

Ensuring Safety in Human-Robot Cooperation: Key Issues and Future Challenges

Abdel-Nasser Sharkawy^{1,*}, Khaled H. Mahmoud², Gamal T. Abdel-Jaber³

^{1,3} Mechanical Engineering Department, Faculty of Engineering, South Valley University, Qena 83523, Egypt

¹ Mechanical Engineering Department, College of Engineering, Fahad Bin Sultan University, Tabuk 47721, Saudi Arabia

² Mechatronics Department, Faculty of Industry and Energy Technology, New Cairo Technological University NCTU, Cairo, Egypt

Email: ¹ abdelnassersharkawy@eng.svu.edu.eg, ² eng.khaledhma@gmail.com, ³ gtag2000@yahoo.com

*Corresponding Author

Abstract—Human-robot cooperation (HRC) is becoming increasingly essential in many different sectors such as industry, healthcare, agriculture, and education. This cooperation between robot and human has many advantages such as increasing and boosting productivity and efficiency, executing the task easily, effectively, and in a fast time, and minimizing the efforts and time. Therefore, ensuring safety issues during this cooperation are critical and must be considered to avoid or minimize any risk or danger whether for the robot, human, or environment. Risks may be such as accidents or system failures. In this paper, an overview of the safety issues of human-robot cooperation is discussed. The main key challenges in robotics safety are outlined and presented such as collision detection and avoidance, adapting to unpredictable human behaviors, and implementing effective risk mitigation strategies. The difference between industrial robots and cobots is illustrated. Their features and safety issues are also provided. The problem of collision detection or avoidance between the robot and environment is defined and discussed in detail. The result of this paper can be a guideline or framework to future researchers during the design and the development of their safety methods in human-robot cooperation tasks. In addition, it shapes future research directions in safety measures.

Keywords—Human-Robot Cooperation, Key Safety Issues, Future Challenges, Robot Classifications, Collision Detection problem, Recommendations

I. INTRODUCTION

To create effective and secure interactions between humans and robots, human-robot cooperation (HRC) is essential. The capacity, acceptance, and success of the robotic systems depend on the effective HRC, [1]. It encompasses a number of elements, such as trust dynamics, communication modalities, and interfaces [2]. Multimodal interaction is a newer concept in HRC that allows people to interact with robots through a combination of communication modes or various modalities such as touch, gestures, and speech [3]. The interaction experience is improved overall by this wide variety of communication techniques, which makes it more natural and intuitive for people to utilize.

This section is divided into six subsections discussing the following topics:

- Human-Robot Interaction (HRI) Forms
- Physical Human-Robot Interaction
- Safety and Trust in Human-Robot Cooperation
- Ethical Issues in Human-Robot Cooperation
- Key Challenges in Human-Robot Cooperation

- The Main Contribution and Outlines of this paper

A. Human-Robot Interaction (HRI) Forms

Humans and robots, particularly collaborative robots, can work simultaneously in varying proximity degrees based on application area. This interaction between the humans and robot called “Human-Robot interaction (HRI)” and has three forms as follows [4]-[8]:

- Human-robot coexistence: In this field, humans and robots can work in neighboring workspaces and safety fencing is not found. However, a common workspace is not shared between them. In addition, each of them works in an independent different task.
- Human-robot cooperation: In this field, humans and robots can work using the same area or workspace. Their work considers different tasks in the process. In addition, direct interaction between them is not found. During the cooperation, the robot may be safe, or sensors are used to protect the workspace.
- Human-robot collaboration: In this field, both humans and robots are interacting in a shared area or workspace. In this field, robots can pass something to the human, or both can simultaneously execute or carry out different tasks in the same area or workspace.

The present study in this paper can be applied to any form of human-robot interaction. However, we consider the human-robot cooperation (HRC) form.

B. Physical Human-Robot Interaction

A subfield of human-robot interaction called physical human-robot interaction (pHRI) is concerned with the direct physical interactions between people and robots. The main purpose of this physical interaction is performing and carrying out independent or common tasks using close or shared area ensuring and considering confirmed performances, human’s ergonomics, and safety, [9], [10]. For robots to perform more than simple duties, such as entering collaborative workplaces or helping with physical tasks, this field is essential. Applications of pHRI [11], [12] include social robots in healthcare [2], [13], rehabilitation [14], [15], collaborative robots in industrial settings and assembly lines [16], [17], education [18], [19], and home use and service [20], [21].

C. Safety and Trust in Human-Robot Cooperation

For robotic systems to be widely adopted and accepted in a variety of sectors, safety and trust in human-robot cooperation are essential [22]. In collaborative human-robot paradigms, safety is particularly important because, although robots are agile, they also might potentially be dangerous for anyone that engage with them, [23], (see Fig. 1, [24]). Fig. 1 shows an accident between the robot and human. This accident may lead to injuries or high risks to the human operator. The trust between workers and collaborative robots may be greatly increased by including dependability strategies at every level of robotic solution development, which addresses safety issues, [25]. Factors that influence trust in HRC include reliability and predictability. Additionally, when incorporating artificial intelligence (AI) into social and collaborative robots, transparency and privacy issues are essential elements for fostering trust [26].



Fig. 1. Risks to which human operators are exposed during cooperation with robots if safety issues are not considered, [24]

D. Ethical Issues in Human-Robot Cooperation

In addition to trust and safety, ethical considerations are also gaining attention within HRC. The HRC community is paying more and more attention to ethical issues in human-robot interaction or cooperation [27]. Researchers and practitioners may strive toward creating more responsible and socially acceptable human-robot cooperation systems by encouraging research and considerations on the ethical aspects of human-robot partnerships [28]. In addition to ensuring people's safety and wellbeing while dealing with robots, ethical issues also help society's general trust in and acceptance of robotic technology. Ethical considerations related to safety and trust in HRC may include the transparency in AI decision-making and the ethical design of safety protocols.

E. Key Challenges in Human-Robot Cooperation

The main key challenges in the field of human-robot cooperation, as shown in Fig. 2, are challenges considering the safety issues, challenges considering the control methods and the accuracy and repeatability achievement, and challenges considering the perceiving of human motion. However, there are other challenges regarding the HRC. The three mentioned challenges can be discussed and summarized as follows.

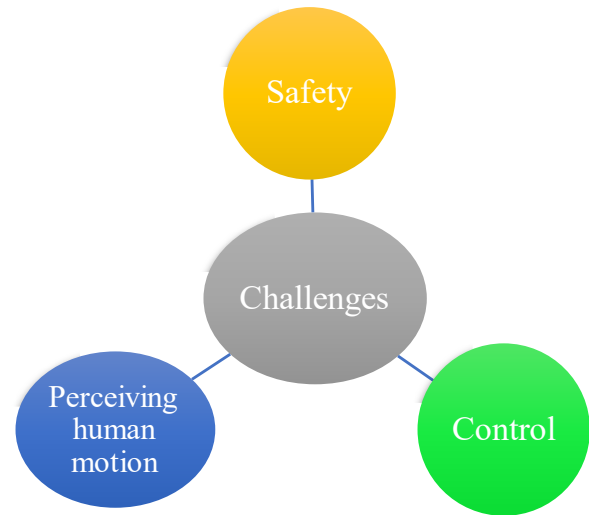


Fig. 2. Some challenges in the field of human-robot cooperation

- Safety: It's critical to maintain supervised and safe interactions. This entails building robots with the right actuators, sensors, and control systems in place to guard against harm during collisions or unforeseen motions.
- Accuracy and control: For robots to handle items or engage in safe and efficient human-robot interaction, they require accurate control over their motions.
- Perceiving human motion: For smooth cooperation, robots need to be able to decipher human gestures, motions, and even predict actions.

F. The Main Contribution and Outlines

From the above challenges, the main contribution of this paper is providing a guide or a framework for the safety aspects of HRC and as a resource for designing safety protocols. This is achieved according to the following points:

- The key challenges in robotics safety are discussed and outlined. The different safety methods are categorized and discussed. In addition, the safety standards are illustrated.
- The differences between industrial robots and cobots are presented. Furthermore, their real applications, safety issues and developed methods are discussed.
- The problem of collision detection or avoidance in human-robot cooperation is presented in detail including its importance, applications, definitions, the different developed methods and algorithms, and the advanced technologies and innovations, the main challenges, and criticism.

