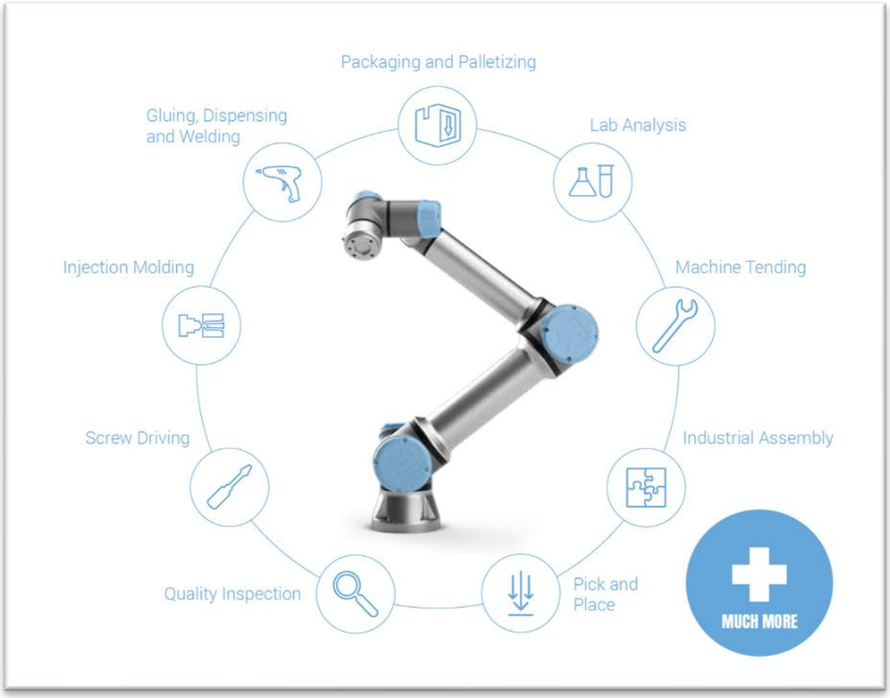


Figure 1.2.2: Universal Robots collaborative robot applications. [27]

Another big advantage of collaborative robots, unlike fully automated robots, is that these robots are designed to be easily programmed and redeployed, providing a big flexibility in the utilization of the collaborative robot. This flexibility provided by collaborative robots allows users to reprogram or create multiple programs in it for multiple tasks within the same station [26]. These Universal collaborative robots have demonstrated that their utilization can potentially solve issues surrounding the previously mentioned applications. An example of the utilization of collaborative robots to solve these issues is the Ford Motor Company; they deployed UR10 collaborative robots to the assembly lines to perform the camshaft greasing, engine oil filling, and perform quality inspections. The deployment of these collaborative robots into the assembly lines helped the company ramp up the speed and production throughput while relieving the employees from performing repetitive tasks [29].

The flexibility of these collaborative robots is that they can work autonomously in tasks where there are safety concerns of any sorts, such as a welding process, as shown in Figure 1.3.3.

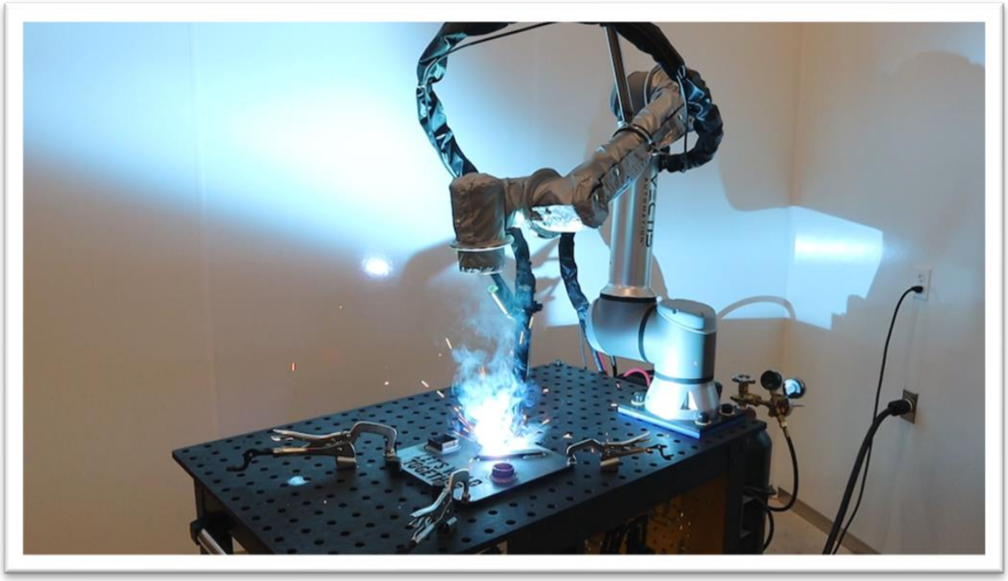


Figure 1.2.3: Universal Robot UR10 with a welding end-effector by Vectis Automation. [30]

To increase efficiency and productivity, companies have invested in the deployment of robots that collaborate and interact with a human operator and optimize human-robot collaboration (HRC), as shown in Figure 1.3.4 [32]. The close and simultaneous interaction between the human operator and robot can allows for accomplishments and deliverables that could not be achieved by either of the two separately [31].

Figure 1.2.4: UR10 with polish pad end-effector working simultaneously with an operator at Paradigm [32]

A study was performed by a group of researchers in Portugal that consisted of 252 articles and journals. These were selected for a preliminary study to identify contributions, recommendations, and guidelines for a safe design of the "collaborative areas", where the human involvement could be maximized and would promote well-being and great quality of work. They performed a systematic review of the design of the Human-Robot Collaboration workspace in industrial settings where only 65 articles were selected for the final analysis. This study considered several areas of expertise to target items such as safety design, ergonomics, sustainability and human-centered workplaces, including multi-human and multi-robot interaction workspaces. Other aspects considered included social and psychological aspects to compliment technical requirements. They concluded that with the evolution of workplaces and the increase in human-robot interactions, it is important to investigate these areas of knowledge for scientific and technical contributions that have an important impact on the factors that are considered when designing human-robot collaboration workspaces [31].

The Human-Robot Collaboration workspace not only needs to ensure the of both the human operator and the robot itself, but it must also be efficient. In modern days, having the flexibility to adjust to meet the demands of mass customization and maintaining high quality and efficiency while continuously improving sustainability is necessary in manufacturing facilities [29]. A study made in 2017 regarding U-shaped work cells and the integration of collaborative robots in production lines led to research on how to integrate automation while showcasing the benefits of selecting a U-shaped cell. By applying lean manufacturing principles in production lines, the U-shaped work cells were considered a solution in the effort to eliminate waste. However, these setups are not optimal for implementing automation utilizing fully automated robots due to the increase in changeover times, which delays the work cycle and creates flow interruptions. Automation, in some cases, can create a setback in the implementation of additional automation systems because fully automated robots' requirements prevent them from working in collaboration with human operators. There were three setups evaluated in the study: fully automated robots in a robotized line, human operator in a U-shaped cell, and human-robot collaboration in a U-shaped cell. The results showed that there was a 22% decrease in labor productivity going from robotized to human labor. However, there was a 225% optimization in floorspace utilization when transitioned to the U-shaped work cells. To conclude, the integration of collaborative robots allowed them to improve 18% from the original setup while keeping the 225% floorspace utilization [34].

As previously mentioned, collaborative robots are designed with the purpose of performing tasks and collaborating in the same workspace with a human operator. The safety sensors integrated in the collaborative robot make the collaboration safe for both the collaborative robot and the human operator. These sensors allow deployment of collaborative robots without the need for additional safety equipment, such as a physical barrier and Safety Protective Equipment (SPE) or other sensors that prevent the robot from injuring any person that comes within the delimited. In an article from Robotics and Computer-Integrated Manufacturing shows industrial robots working in collaboration with human operators for a task on a continuously moving line [35]. In this study, it was suggested that industrial robots can share a workspace only if the control architecture puts in place safety sensors and mechanisms to ensure safe operations. They also considered three main aspects in the planning of the workstation: what the workspace should target, what the tasks are, and the interactions between human and robot. A setup was created to showcase the safe collaboration and effectiveness of the study. Devices and equipment such as warning lamps, physical fences, a safety control box, and light curtains were required to ensure safe collaboration [35][36]. This article also demonstrates that even while using industrial robots for collaborative tasks, collaborative robots do not require a specific workspace design or extra safety features if being deployed for collaborative tasks [33].

Even though collaborative robots are meant to optimize processes and assist with complex tasks, the collaborative robots' technology is still a long way from utilizing its full potential. Collaborative robots are capable of being programmed and loaded with several programs to assists in facilities where different tasks are needed within a process or station [37]. However, a group of researchers theorized that for collaborative robots to react dynamically to different situations that could come up in a process, all the eventualities that the robot could face have to be pre-programmed. Their focus was the implementation of a worker assistance system that could allow tasks to be switched from the operator to the robot and from the robot to the operator for an optimal decision-making situation should these circumstances arise. The reason for their focus was because most collaborative robot HMIs (Human-Machine Interface) are complex and designed for experienced programmers, making it difficult for inexperienced operators to be able to program tasks. Their conclusion showed that a user-friendly worker assistance system was successful in the implementation of what they called “adaptive task sharing” where they analyzed six variables from the people in the study. These variables included mental demand, physical demand, stress, success, effort, and frustration [37].

There are several companies that have opted into implementing collaborative robots to address a variety of issues that they face. To better understand this, several case studies were analyzed to see how the collaborative robots were implemented and what was the impact of their utilization.

1.3 Universal Robots Case Studies

Collaborative robots from Universal Robots have been deployed all over the globe to perform a wide variety of tasks that improve the efficiency and quality of performances. The deployment of these collaborative robots goes from industry giants to locally owned factories to increase productivity in their facilities.

As previously mentioned, the Ford Motor Company is one of the Automotive giants that has deployed UR10 robots in one of their assembly line plants in Romania. The robots were deployed on the engine assembly line where they perform activities such as greasing camshafts, filling engines with oil, and perform quality inspections by having a Cognex camera/gripper end effector. The purpose of the robot deployment was to enhance the manual workforce and add value to the process. These robots were integrated into the process workspace to work collaboratively with the human operators by relieving them from repetitive tasks. This deployment allowed the plant to deliver a faster production throughput besides relieving the operators from the repetitive tasks. The challenges that were overcome were the ability to automate processes without a high capital expenditure, and the ability to allow collaborative robot to work in an independent manner [29].

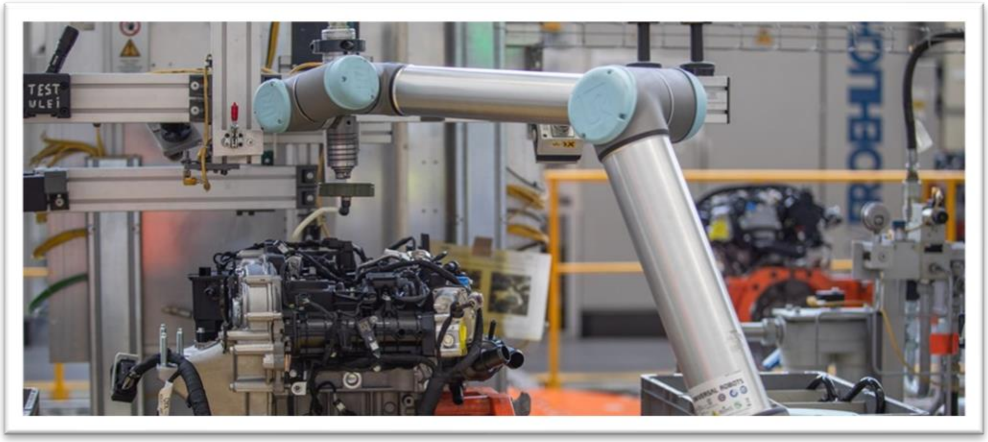


Figure 1.3.1: Universal Robot with dispenser end-effector at Ford performing engine greasing shaft [29]

Suppliers at different tiers have had to adjust to meet the rapidly changing demand while following the technical and quality requirements. This is the case with Lear Corporation in Germany. To satisfy demand with the Just-In-Time assembly production model that was established and the flexibility requirements of its setup with limited space available, Lear determined the need for a small mobile robot that could operate in the same workspace with human operators without the need for physical safety barriers, and at the same time, something that could be easily programmed by the operators that did not have a programming background. The solution was to deploy a Universal Robots UR5 with an end-effector with a screwdriver. This collaborative robot performs 8,500 drilling actions throughout the day. In the production line, each seat arrives with an identification tag to where the robotic arm is stationed. Then a transponder reads the tag, and the robot then starts to tighten the screws specified. If there are missing screws, the robotic arm will pick the seat out and send an alert. This is how Lear Corporation in Germany increased their production speed and product reliability [34].

Figure 1.3.2: Universal Robot with fastener end-effect at Lear performing seat harness fastening [38]

Another automotive company that has opted to deploy collaborative robots from Universal Robots is Stellantis. In one of its assembly plants in Italy for the Fiat 500 electric car, the need of automation technologies was required in the assembly process to meet quality and repeatability metrics, as well as improve ergonomics within the process due to the higher age of the worker. To address these issues, Stellantis deployed a series of UR collaborative robots to address some of the tasks such as the application of the waterproof liner to the vehicle doors, positioning of the soft-top, perform dimensional inspection on soft-top dimensions, riveting of the tailgate, hood mounting, tightening of the rear side-door hinges, and the mudguard mounting. By doing this, ergonomics for complex tasks were addressed, and quality and repeatability was guaranteed [39].

Figure 1.3.3: Universal Robot with a roller end-effector at Fiat (Stellantis) pressing seal tape on door panels [39]

In some cases where these collaborative robots have been deployed, there is the need for creating or developing fixtures or components for rapid prototyping or other uses. For this reason, additive manufacturing comes as an aid. Additive manufacturing may assist in the creation of said fixtures or components to assist collaborative robots to perform certain tasks.

1.4 Additive Manufacturing

Additive Manufacturing (AM), known as 3D-Printing, is a technology that provides the flexibility of manufacturing components that have been previously designed utilizing computer aided design software. 3D-Printing was first created in the 1980s when the developer, Charles W. Hull, created the first 3D-Printer in 1984. Back when it was first introduced, additive manufacturing was not feasible because of the cost of the technology at the time. As time has passed, this technology's cost has decreased dramatically, allowing more companies at different scales to get ahold of this technology [40]. This technology enables the manufacturing of customized and complex geometrical components, as shown in Figure 1.2.1, that cannot be achieved utilizing more traditional methods. Besides assisting in the complexity of the component's geometry or manufacturability, it also enables rapid prototyping while being cost efficient [41]. Additive manufacturing also allows a wide flexibility range, given that there are different techniques or processes that utilize a wide variety of materials [42].

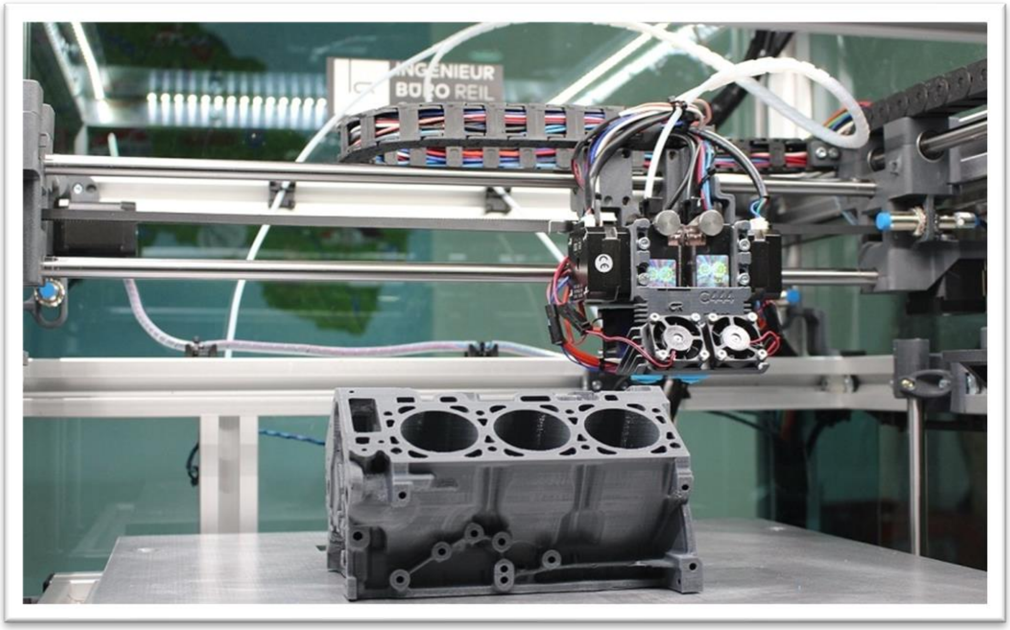


Figure 1.4.1: 3D-Printer printing a 6-Cylinder engine block [43]

In addition to additive manufacturing technologies, the maximization of utilization of collaborative robots allows machines to assist each other in certain processes. To achieve this, the machines can be connected using PLCs to communicate with each other for their respective tasks of the process.

