ACS6503: Manipulator Robotics Assignment 1 – Safety of Collaborative Robots 2023-2024

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1 Introduction

In recent years, the integration of collaborative robotics, often referred to as cobots, has witnessed unprecedented growth, transforming traditional manufacturing processes and industrial workflows. The seamless interaction between humans and robots within shared workspaces has paved the way for increased efficiency, flexibility, and safety in various industries. This report delves into the intricate realm of safety-rated and safety-related systems for collaborative robotics, examining potential modes of operation, sensing systems, and the current state of deployment.

2 Background Study

The landscape of industrial automation has evolved significantly over the years, with collaborative robots emerging as key protagonists in this narrative. Historically, the term 'robot' was coined a century ago, but it wasn't until 2005 that collaborative robots took a revolutionary turn. Spearheaded by researchers at the University of Southern Denmark, the goal was to develop affordable, lightweight, and flexible robots capable of collaborating seamlessly with human workers [7].

Collaborative robots excel in various modes of operation, each characterized by distinct safety measures. These modes, including Safety-Rated Monitored Stop, Hand Guiding, Speed and Separation Monitoring, and Power and Force Limiting, are integral components of the collaborative robotics framework [1]. The safety of these operations is heavily reliant on advanced sensing systems such as distance sensors, pressure sensors, area scanners, proximity sensors, force and torque sensors, and vision systems [2].

3 Literature Review

3.1 Modes of Operation in Collaborative Robotics

The potential modes of operation in collaborative robotics play a pivotal role in defining how humans and robots interact within shared workspaces. Each mode has distinct characteristics and safety measures designed to ensure the well-being of human operators while maximising the collaborative potential of these advanced robotic systems. These modes can be categorised into, monitored stopping, speed and separation monitoring, power and force limiting and hand guiding, as seen in Figure 1.

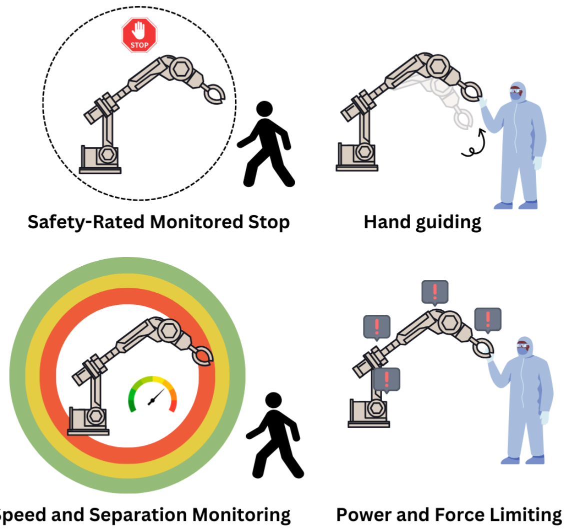

Figure 1: Modes of Operation in Collaborative Robotics

1. Safety-Rated Monitored Stop (ISO 5.10.2): Safety monitored stop allows robots to operate at higher speeds, coming to a halt when a human enters a predefined safety zone. The robot remains stationary until the human exits the area. This mode integrates sensors and monitoring systems that detect human presence, triggering a stop to prevent any potential collisions.

2. Hand guiding (ISO 5.10.3): Hand guiding allows direct physical interaction between the human operator and the robot. The robot can be manually guided by the human, enabling collaborative tasks that require precise control. Safety measures include emergency stops and force feedback mechanisms, ensuring safe hand guiding

3. Speed and Separation Monitoring (ISO 5.10.4): This mode involves the robot adjusting its speed based on the proximity of the human operator. It slows down or stops when a human enters a specified safety zone. Proximity sensors continuously monitor the distance between the human and the robot, imposing preset limits on speed and separation to ensure a secure working environment.

4. Power and Force Limiting (ISO 5.10.5): Power and force limiting mode restricts the robot's power and

force to prevent harm to humans. Force/torque sensors integrated into the robot's joints actively monitor forces during operation, automatically limiting force to prevent any potential injury to the human operator.