The rest of the paper is divided into the following sections. Section II presents the main challenges for the safety of robots. Section III shows the robots classifications and the difference between industrial robots and cobots. In addition, their safety issues. Section IV shows the problem of detection of collisions in robotics and gives some solutions. In section V, the main important points in this paper are summarized and some insights are presented. The content of the presented study can be summarized as shown in Fig. 3.

II. CHALLENGES IN ROBOTICS SAFETY

In this section, an introduction to robotics development is presented. Furthermore, the collision detection approach, different safety methods, ISO standards regarding robotic

safety, and their challenges are discussed. These all points are presented in detail in the following subsections.

A. Introduction to Robotics and Technology Development

One may argue that robotics is the "science of the future". Science fiction is where it all started, and since ancient times, an "automaton" has stood for sophisticated technology. But technological advancement has not happened as quickly as the early robots' advocates may have imagined. Badi-az-Zaman al Jazari (born in 1136 - died in 1206), [29]-[31], was an engineer, mathematician, and an innovator. He was called "The Father of Robotics". He was famous for creating/implementing ingenious pre-modern robots which controlled using different hydraulic-gear systems. Many devices were invented by him, that were precursors to the robots of today. Furthermore, his automation knowledge in the 12th century made inspiration for many scientists' generations. Leonardo da Vinci in about 1492 [32], [33] developed a humanoid robot or automaton which was called the Mechanical Knight. He designed this mechanism to do several motions like human. Otto Mayr [34] analyzes the evolution of machines in terms of advancements in energy conversion in his book about Mechanism and Machine Science. According to Mayr, the history of mechanisms is the tale of improving the efficiency with which energy is converted into work. The efficiency improvements in energy conversion set the stage for the functionality-focused designs found in modern robotics. Put another way, the goal of technology throughout its entire history has been to improve functionality. Currently, for machines to function properly, they need to operate error-free. A machine must be programmed and controlled for it to function independently and provide work that is beneficial to people. When a machine is programmed to carry out activities in a shared environment with people, the capacity to anticipate when a job may lead to a collision is equivalent to the capacity to avert potentially hazardous and destructive accidents. One may say that one of the requirements for successfully automating a process, whether in an industrial context or in daily life, is the detection and prevention of accidents.

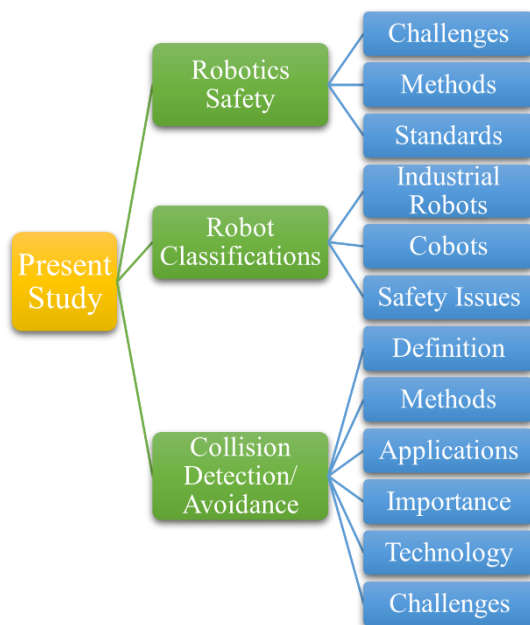


Fig. 3. The content of the presented study of this paper

B. Collision Detection Process in Robotics

Collision detection in robotics is the process of determining if two objects have collided. The robot itself is always one of the objects in the subject of robotics. The other item might be something the robot is trying to avoid, like an obstacle, human operator, environment, or it could be a specific component of the robot, like the robot's end effector trying to manipulate an object. Although a lot of work has been done on collision detection for virtual worlds and animated computer graphics, robotics collision detection is distinct in general because it involves verification and real-time processing. A human-controlled system needs to be able to take input on a course of action and decide whether it can be carried out without causing a collision. An automated system needs to be able to decide on a course of action and determine whether this action will result in a collision. Therefore, collision detection is necessary for any control and decision-making systems that may be included in a robotic system.

C. Risks or Dangers From Robots

In the workplace, robots are becoming more and more prevalent. Although they have numerous advantages, safety must always come first when people and robots are interacting. Industrial robots are potentially very strong devices, and there is a risk of severe harm because of:

- Collisions: Because robots may move swiftly and powerfully, there is a chance that they will run into an employee. In another meaning, in a manufacturing facility, a worker reaching into a robot's work area could be at risk of severe injury due to the robot's powerful, swift movements.
- Crushing: Like human body parts, robot grippers and arms can crush objects.
- Mechanical risks: Cuts, punctures, and abrasions can result from moving parts, sharp edges, and pinch points.

D. Different Safety Methods for Robotics

With collision risks identified, several and various safety techniques or approaches [35]-[40] have been developed to ensure worker safety in robotic environments and to reduce the previously mentioned dangers and risks, as shown in Fig. 4. These approaches are discussed as follows:

- Physical barriers: You may keep uninvited guests out of a robot's workstation by installing cages or fences.
- Safety features: If a human enters a prohibited area, robot movement can be stopped by pressing emergency stop buttons or pressure-sensitive mats.
- Training: Workers need proper training in robotic systems or must get the necessary instruction on robotic systems, including hazard recognition or awareness, safe work practices, and emergency procedures.
- Safety measures: These consist of lockout/tagout routines that guarantee robots are turned off while undergoing programming or maintenance.

E. Safety Standards in Robotics

The principles and criteria for the intrinsic safety of industrial robot designs, safety precautions, and usage information are outlined in ISO 10218-1&2:2011, [41], [42]. It outlines the fundamental concerns connected to robotics

and offers guidelines for getting rid of or significantly lowering the risks brought on by these risks.

In addition to complementing the guidelines and standards for collaborative industrial robot operation provided in ISO 10218-1 and ISO 10218-2, [41], [42], ISO/TS 15066:2016, [43] establishes safety requirements for collaborative industrial robot systems and the work environment.

In designing any safety method in robotics, the previously mentioned ISO standards should be followed and achieved. This is indeed very necessary to improve the safety performance and minimize the risks such as injuries and accidents.

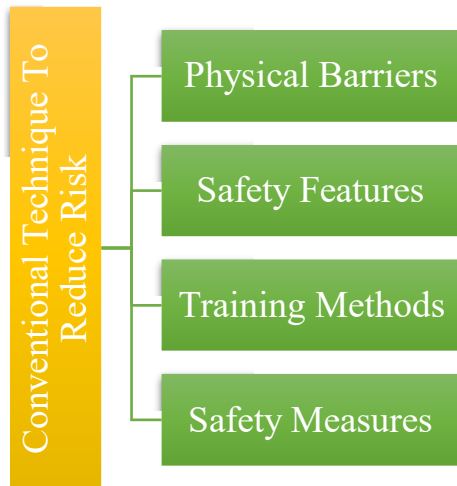


Fig. 4. Conventional techniques to reduce the risk or dangers

III. ROBOT CLASSIFICATIONS

Robots can be classified as shown in Fig. 5, [44]. Any type of them can collaborate with humans in the working area to accomplish a certain task. To do so, the robot must achieve the rules in ISO 10218-1 and ISO 10218-2. In this section, a comparison between robots and cobots is carried out.

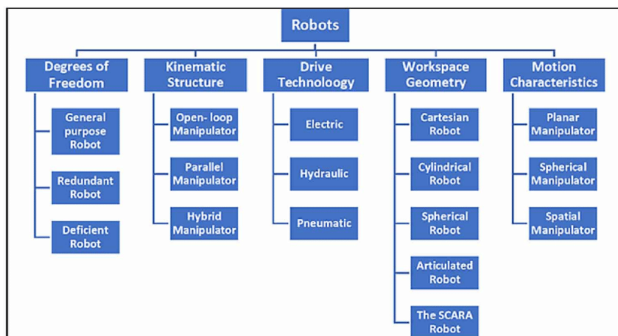


Fig. 5. Robot classifications, [44]

A. Robots and Cobots

Robots are made especially to carry out monotonous duties quickly, accurately, and reliably. Usually seen in assembly lines, large-scale industrial operations, and assembly facilities. Heavy-lifting tasks are a strength of industrial robots. They carry out duties that call for a high level of precision with efficiency. An industrial robot is a typical example of a robot, Fig. 6, [45].

