Selection Criteria for Deployment of Collaborative Robots

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Abstract:

The global market of Collaborative Robots has been growing in the past years, resulting in new and creative applications that fall outside of the typical manufacturing applications. Even though newer generations of Collaborative Robots have been able to thrive in many applications and processes, there are still scenarios in which Collaborative Robots underperform.

The objective of this project is to create a set of criteria for users to determine whether a process can be efficiently performed by a Collaborative Robot based on its limitations. The rationale for this project is to implement new applications for collaborative robots as the industry has struggled to increase market share outside of the industrial sector. The state of the art of Collaborative Robots has been mostly present in manufacturing processes and applications due to their ability to perform repetitive tasks with consistency and precision. The methods used involved data gathering through interviews and surveys with experts across various fields, and testing of a collaborative robot. The results show our data and analysis to create the set of criteria. The conclusions are that establishing a set of criteria for Collaborative Robots applications will help individuals determine if an application is appropriate for a Collaborative Robot to perform, resulting in an expansion and diversification of the current market for Collaborative Robots.

Acknowledgments:

The authors of this report would like to express their sincere gratitude to WPI Business School Associate Teaching Professor Walter Towner for his invaluable guidance and mentorship throughout this MQP.

A very special thank you is also extended to Christopher Savoia for inviting us to the Universal Robots office for a priceless opportunity for our team to attend a training session at Universal Robots and extending an invitation to visit Massrobotics, as well as introducing us to the founders of the startup Flexxbotics.

Lastly, the team would like to acknowledge Dean Debora Jackson for helping us with the acquisition of the UR5e robot for the WPI Business School.

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1. Introduction

The WPI Business School acquired two collaborative robots from Universal Robots with the intent of integrating them as educational tools. However, the unforeseen challenges posed by the pandemic delayed their meaningful utilization on the WPI Campus. In response, our team was assigned the task of creating a set of criteria in order to find applications for collaborative robots.

Our objective was to create a set of criteria where the team would be able evaluate different tasks and test if they passed or failed the set of criteria for an arbitrary application. Throughout this project, the team explored and analyzed innovative possible applications, seeking to understand the potential of these collaborative robots and their capacity.

Figure 1. Picture of the UR5e from Universal Robots.

2. Background

Collaborative robots are transforming the landscape of automation by working safely alongside humans (Sherwani et al. 2020). However, a systematic approach to assessing their opportunities and designing them for maximal efficiency and safety is lacking. This paper presents an axiomatic design-based set of criteria for collaborative robots.

2.1 Labor Market

Since 2018, all but the youngest baby-boomers have reached retirement age. The Baby Boom, which spanned from 1946 to 1964, resulted in the birth of 76 million people (Bureau of Labor Statistics, 2000). This demographic event has had a profound and lasting impact on the economy, labor force, and job market over the past six decades. As Baby Boomers retire, there have been substantial effects on the economy and various industries, creating a need for younger workers to replace them. The aging of the Baby Boomer generation has influenced the composition of the labor force, with Baby Boomers making up a substantial portion of the workforce in the past. However, as they retire, the percentage of workers aged 45 and older increased from 33 percent in 1998 to 40 percent in 2008, reflecting an increasing trend. And aggravating the situation is a much smaller pool of workers immediately following the baby-boomers who have also reached retirement age (Bureau of Labor Statistics, 2000).

Numerous jobs in manufacturing, mining, retail, fast food, data entry, manual labor, telemarketing, and more often struggle to attract new talent due to their repetitive, physically demanding, or low-paying nature. Many people are deterred by the perceived dullness or limited career prospects associated with these positions (Bureau of Labor Statistics, 2000).

In response to the challenges posed by the retirement of the Baby Boomer generation and the reluctance of younger workers to fill certain job roles, many industries have started exploring innovative solutions to bridge the labor gap. One such solution is the introduction of collaborative robots. These robotic systems are designed to work alongside human employees, complementing their skills and automating repetitive and physically demanding tasks. Collaborative robots have revolutionized the way businesses operate by increasing efficiency, productivity, and safety, and they have opened up new avenues for addressing the workforce shortage issue.

2.2 Collaborative Robots

Collaborative Robots are not meant to replace human workers entirely, instead their purpose is intended for direct interaction and handling shared payloads (Peshkin & Colgate, 1999). Collaborative robots are a type of technology that integrates robots and humans in workspaces. Their most relevant feature that separates them from industrial robots is their advanced safety mechanisms that are in place in order to reduce human related accidents (Gurgul, 2018). Collaborative robots are designed with advanced and accurate sensors that provide extra safety to the system. Some advanced safety features that are used when deploying colab robots in a system are the Safety-rated Monitored Stop (SMS), the Hand Guiding (HG), the Speed and Separation Monitoring (SSM) and the Power and Force Limiting (PFL) (Robotic Industries Association. 2012, 2016). SMS is a system in which a motion sensor is installed and when a person is detected near the robot's workspace the operation is stopped and once the sensor is off the robot starts the operation again. Hand guiding only allows the robot to move when it is being operated manually by a worker, it also has a SMS system integrated in order to reduce risk. SSM uses a video sensor and it stops the robot any time a person exceeds the minimum required distance away from the colab robot, once the person leaves the minimum range the robot resumes the operation, sometimes instead of stopping the robot can be programmed to reduce its speed. PFL requires the robot to have accurate pressure sensors built in its hardware, the system programs the robot to stop operations if it encounters any type of pressure or resistance.

2.3 Historical development of collaborative robots

The historical development of collaborative robots is a journey of technological and innovation advancement. The idea of collaborative robots has been around for many years, but some of the early developers were professors J. Edward Colgate and Michael Peshkin at Northwestern University in 1996. At first, they envisioned a new kind of robot that would work hand-in-hand with humans, which was completely different from the isolated industrial robots of the time. Three years later, this vision materialized with the filing of the first cobot patent in 1999, setting a precedent for future developments.

In the early 2000s, in order to enhance the safety and interactivity of these robots, engineers discovered the major breakthroughs should be advanced sensors and control algorithms, which allow collaborative robots to detect and respond to human presence and movements. At the same time, they bring in safety features like force-limited joints and real-time monitoring, which were pivotal in enabling close human-robot interaction.

By the 2010s, due to technological advancements and the increasing demand for flexible automation solutions, the collaborative robot market has begun to expand rapidly. As the leading enterprises in the industry, companies like Universal Robots, KUKA, and Rethink Robotics increased their investment in innovation and introduced more sophisticated and user-friendly models. The collaborative robots produced by these companies not only have complete and detailed operating logic, but are also equipped with intuitive interfaces, allowing buyers who are mostly non-experts to easily program and operate them. One of the most representative events happened when Rethink Robotics released Baxter in 2012, a milestone robot in the field of collaborative robots. Known for its expressive face and ease of demonstration in training, this invention also brought collaborative robots to the attention of the world.

With today's further development of artificial intelligence and machine learning, the capabilities of collaborative robots have been further refined. Today's collaborative robots are not only safer and more efficient, but also, by integrating AI products such as OpenAI and X AI, they are capable of autonomous learning and adapting to new tasks, making them suitable for a wide range of applications. With the enhancement of technology in various fields, collaborative robots have evolved from machines with fixed programming and single-purpose use to adaptive collaborative partners. This has completely changed the way humans interact and work with robots, opening up new areas in automation and labor augmentation.

2.4 Unsuccessful applications of collaborative robots

Integrating collaborative robots and human workers within industrial processes poses multiple challenges. There are inherent risks linked to the integration of collaborative robots. In Korea, there is an increasing use of collaborative robots in the manufacturing sector, where these robots work alongside human operators has created concerns regarding the inherent risks associated with cobot deployment (Wonseok, 2020). These risks arise when collaborative robots do not function as intended and have the potential to cause occupational injuries. As the prevalence of collaborative robots rises, the likelihood of accidents also increases, with accident probabilities similar to the average in the industry, categorized as "average-risky."

There are several factors contributing to these risks. Traditional industrial robots have safety mechanisms that may not be as effective for working in close proximity to humans. A very important factor for accident prevention is the proper installation of the cobot. Despite collaborative robots generally being considered safer than traditional industrial robots, the data indicates that accidents involving collaborative robots are not uncommon, often due to technical errors, human errors, and organizational oversights.With technological advancements, such as virtual safety fences and safety certification systems, the frequency and severity of accidents can be reduced. Safety training for workers to adapt to working with collaborative robots is of the utmost importance. The ultimate goal is to ensure the safe coexistence of humans and collaborative robots in the evolving industrial landscape.

2.5 Collaborative Robots VS Industrial Robots

A case study on the Hirebotics website illustrates how collaborative robots can be more cost effective, productive, and more accepted within an industrial metal shop than traditional caged robots. IMS, an Industrial Manufacturing Services, who fabricates metal in the heavy machinery industry faced challenges in meeting the demand for parts due to a shortage of manual welders, prompting the exploration of automation as a solution. Acquiring traditional robotic cells initially, however, proved expensive, took up too much floor space and required a team of three to handle programming and operation. Seeking a more efficient solution, IMS turned to Hirebotics' Cobot Welder.