3.2 Potential Sensing Systems and Operational Configurations

Safety in collaborative robotics heavily relies on the integration of advanced sensors. Each sensor type serves a unique purpose, contributing to the diverse modes of operation in which collaborative robots excel.

1. Distance Sensors: Distance sensors, including technologies like ultrasonic sensors or LiDAR (Light Detection and Ranging), enable collaborative robots to perceive their surroundings with precision. These sensors are pivotal for applications where maintaining a safe distance between the robot and human operators is essential. In scenarios such as Speed and Separation Monitoring, distance sensors contribute to the robot's ability to gauge proximity and adjust its speed accordingly.

2. Pressure sensors are instrumental in enhancing the safety features of collaborative robots, particularly in modes like Power and Force Limiting. These sensors can detect variations in pressure, resistance, or impacts, allowing the robot to promptly respond by stopping or adjusting its course. The integration of pressure sensors contributes to the overall safety and adaptability of the robot in environments shared with human workers.

3. Area scanners, employing advanced scanning technologies, offer a comprehensive view of the robot's surroundings. This type of sensor is valuable in Safety-Monitored Stop scenarios, where the robot needs to identify the presence of humans or obstacles within its workspace. Area scanners contribute to creating a responsive and secure collaborative workspace by ensuring the robot halts its movements when unexpected entities are detected.

4. Proximity Sensors: Proximity sensors play a pivotal role in collaborative environments, where human-robot interaction is a key consideration. These sensors are designed to detect the presence of objects or humans in the immediate surroundings of the robot. In the context of collaborative robots, proximity sensors find application in the Safety-Monitored Stop mode, causing the robot to cease movement when a human enters its workspace. This capability ensures a swift response to human presence, enhancing overall safety.

5. Force and Torque Sensors: Force and torque sensors are integral for measuring the forces and torques applied to the robot's end effector. In collaborative settings, these sensors contribute to the Power and Force Limiting mode, enabling the robot to stop or reverse its course in response to unexpected forces. This level of sensitivity and responsiveness is paramount for preventing collisions and ensuring a collaborative workspace where humans and robots can work in tandem seamlessly.

6. Vision Systems: Vision systems, incorporating cameras and sophisticated image processing, provide collaborative robots with visual perception capabilities. In Hand Guiding mode, these systems prove invalu-

able as they allow human operators to guide the robot through a sequence of motions required to complete a task. Additionally, vision systems are instrumental in tasks requiring high mix part feeding flow, where the robot needs to detect and select changing parts on moving conveyor belts.

Expanding the repertoire of sensor types, the following table outlines the configurations for additional sensors and their alignment with specific collaborative robot modes:

Modes of Operation	Sensing Systems	Operational Configurations	Outcome
Safety-rated Monitored Stop (ISO 5.10.1)	Infrared sensors, vision systems, area scanners	Monitored stop triggered by integrated sensing systems, dynamic path planning	Prompt cessation of movement
Speed and Separation Monitoring (ISO 5.10.2)	Proximity sensors, vision systems	Dynamic speed adjustment, virtual safety perimeters	Secure working environment
Power and Force Limiting (ISO 5.10.3)	Force/torque sensors, pressure sensors	Adaptive control algorithms, virtual force limiters	Compliance with force limits
Hand Guiding (ISO 5.10.4)	Force/torque sensors, position sensors	Force feedback mechanisms, teleoperation systems	Controlled interaction, precise manual guidance

Table 1: Summary of Sensing Systems, Operational Configurations, and Outcome for Modes of Operation

3.3 Current Deployment and Advantages of Collaborative Robots

Collaborative robots, or cobots, have revolutionized the landscape of industrial automation, offering a dynamic and innovative approach to various manufacturing processes. In contrast to traditional solutions, collaborative robots are designed to work alongside human operators seamlessly, ushering in a new era of flexibility, safety, and efficiency.