The main Benefits of industrial robots, as shown in Fig. 7, can be presented as follows, [46]-[48]:

- Enhanced Productivity:** Industrial robots work nonstop for extended periods of time without rest or tiredness, which boosts output and increases throughput.
- Accuracy and Precision:** These robots execute jobs with remarkable accuracy, which lowers mistakes and raises the standard of the final product.
- Big Load Handling:** Because industrial robots are designed to handle large weights, they are excellent at lifting and transferring big things.



Fig. 6. Industrial robot in automotive industry, [45]

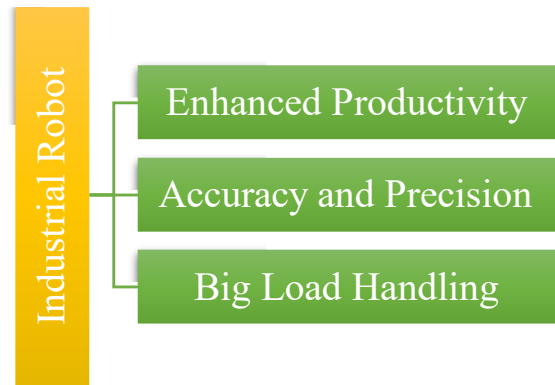


Fig. 7. Some main benefits of industrial robots

Cobots are robots designed to interact directly with people in a shared area or near humans. They are designed for closer human interaction. Typical instances of cobots are those robots that operate in labs alongside humans during experiments, Fig. 8, [49].

The main Advantages of cobots, as presented in Fig. 9, are discussed as follows [50]-[52]:

- Safety:** Cobots are equipped with inbuilt safety measures like force sensors, collision detection, and speed reduction capabilities, which make it safe for human operators to operate in.
- Ease of Use:** Non-experts can quickly program cobots since they are easy to use. Their user-friendly interfaces make it easier to teach robots new tasks.
- Flexibility:** Because of their great adaptability and ease of reconfiguration to carry out various duties, cobots are perfect for small-batch production and frequent product modifications.
- Area Efficiency:** Compared to conventional industrial robots, collaborative robots are smaller and take up less

floor area. Businesses may improve their workspace using this functionality.



Fig. 8. A Cobot working in a laboratory, [49]

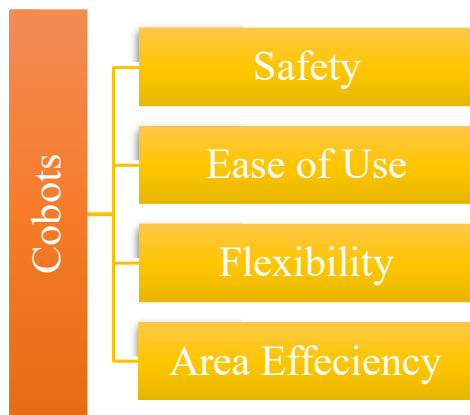


Fig. 9. Some of the advantages of cobots

B. Robots vs. Cobots According to Safety

Many robots, especially those working in industrial field, are not equipped with torque/force sensors. So, strict safety methods are crucial to keep robots working safely with a rare probability of collisions between them and human in working area, e.g. barriers and cages. On other hand, cobots are equipped with joints' torque/force sensors and other safety features to avoid collisions and other risks. This equipment enables cobots from safely cooperation between them and humans. It can be said that:

- Any class of robot can be configured and act as COBOT.
- All traditional cobots are equipped with torque sensors on their joints.
- Cobots must meet all safety requirements such as in standards ISO 10218 and more importantly ISO/TS 15066 to work near people.

IV. DETECTION OF COLLISIONS IN ROBOTICS

Because it guarantees the effectiveness and safety of robotic systems, collision detection is an essential component in robotics. For some years now, collision detection has been a subject of significant research due to various issues in computer graphics, robotics, computer-aided design, and virtual worlds. It is a necessary technological advancement to guarantee the effective, dependable, and safe functioning of robots. Robots may recognize and avoid collisions, reducing damage, increasing productivity, and promoting safe human-robot cooperation by utilizing a variety of sensors, software algorithms, or a mix of the two. Finding pairwise collisions

between a group of entities—let's say a set of n rigid bodies in three dimensions—and returning the timings of the earliest collisions and the pairs of bodies that collide are the main tasks at hand. This subject is the initial stage in modeling the motion of mechanical systems because, with the help of Newtonian impact rules, we can forecast the behavior that follows a collision if we know the location and timing of the collisions. When it comes to virtual environments, this information may be used to animate the objects so that they move through the simulated environment in a way that prevents collisions. This makes collision detection a useful tool as a method of automatically guiding mechanical systems through a designated task while avoiding obstacles.

Robots can successfully traverse their environments, avoid obstacles, and minimize damage to themselves or their surroundings by properly recognizing and predicting future collisions [53]. This is accomplished by utilizing a variety of sensors, including proximity, LIDAR, Radar, Ultrasonic sensors, and video sensors, which offer real-time information about the robot's surroundings. These sensors have good properties as follows; LiDAR provides precise distance measurements for mapping surroundings in 3D, [54]. Radar is useful in detecting objects in diverse weather conditions, [55]. Ultrasonic sensors are effective for short-range detection, [56], [57].

Collision detection systems can recognize possible hazards and take the necessary precautions to prevent collisions by evaluating this data and utilizing artificial intelligence and algorithms. For autonomous robots to function in dynamic and unpredictable settings like factories, warehouses, or even the road, these systems are essential. Industrial robots need high-speed, robust detection to ensure quick decision-making in fast-paced environments, while autonomous vehicles need sophisticated detection to handle complex road scenarios. Robotic systems' ability to detect collisions is essential to their effectiveness and safety.

Robots can successfully traverse their environments, avoid barriers, and stop harm to themselves or their surroundings by precisely detecting and anticipating possible collisions [58]-[60]. Advanced technology is used by autonomous automobiles, trucks, buses, and drone delivery systems. Using cameras and sensors to prevent collisions, lane-changing systems, artificial intelligence (AI) for real-time information analysis, automated vehicle guidance and braking, and deep learning and high-performance computing to adapt to changing conditions using intricate maps are some of these features [61]-[64]. Because it guarantees the effectiveness and safety of robotic systems, collision detection is a critical component in robotics. Robots can successfully traverse their settings, avoid obstacles, and minimize damage to themselves or their surroundings by precisely recognizing and predicting future collisions. To collect real-time data about the robot's surroundings, collision detection systems must make use of sensors such as cameras, LiDAR, radar, and ultrasonic sensors, as well as advances in computer vision. After that, this data is examined by artificial intelligence and algorithms to spot any hazards and determine the best course of action to prevent collisions. Computer Vision and AI Algorithms allow real-time processing and interpretation of visual data, crucial for autonomous decision-making. Robot collision detection systems heavily rely on

computer vision and sensor technologies like LiDAR, radar, and cameras, [65]-[68].

These methods depend on the robot's ability to see its surroundings, which is accomplished using sensors like cameras, radar, LIDAR, and ultrasonic is impossible to overestimate the importance of precise collision detection on robots in the quickly evolving world of today. It offers an essential degree of security and defense for robots as well as for humans and things in their immediate vicinity. Robotic systems' safety and effectiveness depend on their ability to detect collisions. Robots using collision detection systems can precisely identify possible impediments and take preventative action by fusing computer vision with technologies like radar and LiDAR. This entails modifying their course, accelerating, or, if required, completely stopping. However, LiDAR and camera-based systems may struggle in heavy rain or fog, and AI algorithms require significant computational power, which may not be feasible in all robotic systems.

Autonomous vehicles can effectively identify and prevent crashes thanks to these cutting-edge technical capabilities, protecting both the vehicle and its surroundings [69]. Furthermore, robot collision detection is crucial for maximizing efficiency and output [70]. Robots are better able to traverse their environments by anticipating probable accidents and avoiding unneeded pauses or delays.

As robotics continues to evolve, collision detection systems will become increasingly sophisticated, paving the way for a future where robots seamlessly integrate into our lives.

A. Methods and Mechanisms of Collision Detection

There are two primary approaches to collision detection in robotics, as shown in Fig. 10.