After implementing the collaborative robots, IMS found them to be significantly more user-friendly than traditional robots. Programming times were drastically reduced, with tasks that took over an hour with traditional robots now completed in just minutes. The ability to transfer programs between machines seamlessly and troubleshoot in real-time using a mobile app further enhanced operational efficiency.

The implementation of Hirebotics' Cobot Welder resulted in a substantial increase in productivity and cycle times for IMS' welding team. While matching the performance of traditional welding robots in terms of speed and accuracy, the Cobot Welder offered the distinct advantage of simplified programming and operation, contributing to overall operational efficiency and productivity gains.

2.6 Collaborative robot market

The collaborative robot market is on a growth trajectory, the market is a relatively new big technological market. Since the introduction of colab robots the market has been growing due to their high demand in manufacturing sectors. Projections suggest that the cobot market, valued at $1.9 billion, is expected to skyrocket to over $16.8 billion by 2028 (Content Engine, LLC). This growth is driven by several key factors. The automation of collaborative applications is expected to play an important role in exponentially increasing cobot deployment across a wide range of industries. The biggest limitation that collaborative robots have is that they are hard to deploy in a new environment due to system design and safety assessments. Another factor of growth is the need for ergonomic applications in workspaces, due to the increase in musculoskeletal disorders (MSDs) in industries (Maurice et al.). The implementation of collaborative robots in workspaces can offer an increase of ergonomic indicators in industries that results in the protection of the workers. The implementation of collaborative robots has become possible in work environments that require assistance, a common rule used to identify possible applications is the dull, dirty and dangerous rule. If a task is repetitive (Dull), located in an unpleasant environment (Dirty), or it has some risk attached to it (Dangerous), it can be a good fit for a Cobot integration (Appendix A).

2.7 Economic and social impact

The integration of collaborative robots across diverse industries not only fosters technological and scientific advancement but also drives economic and social development.

BMW initiated the incorporation of collaborative robots into its production line at the Spartanburg plant in September 2013. This strategic move resulted in a reduction of workplace injuries and a notable increase in overall productivity, highlighting the tangible economic benefits of cobot integration.

In retail and logistics, the use of collaborative robots in Amazon has significantly enhanced efficiency and productivity. These collaborative robots are trained for tasks like sorting and packaging, streamlining these processes to enable faster order fulfillment. This automation not only reduces operational costs but also improves the overall speed and efficiency of their logistics chain. By integrating collaborative robots into their systems, Amazon has been able to manage large volumes of orders more effectively, demonstrating the substantial benefits of using collaborative robots in high-volume retail operations.

In the social sphere, collaborative robots are driving the transformation of the entire social system towards personalized services, intelligent production, and efficient work models, thereby promoting the innovation of social structures and modes of interaction. The medical and healthcare department, for example, the application of collaborative robots is becoming increasingly important. They are primarily used for assisting in medical procedures, patient care, and rehabilitation training. For example, some collaborative robots are designed for surgical assistance, providing more precise control and thus increasing the success rate of surgeries. Additionally, they are used for transporting medical equipment, reducing the physical burden on medical staff. In rehabilitation training, collaborative robots assist patients in regaining physical functions through precise movement assistance and feedback. These applications not only improve the quality and efficiency of medical services but also enhance the treatment experience for patients.

In addition, in the field of education, collaborative robots developed by companies like ABB are being used as teaching aids in engineering and robotics courses. As collaborative robots evolve, and with the integration of AI and machine learning, this field has created excellent job opportunities for students in robotics. It also opens up more career paths for students in mechanical and programming specializations. Even industrial engineering students can focus on integrating collaborative robots more perfectly into production and supply chains in the future.

These real-life examples highlight how collaborative robots are more than just machines taking over tasks; they are agents of economic efficiency and social change.

2.8 Universal Robots

Universal Robots, founded in 2005, specializes in collaborative robots for various industrial applications. The company, headquartered in Odense, Denmark, has 18 office locations globally. These include multiple locations in the United States (Ann Arbor, Boston, Garden City, Irvine, and Plano), as well as offices in China and Europe (Shanghai, Praha, Suresnes, and München). This global presence allows the company to effectively distribute their collaborative robot technology across various markets and industries.

Their collaborative robots are known for their flexibility, high-quality performance, and ease of integration into various tasks such as palletizing, welding, machine tending, assembly, dispensing, finishing, material handling, and quality inspection. Universal Robots offers a range of cobot models, each designed to suit different industrial needs, with features like varying reach and payload capacities. They also provide a comprehensive UR+ ecosystem, which includes certified kits, components, grippers, software, and safety accessories, ensuring seamless integration with their collaborative robots. The company emphasizes the importance of making automation accessible and efficient for businesses of all sizes, supported by their global installation of over 75,000 collaborative robots . They also offer educational resources through the UR Academy to help users master robotic technology. Our team had the opportunity to participate in the UR Academy training at the company's Boston branch through an alumnus, which allowed us to gain a deeper understanding of the company and its machines, thereby better completing this MQP.

2.9 Universal Robots' UR5e

The UR 5e is a robotic arm developed by Universal Robots, a Danish company specializing in collaborative robotic solutions. Designed for applications demanding a compact yet capable cobot with ample reach and payload capacity. It excels in performing precise and meticulous tasks.

The UR5e is designed to work alongside human operators in a collaborative manner. It is equipped with safety features that allow it to operate in close proximity to humans without the need for physical barriers. The UR5e has six joints or axes, providing it with the flexibility to reach different positions and orientations. This allows it to handle a wide range of tasks in manufacturing and automation, as it has a payload capacity of up to 5 kilograms (11 pounds). Making it suitable for handling a variety of objects and tools in industrial processes. One of the standout features of Universal Robots' robotic arms is their user-friendly programming interface. The UR5e can be programmed using a teach pendant (*Figure 2*) or through graphical user interfaces, making it accessible even to users without extensive programming expertise.

Figure 2. Image of the teaching pendant from Universal Robots.

3. Methods

Our methods section presents the process the team used to achieve our set of criteria. It focused on four aspects: surveys to students and professors around campus, interviews with subject experts in their respective field, testing of the UR5e, and a critical analysis of the information gathered to create the set of criteria.

3.1 Surveys to students and professors

The team designed a survey that was sent to WPI professors from all the departments. This survey aimed to gather the opinion of multiple students and experts from different fields regarding the implementation of Collaborative Robots in their specific field of study. In order to see how interested our chosen demographic was about collaborative robots the team asked the participants to rate the usefulness of Collaborative Robots in their field on a 1 to 5 scale. Then the team asked the participants to provide us with any processes or applications in their field of study that could be performed by a Collaborative Robot. With this data the team could use the set of criteria to pass through each application and grade them.

3.2 Interviews with subject experts

Through the course of the project, the team engaged with subject experts, conducting interviews to gain insights into their perspectives on integrating collaborative robots within their specific industries. To identify these experts, the team searched for individuals in positions of teaching or These interviews aimed to understand each expert’s viewpoint regarding the potential benefits and challenges associated with the incorporation of collaborative robots.

3.3 Testing

The team implemented a testing phase for our project that focused on current applications of collaborative robots. Part of this included training, visual implementation, and a live presentation.

As our robot was set on a table when it was given to us, it was difficult to use. The team decided to implement a mobilization option to move our robot around and be able to use it. To gain a comprehensive understanding of our cart's design, the team utilized SolidWorks to create a detailed 3D model as seen in *Figure 2*. This modeling process helped us visualize the intricacies of the cart before its actual construction.

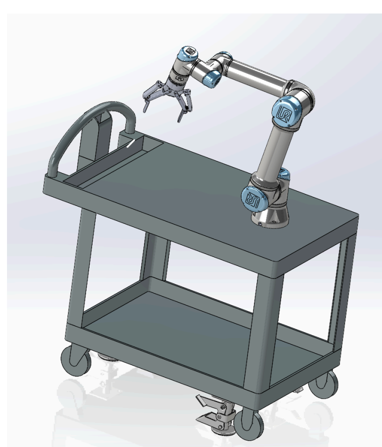


Figure 3. Image of the Solidworks Assembly, UR5e model provided by Universal Robots, and cart model provided by McMaster-Carr.

3.4 Analysis of results

This objective focused on analyzing the gathered data from the surveys, interviews, and published articles online about Collaborative Robots to create the set of criteria. To find these published articles, research was done on Google Scholar. Then, after thorough reading, these were sorted as useful and not useful, depending on their relevance to the objective. It was important to keep in mind the big question: “What other industries can incorporate collaborative robots?”. The team had to keep in mind that collaborative robots are already being used in the manufacturing sector and our analysis had to find what other applications that the team could incorporate.

Our set of criteria will work as a grading system, aiming to use our gathered data while analyzing current applications to make sure the criteria worked. The team also passed our survey data through, to then be able to determine what applications actually make sense to use a collaborative robot in and what applications might be too difficult because of limitations.

4. Results

This section presents the results from our project and the result of the system the team used to create our set of criteria.