1.5 Programmable Logic Controller (PLC)

Programmable Logic Controllers, commonly known as PLCs, are industrial ruggedized computers that can integrate and control automated systems that utilize industrial equipment. PLCs are programmed to achieve specific tasks and control the sequence of the inputs from other machines in the system. The primary purpose of the PLCs is to implement logic by initiate the machines involved in the system during an operation. These systems could be mutli-stage or overly complex operations where the machines operate simultaneously or in a sequence dictated by the PLC [44]. There are several pieces of equipment that can be integrated into one of these systems such as a camera or vision system, pneumatic pistons, several types of actuators, and robots (such as SCARA and multi-joint arms).

PLC usage is not limited to controlling automatic stations as they can also be used as a reliable safety measure when operating machinery. PLC programming allows the capability of assigning conditions before a machine trigger is executed. Safety PLCs are utilized to prevent an unwanted situation in the operation. The negligence of these preventions mentioned in the previous statement could potentially lead to a faulty operation that subsequentially leads to material or human damage [45]. There are many benefits of using PLCs as the main controller application. These benefits include user-friendly programming systems that allow people with basic programming skills the ability to utilize them. There will be an increase in PLC utilization thanks to the development of new technology and applications surrounding PLCs [46].

1.6 Thesis Purpose and Contribution

Small and medium size companies that perform high-repetitive tasks, non-ergonomically favorable tasks, and/or dangerous tasks can benefit from deploying Industry 4.0 technologies, such as collaborative robots, additive manufacturing, IoT, and big data analytics, to optimize their processes and keep up with demand and trends. Also, enterprises that engage with sensitive processes that require minimum human interaction to minimize the risk of contamination for quality compliance, and accuracy in industry such as healthcare and technology. Because of the previous statement the main objective of using this manufacturing station was to show how Industry 4.0 technologies can be deployed on small and medium industry settings to address repetitive tasks such as assembly to improve their quality and productivity.

The purpose of this research is to maximize the utilization of the Smart Manufacturing station and apply Industry 4.0 technologies, which are embedded in this station. The application for these technologies will assist in the evaluation of the productivity and quality in an assembly process utilizing collaborative robots as well as other equipment needed to perform the study.

Originally, the Smart Manufacturing station in the Industrial, Manufacturing and Systems Engineering Department at The University of Texas at El Paso was designed and programmed to utilize the camera integrated in the RobotIQ end-effector to perform the "Pick-and-Place" portion of the assembly.

For the purpose of the research and experimentation, a single method that simulated an industry-like scenario was not enough, and the data collected from such experiment would not be relevant without a different method to make an evaluation. For this reason, utilizing the same setup, a human-operator was added to the experiment to work in collaboration with the robot to tackle another industry-like scenario utilizing collaborative robots. By doing this, the experimentation performed analyzed two different setups: the first analyzed the robot-only assembly, and the second analyzed a human-robot collaboration assembly. Subsequently, through this process, it was determined that another method that simulates a different industry-like scenario should be analyzed. A fixture was created and the station was programmed to perform the assembly process utilizing coordinates instead of the camera in the end-effector to simulate the third industry-like scenario.

The outcome of the study will provide an insight of which industry-like method is the most effective in productivity with the highest quality and use this as a reference for large-scale production assemblies and for potential future researches.

This thesis is organized as follows: in Chapter 2, the equipment included in the Smart Manufacturing station is described in detail to explain its capabilities and usage for the thesis.

Chapter 2 also describes the methodology and steps taken to plan, develop, and execute the experimentation phase of the thesis.

In Chapter 3, the results are shown and explain with details of each setup and the variables implied at each method. The chapter is broken down into two main characteristics: the quality of the assemblies and the productivity of each method to make these assemblies. This chapter also shows tables and other visuals to better interpret the results and reflect on why some failures were present in the experimentation phase.

Chapter 4 focuses on the discussion and conclusion of the results of the experimentation phase. It describes what observations were made during the experimentation phase to better understand why failures happened.

Finally, in Chapter 5, future work suggestions for these Smart Manufacturing setups are defined. These suggestions not only include possible experimentation using the capabilities of this station but also some possible continuations with this research.

Chapter 2: Equipment and Methodology

The Smart Manufacturing station, equipped with machines and technologies that simulate industry-like scenarios, allows for different experimentations for a variety of research topics in Smart Manufacturing and Industry 4.0. This station has the potential to be utilized with the current estate or add machines, sensors, software, and conditions, among other features as required.

The importance of this Smart Manufacturing station is its flexibility, which grants researchers the possibility of recreating different conditions and scenarios without having to interfere or utilize private property for the experimentation.

2.1 Manufacturing Station

The station utilized for this research is property of the Department of Industrial, Manufacturing, and Systems Engineering at the University of Texas at El Paso. This manufacturing station was acquired by the IMSE department to perform different studies and training for students interested in manufacturing by utilizing collaborative robots and automation. As shown in Figure 2.1.1, this Smart Manufacturing station provides hands-on training for students to perform activities and analysis in an industry-like setup that will prepare them for the workforce. It is highly valuable to get the knowledge and training from this Smart Manufacturing station setup and to learn about the pros and cons of utilizing this method in industry-like scenarios. This is because it provides a sense of what to expect when deploying collaborative robots to large-scale manufacturing facilities.

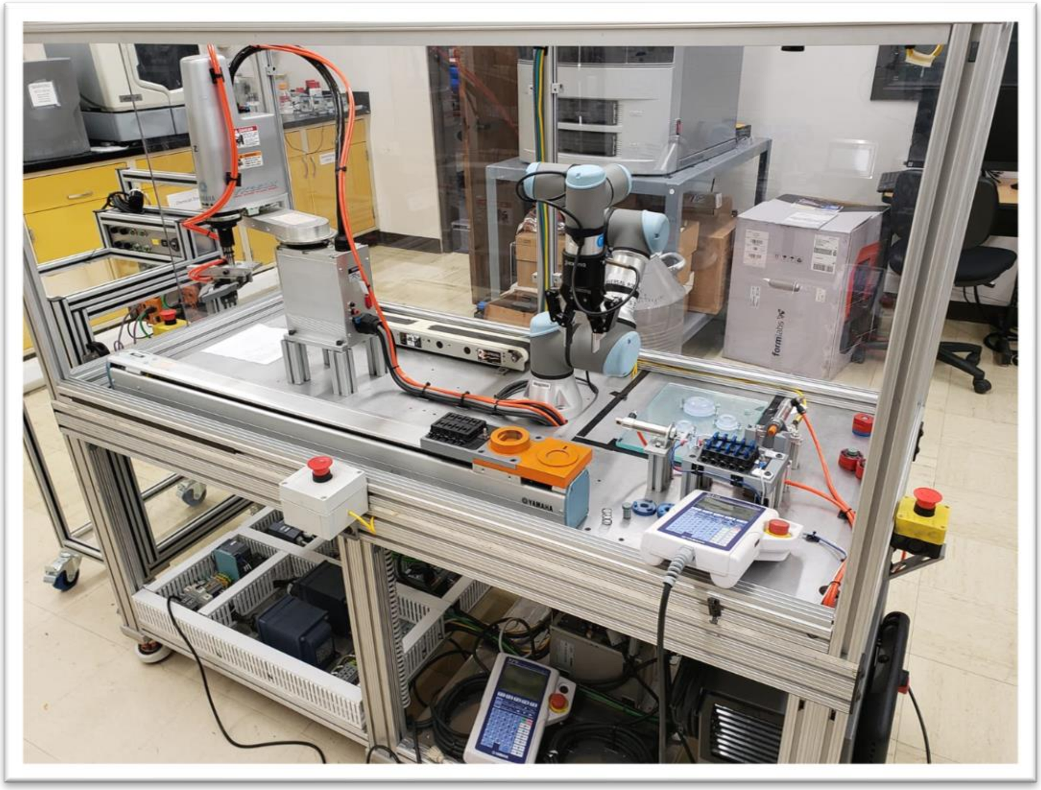


Figure 2.1.1: IMSE Smart Manufacturing Station

2.2 Station Setup

The station is equipped with a collaborative robot and other different tools and equipment interconnected with a set of Siemens PLCs, which perform the controlling of the equipment in the station and execute each machine’s tasks at their corresponding time in the process. This allows the station to perform the complete sequence of assembly and quality inspection of a 4-piece assembly and blade-type fuse relocation program. The 4-piece assembly consists of a pin, a spring that assists the pin to return to its place after inspection, the main body with a cavity to hold the pin and spring, and a cap that prevents the pin and the spring from jumping out of the main body, as shown in Figure 2.2.1.

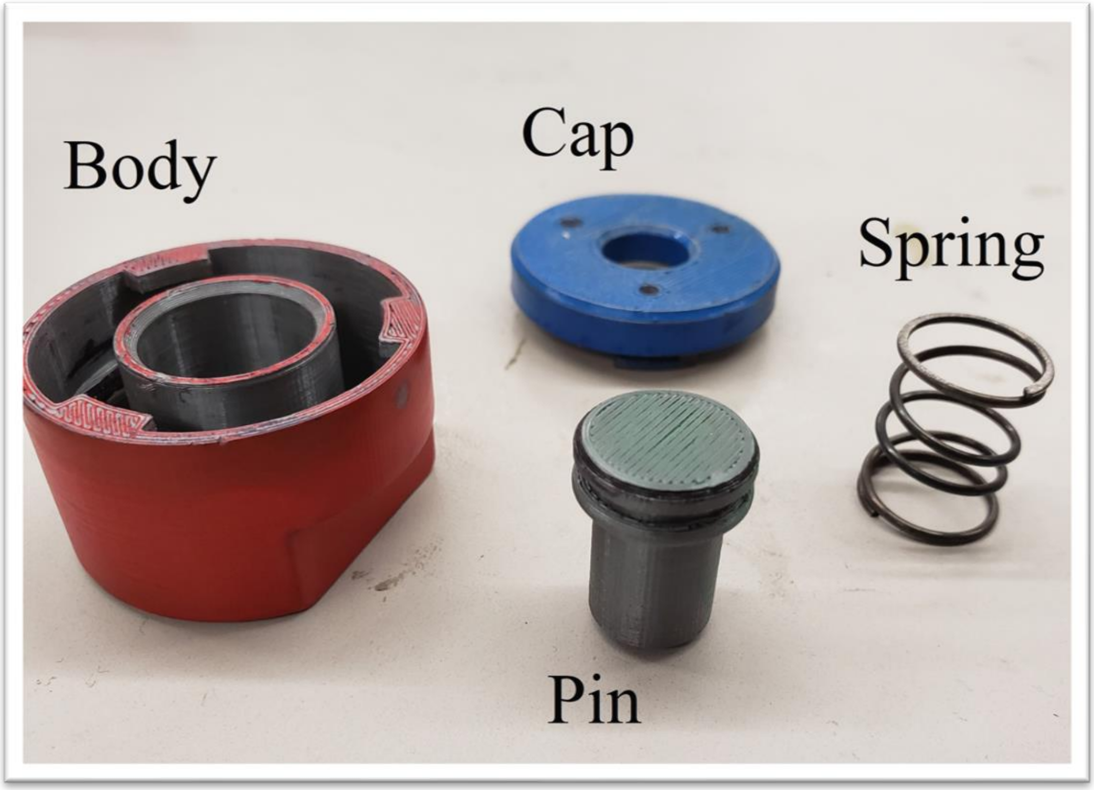


Figure 2.2.1: Assembly components – Body, Pin, Spring, and Cap

The equipment consists of a Universal Robots UR3e collaborative robot equipped with a gripper/camera end effector from RobotIQ which is capable of being programmed to detect components by looking for specific traits and to grab and manipulate said components [26][47].

This Universal Robots UR3e, shown in in Figure 2.2.2, is a compact table-top robotic arm that makes a great fit for bench-tops or tight and restricted workspaces. This collaborative robotic arm is the smallest of the Universal Robots family, with a reach of 500mm and a payload of 3kg. It is also a lightweight robotic arm, making it suitable to be installed directly inside machinery and perform different applications [26].

Figure 2.2.2: Universal Robots UR3e [26]

The collaborative robot in the Smart Manufacturing station, just like all Universal Robots collaborative robots, has a control box and a teach pendant that is used to make modifications to the program, activate the end-effector, regulate the speed settings, make calibrations, and create new programs from scratch or simply to start/stop the routine. As previously mentioned, these collaborative robots have a Human-Machine Interface (HMI) that is user-friendly and allows for fast and easy learning, shown in Figure 2.2.3

Figure 2.2.3: Teach pendant mounted on the control box on the Smart Manufacturing Station

The importance of utilizing this type of end-effector is because the tool provides the capability of manipulating components as needed, such as the “pick-and-place" movements for this experiment, in the assembly process while also having the capability of being programmed to detect specific features of each component to ensure proper selection of said component [47]. To perform the assembly, it is important that the end-effector has the capability of properly “picking” the components in such a way that it would not damage the components. It should also be able to perform the “placing” or assembly without the end-effector interfering with the other components. The RobotIQ end-effector, shown in Figure 2.2.4, offers a simple “2-finger” gripper with a rubber padding to gently grab and secure the components. In addition, the camera integrated in the end-effector is equipped with a software capable of being programmed to detect key features of the components, which enables the robot to pick the right component for the assembly sequence regardless of the location of said component in the “picking area”.

Figure 2.2.4: RobotIQ Camera/Gripper end-effector [47]

For the UR3e robotic arm equipped with the RobotIQ camera/gripper end-effector, the components have to be placed within the robotic arm reach. For this, a “picking” area was designated with a yellow base for the camera to detect the features, as shown in Figure 2.2.5.

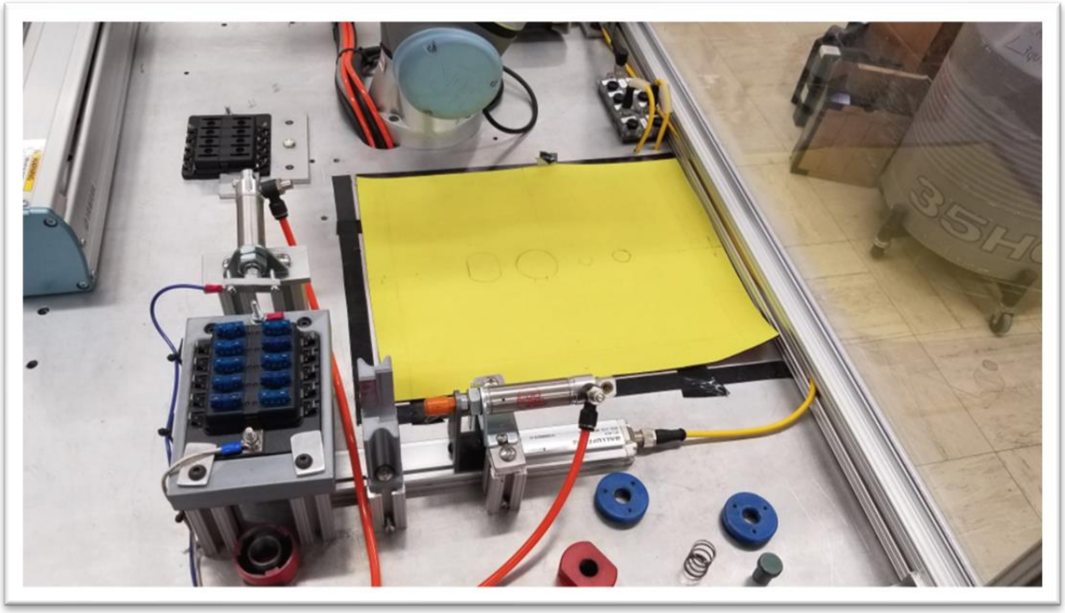


Figure 2.2.5: Designated “picking” area withing the robotic arm reach

In the coordinates-guided setup, there was the need to hold the components the same way and in the same location in a repeatable manner. After evaluations were made, fixtures able to simulate an industry-like scenario had to be created. In collaboration with the Texas Manufacturing Assistance Center (TMAC) at the University of Texas at El Paso, a digital design for the fixtures were created in a STL format, as shown in Figure 2.2.6. Once it was determined that they were the right dimensions, the fixtures were 3D-printed by the Keck Center, a research center that focuses on Additive Manufacturing located at the University of Texas at El Paso.