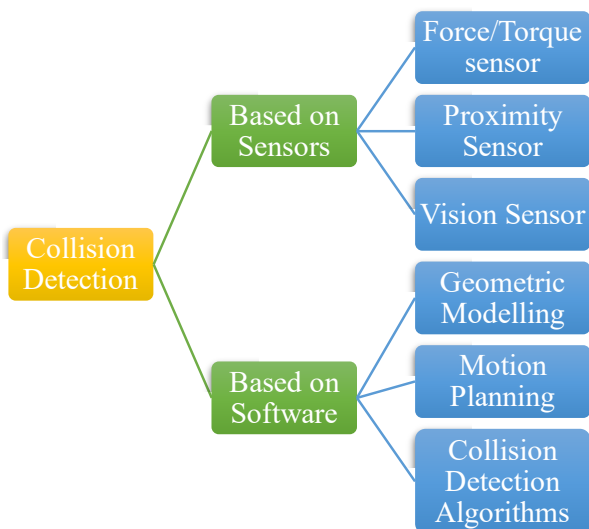


Fig. 10. The used approaches for collision detection during human-robot cooperation

These approaches are discussed as follows:

1) Sensor-based detection: This method utilizes various sensors to detect physical contact between the robot and its environment. Examples of these methods are presented in [71]-[78]. Common sensors include:

- Force/torque sensors: These sensors measure the forces and torques exerted on the robot's end-effector, indicating potential collisions.
 - Proximity sensors: These sensors detect the presence of nearby objects without requiring physical contact. Examples include infrared sensors, ultrasonic sensors, and LiDAR.
 - Vision sensors: Cameras can be used to visually identify obstacles and potential collision points in the robot's workspace.
- 2) Software-based detection (Collision Checking): This method employs computer simulations to predict potential collisions before the robot executes its movements. Examples of these methods are presented in [79]-[99]. Collision checking involves:
- Geometric modeling: Creating accurate 3D models of the robot and its environment.
 - Motion planning: Simulating the robot's planned movements.
 - Collision detection algorithms: These algorithms compare the robot's motion with the environment model to identify potential collisions.

Both sensor-based and software-based detection methods have their advantages and disadvantages. Sensor-based detection provides real-time information but can be susceptible to external factors. Software-based detection allows for proactive collision avoidance but requires accurate models and computational resources. In many cases, a combination of both methods is employed for optimal performance.

B. Applications of Collision Detection in Robotics

Collision detection plays a vital role in various robotic applications, as shown in Fig. 11, including:

- Industrial robotics: Ensuring safe and efficient operation of robots in manufacturing environments.
- Service robotics: Enabling robots to navigate and interact safely in domestic or public settings.
- Medical robotics: Guaranteeing patient safety during robot-assisted surgeries.
- Autonomous vehicles: Preventing collisions between self-driving cars and their surroundings.

By incorporating robust collision detection systems, robots can operate more effectively and safely in diverse environments, expanding their potential applications.

C. Definition of Collision Detection in Robotics

Numerous algorithms have been created recently to solve issues unique to articulated robots. These robots move in complex ways and have several limbs connected by joints. These robots may be exceedingly challenging to detect collisions with, particularly if one wants to take the robot's dynamics into account. Real-time detection and response to collisions is another unsolved issue. This is crucial for computer games and virtual worlds that offer haptic feedback.

Collision detection is an important part of many robotics and virtual environment tasks. Often the motion planning system is the biggest user of collision detection. Motion planning is the computation of a path for a given system to move from its current state to a desired state while avoiding

collisions. Other uses include haptic feedback, physically based simulation, and virtual environments.

The practice of looking for potential collisions between certain objects is known as collision detection. These things may consist of two or more robots, a robot and its surroundings, or individual robot components. When a collision happens, the collision detection system will report it. Additionally, it can record the initial collision site. These inquiries may return extensive data or a yes/no response.

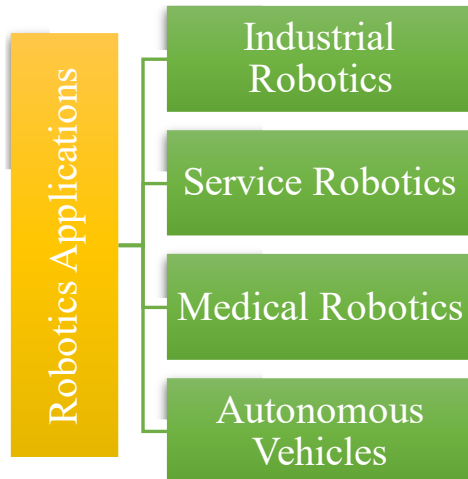


Fig. 11. Some robotics applications need necessary safety methods

D. Importance of Collision Detection in Robotics

The safety in human-robot coexistence makes it important to consider a collision avoidance system. It is convenient to avoid collisions, but it is also important to be prepared for near collisions and know what to do following a collision. It has been noted that in dynamic, real-time situations that action-selection by the robot following a collision may be limited by reduced vehicle/maneuverability constraints and that a good decision pre-collision may fail during the limited control post-collision time. This makes a case for quality local path planning and the ability to directly implement the robot's decision. It was considered before a near-collision to be a situation where a collision cannot be avoided by any steering control input. This implies that near collisions can only be distinguished from actual collisions with knowledge of the robot's steering and handling performance bounds.

The significance of collision detection in industrial robotics extends beyond accident prevention to improving operational efficiency and enhancing human-robot cooperation in high-payload applications [100]. By integrating collision detection systems into industrial robots, manufacturers can increase productivity by reducing downtime caused by collisions, enhance worker safety by minimizing the risk of accidents, and improve the overall reliability and performance of robotic systems

Furthermore, the development of virtual sensors that can detect and distinguish between human contact and collisions further advances the capabilities of industrial robots in ensuring workplace safety and efficiency [101]. As collision detection technology continues to evolve, its applications in industrial robotics will play a pivotal role in shaping the future of automation and robotics in various sectors.

Finally, to implement any sort of collision detection and avoidance method, a robot must have a good understanding

of the environment in which it is moving. This data might be provided by on-board sensors or a priori maps, and the method must be able to handle uncertainties in the environment and changes to the environment dynamics.

E. Technological Advances and Sensors Used for Collision Detection

Sensor technologies play a crucial role in collision detection in industrial robotics, enabling robots to perceive and respond to potential collisions effectively, [1]. These sensors are designed to detect contact and collisions between robots and their surrounding environment, ensuring the safety of both the robotic systems and human operators. Some key sensor technologies used for collision detection in industrial robotics include Force/torque sensors, Proximity sensors, Infrared sensors, and Laser scanners. By leveraging these sensor technologies, industrial robots can detect collisions in real-time, triggering emergency stops to prevent accidents and equipment damage. The integration of advanced sensor technologies not only enhances the safety of industrial robotic operations but also improves overall efficiency and productivity.

Machine learning techniques have revolutionized the field of collision detection in industrial robotics, particularly in predictive collision avoidance systems [102], [103]. By utilizing deep learning approaches, such as neural networks and recurrent neural networks like long short-term memory (LSTM), robots can learn to anticipate and avoid potential collisions based on historical data and real-time inputs [104]. Machine learning algorithms enable robots to make split-second decisions to navigate around obstacles, adjust their trajectories, and prevent collisions proactively. This predictive collision avoidance capability enhances the agility and adaptability of industrial robots in dynamic and complex environments.

The integration of vision systems in collision detection has further advanced the capabilities of industrial robots in identifying and avoiding collisions with precision. Vision-based sensors, such as cameras and 3D laser scanners, provide robots with visual feedback to map their surroundings, detect obstacles, and calculate optimal paths to avoid collisions. By combining sensor data with visual information, robots can enhance their collision detection accuracy and efficiency, enabling smooth and safe operation in various industrial settings [105]. The synergy between sensor technologies, machine learning algorithms, and vision systems has propelled the field of collision detection in industrial robotics towards greater safety, reliability, and performance [102].

F. Future Challenges of Collision Detection in Robotics

The primary focus of the robotic motion planning community has been on the use of collision detection while moving articulated bodies through known static environments, to a given goal configuration [106].

This has been framed as the so-called "discrete" problem where we seek to determine if there exists a sequence of motions for the robot, which moves the end-effector through a specified path in configuration space P , from an initial configuration to a goal configuration. Here the environment is modeled by an implicit representation of the obstacles O , and it has been assumed for simplicity that P is a Euclidean

space, and the robot moves P with unit speed. This restrictive formulation throws up many difficult problems related to collision detection but a recent shift in attention to the less restrictive "compliant motion" framework offers even harder problems and a greater diversity of research opportunities [107].