4.1 Survey Results

The data gathered from the survey responses helped shed light into many innovative applications of collaborative robots in different fields that are not typical manufacturing applications. One of the survey questions asked the participants if they thought the implementation of collaborative robots in their work environment was beneficial, the survey showed that 86.1% of the participants agreed that the implementation of Cobot applications would be beneficial. The survey then asked participants to rank the usefulness of implementing collaborative robots in their work environments from 1 to 5, the results showed that 58.3% of the participants ranked the collaborative robots between 4 and 5. In order to get the participants ideas regarding the implementation of collaborative robots in their work environment, the survey asked the participants to write on ideas of Collaborative robots implementation in their work field. Here are some of the most innovative responses gathered with the survey:

All the possible usage suggestions from the survey write-in responses are already being used in labs and factories around the world. So, the actual feasibility of the task does not need to be tested, but instead, the feasibility of implementation and incorporation at WPI needs to be investigated. This investigation will revolve primarily around the willingness of administrators and educators to utilize these robots. Because space utilization is not a limiting factor due to their compact size. The robot's payload limitation does not affect most of the suggested usages. And lastly the speed of the robot is not a limiting factor since WPI is not mass producing a product for sale.

In the following sections, the team expands on suggestions from our survey:

4.1.1 Repetitive Welding Needs and Working with Hazardous Material

Using a cobot for welding tasks offers a range of benefits in terms of efficiency, precision, and safety in industrial settings. Here is how a cobot can be utilized for welding tasks:

Precise Welding Operations: Universal Robots have advanced sensors and programming capabilities to execute precise and consistent welding operations. Through careful programming and calibration, collaborative robots can perform welds with high accuracy, reducing the need for manual adjustments and minimizing the risk of errors ("Engineering Excellence: Manufacturing Straightening Machines in Punjab", n.d.).

4.1.2 Flexible Automation

Collaborative robots are designed to be highly flexible and adaptable to different welding applications. They can easily be programmed to weld various materials, shapes, and sizes, making them suitable for various welding tasks across different industries.

4.1.3 Collaborative Operation

Unlike traditional industrial robots that require safety barriers or cages, collaborative robots are designed to work collaboratively with human operators collaboratively. This means that collaborative robots can perform welding tasks near human workers, enhancing productivity and efficiency on the shop floor.

4.1.4 Enhanced Safety

Collaborative robots have built-in safety features, such as collision detection and force-limiting technology, that ensure safe operation in dynamic environments. This helps to minimize the risk of accidents and injuries associated with welding operations.

4.1.5 Ease of Programming

Universal Robots offers user-friendly programming interfaces that allow operators to teach the cobot new welding tasks quickly and easily. This reduces the need for specialized programming expertise and enables rapid deployment of automation solutions in welding applications.

4.1.6 Increased Productivity

By automating repetitive welding tasks, collaborative robots can help to increase overall productivity and throughput in manufacturing operations. This allows human operators to focus on more skilled and value-added tasks, improving efficiency and cost savings.

Collaborative Robots offer a versatile and cost-effective solution for automating welding tasks in various industries. By leveraging the capabilities of collaborative robots , manufacturers can achieve higher levels of precision, efficiency, and safety in their welding operations.

However, there are important considerations to address when using a cobot to stir acid. The design of the cobot and its compatibility with acidic environments must be carefully evaluated to prevent corrosion or damage to the robot over time. A cobot can be equipped with protective covers, sensors, and emergency stop buttons to prevent accidents and protect human operators from exposure to hazardous chemicals. Another main reason to consider a cobot to work with acid or other harmful chemicals is that collaborative robots can integrate with safety protocols and systems, such as automated leak detection sensors and ventilation systems, further reducing risks associated with chemical handling. However, even when using a cobot, proper safety protocols, including containment measures and emergency response procedures, should also be established to mitigate any risks associated with handling acid solutions.

4.2 Interview Results

During our interviews with subject experts, a common theme emerged: the recognition of the significant potential for collaborative robots within their respective industries, as was our objective.

Professor Carrick Eggleston, head of the Civil, Environmental, and Architectural Engineering department at Worcester Polytechnic Institute, highlights the increasing adoption of robotics in construction due to industry demands for efficiency and reduced manual labor

(Appendix B). Collaborative robots offer relief from physically demanding and repetitive tasks like painting, insulation, roofing, and board cutting. Precision tasks, such as laser cutting for outlet sockets, are well-suited for robots. He stresses the importance of digital imaging for guiding robots accurately, especially for tasks like hole placement. Prefabrication and off-site manufacturing are emerging trends requiring digital models for precise on-site assembly. However, integrating robotics faces challenges like diverse building designs, regulatory compliance, and sustainability demands. Companies should invest in tailored digital solutions and R&D to overcome these challenges and advance construction robotics effectively.

Through our interactions with students from the biological and chemical laboratories at Gateway, along with interviews conducted with PhDs working there, the team gained insights into the staff's needs regarding collaborative robots. It became evident that the demand for collaborative robots was particularly pronounced for tasks characterized by high levels of repetition or those involving dangerous chemicals. In response to this, the team identified one of the most representative instruments within Gateway to exemplify these needs. Yufei Zhang, a PhD student in Chemical Engineering, expressed a desire for collaborative robots to take over this routine task that not only involves repetitive actions but also exposes her to hazardous chemical solvents.

Figure 4. Chromatography column.

In the chemical laboratory a prominent apparatus frequently encountered is a large chromatography column. This instrument is pivotal for the separation of polar and non-polar chemical substances. The typical procedure involves sequentially filling the column with cotton, silicon, fine sand, and a solvent, establishing the foundation for the experiment. Subsequently, the chemical solution intended to be separated or analyzed is incrementally introduced from the top. This process is complemented by the continuous addition of various solvents and the adjustment of reaction times, tailored to elicit the desired outcomes. Such meticulous methodology enables researchers to isolate and collect the targeted compounds efficiently.

In enhancing laboratory efficiency, productivity, and precision in experiments, our collaborative robot can perform several tasks in conjunction with the chromatography column. After discussions with PhD researchers in the lab, it has been determined that the cobot can significantly assist lab personnel by:

- Automating the solvent addition process: The cobot can be programmed to use a pipette, applying a predetermined force and adjusting its mechanical grip to accurately dispense solvents into the column at set intervals. This automation relieves researchers of monotonous, repetitive tasks, allowing them to focus on more complex aspects of their work. Moreover, the cobot's ability to precisely control the force of dispensation and the timing of solvent addition not only reduces human error but also enhances the accuracy and reliability of experimental outcomes.
- Collecting experimental products at predetermined intervals: A cobot designated for collecting products can be networked with the one responsible for adding solvents. This enables the product-collecting cobot to be pre-set to pick up a new tube and collect different experimental products at specific times. This systematization not only

streamlines the experimental process but also enhances the accuracy and efficiency of the laboratory work.

By leveraging the cobot's capabilities, laboratory workflows can be optimized, leading to increased efficiency and higher-quality results. This integration represents a significant step forward in the application of robotics in school's scientific research, showcasing the potential of collaborative robots to revolutionize traditional campus laboratory practices.

4.3 Testing Results

Part of our testing results not only included our own testing on campus, but also simulations of different Universal Robots models doing their assigned tasks. As mentioned before, these robots are best for working in industrial settings so most of our results were in that sector.

At the beginning of the project, Chris Savoia, a former WPI alumni currently employed at Universal Robots, played a pivotal role in supporting our team (Appendix A). He facilitated a valuable opportunity for our team to attend a training session at Universal Robots office in Seaport from 09/26/2023 to 09/27/2023. This training equipped us with the essential knowledge of operating the robot and identifying optimal areas for its deployment (*Figure 5 - 6*).

Figure 5. UR3e used for training with a conveyor belt simulating end of line pick-up.

Figure 6. UR3e used for training with a conveyor belt simulating palletizing.

After going back to campus and implementing some programs into our robot, the team did not find many applications, as tasks were not repetitive enough in a University Campus. So Chris invited us back to the office in Seaport to see live demonstrations of their different models working (Appendix A). He also brought us to Mass Robotics, an incubator funded by Universal Robots to incorporate new grippers into their robots to find new applications. This visit helped us identify places where cobot integration works and also where it might be less advantageous.

Chris shared Universal Robots' criteria for identifying suitable applications, termed as their "list for implementation." According to this guideline, the activities assigned for robot implementation should align with the descriptors “Dull, Dirty, or Dangerous”. Some examples of repetitive applications include palletizing, soldering, and gluing, which the team was able to visualize during our visit through some demos (*Figure 7 - 8*).

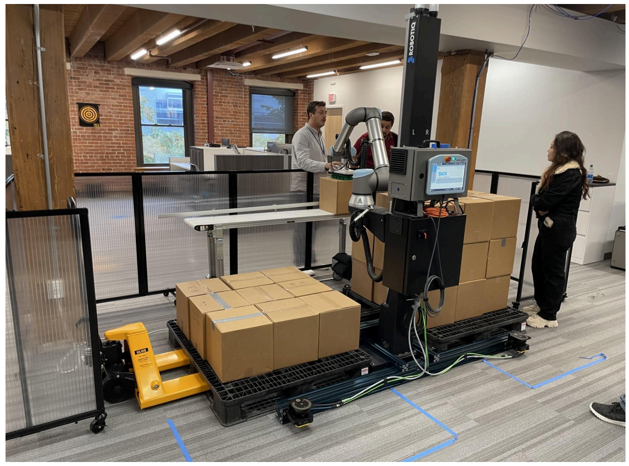


Figure 7. UR10e implemented into a cart with a suction gripper for palletizing.