3.3.1 Evolution of Collaborative Robots

The dawn of collaborative robots can be traced back to the coining of the term ’robot’ a century ago. However, it wasn’t until 2005 that the concept of collaborative robots took a revolutionary turn. The pioneers of this transformation were a team of researchers at the University of Southern Denmark, including Esben Østergaard, Kristian Kassow, and Kasper Støy. Their goal was to develop an affordable, lightweight, and flexible collaborative robot that could deliver a rapid return on investment for the manufacturing industry. [7]

3.3.2 Collaborative Robots advantages over Traditional Solutions

Unlike their traditional counterparts, collaborative robots are designed to operate in shared workspaces without the need for extensive safety barriers. Their smaller size and lightweight construction make them suitable for a range of applications, particularly those involving intricate tasks and smaller parts. Collaborative robots excel in several areas compared to traditional solutions. One of their primary advantages lies in their ability to adapt to varying part specifications, making them ideal for low to medium-sized components. The ease of programming and integration, facilitated by user-friendly interfaces, has significantly reduced the barriers to automation for a broader range of industries.

Work settings benefit from the collaborative nature of these robots, as they can operate safely alongside human employees, leading to space-saving solutions. This collaborative approach not only enhances safety but also promotes a more efficient and dynamic manufacturing environment.

In terms of cost-effectiveness, collaborative robots boast lower upfront costs and reduced operational expenses compared to their traditional counterparts. The shift towards user-friendly programming interfaces has made them accessible to a broader range of users, minimizing the need for highly specialized expertise. Their notable Return on Investment (ROI) is seen in many applications achieving positive returns in less than a year. By working alongside human counterparts, cobots minimize barriers and lost time, enhancing productivity and cutting labor costs. The integration of cutting-edge technology adds to their broad appeal among customers. [5]

The flexibility in deployment is a key highlight, as collaborative robots can seamlessly adapt to various tasks and operational needs. This stands in stark contrast to traditional robots that often require significant reconfiguration for different applications.[4]

3.4 Potential Applications

The flexibility and financial accessibility of collaborative robots position them as an ideal solution in a diverse range of industries. Some notable sectors include automotive, electronics, general manufacturing, metal fabrication, packaging, plastics, food and agriculture, furniture, pharmaceuticals, and scientific research. The Association for Advancing Automation predicts that collaborative robots will continue to gain market share as industries realize the productivity benefits and technological advancements in this rapidly evolving field [6]

Criteria	Collaborative Robotics	Traditional Robots
Size, Weight, and Location of Parts	Ideal for low to medium part specifications; dependent on reach	Suitable for heavy, large parts; potentially hard-to-reach
Ease of Programming and Integration	User-friendly interfaces, quick integration	Potentially complex programming, may require specialized expertise
Work Settings	Safely works alongside employees; space-saving solution	Requires safety fences; takes up more space
Cost-Effectiveness	Lower upfront costs, lower operational costs	Higher upfront costs, potentially higher maintenance expenses
Human-Robot Collaboration	Promotes close interaction with human workers	Limitations in working alongside humans
Flexibility in Deployment	Adaptable to various tasks and needs	More rigid, may require significant reconfiguration
Performance and Cycle Time	Advancing in performance; suitable for various applications	Often faster, more accurate, powerful, and with longer reach
Human Resources	User-friendly programming; accessible to a broader range	Requires technical skills; automation-expert engineers
Sensing Capabilities	Relies on various sensing technologies, including force, motion and vision	Standard robots primarily rely on vision with limited perception capabilities

Table 2: Comparison of Benefits between Collaborative Robotics and Traditional Robots

4 Case Study Evaluation

Napco Brands, a prominent coffee company based in Chicago, has successfully integrated collaborative robotics into its operational framework, specifically employing the UR10e cobot from Universal Robots for palletizing operations where the cobot collaborates seamlessly with human workers in palletizing coffee beans. The collaborative mode applied prioritizes safety and efficiency in this shared workspace, contributing to increased productivity, labor savings, and reduced injury risks.

Collaborative robot palletisers simplify the intricacies linked with palletising cells, utilizing user-friendly programming and pallet configuration software. Within a robotic palletising cell, various fundamental components work in harmony to ensure the smooth and effective functioning of the system as seen in the figure below

1. Gripper: Responsible for grasping boxes from the conveyor and placing them on the pallet. A vacuum gripper ensures optimal pick quality and repeatability.