Collision detection has been a topic of substantial research for several years motivated by numerous problems in computer graphics, robotics, computer-aided design, and virtual environments. The problem is essentially to determine if there are any pairwise collisions between a collection of bodies, say a set of n rigid bodies in 3D, and if there are, to return the times of the earliest collisions and the pairs of bodies which collide. This topic is the first step in simulating the motion of mechanical systems, for if we know when and where the collisions occur, we can predict the post-collision behavior using Newtonian impact laws. In the case of virtual environments, we can use this information to animate the objects through the simulated environment, so that they move in such a way as to avoid these collisions. This makes collision detection a useful tool as a method of automatically guiding mechanical systems through a designated task while avoiding obstacles.

Eventually, the integration of AI methods with IoT for predictive maintenance or advances in 3D mapping for better environmental understanding, needs to be applied and deeply investigated.

V. CONCLUSION AND MAIN INSIGHTS

In this paper, an overview of safety of human-robot cooperation is presented. Furthermore, the main challenges are outlined and illustrated. Implementing a safety method during any control process, decision-making systems, or any human-robot cooperation task, is very necessary and must be included in a robotic system to minimize the risk or danger. During the development of any robotic safety method, ISO standards should be followed to avoid any risk or danger during the cooperation between human and robot. Sensor-based or software-based collision detection or avoidance methods have their advantages and disadvantages. Sensor-based safety methods provide real-time information but can be susceptible to external factors. Whereas software-based safety methods allow for proactive collision avoidance or detection but require accurate models and computational resources. In many cases, a combination of both methods is employed for optimal performance. The synergy between sensor technologies, and advanced algorithms such as machine learning can improve and give greater safety, reliability, and performance. In addition, this synergy can provide a balanced approach, enhancing real-time responsiveness and predictive capabilities. Machine learning is a promising area for enhancing adaptability and accuracy in safety systems.

The main future challenges in safety of human-robot cooperation can be presented in the following points:

- Developing a safety method that has advantages such reliability, high accuracy, high effectiveness and performance in collision detection or avoidance, less complexity and processing time, and cost effectiveness.
- Furthermore, achieving specific goals for future safety methods is recommended, such as reduced system

latency, robustness to environmental changes, and cost-effective implementation.

- Improving sensor accuracy, reducing computational complexity, or better integration of machine learning for predictive safety methods, can also be some future challenges.

Eventually, the presented study can be a short guideline or framework for researchers during the development of their future safety methods. The growing importance of human-robot safety can make collaborative robotics become more widespread.

LIST OF ABBREVIATIONS

Abbreviation	Meaning
HRI	: Human-robot interaction
HRC	: Human-robot cooperation
pHRI	: Physical human-robot interaction
ISO	: International Organization for Standardization
Cobot	: Collaborative robot
AI	: Artificial Intelligence
3D	: Three dimensions
LSTM	: Long short-term memory
IoT	: Internet of Things

REFERENCES

- [1] W. K. P. Barros, M. T. Barbosa, L. A. Dias, and M. A. C. Fernandes, "Fully Parallel Proposal of Naive Bayes on FPGA," *Electronics*, vol. 11, no. 16, p. 2565, 2022, <https://doi.org/10.3390/electronics11162565>.
- [2] I. N. Weerarathna, D. Raymond, and A. Luharia, "Human-Robot Collaboration for Healthcare: A Narrative Review," *Cureus*, vol. 15, no. 11, pp. 1–11, 2023, <https://doi.org/10.7759/cureus.49210>.
- [3] H. Su, W. Qi, J. Chen, C. Yang, J. Sandoval, and M. A. Laribi, "Recent advancements in multimodal human-robot interaction," *Frontiers in Neurobotics*, vol. 17, pp. 1–21, 2023, <https://doi.org/10.3389/fnbot.2023.1084000>.
- [4] KUKA, "Human-robot collaboration: Welcome, fellow robot!," *KUKA Website*, 2024, <https://www.kuka.com/en-de/future-production/human-robot-collaboration>.
- [5] D. F. N. Gordon, A. Christou, T. Stouraitis, M. Gienger, and S. Vijayakumar, "Adaptive assistive robotics: a framework for triadic collaboration between humans and robots," *Royal Society Open Science*, vol. 10, no. 6, pp. 1–15, 2023, <https://doi.org/10.1098/rsos.221617>.
- [6] J. Bütepage and D. Kragic, "Human-Robot Collaboration: From Psychology to Social Robotics," *arXiv Robotics*, 2017, <https://doi.org/10.48550/arXiv.1705.10146>.
- [7] R. Galin, R. Meshcheryakov, and S. Kamesheva, "Distributing Tasks in Multi-agent Robotic System for Human-Robot Interaction Applications," *Interactive Collaborative Robotics*, pp. 99–106, 2020, https://doi.org/10.1007/978-3-030-60337-3_10.
- [8] A. Dąbrowska, R. Giel, and S. Werbińska-Wojciechowska, "Human Safety in Autonomous Transport Systems – Review and Case Study," *Journal of KONBiN*, vol. 51, no. 1, pp. 57–71, 2021, <https://doi.org/10.2478/jok-2021-0005>.
- [9] M. Benoussaad, G. Grioli, W. Wan, and M. Rakotondrabe, "Editorial: 'Physical human-robot interaction and co-manipulation: Mechatronics approaches,'" *Mechatronics*, vol. 86, p. 102877, 2022, <https://doi.org/10.1016/j.mechatronics.2022.102877>.
- [10] C. Fang, L. Peternel, A. Seth, M. Sartori, K. Mombaur and E. Yoshida, "Human Modeling in Physical Human-Robot Interaction: A Brief Survey," *IEEE Robotics and Automation Letters*, vol. 8, no. 9, pp. 5799–5806, 2023, <https://doi.org/10.1109/LRA.2023.3296349>.
- [11] A.-N. Sharkawy, "A Survey on Applications of Human-Robot Interaction," *Sensors & Transducers*, vol. 251, no. 4, pp. 19–27, 2021, https://sensorsportal.com/HTML/DIGEST/april_2021/Vol_251/P_32_21.pdf.
- [12] A. Sharkawy, "Human-Robot Interaction: Applications," *arXiv Robotics*, 2021, <http://dx.doi.org/10.48550/arXiv.2102.00928>.
- [13] H. Su, A. Di Lallo, R. R. Murphy, R. H. Taylor, B. T. Garibaldi, and