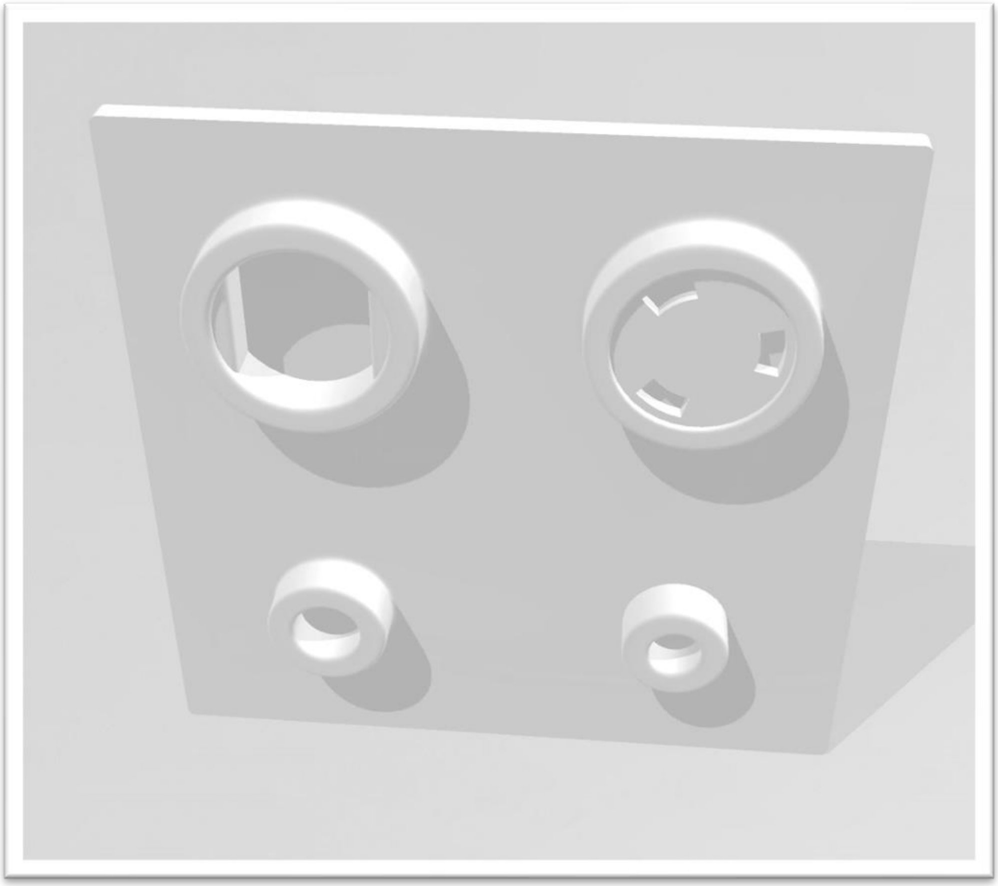


Figure 2.2.6: Custom fixture design in STL format for 3D-printing

After the fixtures were 3D-printed, they were fixed onto a plexiglass plate that was then bolted into the base of the Smart Manufacturing station, as shown in Figure 2.2.7. The fixture plate was placed and removed as needed to alternate between the camera-guided setup and coordinates-guided setup.

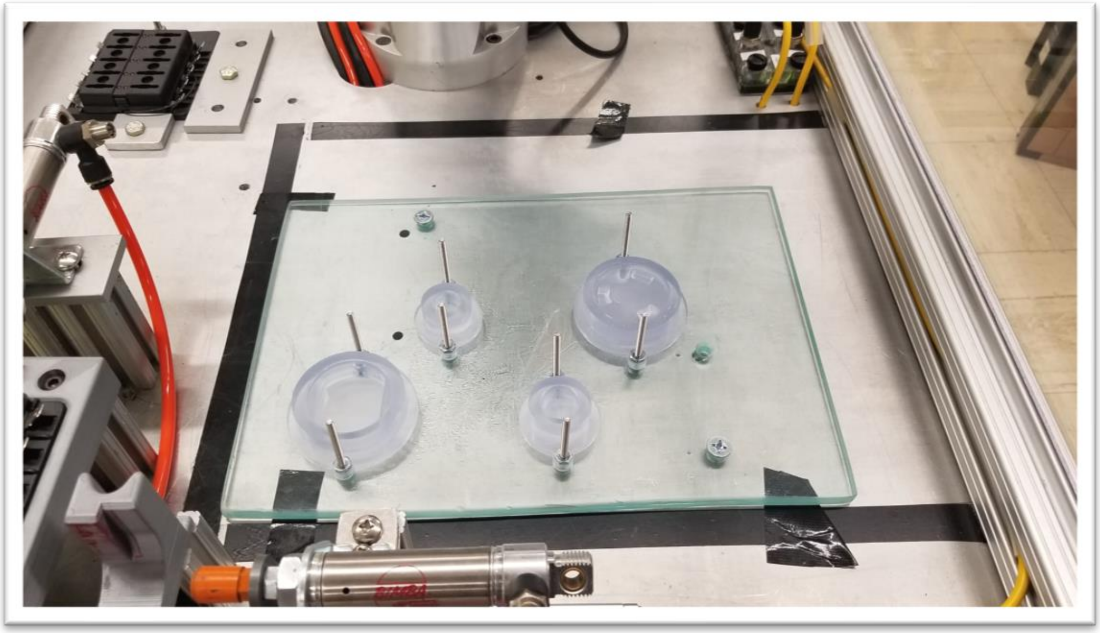


Figure 2.2.7: First placement of the fixture plate on the “Picking” area

Once the plexiglass plate with the fixtures was properly secured to the base of the Smart Manufacturing station, the components were placed in their corresponding fixture. This way, the robotic arm repeatedly picked the components in the same way, as shown in Figure 2.2.8

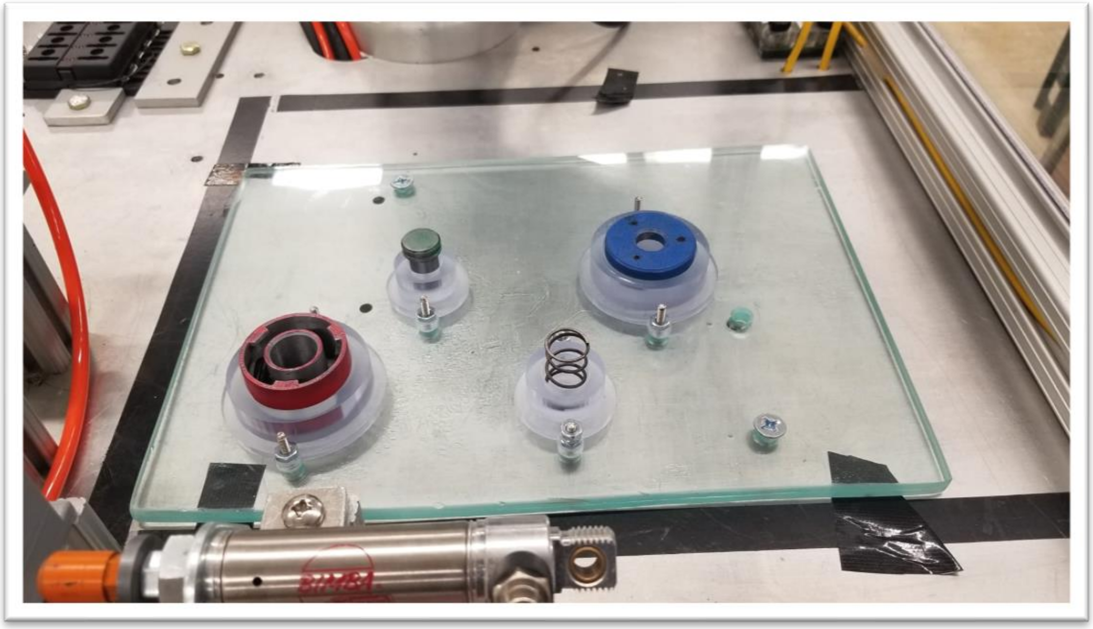


Figure 2.2.8: Components placed in their corresponding fixtures for "Picking"

For the assembly process, a fixture specifically designed to fit the main body of the assembly was mounted on a linear actuator that served as an assembly platform for the robotic arm to place the components and perform the assembly, as shown in Figure 2.2.9. After the assembly was completed, it was transferred to the quality inspection process and back to the fixture to be transported to the "good assemblies' area".

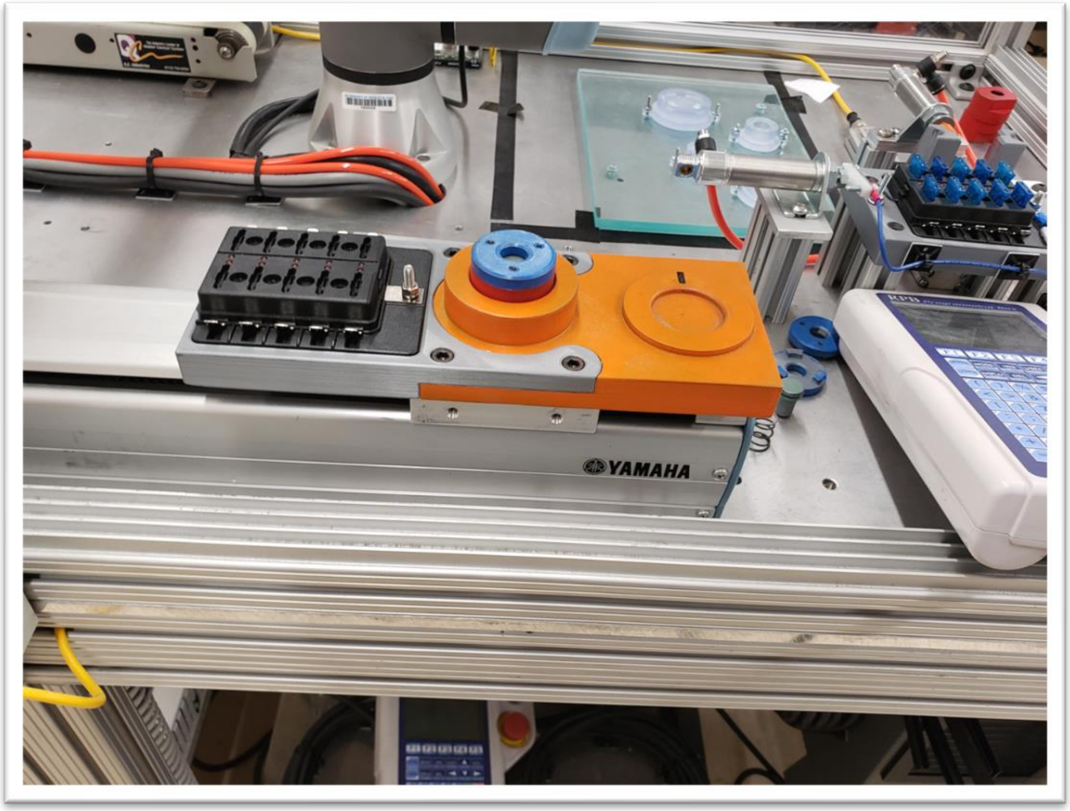


Figure 2.2.9: Assembly & blade-type fuse fixtures mounted on top of the “Good Assemblies” linear actuator

The Smart Manufacturing station also has another linear actuator for discarding assemblies that have failed the quality inspection, as shown in Figure 2.2.10. This band conveyor simulates an industry-like scenario to dispose of failed assemblies for rework or scrap.

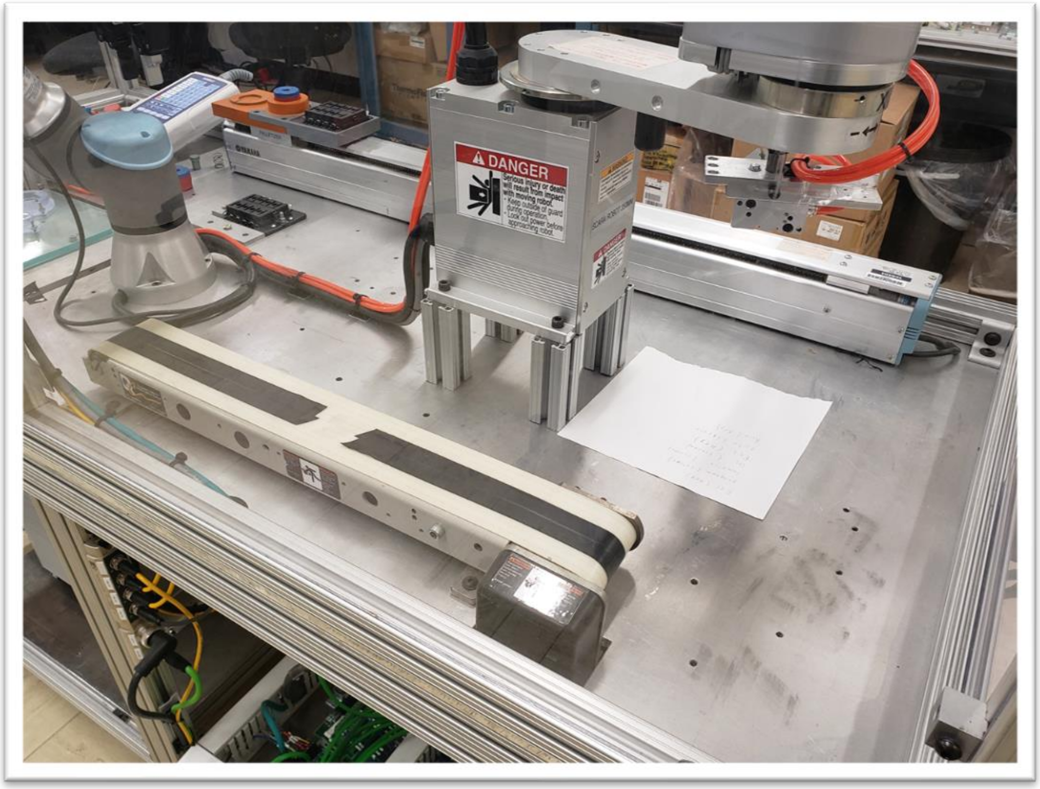


Figure 2.2.10: Linear actuator for failed assemblies

To perform the quality inspection, a Teledyne inspection camera with embedded *iNspection Express Software* was used to determine if the components were properly assembled. This vision system functions by taking a picture and looking for traits of the proper assembly, as shown in Figure 2.2.11 [48]. The quality inspection camera software allows for programming the camera to look and detect for certain features to ensure that the assembly was done correctly.

Figure 2.2.11: Teledyne Dalsa inspection camera located on top of the inspection fixture.

The Smart Manufacturing station is connected to a supply of compressed air that allows the pneumatic piston to activate and execute the quality inspection process. Once the components were properly assembled on the assembly fixture, the completed assembly was transferred to another fixture where the quality inspection was performed. The pneumatic piston connected to the compressed air supply was triggered to assist with the inspection portion by pushing the pin inside the assembly for the camera to perform the inspection, as shown in Figure 2.2.12.