2. Conveyors Belt: Plays a crucial role in directing boxes to robots for efficient palletizing.

Figure 2: Applications of Collaborative Robots

3. Robot: The UR10e cobot, the core performer, executes palletizing actions under the guidance of the operator.
4. Safeguarding: Measures like fences are implemented to ensure a secure working environment.
5. Status Lights: Convey important information about the machine's status, including pallet readiness, errors, and emergency stops.
6. Teach Pendant: Equipped with a teach pendant for straightforward program creation and easy recall of existing programs.
7. Operator: Manages the collaborative robot within the robotic cell, ensuring smooth and efficient palletising operations.
8. Pallet: The robot places boxes on the pallet, which the operator then relocates once the selected quantity is loaded.

4.1 Advantages of Collaborative Robotics in Napco

1. Increased Productivity: The UR10e cobot, coupled with Robotiq's Palletizing Solution, has delivered a significant 15 % increase in overall productivity, efficiently handling 1,500 boxes per day during two shifts.
2. Labor Savings: The successful integration of collaborative robotics has led to the redeployment of eight workers per day, showcasing the economic efficiency achieved through automation.

Figure 3: Anatomy of a Palletising Cobot Diagram

3. Safety and Injury Reduction: Notably, the collaborative palletizing system has significantly reduced opportunities for injuries, addressing concerns associated with repetitive and potentially hazardous tasks.

4. Empowered Workforce: With the UR10e cobot handling palletizing operations, human workers are freed from monotonous and physically demanding tasks. This empowers the workforce to engage in more valuable and meaningful tasks that require human skills, creativity, and problem-solving.

4.2 Safety Considerations

1. Employee Training: Training programs ensure that employees possess the necessary skills for safe robot operation. The lead worker undergoes training to collaborate effectively with the UR10e, reducing the likelihood of errors during operation and contributing to a safer working environment.

2. Physical Safety Measures The placement of yellow physical fences around the robot's perimeter creates a visible and physical boundary, reducing the risk of collisions and ensuring a safe distance between the robot and human workers.

3. Emergency Stop and Visual Indicators: Visual indicators communicate the status of the emergency stop, ensuring that workers are promptly aware of any safety conditions and can take immediate action to halt operations if necessary.

4. Correct Installation Procedures: orrect installation procedures is crucial to ensure that the robot is securely mounted and configured according to design and safety requirements. It also minimizes the risk of structural issues or malfunctions, ensuring that the robot operates as intended and adheres to safety standards.

5. Test Runs and Validation: Test runs are performed using the simulation tool to validate cycle times and configurations, allowing the lead worker to identify and rectify any operational mistakes or issues in a controlled environment before full production.

The safety considerations in the development of the palletizing cell at Napco Brands are integral to ensuring the efficient and secure collaboration between the UR10e robot and human workers, as well as the overall safety and reliability of the automated palletizing system.

4.3 Analysis of Collaborative Modes

In the collaborative workspace at Napco Brands, the modes employed contribute to a balance between safety and efficiency. Monitored stopping ensures immediate safety in the presence of human workers who walk around the robot, and the visual indicators on yellow fences enhance awareness. Speed and separation monitoring facilitates dynamic adjustments, optimizing collaboration without compromising safety. Power and force limiting allows for close collaboration, and hand guiding accommodates intricate tasks within the shared workspace.

1. Monit : The use of Monitored Stopping proves advantageous by ensuring immediate safety in the presence of human workers, preventing collisions, and allowing for a secure environment for workers to navigate around robots. However, this approach may introduce disruptions in workflow if frequent stops occur, potentially impacting overall productivity. An improvement could involve the implementation of predictive algorithms to minimize unnecessary pauses and the integration of advanced sensors for more accurate detection of human presence, enhancing the mode's effectiveness.

2. Speed and Separation Monitoring: It allows for flexible working conditions with varying robot speeds, balancing efficiency by adapting to the pace of human workers. However, setting up and calibrating speed and separation parameters can be complex, and achieving an optimal balance between speed and safety may pose challenges. To enhance this mode, improvements could involve integrating machine learning algorithms for adaptive speed adjustments and real-time analytics to optimize separation distances based on historical data.