- A. Krieger, "Physical human–robot interaction for clinical care in infectious environments," *Nature Machine Intelligence*, vol. 3, no. 3, pp. 184–186, 2021, <https://doi.org/10.1038/s42256-021-00324-z>.
- [14] H. Yu, S. Huang, G. Chen, Y. Pan and Z. Guo, "Human–Robot Interaction Control of Rehabilitation Robots With Series Elastic Actuators," *IEEE Transactions on Robotics*, vol. 31, no. 5, pp. 1089–1100, 2015, <https://doi.org/10.1109/TRO.2015.2457314>.
- [15] A. Mohebbi, "Human-Robot Interaction in Rehabilitation and Assistance: a Review," *Current Robotics Reports*, vol. 1, no. 3, pp. 131–144, 2020, <https://doi.org/10.1007/s43154-020-00015-4>.
- [16] A. Keshvarparast, D. Battini, O. Battaia, and A. Pirayesh, "Collaborative robots in manufacturing and assembly systems: literature review and future research agenda," *Journal of Intelligent Manufacturing*, vol. 35, no. 5, pp. 2065–2118, 2024, <https://doi.org/10.1007/s10845-023-02137-w>.
- [17] U. Othman and E. Yang, "Human–Robot Collaborations in Smart Manufacturing Environments: Review and Outlook †," *Sensors*, vol. 23, no. 12, pp. 1–17, 2023, <https://doi.org/10.3390/s23125663>.
- [18] H. Wang, N. Luo, T. Zhou, and S. Yang, "Physical Robots in Education: A Systematic Review Based on the Technological Pedagogical Content Knowledge Framework," *Sustainability*, vol. 16, no. 12, p. 4987, 2024, <https://doi.org/10.3390/su16124987>.
- [19] M. Farajtabar and M. Charbonneau, "The path towards contact-based physical human–robot interaction," *Robotics and Autonomous Systems*, vol. 182, p. 104829, 2024, <https://doi.org/10.1016/j.robot.2024.104829>.
- [20] C. S. Song and Y. Kim, "The role of the human-robot interaction in consumers' acceptance of humanoid retail service robots," *Journal of Business Research*, vol. 146, pp. 489–503, 2022, <https://doi.org/10.1016/j.jbusres.2022.03.087>.
- [21] B. Cagiltay, "Designing for In-Home Long-Term Family-Robot Interactions: Family Preferences, Connection-Making, and Privacy," *CHI EA '23: Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–6, 2023, <https://doi.org/10.1145/3544549.3577035>.
- [22] I. Maurtua, A. Ibarguren, J. Kildal, L. Susperregi, and B. Sierra, "Human-robot collaboration in industrial applications: Safety, interaction and trust," *International Journal of Advanced Robotic Systems*, vol. 14, no. 4, pp. 1–10, 2017, <https://doi.org/10.1177/1729881417716010>.
- [23] M. Hamad, S. Nertinger, R. J. Kirschner, L. Figueredo, A. Naceri, and S. Haddadin, "A Concise Overview of Safety Aspects in Human-Robot Interaction," *Human-Friendly Robotics 2023*, pp. 1–18, 2024, https://doi.org/10.1007/978-3-031-55000-3_1.
- [24] JICOSH, "Outline of Japan's Industrial Safety and Health Law: 18. Regulations concerning Industrial Robots," *JICOSH Home*, 2008, <https://www.jisha.or.jp/international/jicosh/english/osh/outline/18.htm>.
- [25] A. Zacharaki, I. Kostavelis, A. Gasteratos, and I. Dokas, "Safety bounds in human robot interaction: A survey," *Safety Science*, vol. 127, p. 104667, 2020, <https://doi.org/10.1016/j.ssci.2020.104667>.
- [26] A. Martinetti, P. K. Chemweno, K. Nizamis, and E. Fosch-Villaronga, "Redefining Safety in Light of Human-Robot Interaction: A Critical Review of Current Standards and Regulations," *Frontiers in Chemical Engineering*, vol. 3, pp. 1–12, 2021, <https://doi.org/10.3389/fceng.2021.666237>.
- [27] K. S. Haring, M. M. Novitzky, P. Robinette, E. J. de Visser, A. Wagner and T. Williams, "The Dark Side of Human-Robot Interaction: Ethical Considerations and Community Guidelines for the Field of HRI," *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 689–690, 2019, <https://doi.org/10.1109/HRI.2019.8673184>.
- [28] M. M. A. D. Graaf, "An Ethical Evaluation of Human–Robot Relationships," *International Journal of Social Robotics*, vol. 8, no. 4, pp. 589–598, 2016, <https://doi.org/10.1007/s12369-016-0368-5>.
- [29] L. Romdhane and S. Zeghloul, "Al-jazari (1136–1206)," *Distinguished Figures in Mechanism and Machine Science*, pp. 1–21, 2009, https://doi.org/10.1007/978-90-481-2346-9_1.
- [30] B. Ahmed, "The Muslim Father of Robotics," *IslamiCity*, 2022, <https://www.islamicity.org/79783/the-muslim-father-of-robotics/>.
- [31] J. Elices, "Medieval robots? They were just one of this Muslim inventor's creations," *National Geographic*, 2020, <https://www.nationalgeographic.com/history/history-magazine/article/ismail-al-jazari-muslim-inventor-called-father-robotics>.
- [32] R. Ren, "Ahead of His Time: Leonardo da Vinci's Contributions to Engineering," *Journal of Education, Humanities and Social Sciences*, vol. 21, pp. 18–25, 2023, <https://doi.org/10.54097/ehss.v21i.13025>.
- [33] M. Manuel, "Leonardo da Vinci's Robots and Their Modern-Day Influence," *ARTpublika Magazine: Art Culture for The People*, 2019, <https://www.artpublikamag.com/post/leonardo-da-vincis-robots-and-their-modern-day-influence>.
- [34] M. Coeckelbergh, "Can machines create art?," *Philosophy & Technology*, vol. 30, no. 3, pp. 285–303, 2017, <https://doi.org/10.1007/s13347-016-0231-5>.
- [35] A. Giallanza, G. La Scalia, R. Micale, and C. M. La Fata, "Occupational health and safety issues in human-robot collaboration: State of the art and open challenges," *Safety Science*, vol. 169, no. 106313, pp. 1–18, 2024, <https://doi.org/10.1016/j.ssci.2023.106313>.
- [36] A. Bicchi, M. A. Peshkin, and J. E. Colgate, "Safety for Physical Human–Robot Interaction," *Springer Handbook of Robotics*, pp. 1335–1348, 2008, https://doi.org/10.1007/978-3-540-30301-5_58.
- [37] L. Gualtieri, E. Rauch, and R. Vidoni, "Development and validation of guidelines for safety in human-robot collaborative assembly systems," *Computers & Industrial Engineering*, vol. 163, p. 107801, 2022, <https://doi.org/10.1016/j.cie.2021.107801>.
- [38] N. Wang, Y. Zeng, and J. Geng, "A Brief Review on Safety Strategies of Physical Human-robot Interaction," *ITM Web of Conferences*, vol. 25, p. 1015, 2019, <https://doi.org/10.1051/itmconf/20192501015>.
- [39] M. Dianatfar, J. Latokartano, and M. Lanz, "Concept for virtual safety training system for human-robot collaboration," *Procedia Manufacturing*, vol. 51, pp. 54–60, 2020, <https://doi.org/10.1016/j.promfg.2020.10.009>.
- [40] A. Sharkawy and P. N. Koustoumpardis, "Human–Robot Interaction: A Review and Analysis on Variable Admittance Control, Safety, and Perspectives," *Machines*, vol. 10, no. 7, p. 591, 2022, <https://doi.org/10.3390/machines10070591>.
- [41] C. Franklin, "The Role of Standards in Human–Robot Integration Safety," *The 21st Century Industrial Robot: When Tools Become Collaborators*, pp. 155–171, 2022, https://doi.org/10.1007/978-3-030-78513-0_9.
- [42] Z. Bi, "Overview of Testing Platform for Development of Integrated Robotic Systems at NIST," *2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pp. 899–904, 2019, <https://doi.org/10.1109/ICIEA.2019.8833685>.
- [43] B. Matthias and T. Reisinger, "Example Application of ISO/TS 15066 to a Collaborative Assembly Scenario," *Proceedings of ISR 2016: 47th International Symposium on Robotics*, pp. 1–5, 2016, <https://ieeexplore.ieee.org/abstract/document/7559102>.
- [44] N. Darapureddy, M. Kurni, and K. Saritha, "A comprehensive study on artificial intelligence and robotics for machine intelligence," *Methodologies and Applications of Computational Statistics for Machine Intelligence*, pp. 203–222, 2021, <https://doi.org/10.4018/978-1-7998-7701-1.ch011>.
- [45] W. E. Keeling, "Pick and Place Robots – How do Robotic Arms Help Industries in Pick and Place of Products?," *iCharts*, 2019, <https://www.icharts.org/pick-and-place-robots-how-do-robotic-arms-help-industries-in-pick-and-place-of-products/>.
- [46] Ş. Çiğdem, I. Meidute-Kavaliauskiene, and B. Yıldız, "Industry 4.0 and Industrial Robots: A Study from the Perspective of Manufacturing Company Employees," *Logistics*, vol. 7, no. 1, pp. 17, 2023, <https://doi.org/10.3390/logistics7010017>.
- [47] Y. Zhao, R. Said, N. W. Ismail, and H. Z. Hamzah, "Impact of industrial robot on labour productivity: Empirical study based on industry panel data," *Innovation and Green Development*, vol. 3, no. 2, p. 100148, 2024, <https://doi.org/10.1016/j.igd.2024.100148>.
- [48] W. Yuan and W. Lu, "Research on the impact of industrial robot application on the status of countries in manufacturing global value chains," *PLoS One*, vol. 18, no. 6, p. e0286842, 2023, <https://doi.org/10.1371/journal.pone.0286842>.
- [49] KUKA, "Cobots: Your entry into automation with collaborative robots," *KUKA Website*, 2023, <https://www.kuka.com/en-au/future-production/human-robot-collaboration/cobots>.