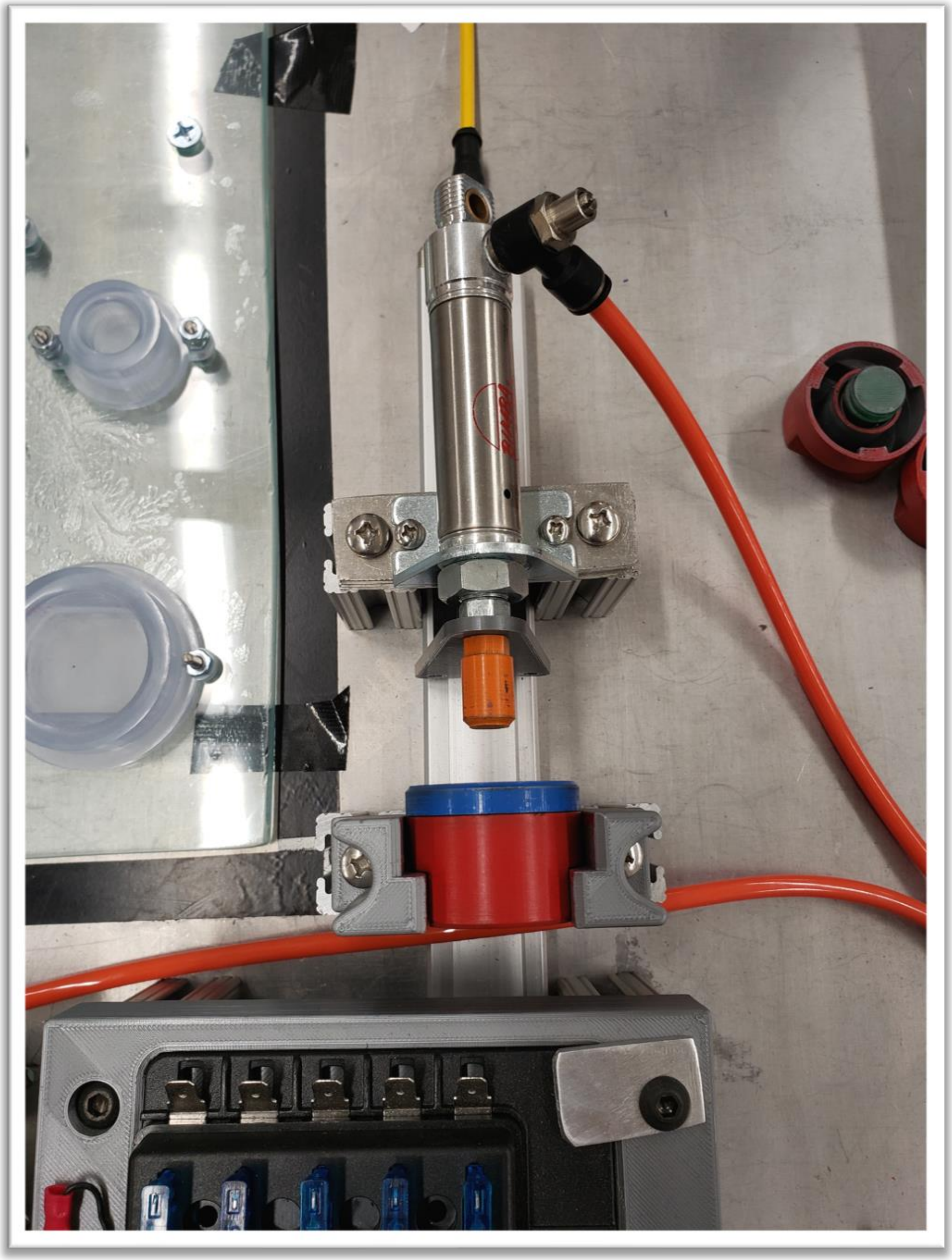


Figure 2.2.12: Completed assembly in quality inspection fixture & pneumatic piston connected to the air supply.

The Siemens PLCs were programmed using the Siemens programming software *Totally Integrated Automation Portal v17 (TIA Portal v17),* which allowed the ability to interconnect the collaborative robot, the camera, the pneumatic pistons, and the linear actuators to perform the routine created for the assembly and inspection process [49]. The program created in TIA Portal sends the information to the PLCs and allows them to communicate and trigger each of the machines integrated in the Smart Manufacturing station by utilizing variables for the decision-making algorithm integrated in the program, as shown in Figure 2.2.13.

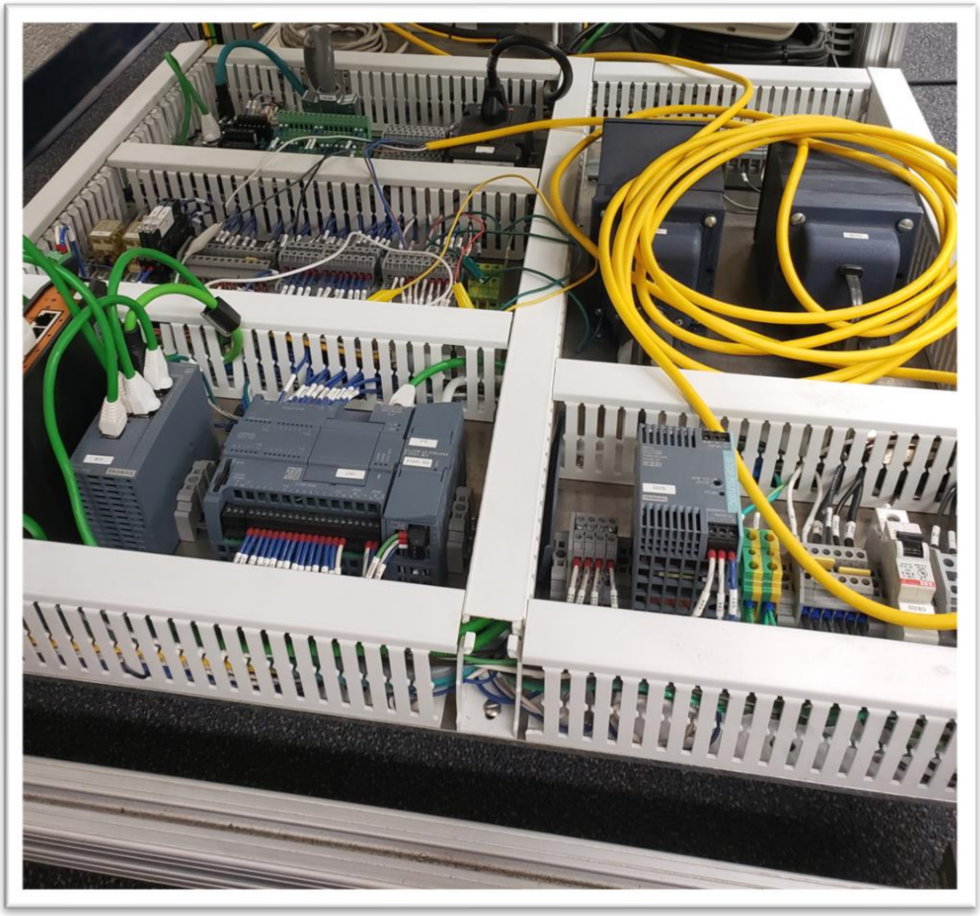


Figure 2.2.13: Set of Siemens PLCs integrated in the Smart Manufacturing Station

The programming of this manufacturing station was performed by Process Control & Engineering, a Tucson-based company that focuses on PLCs & HMIs (Human Machine Interface) Programming, Robotics & Vision, and Drives AC/DC & Motion [50]. The company was also responsible for the design and manufacture of the 4-piece assembly. These components were designed utilizing computer-aided design software and 3-D printed for the purpose of this assembly routine.

Once the integration of the machines was completed, a Human-Machine Interface (HMI) was developed so the people utilizing the station could interact with the setup. The HMI "MAIN" tab shows a digital model of the whole Smart Manufacturing station with all the technologies that are integrated in the station, as shown in Figure 2.2.14. In addition, this HMI has embedded features that allow the operator to activate or deactivate some of the machines such as the actuators or the pneumatic pistons under the "MANUAL" tab. This HMI displays any error or alert under the "ALARMS" tab.

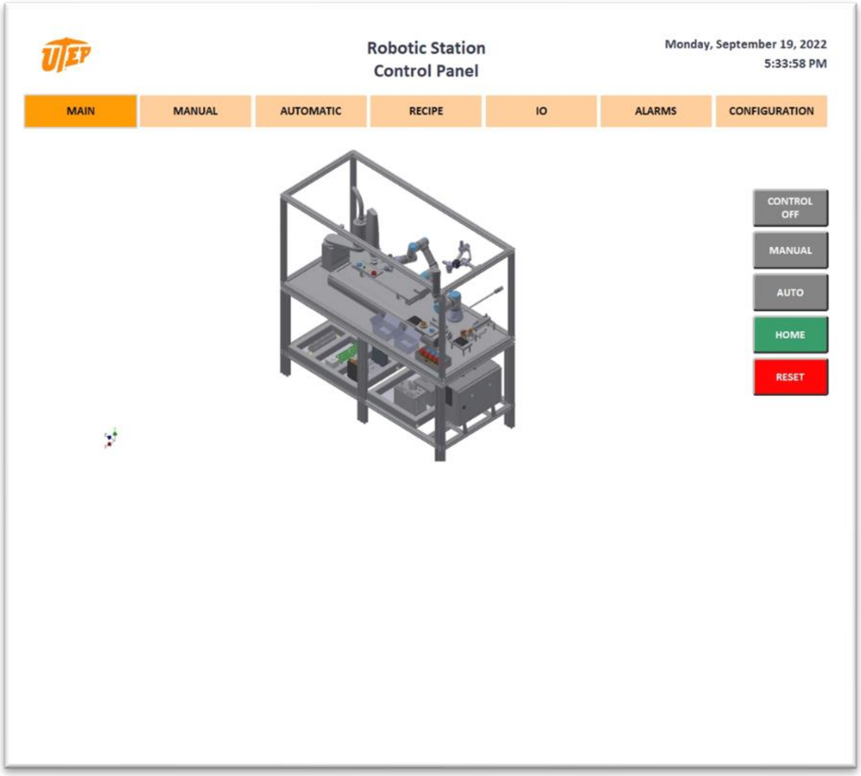
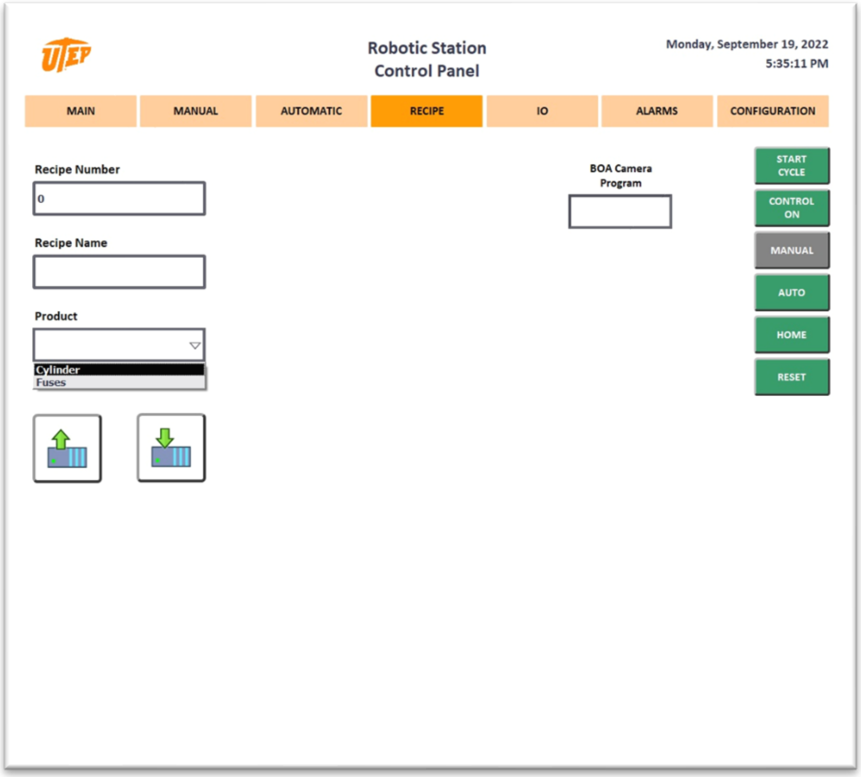


Figure 2.2.14: HMI Main screen showing the digital display.

In a previous statement, it was mentioned that the Smart Manufacturing station has two programs for assembly: the 4-piece assembly and the blade-type fuse. The HMI allows the operator to select which program the station will run. The HMI requires the operator to select the sequence of the components for a successful 4-piece assembly, as shown in Figure 2.2.15 and Figure 2.2.16.



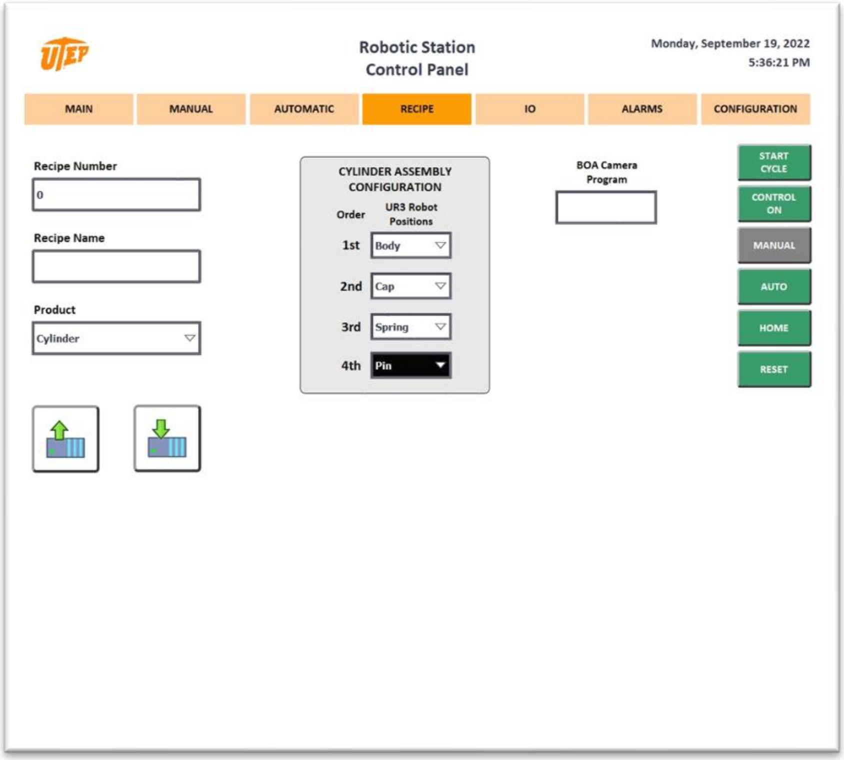
Recipe Number: 0

Recipe Name:

Product:

BOA Camera Program:

Figure 2.2.15: HMI under the "RECIPE" tab with the drop-down menu



Recipe Number: 0

Recipe Name:

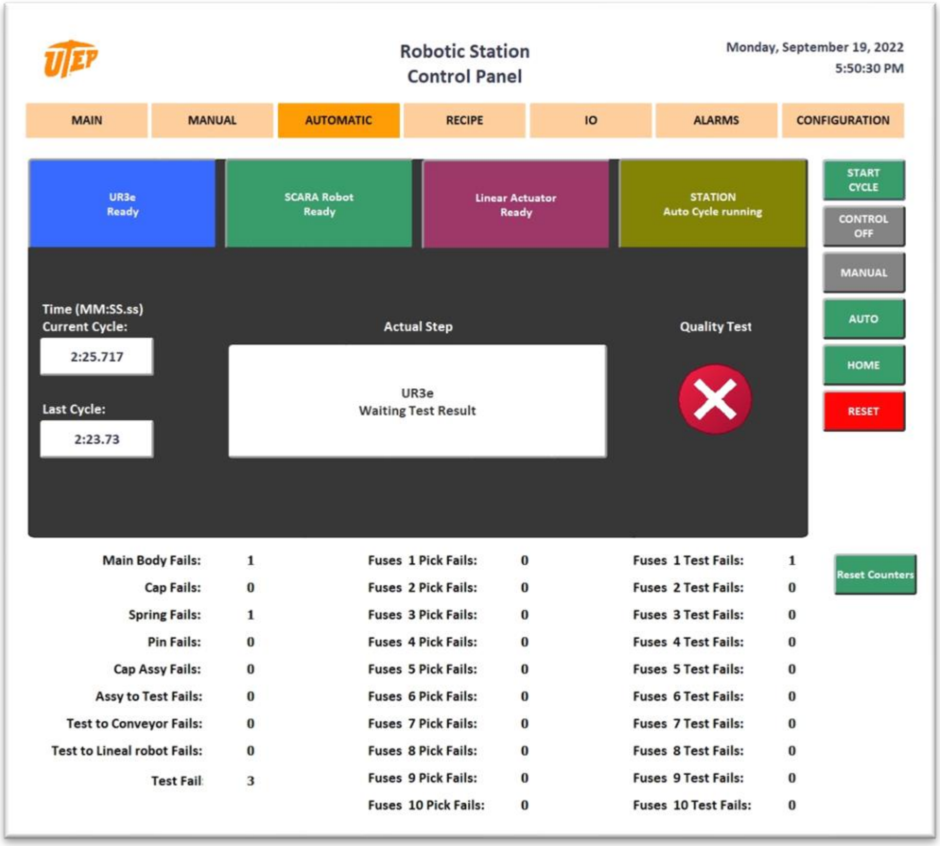
Product: Cylinder

CYLINDER ASSEMBLY CONFIGURATION

Order	UR3 Robot Positions
1st	Body
2nd	Cap
3rd	Spring
4th	Pin

Figure 2.2.16: HMI under the “RECIPE” tab with the components order

After the first interactions with the Smart Manufacturing station and understanding the capabilities of the station and the extent of the interactions between operator and machine, it was determined that extra features were needed on the HMI to have a better display and data gathering. In the first version of the HMI, the “AUTOMATIC” tab only displayed the “Actual Step” window, which showed the task the station was at during the assembly process. It also showed the “Quality Test” result, displayed by a green circle with a white check mark when an assembly successfully passed the quality inspection and a red circle with a white cross when an assembly did not pass the quality inspection, as shown in Figure 2.2.17.