3. Power and Force Limiting: facilitates close collaboration between human workers and robots, reducing the risk of injury during collaborative activities. Yet, limitations arise in the predefined force limits, potentially restricting certain tasks and requiring careful calibration. Continuous monitoring and adjustment of force limits based on task requirements, along with real-time force feedback, could be integrated to enhance this mode and address these limitations effectively.

4. Hand Guiding: allows for intricate tasks within the shared workspace, offering precision and flexibility in collaborative operations. While advantageous, this mode requires training and skill development for effective hand guiding, and errors may occur if the operator lacks adequate training. Improvements could focus on the development of intuitive interfaces to reduce the learning curve and the integration of haptic

feedback for better operator control and awareness, further enhancing the versatility of this collaborative mode at Napco Brands.

4.4 Potential Improvements

Napco Brands can significantly enhance its simulation tool by incorporating interactive and user-friendly features, elevating the testing and configuration adjustment experience. An immersive interface, potentially utilizing virtual reality (VR) or augmented reality (AR), would empower operators to intuitively visualize and manipulate the virtual environment. Real-time performance monitoring integrated into the simulation tool enables operators to track key metrics, identify bottlenecks, and assess configuration changes' impact before implementation. Developing specific training modules within the simulation tool, including guided tutorials and scenario-based training, ensures operators are well-prepared for diverse live production challenges. Introducing predictive maintenance simulations allows operators to anticipate maintenance needs, proactively planning and minimizing downtime. Extending simulation use to virtual commissioning for system integration, encompassing the entire production line, identifies and resolves integration issues beforehand. Allowing users to create and share simulation scenarios fosters collaboration and knowledge-sharing, creating a dynamic platform for innovation and efficiency improvement. Simulating collaborative workspaces, including human-robot interactions, ensures safety and efficiency validation in scenarios involving multiple robots or dynamic worker-robot collaboration. These improvements capitalize on existing technology, enabling Napco Brands to optimize training, testing, and overall operational efficiency within a virtual environment prior to physical implementation in the production setting.

5 Future Directions of Collaborative Robots

As we stand on the precipice of a new era in automation, the future of work is being reshaped by the advent of collaborative robots, or cobots, powered by artificial intelligence (AI). This paradigm shift envisions a workplace where humans and robots work together seamlessly, unlocking unprecedented levels of productivity and efficiency.

AI-driven cobots represent the pinnacle of human-robot collaboration, leveraging advanced AI algorithms to augment their capabilities. Unlike traditional fears of job displacement, these robots are designed to complement human skills, leading to a symbiotic relationship that fosters innovation and creates new opportunities.

Contrary to concerns about automation leading to job losses, studies show that AI-driven cobots generate new avenues for employment. By automating mundane and repetitive tasks, these cobots empower human workers to focus on tasks that require creativity, problem-solving, and unique human skills. [8]

5.1 Suggestions for Improvement

1. User-Friendly Programming Interfaces: Focus on developing even more user-friendly programming interfaces to encourage broader adoption of collaborative robots across different industries. This could involve intuitive graphical interfaces or simplified programming languages.

2. Incorporation of Environmental Sensors: Consider integrating environmental sensors that can detect factors such as temperature, humidity, or air quality. This additional information can contribute to a safer and more comfortable working environment for both humans and robots.

3. Customizable Safety Parameters: Investigate the feasibility of allowing users to customize safety parameters for different collaborative tasks. This customization could provide more flexibility while maintaining safety standards.

4. Energy-Efficient Operational Modes: Explore the development of operational modes that are not only safe but also energy-efficient. This could involve optimizing robot movements and power usage based on the specific task requirements.

5. Enhanced Vision Systems: Invest in research to improve vision systems, enabling collaborative robots to have a more detailed and accurate perception of their surroundings. This can be crucial for tasks requiring high precision and complex visual recognition.

6. Human Behavior Prediction: Develop systems that can predict human behavior within a shared workspace. This could involve machine learning models trained on historical data to anticipate movements and actions of human operators, enabling proactive adjustments in robot behavior.

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