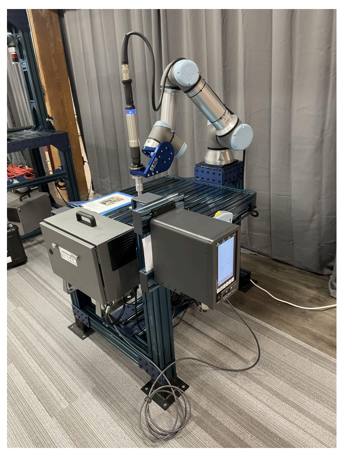


Figure 8. UR5e implemented into a stand with a rotary gripper for creating parts.

With this knowledge, the team came back to campus and integrated our collaborative robot into the cart the team had previously designed (*Figure 3*). The team used our solidworks model to build the cart for our robot. Although, challenges arose during the building phase. Upon closer examination, it became evident that constructing a robust support board posed a significant challenge in our utility cart. Recognizing the complexity of this task, the team sought assistance from the Mechanical Engineering department. They provided us with a specially crafted metal cart that featured integrated brakes for added control. This metal cart, fabricated from stainless steel, emerged as an ideal solution.

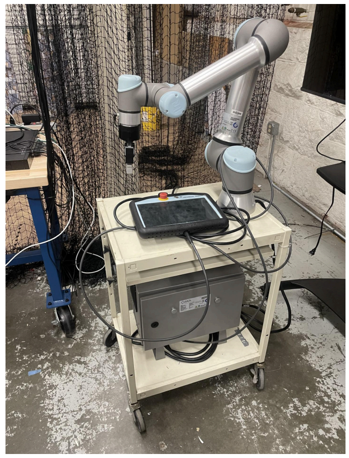


Figure 9. Picture of UR5e mounted in the metal cart.

Part of our testing phase involved creating a presentation for a business class at WPI to demonstrate the power of Robotics in the Industrial Automatization sector. The team created a presentation using slides to show to business school students the difference of automatic processes vs manual labor. Thanks to our training at Universal Robots, we also implemented a program to demonstrate automatic palletizing and depalletizing of soda cans for students to see a live working robot (Figure 10). We also displayed a link at the end of the presentation for our survey to receive more responses from students who might have more ideas for tasks or applications (Appendix E).

Figure 10. Picture of the team after the presentation to Business School students.

One of our team members had the opportunity to attend JEC World 2024, a convention where multiple composite material companies showcase their products and inventions. This convention is mainly a networking event where companies share their ideas. Our team member was able to visualize multiple Universal Robots models doing innovative tasks and applications, including new grippers for automation of processes in the composites industry.

Flex trim is a leader in the brush sanding technology business, creating innovative solutions from the beginning of a grit sequence to end polishing (Flex Trim, n.d.). In *Figure 11* we can see a demo of their newly created sanding brush gripper for incorporation with a Universal Robots model. In this image it is demoing a sanding simulation with a metal tube for end polishing.

Figure 11. Universal Robot at JEC World 2024 from Flex Trim.

Airborne is an automation company in the composites materials sector, they help companies automate their production processes with new technologies (Airborne, n.d.). In figure

12, their gripper employs a magnetic force to grasp metal parts from the aerospace industry. The robot then positions the part adjacent to a precision gluing deployment tool, seamlessly rotating. The robotic arm ensures that the adhesive is precisely dispensed onto the designated areas of the component.

Figure 12. Universal Robot at JEC World 2024 from Airborne.

Testia, a subsidiary of the aerospace manufacturing company Airbus, specializes in the development of advanced inspection techniques for aerospace composite materials (Testia, n.d.). Their primary objective is to meticulously analyze parts and components to guarantee their integrity and absence of defects before integration into aircraft assemblies. In *Figure 12*, we can see the implementation of a Universal Robots model into one of their processes. Here they are scanning a carbon fiber component with a 3D camera and a computer implemented into a gripper to find defects.

Figure 12. Universal Robot at JEC World 2024 from Testia.

Zund Systemtechnik specializes in developing and manufacturing digital cutting systems. Since 1984, they have been developing, manufacturing, and marketing modular cutting systems and is globally recognized as a market leader (Zund Systemtechnik, n.d.). In *Figure 13*, we can see one of their cutting machines demoing with a Universal Robots model with a suction gripper. Here the robot is being used for a simulation of end of line palletizing. Their cutting systems are used in the graphics, packaging, garment and leather, as well as technical textile and composites industries.

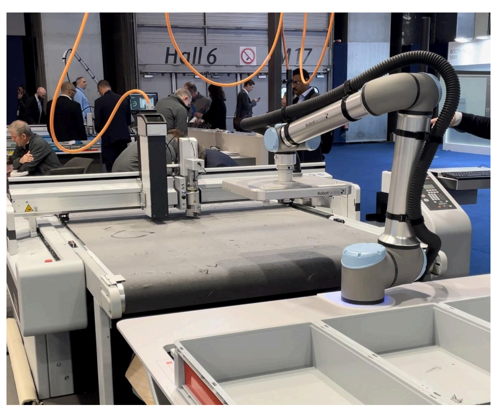


Figure 13. Universal Robot at JEC World 2024 from Zund Systemtechnik.

From this section, it becomes apparent that many companies are embracing the shift from human labor to robotic automation. They are innovating grippers for collaborative robots even outside of the Universal Robot's network, depending on the intended use of the robot. Furthermore, they're leveraging current implementations of industrial robot setups to integrate collaborative robots, primarily due to the increased safety features they offer. However, a notable gap remains: the exploration of applications beyond industrial automation.

4.4 Critical Analysis Results

Collaborative robots offer a wide range of usage and deployability as shown in our previous sections. However, they have multiple limitations that limit incorporation in industries out of the manufacturing sector.

To begin, there is the max allowable payload that collaborative robots can lift and operate with. Which ranges in weight from around 4 kg to 50 kg depending on the model. This relatively low max payload weight is designed purposely, these robots were never intended to replace the larger and more robust industrial robots that can lift and move drastically more weight. However these robots are not designed to replace human workers hence the "collaborative" part of the name. What they are specifically designed to do is work alongside humans with more intricate, delicate or dull processes.

The second thing to consider is the size of these robots. Due to collaborative robots being in close proximity to humans, their footprints are small, even as some of the larger ones are still measured in millimeters. Small footprints allow for maximum space efficiency when planning for workspace layouts. This space utilization is further enhanced by the multiple joints and degrees of freedom of the robots that allow work in cramped or tight workstations while still allowing the robot to stretch out and utilize a wider space. This goes even further when looking at the actual weight of the robot where they cap out at around 90 kg while the smaller ones can be around 3 kg. With all of these factors taken in account these robots can be used almost anywhere with electricity such as large factory sites to home workshops.

Third, there is the adaptability of collaborative robots. These robots were designed to have different “end attachments” which range from gripers to soldering irons and much more. This design feature allows for hundreds of possible attachments with many being purchasable from collaborative robot manufacturers and third parties. However if a collaborative robot user needs a specific part that is not offered then they can create a “personalized parts” by using a 3D printer or CC machine or any other method in order to adapt the collaborative robot to fit their needs.

Lastly, the needed prior knowledge such as in depth computer skills, robotic knowledge, and programming experience that went into creating these robots is not needed in order to utilize them. This is due to manufacturers creating streamlines and user-friendly interfaces that allow those who are more advanced to go deeper while allowing those who are lacking in knowledge or experience to understand what is going on. However, some training is required just like any machine would and many of these manufacturers offer online or in person learning opportunities allowing even the most inexperienced worker to gain an operational understanding.

4.4.1 The Viability of Collaborative Robots on the WPI Campus

Based on our research, and the interviews with Chritopher Savoia, Associate Teaching Professor Walter Towner, the founders of Flexxbotics, and the information we gained during the training at Universal Robotics, we have put together a set of criteria for implementing collaborative Robotics on campus at Worcester Polytechnic Institute. Some of the key factors of implementing collaborative robots in campus are the following:

1. Task Complexity: Identify tasks that are repetitive, precise, and often involve manipulation of objects. Collaborative Robots are suitable for tasks that require consistent performance and can be programmed for various levels of complexity.

A department at WPI that could benefit from a Collaborative Robot is the mail department. Collaborative Robots have been placed in different mailrooms to take over repetitive manual processes such as sorting mail and filling a tray. One company that is marketing collaborative robots to increase productivity, cut down on labor costs and “fosters a dependable work environment”, is Bluecrest. Bluecrest manufactures innovative solutions for mail sorting and parcel automation. Their Collaborative Robotic solution is OttoMate (BlueCrest Inc., 2024).

> “One of the key features of OttoMate is its ability to significantly enhance manpower efficiency. By effortlessly managing repetitive manual processes, OttoMate frees up human workers to concentrate on more intricate and impactful tasks, thereby augmenting available manpower and productivity levels substantially” (BlueCrest Inc., Oct. 2017).

2. Safety Requirements: Look for tasks where human-robot interaction is necessary or beneficial, especially in environments where safety is a priority. Collaborative robots are designed to work alongside humans without the need for extensive safety barriers, making them ideal for applications where workers and robots share the same workspace.