Monday, September 19, 2022
5:50:30 PM

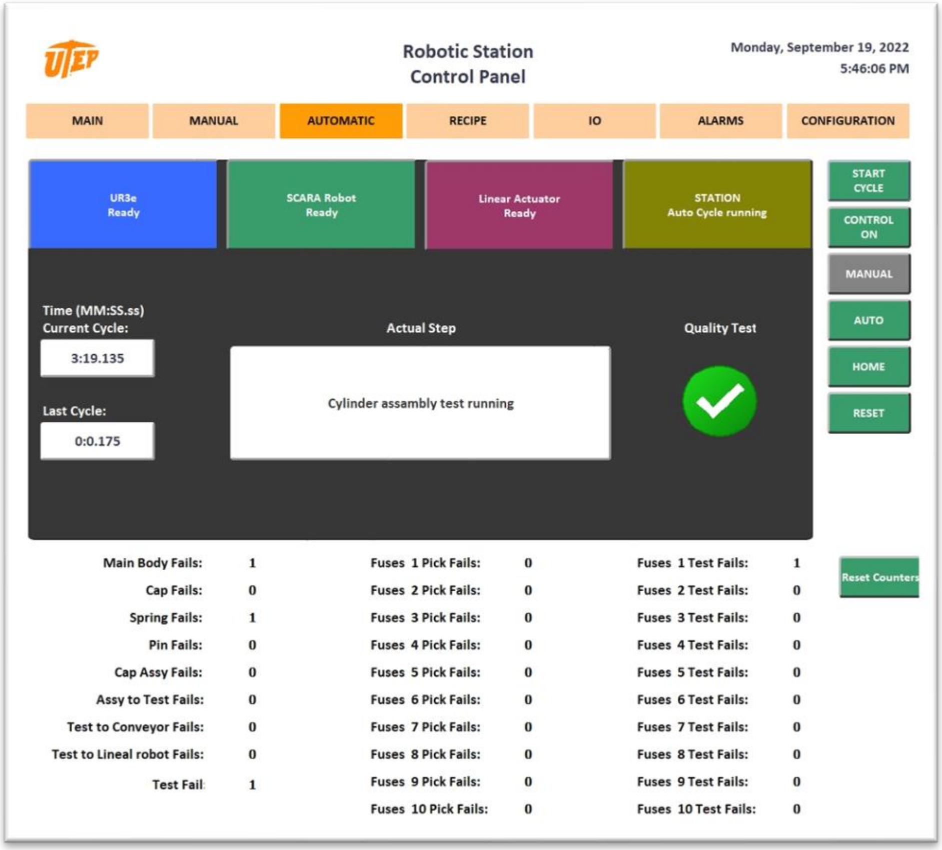
UR3e Ready
SCARA Robot Ready
Linear Actuator Ready
STATION Auto Cycle running

Time (MM:SS.ss) Current Cycle: 2:25.717
Last Cycle: 2:23.73
Actual Step: UR3e Waiting Test Result
Quality Test

Main Body Fails:	1	Fuses 1 Pick Fails:	0	Fuses 1 Test Fails:	1
Cap Fails:	0	Fuses 2 Pick Fails:	0	Fuses 2 Test Fails:	0
Spring Fails:	1	Fuses 3 Pick Fails:	0	Fuses 3 Test Fails:	0
Pin Fails:	0	Fuses 4 Pick Fails:	0	Fuses 4 Test Fails:	0
Cap Assy Fails:	0	Fuses 5 Pick Fails:	0	Fuses 5 Test Fails:	0
Assy to Test Fails:	0	Fuses 6 Pick Fails:	0	Fuses 6 Test Fails:	0
Test to Conveyor Fails:	0	Fuses 7 Pick Fails:	0	Fuses 7 Test Fails:	0
Test to Lineal robot Fails:	0	Fuses 8 Pick Fails:	0	Fuses 8 Test Fails:	0
Test Fail	3	Fuses 9 Pick Fails:	0	Fuses 9 Test Fails:	0
		Fuses 10 Pick Fails:	0	Fuses 10 Test Fails:	0

Figure 2.2.17: HMI “AUTOMATIC” tab showing a failed quality assembly result and counters added for the failures.

It was decided that more accurate data had to be displayed on the HMI. The data shown and gathered should be displayed in real-time to help the analysis and record keeping on what is happening in the assembly. A member of the team from the PC & Engineering, whose primary specialization is in creating programs and HMIs, was sent to work and assist with the reprogramming and implementation of additional features to the system. This task was a 2-day effort to achieve the desired results. The features added to the HMI “AUTOMATIC” tab were counters that showed the number of failures in the quality testing. They also added counters for each component that made the assembly process fail, as shown in Figure 2.2.17. For the fuse assembly, the counters were created to count the failures from the picking process as well the placing process.



Time (MM:SS.ss)
Current Cycle: 3:19.135

Last Cycle: 0:0.175

Actual Step: Cylinder assembly test running

Main Body Fails:	1	Fuses 1 Pick Fails:	0	Fuses 1 Test Fails:	1
Cap Fails:	0	Fuses 2 Pick Fails:	0	Fuses 2 Test Fails:	0
Spring Fails:	1	Fuses 3 Pick Fails:	0	Fuses 3 Test Fails:	0
Pin Fails:	0	Fuses 4 Pick Fails:	0	Fuses 4 Test Fails:	0
Cap Assy Fails:	0	Fuses 5 Pick Fails:	0	Fuses 5 Test Fails:	0
Assy to Test Fails:	0	Fuses 6 Pick Fails:	0	Fuses 6 Test Fails:	0
Test to Conveyor Fails:	0	Fuses 7 Pick Fails:	0	Fuses 7 Test Fails:	0
Test to Lineal robot Fails:	0	Fuses 8 Pick Fails:	0	Fuses 8 Test Fails:	0
Test Fail	1	Fuses 9 Pick Fails:	0	Fuses 9 Test Fails:	0
		Fuses 10 Pick Fails:	0	Fuses 10 Test Fails:	0

Figure 2.2.18: HMI "AUTOMATIC" tab showing a successful quality assembly result and counters added for the failures.

2.3 Experiment Setups & Sequence

For the experimentation portion of this research, the original program and setup was the only setup thought to be utilized for evaluation. As was previously stated, after further discussion and analysis, a second setup was proposed for evaluation of the productivity and quality of the assembly using collaborative robots. The Universal Robot with the RobotIQ end-effector can be programmed in such a way where the camera detects the components in a delimited area by taking a picture of the area and picking the component corresponding to the step of the assembly. In addition, as previously mentioned in the Manufacturing Station setup description, the collaborative robot can also be programmed using coordinates rather than using the camera in the end-effector to pick and place the components. For this reason, the fixtures were created and a new coordinate-guided setup was proposed.

The experiment for this research consisted of the two different setups of the manufacturing station that simulate industry-like scenarios: a camera-guided setup and a coordinate-guided setup.

For the manufacturing station to successfully execute the programs, it must be connected to a computer equipped with the Siemens TIA Portal utilizing an ethernet cable. From the TIA Portal, an HMI (Human Machine Interface) was developed and customized for this specific assembly for the operator to start and control the program. This HMI can show whether the assembly task failed or was successful. If a failure occurred, it determined which component was responsible for the assembly failure. This program provides directions to the PLCs, which trigger the equipment in the station to complete the sequence of assembly and inspection. The sequence starts with placing the main body in the assembly fixture. This is then followed by the spring and the pin assembly. Finally, the cap is placed on top of the assembly and twisted to secure the components.

After the assembly is completed, the collaborative robot transfers the assembly into another fixture where the pneumatic piston is triggered to press the pin inside the assembly, as shown in Figure 2.3.1.

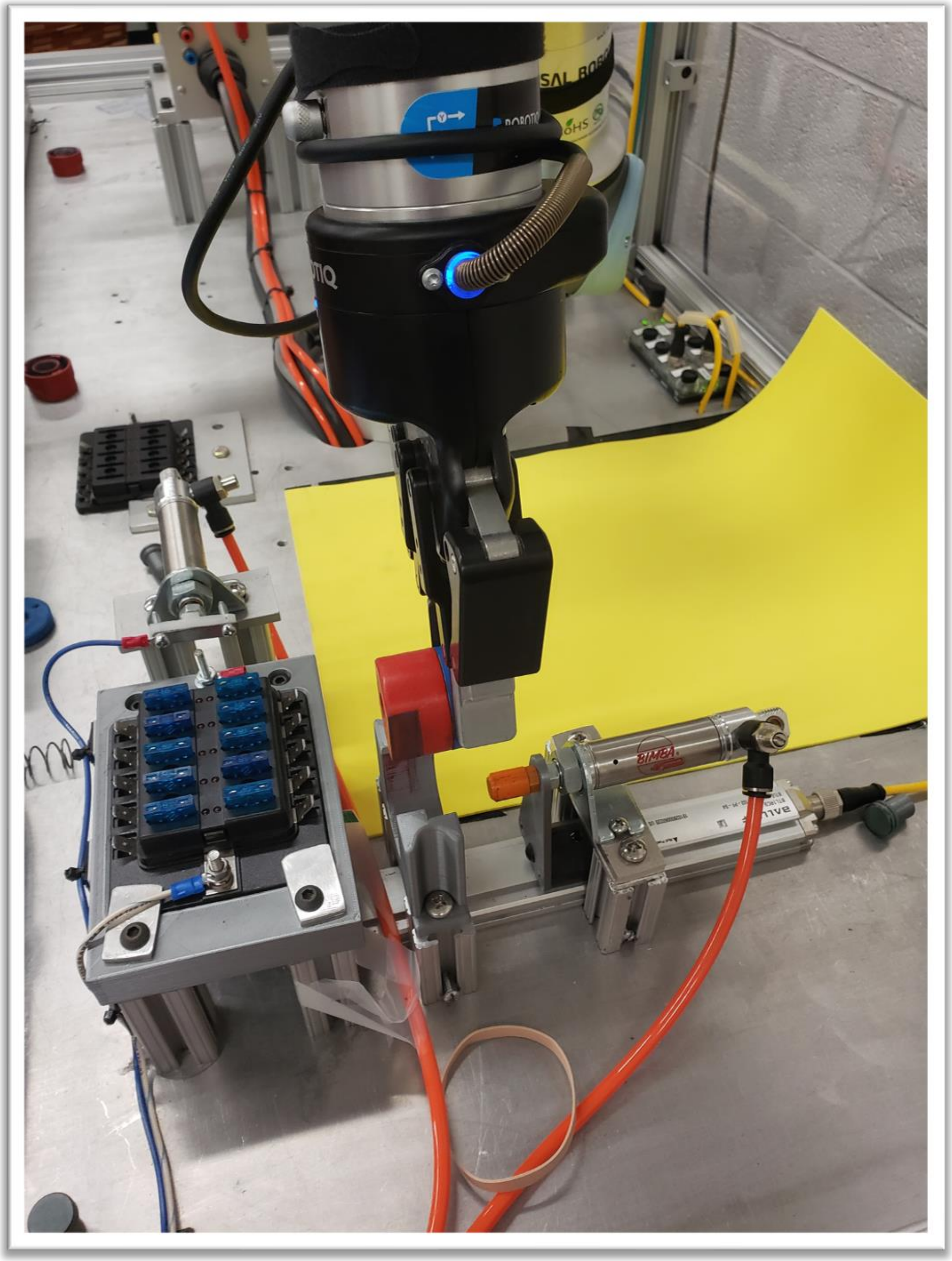


Figure 2.3.1: Robotic arm transferring assembly to quality test fixture

The pin is pressed by the pneumatic piston to expose the opposite end through the other side of the main body, as shown in Figure 2.3.2. Once the quality inspection is performed by the camera, the results are displayed on the screen of the HMI. A green circle with a check mark represents that successful assembly, and a red circle with a cross represents the failure. Depending on the inspection result, the assembly is transferred by the UR3e robot into one of the two designated linear actuators to complete the full routine of the program.