- [50] A. N. Sharkawy, "Task Location to Improve Human-Robot Cooperation: A Condition Number-Based Approach," *Automation*, vol. 4, no. 3, pp. 263–290, 2023, <https://doi.org/10.3390/automation4030016>.
- [51] M. M. Rahman, F. Khatun, I. Jahan, R. Devnath, and M. A.-A. Bhuiyan, "Cobotics: The Evolving Roles and Prospects of Next-Generation Collaborative Robots in Industry 5.0," *Journal of Robotics*, vol. 2024, no. 1, pp. 1–22, 2024, <https://doi.org/10.1155/2024/2918089>.
- [52] S. Patil, V. Vasu, and K. V. S. Srinadh, "Advances and perspectives in collaborative robotics: a review of key technologies and emerging trends," *Discover Mechanical Engineering*, vol. 2, no. 13, pp. 1–19, 2023, <https://doi.org/10.1007/s44245-023-00021-8>.
- [53] B. Hermans, P. Patrinos, and G. Pipeleers, "A Penalty Method Based Approach for Autonomous Navigation using Nonlinear Model Predictive Controls," *IFAC-PapersOnLine*, vol. 51, no. 20, pp. 234–240, 2018, <https://doi.org/10.1016/j.ifacol.2018.11.019>.
- [54] J. Young and M. Simic, "LIDAR and monocular based overhanging obstacle detection," *Procedia Computer Science*, vol. 60, pp. 1423–1432, 2015, <https://doi.org/10.1016/j.procs.2015.08.218>.
- [55] X. Chen, W. Ren, M. Liu, L. Jin, and Y. Bai, "An obstacle detection system for a mobile robot based on radar-vision fusion," *Proceedings of the 4th International Conference on Computer Engineering and Networks*, vol. 355, pp. 677–685, 2015, https://doi.org/10.1007/978-3-319-11104-9_79.
- [56] M. H. Setiawan, A. Ma'arif, H. M. Marhoon, A. Sharkawy, A. Çakan, "Distance Estimation on Ultrasonic Sensor Using Kalman Filter," *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 5, no. 2, pp. 210–217, 2023, <https://doi.org/10.12928/biste.v5i2.8089>.
- [57] V. A. Zhmud, N. O. Kondratiev, K. A. Kuznetsov, V. G. Trubin, and L. V. Dimitrov, "Application of ultrasonic sensor for measuring distances in robotics," *Journal of Physics: Conference Series*, vol. 1015, no. 3, p. 032189, 2018, <https://doi.org/10.1088/1742-6596/1015/3/032189>.
- [58] H. Qin, S. Shao, T. Wang, X. Yu, Y. Jiang, and Z. Cao, "Review of Autonomous Path Planning Algorithms for Mobile Robots," *Drones*, vol. 7, no. 3, p. 211, 2023, <https://doi.org/10.3390/drones7030211>.
- [59] L. Cofran *et al.*, "Barriers to safety and efficiency in robotic surgery docking," *Surgical Endoscopy*, vol. 36, no. 1, pp. 206–215, 2022, <https://doi.org/10.1007/s00464-020-08258-0>.
- [60] K. Katona, H. A. Neamah, and P. Korondi, "Obstacle Avoidance and Path Planning Methods for Autonomous Navigation of Mobile Robot," *Sensors*, vol. 24, no. 11, p. 3573, 2024, <https://doi.org/10.3390/s24113573>.
- [61] A. Gupta, A. Anpalagan, L. Guan, and A. S. Khwaja, "Deep learning for object detection and scene perception in self-driving cars: Survey, challenges, and open issues," *Array*, vol. 10, p. 100057, 2021, <https://doi.org/10.1016/j.array.2021.100057>.
- [62] G. Bathla *et al.*, "Autonomous Vehicles and Intelligent Automation: Applications, Challenges, and Opportunities," *Mobile Information Systems*, vol. 2022, no. 1, pp. 1–36, 2022, <https://doi.org/10.1155/2022/7632892>.
- [63] M. Sadaf *et al.*, "Connected and Automated Vehicles: Infrastructure, Applications, Security, Critical Challenges, and Future Aspects," *Technologies*, vol. 11, no. 5, pp. 1–63, 2023, <https://doi.org/10.3390/technologies11050117>.
- [64] F. Mirzarazi, S. Danishvar, and A. Mousavi, "The Safety Risks of AI-Driven Solutions in Autonomous Road Vehicles," *World Electric Vehicle Journal*, vol. 15, no. 10, p. 438, 2024, <https://doi.org/10.3390/wevj15100438>.
- [65] S. Seo and H. Jung, "A robust collision prediction and detection method based on neural network for autonomous delivery robots," *ETRI Journal*, vol. 45, no. 2, pp. 329–337, 2023, <https://doi.org/10.4218/etrij.2021-0397>.
- [66] J. Park and N. Cho, "Collision avoidance of hexacopter UAV based on lidar data in dynamic environment," *Remote Sensing*, vol. 12, no. 6, p. 975, 2020, <https://doi.org/10.3390/rs12060975>.
- [67] I. Arrouch, N. S. Ahmad, P. Goh, and J. Mohamad-Saleh, "Close Proximity Time-to-collision Prediction for Autonomous Robot Navigation: An Exponential GPR Approach," *Alexandria Engineering Journal*, vol. 61, no. 12, pp. 11171–11183, 2022, <https://doi.org/10.1016/j.aej.2022.04.041>.
- [68] X. B. Hoang, P. C. Pham, and Y. L. Kuo, "Collision Detection of a HEXA Parallel Robot Based on Dynamic Model and a Multi-Dual Depth Camera System," *Sensors*, vol. 22, no. 15, p. 5923, 2022, <https://doi.org/10.3390/s22155923>.
- [69] X. Dong and M. L. Cappuccio, "Applications of Computer Vision in Autonomous Vehicles: Methods, Challenges and Future Directions," *arXiv Computer Vision and Pattern Recognition*, 2023, <http://arxiv.org/abs/2311.09093>.
- [70] S. M. Patole, M. Torlak, D. Wang and M. Ali, "Automotive radars: A review of signal processing techniques," *IEEE Signal Processing Magazine*, vol. 34, no. 2, pp. 22–35, 2017, <https://doi.org/10.1109/MSP.2016.2628914>.
- [71] F. Flacco, T. Kröger, A. De Luca and O. Khatib, "A depth space approach to human-robot collision avoidance," *2012 IEEE International Conference on Robotics and Automation*, pp. 338–345, 2012, <https://doi.org/10.1109/ICRA.2012.6225245>.
- [72] T. Borangiu, A. Thomas, D. Trentesaux, "Service Orientation in Holonic and Multi Agent Manufacturing and Robotics," *Springer Berlin*, 2013, <https://doi.org/10.1007/978-3-642-35852-4>.
- [73] M. Kitaoka, A. Yamashita, and T. Kaneko, "Obstacle Avoidance and Path Planning Using Color Information for a Biped Robot Equipped with a Stereo Camera System," *Proceedings of the 4th Asia International Symposium on Mechatronics*, pp. 38–43, 2010, https://doi.org/10.3850/978-981-08-7723-1_P134.
- [74] S. Lenser and M. Veloso, "Visual sonar: fast obstacle avoidance using monocular vision," *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003) (Cat. No.03CH37453)*, vol. 1, pp. 886–891, 2003, <https://doi.org/10.1109/IROS.2003.1250741>.
- [75] B. Peasley and S. Birchfield, "Real-time obstacle detection and avoidance in the presence of specular surfaces using an active 3D sensor," *2013 IEEE Workshop on Robot Vision (WORV)*, pp. 197–202, 2013, <https://doi.org/10.1109/WORV.2013.6521938>.
- [76] F. Flacco, T. Kroeger, A. De Luca, and O. Khatib, "A Depth Space Approach for Evaluating Distance to Objects," *Journal of Intelligent & Robotic Systems*, vol. 80, pp. 7–22, 2014, <https://doi.org/10.1007/s10846-014-0146-2>.
- [77] D. Gandhi and E. Cervera, "Sensor covering of a robot arm for collision avoidance," *SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme - System Security and Assurance (Cat. No.03CH37483)*, vol. 5, pp. 4951–4955, 2003, <https://doi.org/10.1109/ICSMC.2003.1245767>.
- [78] T. L. Lam, H. W. Yip, H. Qian and Y. Xu, "Collision avoidance of industrial robot arms using an invisible sensitive skin," *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura-Algarve*, pp. 4542–4543, 2012, <https://doi.org/10.1109/IROS.2012.6386294>.
- [79] S. Haddadin, A. Albu-Schaffer, A. De Luca and G. Hirzinger, "Collision Detection and Reaction: A Contribution to Safe Physical Human-Robot Interaction," *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3356–3363, 2008, <https://doi.org/10.1109/IROS.2008.4650764>.
- [80] C. Cho, J. Kim, S. Lee, and J. Song, "Collision detection and reaction on 7 DOF service robot arm using residual observer," *Journal of Mechanical Science and Technology*, vol. 26, no. 4, pp. 1197–1203, 2012, <https://doi.org/10.1007/s12206-012-0230-0>.
- [81] B. -j. Jung, H. R. Choi, J. C. Koo and H. Moon, "Collision detection using band designed Disturbance Observer," *2012 IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 1080–1085, 2012, <https://doi.org/10.1109/CoASE.2012.6386389>.
- [82] P. Cao, Y. Gan, and X. Dai, "Model-based sensorless robot collision detection under model uncertainties with a fast dynamics identification," *International Journal of Advanced Robotic Systems*, vol. 16, no. 3, pp. 1–15, 2019, <https://doi.org/10.1177/1729881419853713>.
- [83] S. Morinaga and K. Kosuge, "Collision detection system for manipulator based on adaptive impedance control law," *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*, vol. 1, pp. 1080–1085, 2003, <https://doi.org/10.1109/ROBOT.2003.1241736>.
- [84] J. Kim, "Collision detection and reaction for a collaborative robot with