An area within the WPI campus that can benefit from Collaborative Robotics, is in any labs that require the handling or manipulation of toxic chemicals, dangerous machinery or heavy lifting or moving. WPI labs are often limited in space, funding, and resources to cover all tasks that do not need skilled human resources to do. For example, one of the suggestions that came out of the survey was to use Collaborative robots to stir acid that dissolves uniforms. This is not a highly skilled task, but it is potentially a dangerous job that can cause injury to a human. “Collaborative robots can take on tasks that are potentially dangerous and put people at risk, be it from handling dangerous parts, working in harsh environments, or injuries caused by poor ergonomics” ("Collaborative Robotics in Hazardous Environments," 2020).

3. Flexibility and Adaptability: Consider applications that require adaptability to different innovative solutions, configurations, or processes. Collaborative robots can be easily reprogrammed and redeployed, making them well-suited for tasks that may change frequently.

An example of Collaborative robot that needs to be flexible and adaptive deployed on the WPI campus, would be one that could be used during many diverse events held on campus. This collaborative robot could be programmed to hand-out information fliers in different locations on campus, or deployed to scan tickets for entrance at a sporting event, or to keep time during a wrestling match.

A well known company, Schneider Electric, had a global strategy “to automate as many repetitive tasks as possible in the production line ("Schneider Electric Belgium," n.d.)”. They started a smart project to find flexible ways to improve throughput, precision and generate cost savings on their production lines. That project decided that Collaborative robots, specifically Universal Robotics collaborative robots , was the answer to finding a flexible enough solution that could adapt to handle product variations for repetitive tasks as part of a production line. "The main advantage of Universal Robots’ cobot is its flexibility, which allows it to be adapted to different projects," says Simon Broze from ICA Industrial Automation. "Even with relatively complex movements, the mechanical integration poses few problems. Add to that the high precision and repetition of the movement, and you have a very satisfactory solution for the challenge that had to be met" ("Schneider Electric Belgium," n.d.).

4. Cost-effectiveness: Assess applications where the cost of implementing collaborative robots provides a favorable return on investment. While collaborative robots may have higher initial costs compared to traditional automation solutions, their flexibility, safety features, and ease of integration can result in long-term cost savings.

There are many examples of applications for deploying a Collaborative robot on the WPI campus for cost-effectiveness. A few examples could be: Showcasing WPI innovation during prospective student week and tours will clearly demonstrate WPI's commitment to innovation and providing access to new technologies. That same cobot can be reused as a learning tool for running innovative experiments. Other examples are the above examples given under "Flexibility and Adaptability". These examples could potentially replace anywhere from 4 to more human resource costs that would be needed to handle these tasks. Plus the ROI for influencing a college decision from a visiting student, though a challenge to calculate, could easily cover the initial cost of a cobot. In a Universal Robotics promotional material piece on Collaborative robots in education & science, Ritch Ramey, Coordinator, RAMTEC is quoted to have said, "We did some research and realized that Universal Robots had one of the best collaborative robots on the market. We always want to stay ahead of where manufacturing is going to ensure that when our students leave this facility, they can use the equipment adapted by industry" (Universal Robots, n.d.).

A simple list of applications for cobot deployment for cost savings, is offered up from Productive Robotics in their article “Financial Benefits of collaborative robotsin CNC” (Productive Robotics, 2023). Their list below helps you think of applications for cobot deployment that will save money:

- Handling Parts [applications] and steps that are error prone
- Jobs you have trouble staffing
- Areas in which you want to increase production
- Handling simple repetitive tasks
- [Performing] Operations with ergonomic or safety risks

5. Human-Robot Collaboration: Identify tasks that benefit from human-robot collaboration, where humans and robots can work together to enhance productivity, efficiency, and overall performance. Collaborative robots can assist humans with tasks that require strength, precision, or repetitive actions, allowing workers to focus on more skilled or complex aspects of the job.

An application that is often not thought of in Collaborative robot applications, is in food production. With the small footprint, lightweight frame, ease of reprogramming and redeployment, safe to work alongside with humans and without fencing or work alone to prevent cross food contamination, collaborative robots are a smart and cost-effective addition to restaurants and other food service businesses.

Our different cafeterias could deploy a cobot to stock ingredients in a store room, add ingredients to a pan then cook that recipe as both a cost-saving and an innovation demonstration.

A company that is revolutionizing the use of collaborative robots in the kitchen is Moley. Moley has developed the world's first robotic chef and intelligent RFID-enhanced IoT kitchen system. "Two highly complex, fully articulated hands comprise the kitchen's enabling technology. With the ability to faithfully reproduce the movements of a human hand, they give the Kitchen the capability to cook anything a human chef can" (Moley Robotics, n.d.). This application of cobot innovation is not for the rich that want a beautiful and technology advanced kitchen, it is also for physically or mentally handicapped individuals that could benefit from help with food preparation.

By considering these criteria, we can identify potential applications where collaborative robots can effectively enhance productivity, safety, and efficiency in various work environments.

4.4.2 Axiomatic Design:

Functional Requirements (FR)	**Design Parameters (DP)**
FR 0 - Explore current applications and limitations of collaborative robots in diverse environments.	DP 0 - Set of criteria to assess and prioritize possible applications.
FR 1 - Create a list of possible applications for the robot in our campus environment.	DP 1 - Platform to enable testing in diverse environments.
FR 2 - Mobilization option for the robot	DP 2 - Design and implement a mobilization option for the robot.

FR 3 - Deployment of the robot	DP 3- Deployment schedule.
FR 4 - Data to define a set of applications and limitations criteria.	DP 4 - Criteria for defining the applications and limitations based on the collected data.

The implementation of an Axiomatic Design helped understand the goal of the project, reduced random searches for solutions that can be ineffective and used design tools to identify innovative ways to fulfill functional Requirements (Functional Specs, Inc., 2022). By implementing an axiomatic design we were able to clearly define our goal and create a path of necessary steps to fulfill each of our requirements. The overall organization and productivity of the process was increased and we were able to avoid unnecessary steps in the process.

4.5 Set of Criteria for Collaborative Robot applications

Task Characteristics	**Grade (1-3)**	**Description**
Dull, Dirt or Dangerous	1	Is the task either dull, dirty or dangerous?
Decision Making Involved	3	Is there a lot of decision making involved? Do you have enough sensors incorporated to make it work?
Within Robot Weight Capacity	3	Can the robot lift the object on the proposed task?
Within Robot Reach	3	Is the workspace within arm robot reach?
Efficiency Improvement	2	Is efficiency improved because of incorporating a Collaborative Robot?
Material Rigidity	2	Can the gripper sense and

		grab the material?
Social Viability	2	Is the task improved by implementing a Collaborative Robot or is it better to hire a human?

1 - Not very important

2 - Important

3 - Very Important

There is a difference between collaborative robots and collaborative applications. Collaborative robots can be applied in many environments, but there are some tasks where it is better to have human interaction. For example, will the environment or interaction be improved by implementing a collaborative robot to replace a cashier? Or a bartender? Or a server? Will the business improve efficiency but lose clients that were specifically looking for human interaction? These questions are important to ask but as they are on an ethical standpoint we can leave them for the person who will do their own economical and moral analysis.

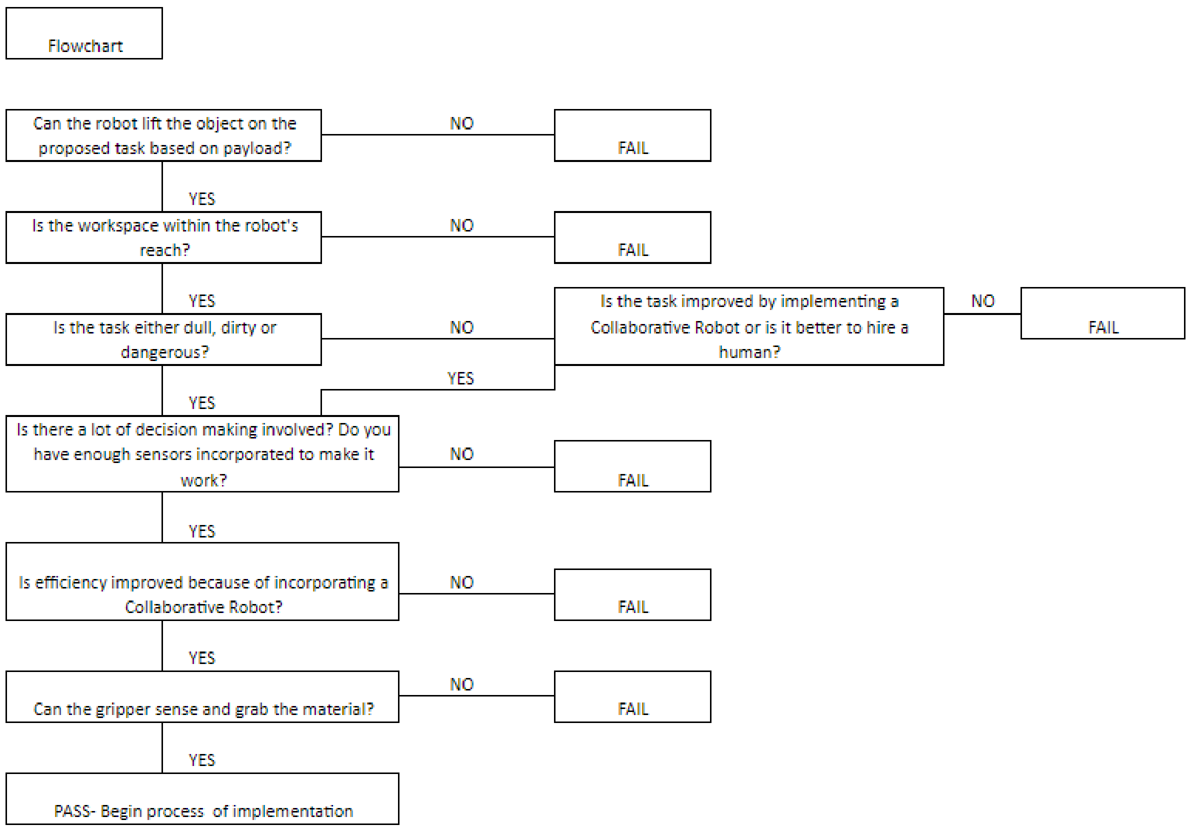
Our set of criteria focuses specifically on task and robot limitations. We created it as a sort of grading system for individual tasks. We were able to determine our set of criteria after a thorough analysis of the multiple limitations that the team faced by the tasks proposed in the surveys and interviews (Appendix A - E). As the team went through the set of criteria, we noticed that some task characteristics are more important than others, as the task will not pass the test if that characteristic is not met. So we created a grading system, because the task might fail a certain characteristic but that does not mean it cannot be done.