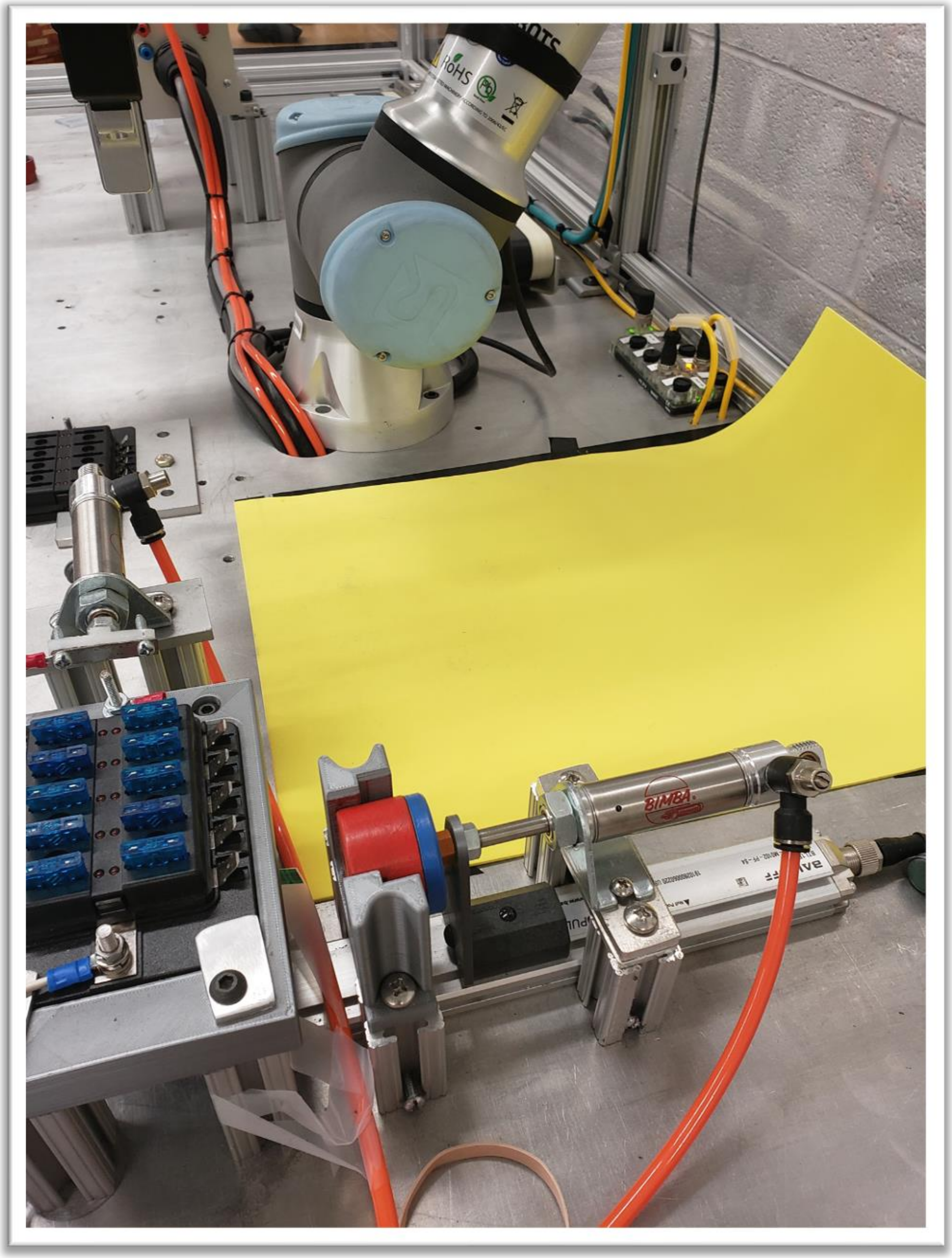


Figure 2.3.2: Pneumatic piston pressing assembly pin.

2.4 Methodology

The stopwatch with decimal minute capability that was utilized to register the process time of the assembly and inspection for the data collection during the experiment is shown in Figure 2.4.1. The experiment consisted of analyzing three methods with the two different setups: the camera-guided setup (as shown in Figure 2.4.2) and the coordinate-guided setup (as shown in Figure 2.4.3). There were three trials with thirty samples for each method at three speed settings. The three methods that were used for the experimentation were:

- Robot only with camera-guided setup
- Robot only with coordinates-guided setup
- Collaboration human-robot with camera-guided setup

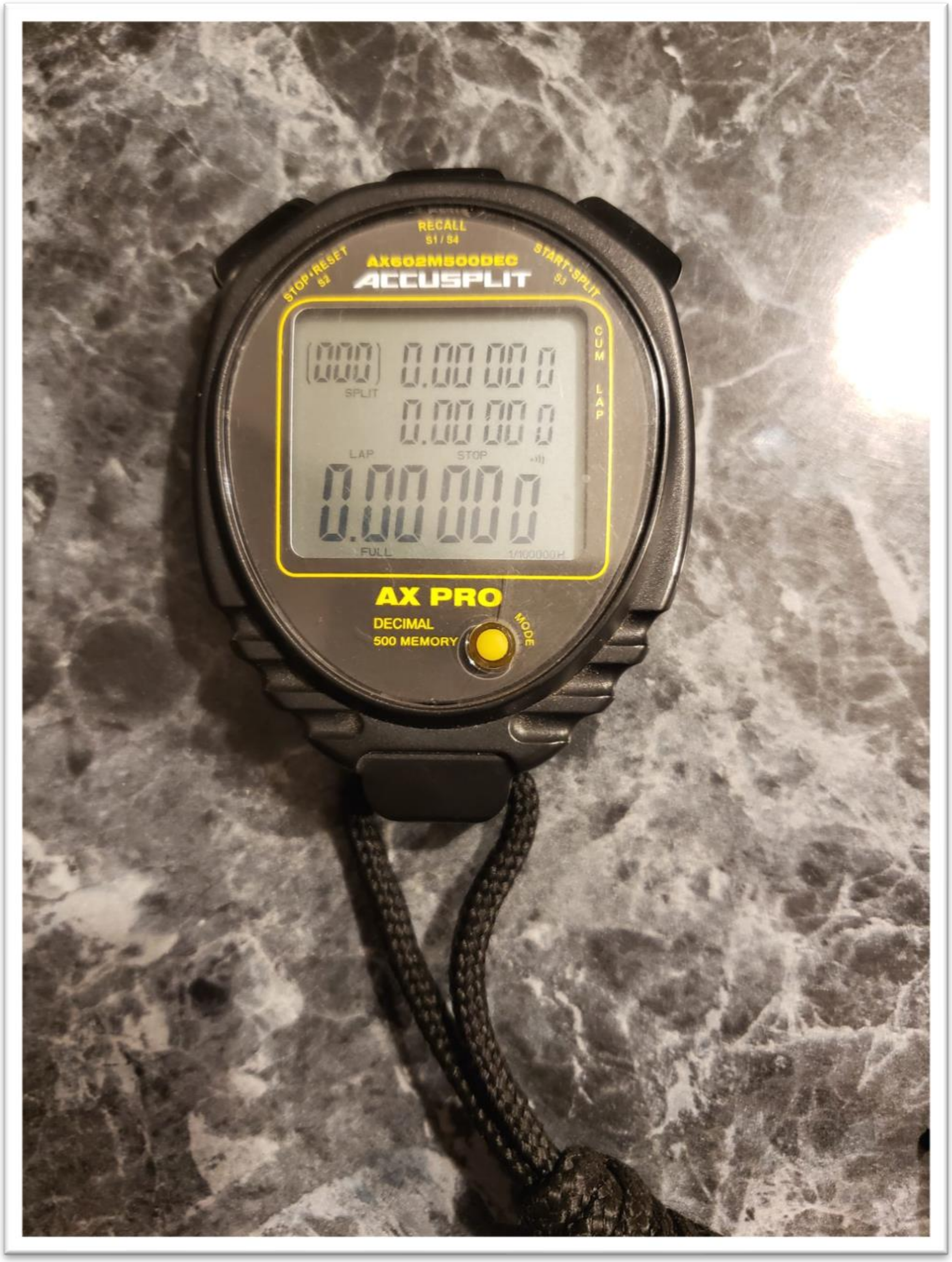


Figure 2.4.1: Accusplit stopwatch with decimal minute capability used for timing

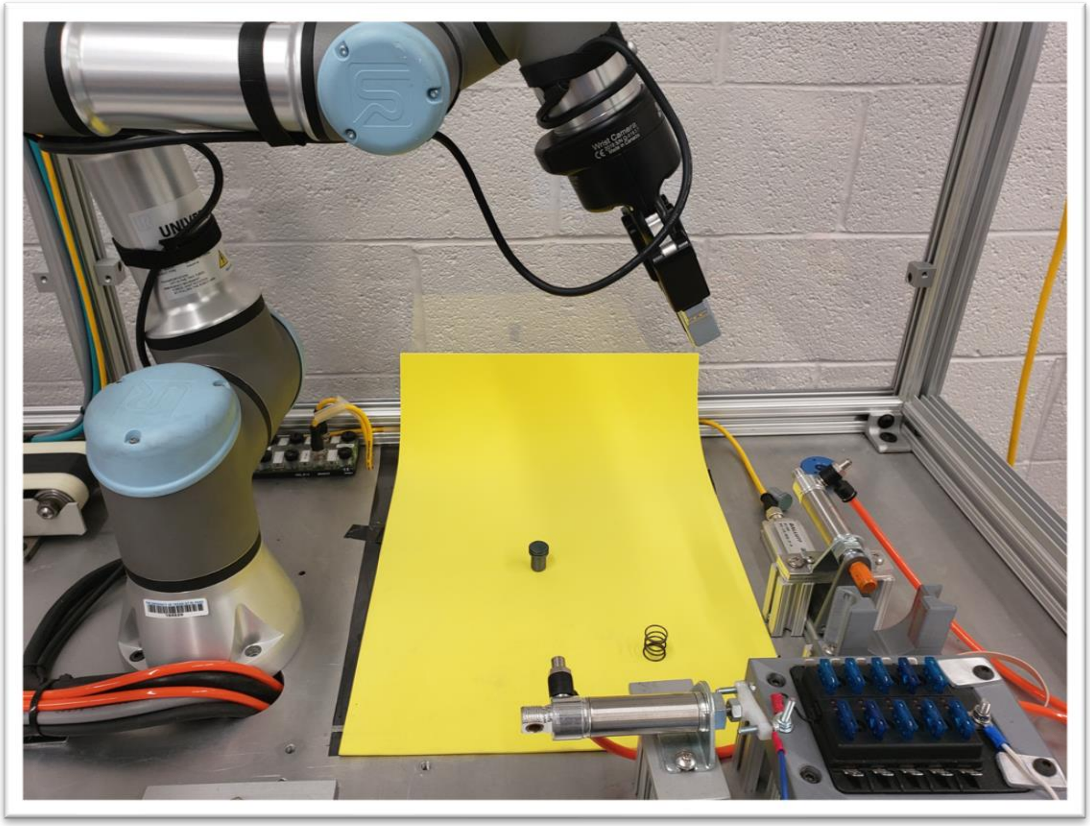


Figure 2.4.2: UR3e collaborative robot utilizing its end-effector camera to detect components

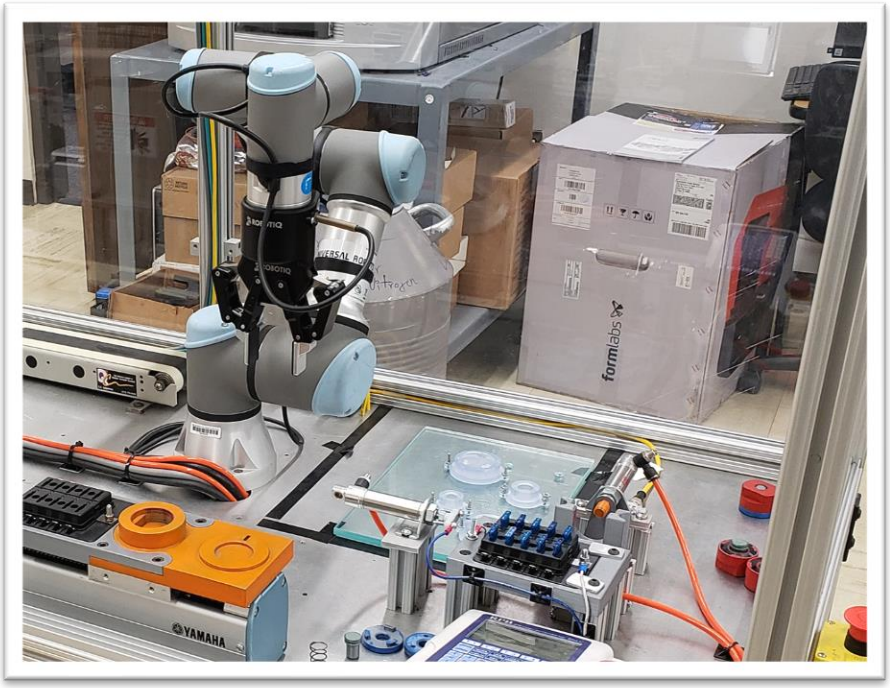


Figure 2.4.3: Fixture plate mounted on station base for coordinate-guided sequence

The Universal UR3e robot speed rating can be adjusted from 0% to 100% as needed by the operator to perform different activities or be adjusted for diverse needs. For these experiments, the assembly and inspection sequence were timed using the two setups and the three methods previously mentioned, with three speeds settings: 50%, 75%, and 100%. The purpose of these experiments was to compare the quality of the assembly and the productivity of the collaborative robot utilizing the two setups and simulating an industry-like scenario where the collaborative robot and the operator work together within the same space.

The assembly programs were created in a way that if the gripper's sensors do not detect the components properly or it misplaces the components and interrupts the assembly process, the collaborative robot would automatically return to the home position and the program stops executing. Once the program faults, it is necessary for the operator to manually restart the program for the next assembly. Because of this, the collaboration of the operator with the camera-guided setup provides a distinct perspective of the productivity of the robot. The intent of the operator collaborating with the robot is to adjust components and assist the robot through the assembly and inspection process to ensure a successful assembly.

Chapter 3: Results

After randomly performing these trials with the different setups and speed settings, the data collected as a result of the trials is presented in this chapter. In this report, the data is organized to present the results and analysis. However, the test trials were randomly performed to avoid any type of trend and gather the most accurate results.

3.1 Quality

After performing the trials and determining the data, one of the variables analyzed was the quality of the assembly. The quality was analyzed through the three different methods: camera-guided setup, coordinate-guided setup, and human-robot collaboration, all performed at the three different speed settings.

The camera-guided setup was the least effective in terms of successful assemblies. This setup when at 100% speed rating was only capable of successfully assembling 1 out of 30 attempts. The 29 failures were caused by different components at different phases of the assembly. It was observed that with this setup, the main cause of the failures was the misplacement of the body in the fixture. The body is the first component in the assembly sequence; if it fails at this step, it is impossible for the other components to be properly assembled. The second main cause of failures happened in the "picking" process. By failing to secure the body with the gripper, the robot returned to its home position causing the program to stop running.

Table 3.1.1: Camera-guided setup – speed 100% quality table

Camera 100%	
Inspection	
Pass	1
Fail	29
Fails by component	
Cap	10
Spring	1
Body	17
Camera	0
Gripper	1
Pin	0

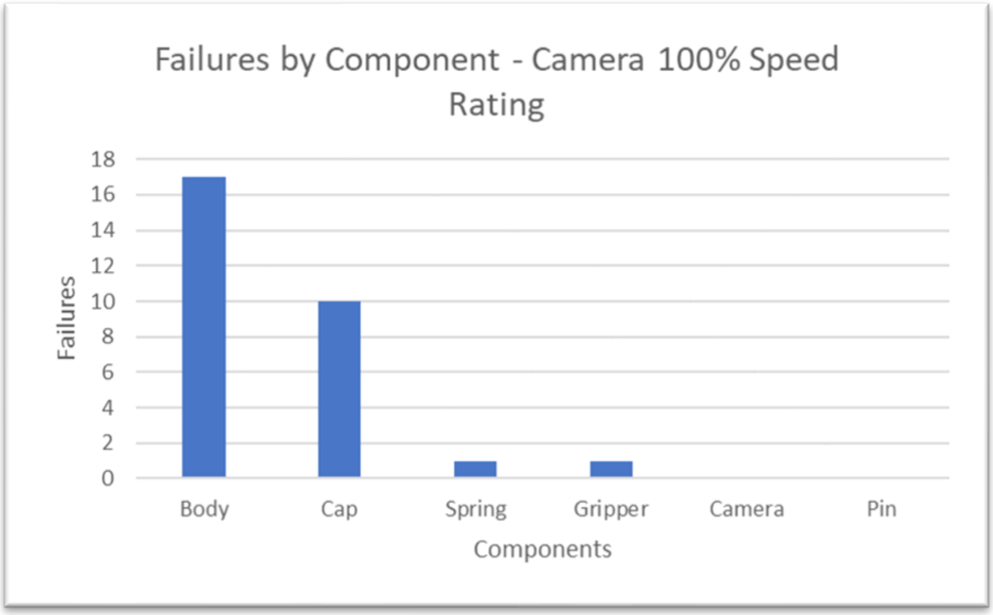


Figure 3.1.1: Failures by component for camera-guided with robot-only method at 100% speed rating

The next speed rating in the camera-guided setup was 75%, which also reflected a low-quality performance rate, successfully assembling 1 out 30 successful assembly attempts. Similar to the 100% speed rating, the components involved in the failures of the assembly were varied.

The reasons for failures were either the misplacement of the body in the fixture or the misplacement of either the spring or cap in the assembly process. It also failed in the "picking" process by not successfully securing the body at the beginning of the assembly.