- sensorless admittance control," *Mechatronics*, vol. 84, p. 102811, 2022, <https://doi.org/10.1016/j.mechatronics.2022.102811>.
- [85] O. Castillo, P. Melin, "Forecasting of COVID-19 time series for countries in the world based on a hybrid approach combining the fractal dimension and fuzzy logic," *Chaos, Solitons & Fractals*, vol. 140, p. 110242, 2020, <https://doi.org/10.1016/j.chaos.2020.110242>.
- [86] F. Dimeas, L. D. Avendano-valencia, and N. Aspragathos, "Human - Robot collision detection and identification based on fuzzy and time series modelling," *Robotica*, vol. 33, no. 9, pp. 1886-1898, 2014, <https://doi.org/10.1017/S0263574714001143>.
- [87] F. Franzel, T. Eiband and D. Lee, "Detection of Collaboration and Collision Events during Contact Task Execution," *2020 IEEE-RAS 20th International Conference on Humanoid Robots (Humanoids)*, pp. 376-383, 2021, <https://doi.org/10.1109/HUMANOIDS47582.2021.9555677>.
- [88] G. Cioffi, S. Klose and A. Wahrburg, "Data-Efficient Online Classification of Human-Robot Contact Situations," *2020 European Control Conference (ECC)*, pp. 608-614, 2020, <https://doi.org/10.23919/ECC51009.2020.9143644>.
- [89] Shujun Lu, J. H. Chung and S. A. Velinsky, "Human-Robot Collision Detection and Identification Based on Wrist and Base Force/Torque Sensors," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pp. 3796-3801, 2005, <https://doi.org/10.1109/ROBOT.2005.1570699>.
- [90] N. Briquet-Kerestedjian, A. Wahrburg, M. Grossard, M. Makarov and P. Rodriguez-Ayerbe, "Using Neural Networks for Classifying Human-Robot Contact Situations," *2019 18th European Control Conference (ECC)*, pp. 3279-3285, 2019, <https://doi.org/10.23919/ECC.2019.8795649>.
- [91] A.-N. Sharkawy and N. Aspragathos, "Human-Robot Collision Detection Based on Neural Networks," *International Journal of Mechanical Engineering and Robotics Research*, vol. 7, no. 2, pp. 150-157, 2018, <https://doi.org/10.18178/ijmerr.7.2.150-157>.
- [92] A.-N. Sharkawy, P. N. Koustoumpardis, and N. Aspragathos, "Manipulator Collision Detection and Collided Link Identification based on Neural Networks," *Advances in Service and Industrial Robotics*, pp. 3-12, 2018, https://doi.org/10.1007/978-3-030-00232-9_1.
- [93] A. N. Sharkawy, P. N. Koustoumpardis, and N. Aspragathos, "Neural Network Design for Manipulator Collision Detection Based only on the Joint Position Sensors," *Robotica*, vol. 38, no. 10, pp. 1737-1755, 2020, <https://doi.org/10.1017/S0263574719000985>.
- [94] A. N. Sharkawy, P. N. Koustoumpardis, and N. Aspragathos, "Human-robot collisions detection for safe human-robot interaction using one multi-input-output neural network," *Soft Computing*, vol. 24, no. 9, pp. 6687-6719, 2020, <https://doi.org/10.1007/s00500-019-04306-7>.
- [95] A.-N. Sharkawy and A. A. Mostfa, "Neural Networks' Design and Training for Safe Human-Robot Cooperation," *Journal of King Saud University - Engineering Sciences*, vol. 34, no. 1, pp. 582-596, 2021, <https://doi.org/10.1016/j.jksues.2021.02.004>.
- [96] A.-N. Sharkawy and M. M. Ali, "NARX Neural Network for Safe Human-Robot Collaboration Using Only Joint Position Sensor," *Logistics*, vol. 6, no. 4, pp. 75, 2022, <https://doi.org/10.3390/logistics6040075>.
- [97] A.-N. Sharkawy, "Intelligent Control and Impedance Adjustment for Efficient Human-Robot Cooperation," *University of Patras*, 2020, <https://www.didaktorika.gr/eadd/handle/10442/47954>.
- [98] A. N. Sharkawy, A. Ma'arif, Furizal, R. Sekhar, and P. Shah, "A Comprehensive Pattern Recognition Neural Network for Collision Classification Using Force Sensor Signals," *Robotics*, vol. 12, no. 5, p. 124, 2023, <https://doi.org/10.3390/robotics12050124>.
- [99] K. H. Mahmoud, G. T. Abdel-Jaber, and A. N. Sharkawy, "Neural Network-Based Classifier for Collision Classification and Identification for a 3-DOF Industrial Robot," *Automation*, vol. 5, no. 1, pp. 13-34, 2024, <https://doi.org/10.3390/automation5010002>.
- [100] K. Katsampiris-Salgado *et al.*, "Collision detection for collaborative assembly operations on high-payload robots," *Robotics and Computer-Integrated Manufacturing*, vol. 87, p. 102708, 2024, <https://doi.org/10.1016/j.rcim.2023.102708>.
- [101] Z. Li, J. Ye, and H. Wu, "A virtual sensor for collision detection and distinction with conventional industrial robots," *Sensors*, vol. 19, no. 10, p. 2368, 2019, <https://doi.org/10.3390/s19102368>.
- [102] Y. J. Heo, D. Kim, W. Lee, H. Kim, J. Park and W. K. Chung, "Collision Detection for Industrial Collaborative Robots: A Deep Learning Approach," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 740-746, 2019, <https://doi.org/10.1109/LRA.2019.2893400>.
- [103] K. H. Mahmoud, A. N. Sharkawy, and G. T. A. Jaber, "Development of safety method for a 3-DOF industrial robot based on recurrent neural network," *Journal of Engineering and Applied Science*, vol. 70, no. 44, pp. 1-20, 2023, <https://doi.org/10.1186/s44147-023-00214-8>.
- [104] T. Zhang, Y. Chen, P. Ge, and Y. Zou, "LSTM-based external torque prediction for 6-DOF robot collision detection," *Journal of Mechanical Science and Technology*, vol. 37, pp. 4847-4855, 2023, <https://doi.org/10.1007/s12206-023-0837-3>.
- [105] S. Makris and P. Aivaliotis, "AI-based vision system for collision detection in HRC applications," *Procedia CIRP*, vol. 106, pp. 156-161, 2022, <https://doi.org/10.1016/j.procir.2022.02.171>.
- [106] X. Xiao, B. Liu, G. Warnell, and P. Stone, "Motion planning and control for mobile robot navigation using machine learning: a survey," *Autonomous Robots*, vol. 46, no. 5, pp. 569-597, 2022, <https://doi.org/10.1007/s10514-022-10039-8>.
- [107] J. Guzzi, R. O. Chavez-Garcia, M. Nava, L. M. Gambardella and A. Giusti, "Path Planning With Local Motion Estimations," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2586-2593, 2020, <https://doi.org/10.1109/LRA.2020.2972849>.