Our set of criteria started off with Universal Robot's given criteria during our visit to their Seaport Office (Appendix A). This criteria describes if a task is dull, dirty or dangerous, then we can implement collaborative robots because the benefits are good, but we think this set of criteria was missing more questions that we found as we were going through the process of implementing new tasks.

The rest of the questions were created because of the two main limitations we found: task limitations or robot limitations. Task limitations include any non repetitive tasks, in order for the robot to properly function it needs to know when and where to be at certain stages of the process. If a task is complex and has high variation, it becomes harder to program the robot because of the amount of possible scenarios, it can also affect the robot's efficiency. The second type is robot limitations. Collaborative robots have weight and size limitations that affect any activity they do because of how they were built. We used these two types of limitations in order to grade the characteristics in our set of criteria.

One of the biggest benefits of collaborative robots is the large amount of grippers and external tools that can be attached to the robot for working with different materials, however some materials are hard to work with, materials that can create limitations for collaborative robots are soft and small materials like fabric, that can be hard for the robot to handle consistently. These need to also be taken into account when grading a collaborative robots task.

4.5.1 Flowchart



5. Conclusion

5.1 MQP Conclusion

Through the course of the project we ran into some challenges. At the beginning, we had some interdepartmental issues for access to the robot on campus that resulted in delays for its deployment. Our team had to delve into university politics in order to regain access to the robot and be able to use it. Also, two more people were added into our team midway through and our team had to adapt. The learning curve for the new members was also another delay. Due to these issues, our objective was constantly changing. In addition, the majority of the team had an industrial and management background which made it challenging to to work in a robotic focused project. Even though we had these challenges through this project, our team was able to complete the assigned task and have a great learning experience due to the diversity of the skills we had to use to solve our issues.

5.2 Project Conclusion

This project resulted in a structured analysis into current applications of collaborative robots and their potential into new tasks. Various limitations such as reach, capacity, and programming complexity were identified, and these ultimately dictate which tasks collaborative robots can effectively perform. Using our engineering knowledge, the team conducted thorough analyses across diverse industries to assess the applicability and adaptability of collaborative robots to different tasks.The outcome of our analysis resulted in a set of criteria and a grading system designed to assess the feasibility of new tasks for collaborative robots. This system aims to determine whether a task is achievable or not based on predefined parameters. It is our hope that this selection criteria will undergo further development and implementation within the industry, paving the way for more effective utilization of collaborative robots in more applications.

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Appendix A:
Below are the notes from our visit to Universal Robots and Mass Robotics, which took place on 10/26/2023.

Notes from Universal Robots and Mass Robotics Visit

Introduction to Collaborative Robots:

- Collaborative robots are often used for "dull, dirty, and dangerous" tasks, 3Ds from Universal Robots set of criteria.
- These tasks include mechanical tasks that are repetitive and boring, work in dirty or hostile environments, or involve inherently dangerous activities.

Key Characteristics of Collaborative Robots:

- Designed for human-scale automation.
- Have similar speed, reach, and payload capacity as a human worker (e.g., 55-pound weight limit as per OSHA regulations).
- Feature power and force limitation, including sensors to prevent harm to humans.

Collaborative Robots vs. Collaborative Applications:

- Distinguishing between a collaborative robot and a collaborative application is crucial.
- A collaborative robot refers to the physical robot itself, while a collaborative application relates to the specific tasks it performs.

Safety and Sensing Mechanisms:

- Safety is paramount, and many collaborative robots, like those from Universal Robots, use safety scanners to detect and respond to the presence of humans.
- Safety features are critical to ensure safe human-robot interaction.

Common Collaborative Robot Applications:

- Mentioned specific applications for collaborative robots, including end-of-line palletizing and machine tending.

Teaching Pendant:

- Mentioned that the teaching pendant uses the language spoken by welders, making it more user-friendly for specific industries.

Mass Robotics and Universal Robots' Involvement:

- Universal Robots sponsors Mass Robotics, which serves as an incubator for small companies.
- Some companies at Mass Robotics create UR caps for Universal Robots' products.

Robotics Gripper and Flexbotics:

- Universal Robots has a Robotic Gripper and provides variable fingertip sets for more flexibility in implementation.
- Flexbotics offers solutions for machine tending and software that can integrate with various CNC machines on the market.
- They also have a comprehensive management system.

Redeployment and Feature Programming:

- Mentioned the importance of redeployment and feature programming.
- Emphasized the significance of tasks like feed work-holding, blow off, mobile base setup, and calibrating the robot's base.

Bill of Materials and Ventio.io:

- Recommended having both an existing bill of materials and an infinite bill of materials.
- Suggested using McMaster-Carr for sourcing parts and tools.
- Ventio.io can assist in designing an ideal layout and creating 3D models for projects.

Risk Assessment:

- Advised conducting a comprehensive risk assessment to identify potential hazards.
- Parameters for assessment should include identifying the task, assessing the severity of potential harm, and evaluating the probability of harm.
- Mentioned that the product of severity and probability is used to prioritize safety measures.

Appendix B

Below is the summary of our interview with Professor Carrick Eggleston about the implementation of Collaborative Robots in the construction sector, which took place on 1/29/2024.

Professor Carrick Eggleston Interview Summary

Professor Carrick Eggleston is a professor and department head of the Civil, Environmental, and Architectural Engineering department at Worcester Polytechnic Institute. The integration of collaborative robots in construction is gaining traction, driven by the industry's desire for increased efficiency and reduced manual labor strain.

Collaborative robots offer a solution to physically demanding and monotonous tasks in construction. Tasks such as spraying paint, applying insulation, nailing down roofing tiles, and cutting boards are good candidates for automation, alleviating the burden on human workers. Robots can excel in precision tasks, such as cutting boards or creating holes for outlet sockets with a laser cutter. The professor emphasized the necessity of digital imaging to guide robots in accurately placing holes for various fixtures, particularly in the context of handling diverse building sizes and configurations. The application of robots in handling sheets of drywall showcases has potential to streamline construction processes. But, for all these potential tasks digital imaging would be crucial because robots would need to know where the placement of holes or nails need to be.

Another growing trend in construction involves prefabrication and off-site manufacturing. This would need the use of digital models to ensure accurate on-site assembly. Companies must invest in developing digital solutions that accommodate the industry's unique demands and regulatory requirements.

The complexity of the construction industry poses challenges for the seamless integration of robotics. Variables such as building codes, unique designs for each building, and the increasing demand for environmentally sustainable structures need to be addressed. The industry must find solutions to these challenges for widespread adoption of robotic technologies. The professor emphasized that companies need to proactively tackle these challenges to make progress in construction robotics. This involves investing in research and development to create solutions that cater to the industry's specific needs, including the integration of digital models and adherence to building codes.

Appendix C
Below is the summary of our interview with PhDs about the implementation of Collaborative Robots at WPI Gateway Park, which took place through 1/25/2024 to 2/10/2024.

PhDs at Gateway Park WPI Interview

Gateway Park at Worcester Polytechnic Institute (WPI) is a prominent center for research, innovation, and commerce. It houses the Life Sciences and Bioengineering Center (LSBC) within the flagship complex at 60 Prescott Street, offering 125,000 square feet dedicated to graduate research laboratories. These labs focus on areas such as biotechnology, biomedical engineering, chemistry and biochemistry, and chemical engineering.