Table 3.1.2: Camera-guided setup – speed 75% quality table

Camera 75	
Inspection	
Pass	1
Fail	29
Fails by component	
Cap	5
Spring	2
Body	21
Camera	0
Gripper	1
Pin	0

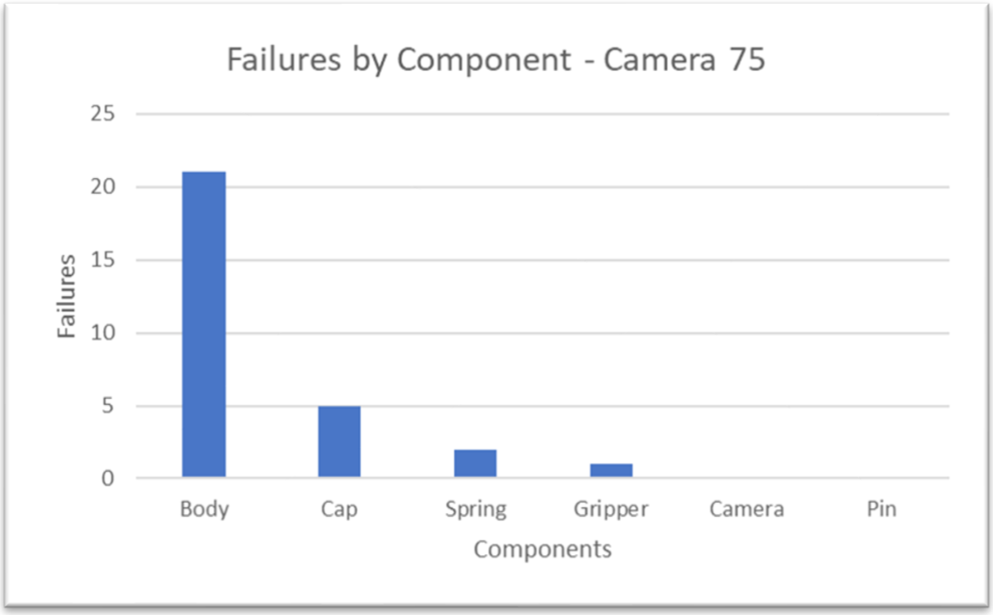
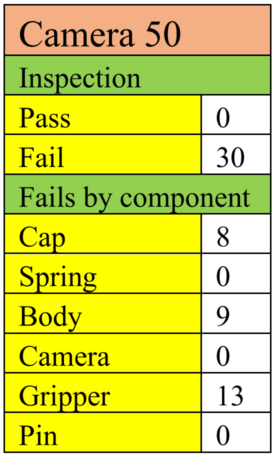


Figure 3.1.2: Failures by component for camera-guided with robot-only setup at 75% speed rating

The final speed rating of 50% showed complete failure, with all trials being unsuccessful attempts. Similar to the other two speed settings, several components were involved in these failures. Out of the three different speed ratings, the least effective in terms of quality is the 50% speed rating. Unlike the other two speed ratings, the failures that occurred at this speed rating were 17 misplacements and 13 failures occurring in the "picking" process.

Table 3.1.3: Camera-guided setup – speed 50% quality table



Camera 50	
Inspection	
Pass	0
Fail	30
Fails by component	
Cap	8
Spring	0
Body	9
Camera	0
Gripper	13
Pin	0

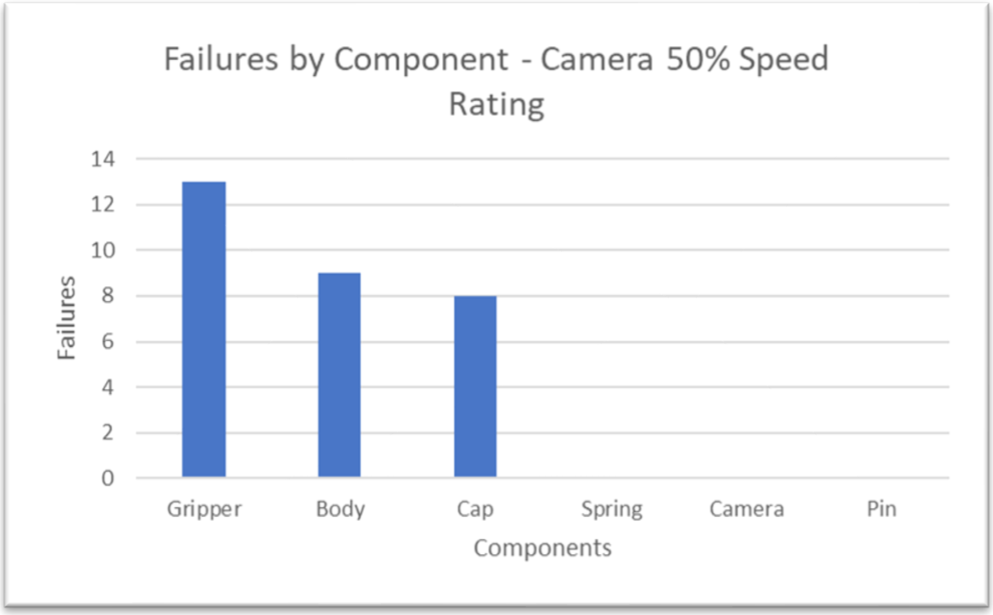
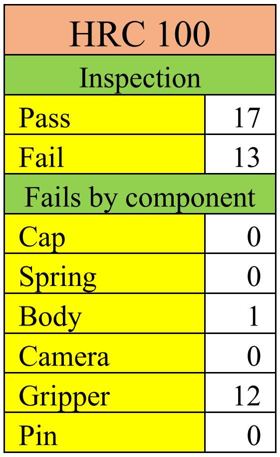


Figure 3.1.3: Failures by component for camera-guided with robot-only setup at 50% speed rating

Continuing with the camera-guided setup utilizing human-robot collaboration, there was an increase in the quality rating when a human operator assisted the robot when it failed to properly place the components. Through this method, most of the failures that occurred with the camera-guided setup with robot-only utilization were addressed by the human collaboration.

At 100% speed rating, the results showed 17 successful assemblies and 13 failures. This represents 16 more successful assemblies when comparing to the robot only camera-guided setup. For the failures that occurred during this speed rating, the only variable that a human-operator cannot assist with is the failure caused by the camera in the end-effector when it is unable to detect the components involved in the "picking" process. This statement was reflected in the results. However, it was observed that the misplacements of the components were easily detected and corrected during the assembly process due to the input of the human factor in this setup. For this setup and speed rating, 12 failures were caused by the gripper when it failed to grab the components. One failure was caused due to a misalignment between the component and the fixture, which caused the robot to engage the protective stop.

Table 3.1.4: HRC – speed 100% quality table



HRC 100	
Inspection	
Pass	17
Fail	13
Fails by component	
Cap	0
Spring	0
Body	1
Camera	0
Gripper	12
Pin	0

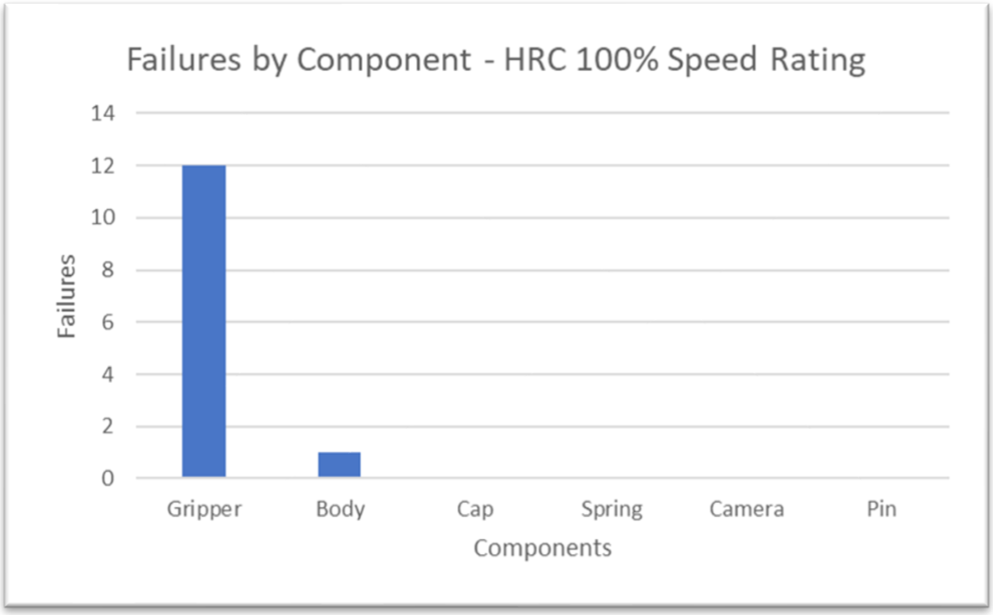


Figure 3.1.4: Failures by component for camera-guided with human-robot collaboration method at 100% speed rating

At 75% speed rating, there was a slight improvement compared to the 100% speed rating, showing 7 more successful assemblies for a grand total of 24 successes and 6 failed assemblies. Similar to the 100% speed rating, all of the failures were caused by the gripper when the robot failed to "pick" the components from their area, automatically stopping the program.

Table 3.1.5: HRC – speed 75% quality table

HRC 75	
Inspection	
Pass	24
Fail	6
Fails by component	
Cap	0
Spring	0
Body	0
Camera	0
Gripper	6
Pin	0

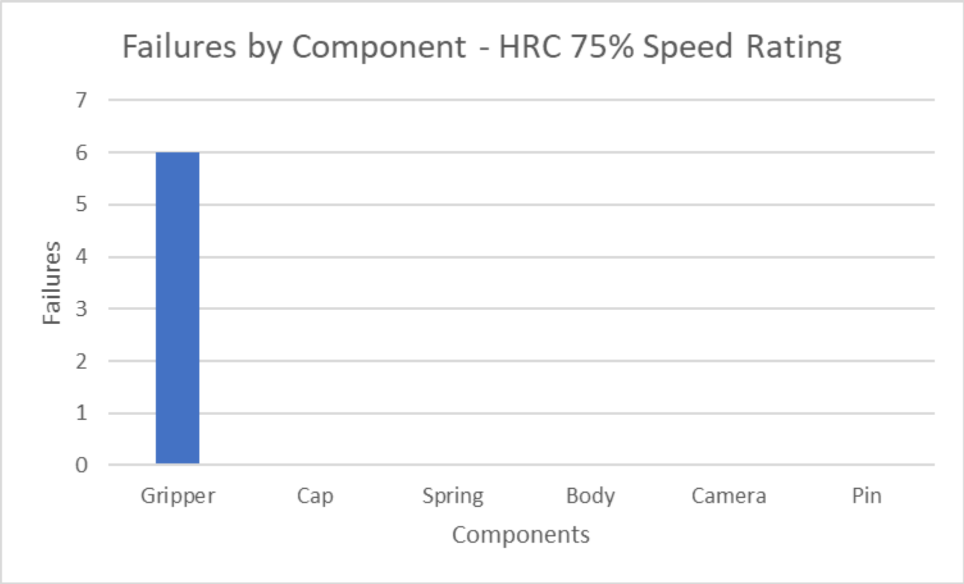


Figure 3.1.5: Failures by component for camera-guided with human-robot collaboration method at 75% speed rating

For the 50% speed rating, the results were very similar to the previous two speed ratings, showing a total of 25 successful assemblies. Just like the other speed ratings, even with having the human factor, because the sensors in the gripper were unable to properly detect and "pick" the component, it was clear that the failures were caused by the gripper, preventing the program from running.

Table 3.1.6: HRC – speed 50% quality table

HRC 50	
Inspection	
Pass	25
Fail	5
Fails by component	
Cap	0
Spring	0
Body	0
Camera	0
Gripper	5
Pin	0

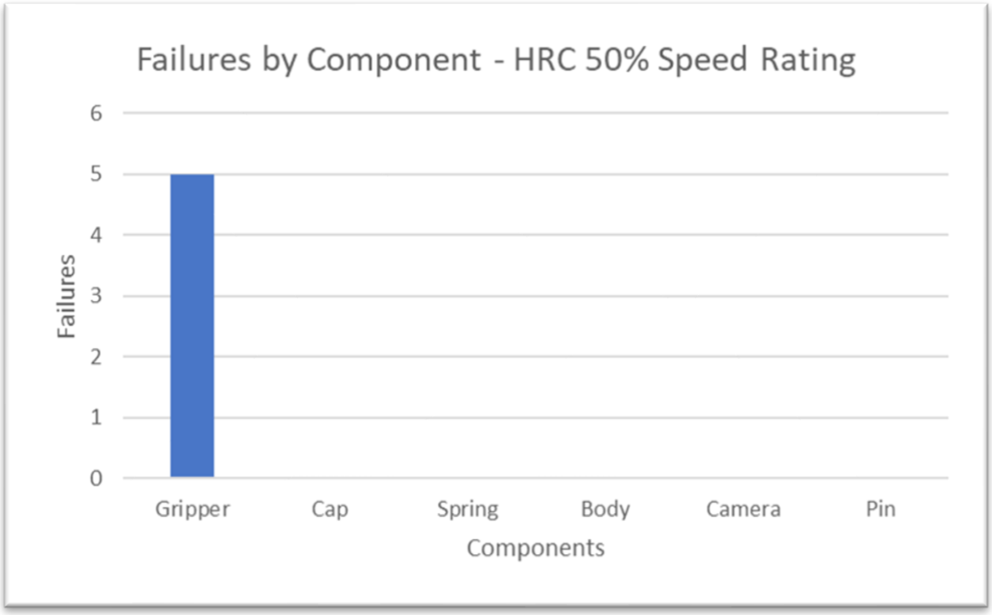


Figure 3.1.6: Failures by component for camera-guided setup with human-robot collaboration method at 50% speed rating

The last method analyzed was the coordinate-guided setup that was assisted by the 3D printed fixture. This fixture ensured the program avoided the need for the camera in the end-effector to locate the components due to the fact that the robot as programmed to repeatedly "pick" from the set location.

Similar to the other two setups, the coordinate-guided setup was analyzed with the three different speed settings. Unlike the camera-guided setup, this method was analyzed with robot-only assembly. The coordinate-guided setup shows a huge improvement in the quality rating compared to the camera-guided setup when utilizing robot-only assembly.

At 100% speed rating, the data shows that there were 28 successful assemblies and only 2 failures. Unlike the other methods, the component involved in these failures was the spring, when the robot failed to properly insert it into the body component. The coordinate-guided setup had significantly less failures than the previous two methods utilized.

Table 3.1.7: Coordinate-guided setup – speed 100% quality table

Coordinates 100	
Inspection	
Pass	28
Fail	2
Fails by component	
Cap	0
Spring	2
Body	0
Camera	0
Gripper	0
Pin	0

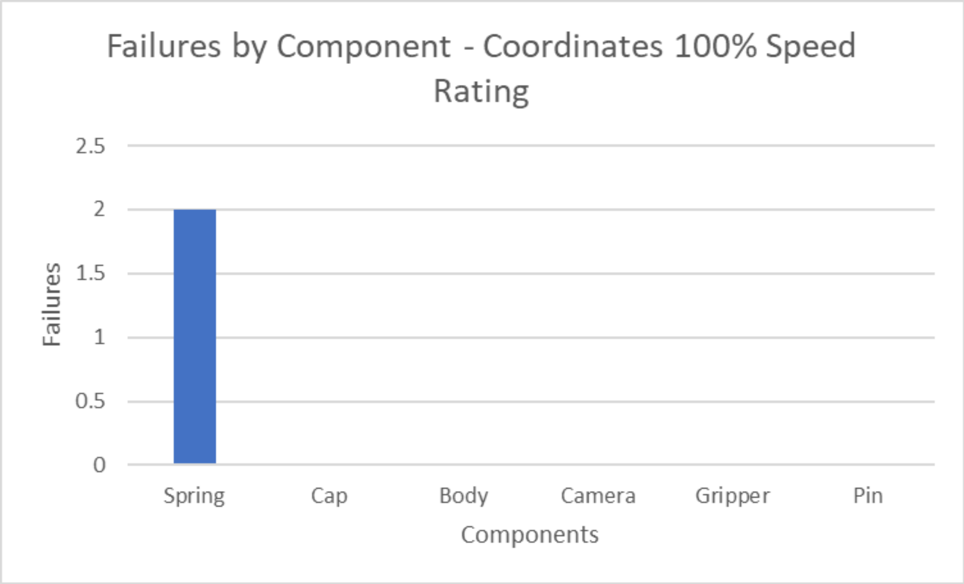


Figure 3.1.7: Failures by component for coordinate-guided method at 100% speed rating

For the 75% speed rating, there was a slight improvement in the number of successful assemblies with 29 successful assemblies. This means that out of the 30 assemblies, only 1 was unsuccessful. Once again, the component that caused that failure was the spring when the robot failed to insert it into the body component.

Table 3.1.8: Coordinate-guided setup – speed 75% quality table

Coordinates 75	
Inspection	
Pass	29
Fail	1
Fails by component	
Cap	0
Spring	1
Body	0
Camera	0
Gripper	0
Pin	0

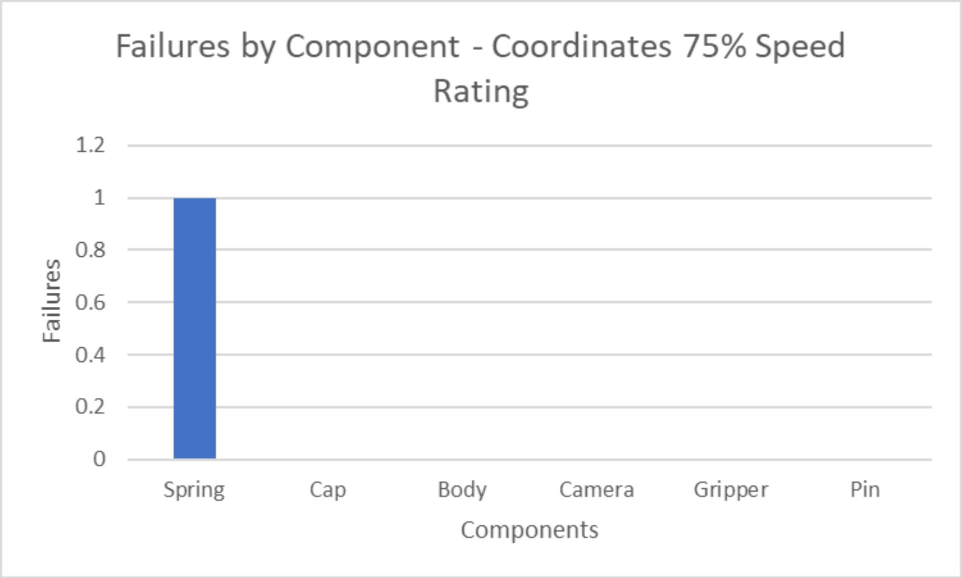


Figure 3.1.8: Failures by component for coordinate-guided method at 75% speed rating

During the 50% speed rating, the spring was once again the component responsible for the failures in the assembly process. At this speed rating, the number of successful assemblies was 27 and there were 3 failures caused by the spring. Again, just like the other speed ratings, the process failed when inserting the spring into the body component, making it impossible for the assembly to be completed successfully.

Table 3.1.9: Coordinate-guided setup – speed 50% quality table

Coordinates 50	
Inspection	
Pass	27
Fail	3
Fails by component	
Cap	0
Spring	3
Body	0
Camera	0
Gripper	0
Pin	0

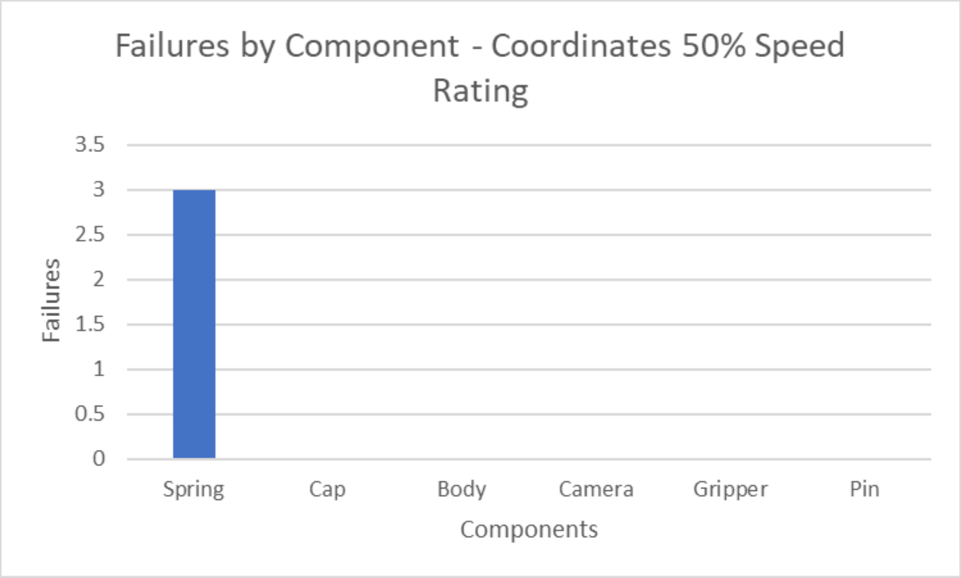


Figure 3.1.9: Failures by component for coordinate-guided method at 50% speed rating

In conclusion, at 100% speed rating, the camera-guided setup with robot-only assembly showed a 3.33% assembly success rate, while the human-robot collaboration showed an assembly success rate of 56.6%, and the coordinate-guided setup showed an assembly success rate of 93.3%.

At 75% speed rating, the camera-guided setup with the robot-only assembly showed a 3.33% assembly success rate, while the human-robot collaboration showed an assembly success rate of 80.0%, and the coordinate-guided setup showed an assembly success rate of 93.3%.

Finally, at 50% speed rating, the coordinate-guided setup with the robot-only assembly showed a 0.0% assembly success rate, while the human-robot collaboration showed an assembly success rate of 83.3%, and the coordinate-guided setup showed an assembly success rate of 90.0%.

3.2 Productivity

Another variable analyzed during the experimentation portion of this investigation was productivity. To measure the productivity, the time that the station took to complete a successful assembly was measured. The average time was analyzed for all methods at the three different speed settings.

At 100% speed setting, the average times between camera-guided setup with the robot-only versus the human-robot collaboration were virtually the same, with the first measuring at 2.94 minutes per assembly and the latter measuring at 2.96 minutes per assembly. However, there was an increase in the productivity when utilizing the coordinate-guided setup, measuring at 2.00 minutes per assembly.

Table 3.2.1: Average time at 100% speed rating

Camera 100		HRC 100		Coordinates 100	
Average Time		Average Time		Average Time	
Minutes	2.94	Minutes	2.96	Minutes	2.00
Seconds	176.4	Seconds	177.71	Seconds	119.76

For the 75% speed rating there was a logical increase in the cycle time due to the reduction in the speed. However, there was greater increase in the cycle time when using the camera-guided setup and robot-only assembly, resulting in a cycle time of 3.52 minutes, while the human-robot collaboration increased to 3.39 minutes. The average cycle time for the coordinate-guided setup increased to 2.39 minutes.

Table 3.2.2: Average time at 75% speed rating

Camera 75		HRC 75		Coordinates 75	
Average Time		Average Time		Average Time	
Minutes	3.52	Minutes	3.39	Minutes	2.39
Seconds	211.2	Seconds	203.28	Seconds	143.46

Finally, at the slowest speed rating of 50%, the camera-guided setup with robot-only assembly did not record any time since none of the 30 trials were successful. In the human-robot collaboration, the recorded average cycle time was 4.70 minutes, while the coordinate-guided setup recorded an average cycle time of 3.27 minutes.

Table 3.2.3: Average time at 50% speed rating

Camera 50		HRC 50		Coordinates 50	
Average Time		Average Time		Average Time	
Minutes	N/A	Minutes	4.70	Minutes	3.27
Seconds	N/A	Seconds	282.14	Seconds	196.47

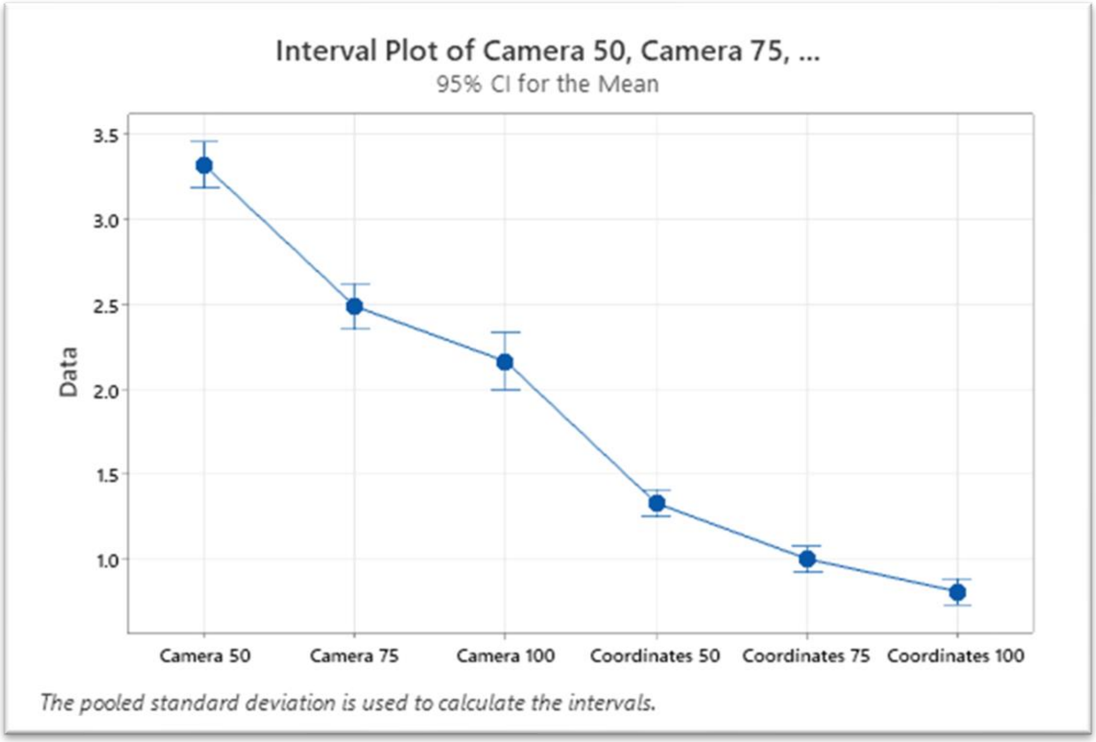


Figure 3.2.1: Statistical analysis cycle time plot

Chapter 4: Conclusion and Discussion

The purpose of this experiment was to demonstrate how the collaborative robot and the other Industry 4.0 technologies embedded in the Smart Manufacturing station can be deployed to small and medium size companies that desire to automate without the excessive upfront high cost of fully automated robots, as well as to maximize the flexibility of the applications and programs this technologies offer. At the same time demonstrate how this collaborative robot can collaborate with a human-operator to optimize tasks, or to fully relieve the human factor from performing dangerous tasks such as welding and handling hazardous materials while increasing its accuracy. Also, these collaborative robots can replace human-operators in highly controlled environments to minimize risk of contamination in industries such as healthcare and technology.

Based on the results and the observations, from the productivity standpoint, the camera-guided setup with the robot-only assembly method showed the lowest productivity rate and had a 3.33% assembly success rate at both 75% and 100% speed rating. At the 50% speed rating, this method showed a 0% assembly success rate. This setup also recorded the highest cycle time when compared to the coordinate-guided setup. However, when incorporating the human factor to collaborate with the robot, the quality increased and reflected an 83.3% assembly success rate at the 75% speed rating, while the 100% speed rating showed a 56.6% assembly success rate, which shows a significant improvement compared to robot-only.

The most effective setup in terms of quality was the coordinate-guided setup, which also was the most consistent through the different speed rating changes. This setup gave a 93.3% assembly success rate while also having the lowest cycle time out of the three methods observed. At the 100% speed rating, the coordinate-guided setup showed a 0.95-minute improvement in the cycle time compared to the two methods using a camera-guided setup.

The reasons for the failures varied highly from one method to another, making it difficult to determine which particular variable affected the assembly process. For the camera-guided setup, most of the failures that occurred were misplacements with the body component in the fixture, representing 71.5% of the failures.

Implementing a human operator in the camera-guided setup created an improvement in the successful assembly rates. By having a human-operator working in collaboration with the robotic arm, the human-operator assisted with some of the errors created by the robot, like the misplacements. When a component was misplaced by the robotic arm, the human-operator would fix the error and properly aligned the component for the assembly sequence to properly continue. However, if an error happened during the “picking” process, the human-operator would not be able to assist the collaborative robot due to the nature of the safety features and the way the program was created. By analyzing the data, it is clear that having a human-robot collaboration improved the quality in the process due to the previously mentioned statements. The coordinate-guided setup showed the most positive results in terms of both productivity and quality. The failures in this setup happened at the same step of the assembly, which occurred when inserting the spring into the body component.

The reason for this productivity and quality rate is presumed to be due to the high repetitiveness that the coordinates and the fixtures offer. However, to maximize the benefits of the camera in the end-effector that the coordinate-guided setup cannot provide, such as proper detection of components and to automate with the autonomy of the robots, it is necessary to address certain technical aspects of this technologies. The camera-guided setup showed that the lack of repeatability or consistency in the placement of the components during the “picking” process could have altered the effectiveness of the camera in the end-effector. Because of this, a higher definition camera is required, as well as retraining the camera to look for certain features that could potentially facilitate the decision-making process of the robot regardless of the placement. In addition, the lack of conducting the experiment in a controlled environment may have presented additional variables; one example is the lighting in the lab, which may have altered the effectiveness of the cameras.

In conclusion, to maximize the deployment of the Industry 4.0 technologies, it is important to determine the technical requirements of the process and to determine the right equipment for the process. In this case a better camera is needed for the collaborative robot to autonomously perform this process and do the decision making. In the meantime, using the coordinate-guided setup could be useful as a backup plan since it show good quality and efficiency; however certain aspects of quality cannot be addressed such as similar components that could alter the assembly.

Chapter 5: Future Work

A continuation of this research is recommended in order to determine additional and more accurate results. Based on the conclusion, it was determined that to maximize the camera-guided setup, utilizing an end-effector with a high-definition camera could potentially assist in a more efficient in the process of component detection. Besides that, it is recommended once this is addressed, to challenge the assembly by integrating components with similar characteristics to use the camera as an error-proofing mechanism and improve quality.

Also, performing the examination in a controlled environment, to simulate processes performed under control environments to mitigate external factors for the Smart Manufacturing station is recommended. Additionally, calibration of the equipment in the Smart Manufacturing station is recommend before performing new studies. It is also recommended to implement I/O link sensors that create data from temperature, voltage, counters, and additional variables in order to gather additional data from the Smart Manufacturing station. This is to be able to keep integrating Industry 4.0 technologies and gain additional real-time data from multiple factors. This would also enable data analytics given that all the data would need to be sorted and cleaned to reflect the most accurate results.

Figure 5.1: Motion detection/counter I/O link sensor

Figure 5.2: Mobile I/O link cart showing different types of connections

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Vita

Carlos Felipe Manzanares Vega is the second child of Carlos Manzanares Reaza & Flor Ma.Vega Rodriguez. Born and raised in Chihuahua, Chihuahua, Mexico, he attended to Colegio Bachilleres #3 for high school before enrolling in the Electromechanical Engineering program at the Instituto Tecnologico de Chihuahua in 2010. After a semester he transferred to the Universidad Autonoma de Chihuahua to pursue a bachelor's in Aerospace Engineering. After a year in the program, Carlos transferred in 2012 to the University of Texas at El Paso to pursue a bachelor's in Industrial Engineering. While at UTEP, Carlos served as VP of Finance and President for the Institute of Industrial and Systems Engineers UTEP chapter. After graduating in 2017, Carlos started working as an Industrial Engineering consultant at IET, Inc, a consulting firm based in Toledo, OH.

During his time as a consultant, Carlos had the opportunity to work at several companies from the automotive, food, logistics, and oils & additives industries, such as WIT Logistics, Bimbo Bakeries, among others.

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