First PhDs the team interviewed was a PhD candidate specializing in Organic Chemistry, Yufei Zhang. In her interview, she shared her insights on the potential role of collaborative robots in the organic chemistry laboratory setting. She highlighted her daily encounters with potentially hazardous organic substances, underscoring the inherent risks and the repetitive nature of tasks such as handling titration tubes and stirrers. From her perspective, collaborative robots could offer significant benefits in two main areas: mitigating exposure to toxic substances and addressing the monotony of repetitive tasks. Zhang expressed concern over the frequent handling of toxic organic chemicals, which could pose health risks to researchers. She envisioned collaborative robots as a solution to minimize direct human exposure to these hazardous materials. By automating the transfer and manipulation of chemicals, robots could significantly reduce the safety risks, ensuring that researchers like herself can maintain a safer distance from direct contact with harmful substances. Moreover, Zhang pointed out the high degree of repetition involved in her laboratory work, particularly in tasks requiring precision and consistency, such as titration. She believes that collaborative robots, with their ability to perform tasks with exacting precision, could relieve researchers of these tedious and physically demanding activities. This would not only enhance laboratory safety and efficiency but also allow her and her colleagues to allocate more time to complex problem-solving and analytical tasks, thereby boosting overall productivity. Zhang further stated that beyond handling hazardous materials and repetitive tasks, collaborative robots could play a pivotal role in ensuring compliance with laboratory safety protocols. Equipped with sensors and programmed to follow safety guidelines, these robots could help maintain a secure environment, monitoring for potential hazards and ensuring that laboratory operations meet stringent safety standards. In summary, Zhang's insights reveal a vision for the future of organic chemistry laboratories where collaborative robots play a crucial role in enhancing safety, efficiency, and precision. Her perspective underscores the potential of robotics to transform laboratory practices, making them safer and more productive while allowing researchers to focus on the innovative aspects of their work.

In the course of our interviews with PhD candidates at Gateway Park, the conversations shed light on the diverse and complex nature of research being undertaken. Junyong Li, a PhD student specializing in Biochemistry, offered unique insights into his intricate world of cell and bacterial cultures, encompassing a wide array of specimens from plant and animal tissues to even human organs and tendons. His research notably includes cutting-edge projects such as dissecting pig hearts and cultivating human Achilles tendons, aiming to pioneer new avenues for patient rehabilitation. Li highlighted the meticulous attention to detail required in cell culture, emphasizing the critical importance of precise temperature control and, most significantly, the timing of various processes. His research routine often necessitates middle-of-the-night visits to the Gateway labs to monitor cell growth or frequent weekend check-ins, disrupting not just his personal life but also posing logistical challenges. He envisioned collaborative robots as a transformative solution to these hurdles. By setting up automated tasks for robots, such as changing petri dishes and managing cultures at scheduled intervals, Li could significantly reduce his lab visits, saving valuable time currently spent commuting. Moreover, Li pointed out a critical advantage of employing collaborative robots in biochemistry labs: their innate ability to operate in sterile environments without the risk of contaminating the cultures. Unlike human researchers, robots don't carry bacteria or other microorganisms, making them ideal for handling sensitive biological materials. This not only enhances the reliability of experimental results but also minimizes the risk of sample contamination, a common challenge in biochemistry research. Through Li's perspective, it becomes evident that collaborative robots hold the potential to revolutionize the field of biochemistry. By automating routine and time-sensitive tasks, these robots can not only improve the efficiency and accuracy of scientific research but also significantly enhance the work-life balance of dedicated researchers like Li. This integration of robotics into biochemistry labs underscores a broader trend towards leveraging technology to optimize research outcomes, ensuring that scientists can devote more time to critical analytical work and innovation.

Appendix D

Below is the list of our survey responses about the implementation of Collaborative Robots in different academic fields of study, which took place between December 2023 and February 2024.

Survey Results

The model of this robot is the UR5e, and it can lift up to 11 pounds. Can you think of any process or task that the robot could be used for in your work environment?
Possibly for loading paper into printers or assembling documents and packaging them
Toxic chemical handling.
stirring solution
assembly battery, moving solutions and grinding powders
repeated pipetting, pdms preparation
This work may can help us grinding and mixing the powder.
Laboratory Sample Handling
Do some administrative tasks
This can be used in basic experiments like grinding the material particles and mixing various materials
Yes, I believe this robot could be a character in a new play and actually perform onstage. It could be incorporated into performances in other ways as well: for instance, it might be a dance partner in a dance piece, or a performer in an interactive art setting.
passing test samples and tools?
Reception roles, such as greeting visitors, providing necessary directions, location instructions, scheduling, or serving documents or beverages.
Controlling interactive displays or touchscreens; Fetching items from shelves or designated areas; Assisting in packing and unpacking of parcels and packages; Organizing and sorting documents on desks or shelves; Filing paperwork in cabinets or storage units.

Sample weighting, equipment holding and stabilization, water carrying
I work in the office and do not have repetitive or dangerous jobs, however I can use that robot for massages during work hours.
No. As an administrator, there are few physical aspects of my job.
Automation test/manufacturing
In mine not really
I think potentially moving files or papers around an office.
Production: repetitive task or assembly of a product
I know it would be very helpful in a lot of areas of work, specifically mine over the summer I probably had not, but in many others yes. It could be somewhat useful in mine tho
Stacking WIP, performing cycle testing
Pour hot aluminum
They can be used to hang monitors and move them around. I cannot think of other better usage of this robot arm in the CS field at this moment.
Collect data
Help with experiment set up
Help measurement of chemicals
Help to manipulate chemical synthesis

Do you believe the addition of collaborative robots to your work environment is beneficial?	How useful do you think the implementation of automation is in your work environment?

No	2
Yes	3
Yes	4
Yes	4
Yes	5
Yes	4
Yes	4
Yes	3
Yes	3
Yes	5
Yes	5
Yes	4
Yes	2
Yes	4
Yes	4
Yes	2
Yes	4
No	4
Yes	3
Yes	2
No	2
No	2
Yes	3

Yes	3
Yes	4
Yes	5
Yes	3
Yes	2
Yes	5
Yes	4
Yes	5
No	2
Yes	5
Yes	5
Yes	5
Yes	4

Appendix E

Below are the slides from our presentation to professor Walter Towner's Achieving Effective Operation class.

Collaborative Robots Presentation Slides

Figure 1. Image from Engineering.com (Courtesy of Universal Robots).

Universal Robots

- Universal Robots, founded in 2005, specializes in collaborative robots for various industrial applications.
- The company, headquartered in Odense, Denmark,
- Their main problem is they are not selling enough robots.

Figure 2. Image from UniversalRobots.com

Limitations of the UR5e

- **Reach -** Max reach of 850mm or 33.5in (about the size of a baseball bat)
- **Payload -** Max payload of 5kg or 11lb (around the weight of a cat)
- **Material interaction** - The gripers do have trouble with fabrics and other lighter material
- **Task limitations -** specifically designed for repetitive and non-decision making task

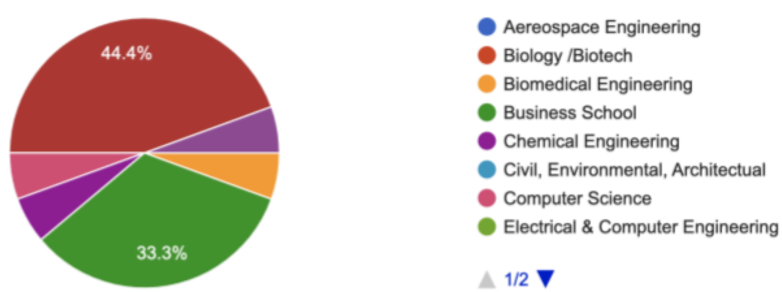
What is our MQP objective?

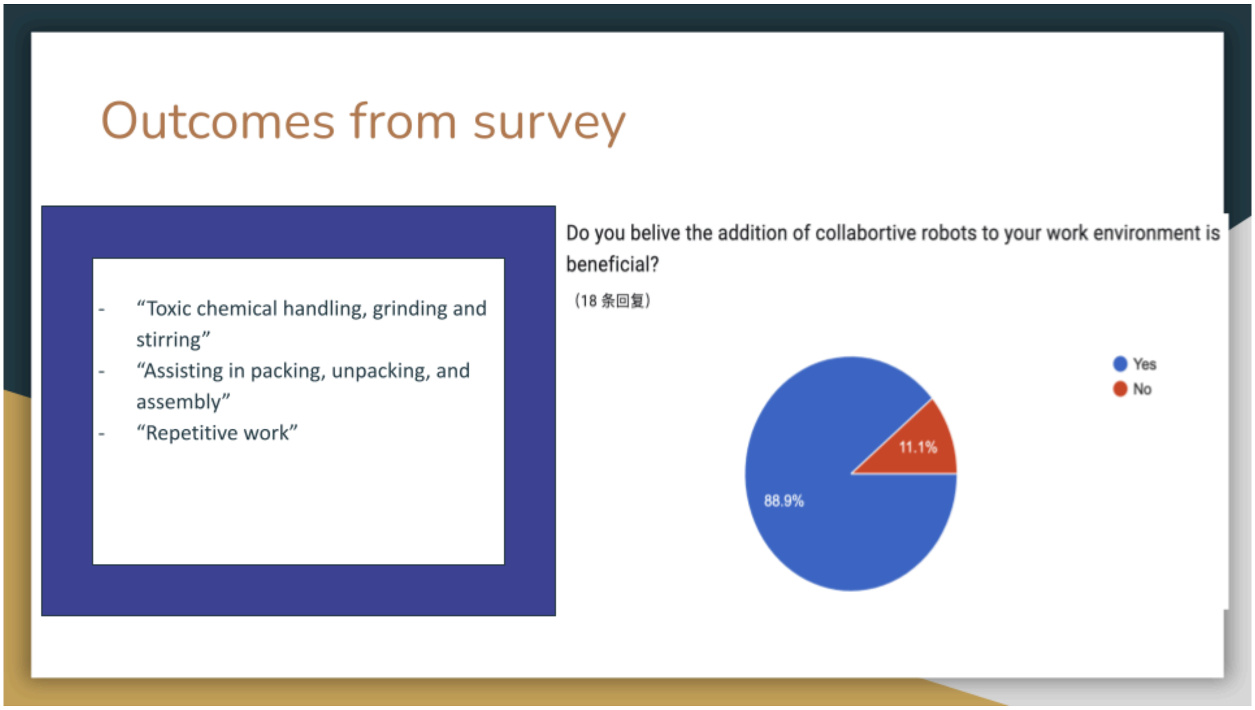
The goal of this project is to create a set of criteria for Collaborative Robot users to determine whether a process can be efficiently performed by the Collaborative Robot based on its limitations.

Establishing a set of criteria for Collaborative Robots applications will help individuals determine if an application is appropriate for a Collaborative Robot to perform.

Some Methods for our MQP

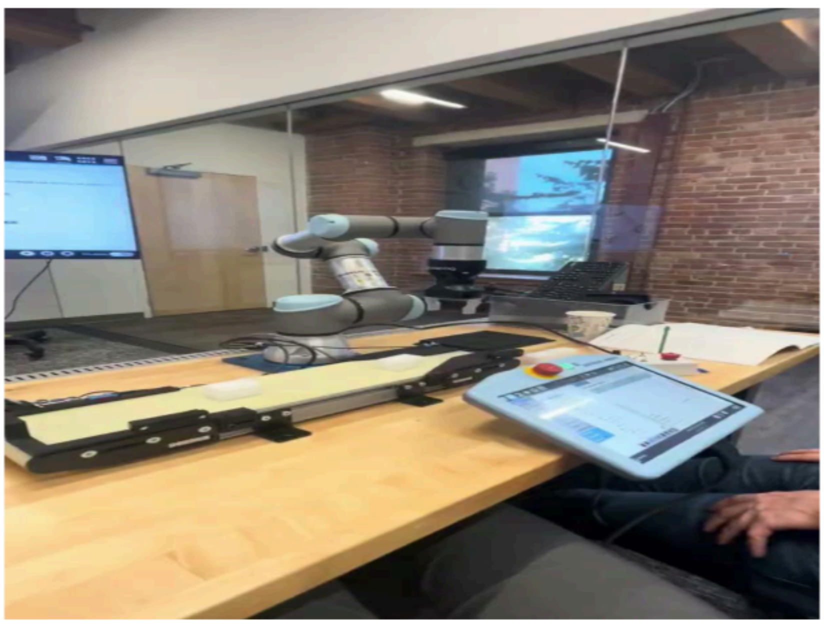
- In order to get an accurate set of criteria the team will create a set of criteria for the applications of Collaborative Robots based on the data collected from experts in different fields via surveys, interviews and testing.

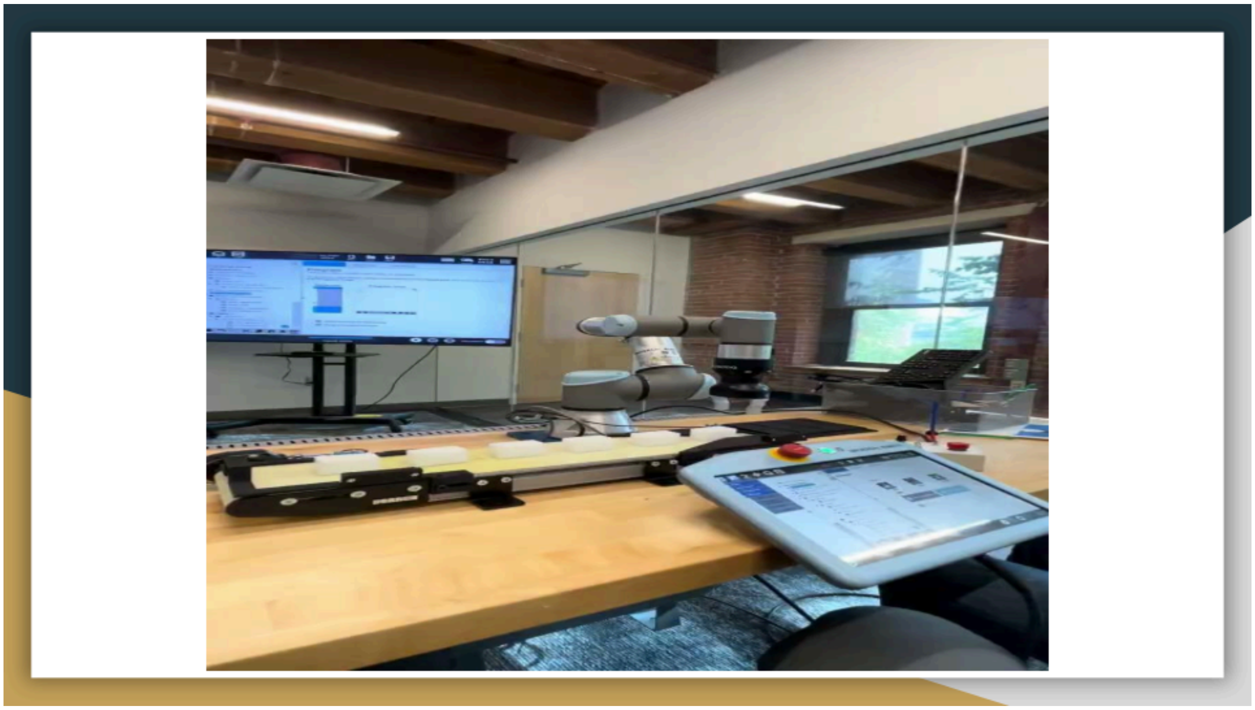


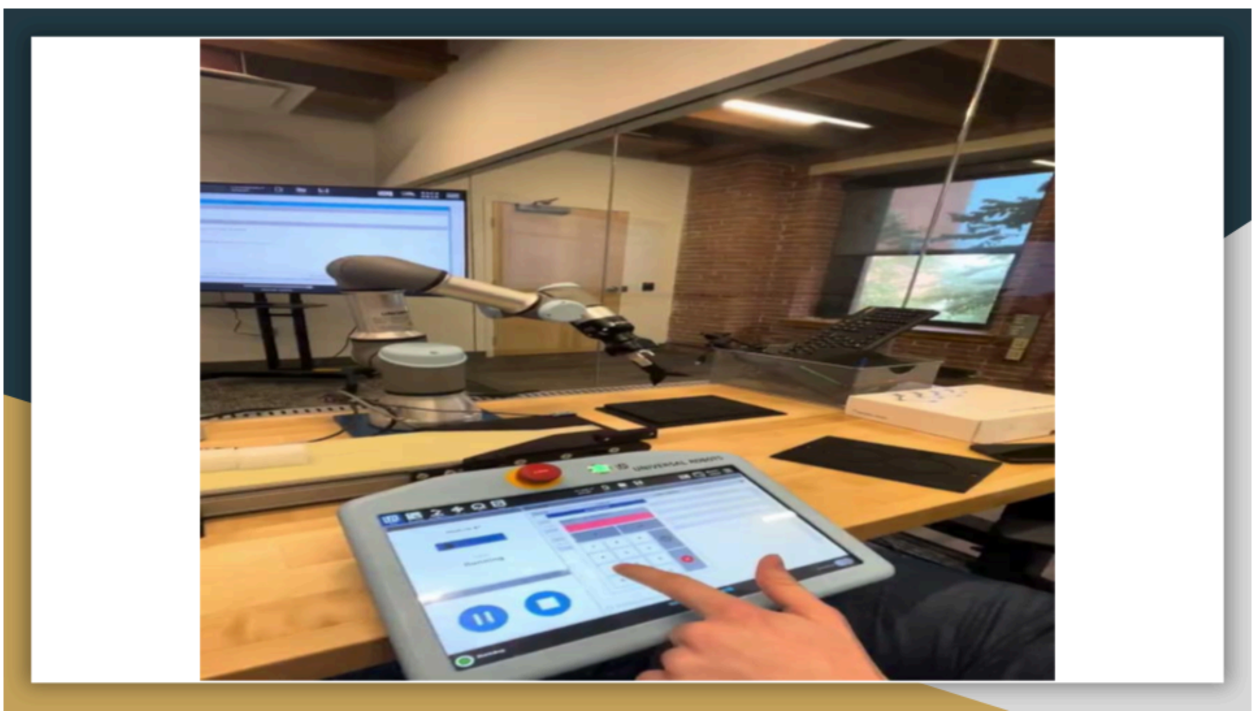

Outcomes from survey
- "Toxic chemical handling, grinding and stirring"
- "Assisting in packing, unpacking, and assembly"
- "Repetitive work"
Do you belive the addition of collabortive robots to your work environment is beneficial?
（18 条回复）
Yes
No
11.1%
88.9%

Demonstration

- Palletizing
- Depaletizing







Questions?

Please help us by filling the survey

Scan me!