Authors' accepted manuscript
Paper presented at *32nd IEEE International Conference on Robot and Human Interactive Communication (IEEE RO-MAN)*.
Busan, Korea. Aug. 28-31, 2023

From Assistive Devices to Manufacturing Cobot Swarms

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***Abstract*— This paper provides an overview of the latest trends in robotics research and development, with a particular focus on applications in manufacturing and industrial settings. We highlight recent advances in robot design, including cutting-edge collaborative robot mechanics and advanced safety features, as well as exciting developments in perception and human-swarm interaction. By examining recent contributions from Kinova, a leading robotics company, we illustrate the differences between industry and academia in their approaches to developing innovative robotic systems and technologies that enhance productivity and safety in the workplace. Ultimately, this paper demonstrates the tremendous potential of robotics to revolutionize manufacturing and industrial operations, and underscores the crucial role of companies like Kinova in driving this transformation forward.**

I. INTRODUCTION

Over the past century, the manufacturing industry has been at the forefront of adopting robotic systems. Although the electronics, automotive, and metal industries are currently the largest markets for robots [1], new paradigms in the industry have emerged, such as collaborative robotics. This sector has grown significantly in recent years, penetrating many new markets, particularly between SMEs that were previously hesitant to install robotic and automated devices. Collaborative robots, also known as cobots, have been developed to work in close proximity with humans without posing a risk to human safety[2], thus not requiring costly safety equipment. Cobots have integrated speed and force limitations to ensure any accidental collision with an operator does not result in serious injuries or inconvenience, according to ISO/TS 15066:2016 [3]. This development has led to further research on human-robot collaboration, which is a significant focus in both academic and industry-driven robotics research. However, there are notable differences between these two approaches to the subject: academic research has focused more on developing safe, intuitive, and user-friendly human-robot collaboration methods while considering the cognitive aspects of the collaboration process; while industry-driven research has prioritized developing technologies that can improve efficiency, reduce costs, and increase productivity. This last approach requires a more practical and application-driven perspective, with a focus on real-world deployment and scalability.

*This work was supported by NSERC, Kinova Robotics and PROMPT.

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The industrial robots have been successfully deployed in manufacturing for the last decades. However, the setup of the layout and the controller for these inflexible machine soften cost much time and money when the design of the product changes. Thus, mobile robots like unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV) with good maneuverability can be appropriately utilized to make a difference. Moreover, as the manufacturing environment is dynamic and uncertain, we cannot expect one single robot to fulfil all the tasks. Therefore, to enhance the efficiency and robustness of the system, the concept of swarm robotics which is inspired by the collective behaviours of social insects can be introduced. Swarm robotics, which aims to overcome the current constraints of, is also tackled in order to let the robot team collectively handle real-world manufacturing difficulties [4].

To obtain a general view of current research in the field, we review a selection of industrial patents (Sec. II-A) and research papers (Sec. II-B). The industrial patents were chosen based on relevance to the topic, while the research papers were selected for their novelty and impact; both limited to the last decade. We then present the case of Kinova Robotics, a Canadian robot arm manufacturer, through its latest product development, the Link6 (Sec. III-A), and its participation in fundamental exploratory research with academic partners (Sec. III-B). By exploring the different visions and research ecosystems in the industry and academia, we suggest waysin which the two sectors can benefit each other.

II. CURRENT TRENDS IN MANUFACTURING ROBOTS

A. Industry perspective

The field of human-robot interaction (HRI) has seen a range of advancements through industrial patents and research efforts. Patents have focused on different aspects of HRI, such as detecting anomalies during task execution, flexible human-machine collaboration, and the use of sensors for specific tasks. For example, Laftchiev and Romeres presented a system for detecting anomalies during mixed human-robot processes [5], while Guerin et al. proposed a system for flexible human-machine collaboration [6], including a generalizable framework that supports dynamic adaptation and reuse of robotic capability representations and human-machine collaborative behaviors. Additionally, Robotiq Inc's patent focused on a force/torque sensor for teaching tasks to a manipulator [7], and SMS Siemag AG's patent discussed a robot interaction system with flexible adaptation to operating modes of interaction [8], which influenced the associated human-robot interface designed to be matched to different automation degrees of the robot to different temporal and/or spatial positionings of the interacting human and robot partners in the work area. Tolgyessy's patent introduced a collaborative robotic system that allows interaction through gestures [9] with the help of vision sensors. Franka Emika's patent also proposed the use of predetermined haptic gestures to control the robot in a simpler and safer way [10].

Additionally, vision-based interaction has also been a focus of HRI research. For instance, Kinova's vision-guided robot arm system [11] being able to identify objects of interest using a camera and determine the potential actions necessary to complete the task. Fanuc also applied LIDARs onto cobots to adjust speed levels based on human proximity. The system includes at least one laser device, a processing head, an output light detection unit, a reflection light detection unit, a processing result observation unit, and a drive device. The apparatus comprises a state variable observation unit, an operation result acquisition unit, a learning unit, and a decision unit [12].

In recent years, cobots have gained popularity due to their ability to work in close proximity to humans with near-zero risk for human co-workers. Patents have focused on enhancing the capabilities of multi-axis manipulators using sensors, such as KUKA Systems GmbH's patent [13]. This method involves using the end effector in a first operating mode and then operating it with reduced power. The system continuously monitors whether the object is being manipulated by a human while in the end effector: if it is, it decreases the power to operate the end effector, switching to a different operating mode and monitoring the human manipulation of the object.

Universal Robot's personal authentication device adds an extra layer of security to collaborative robot operations using an individual's palm print and vein pattern [14]. Rethink Robotics and ABB AG's patents ensure safe collaboration between humans and robots by reducing speed in the danger zone around the robot to prevent harm to a person's torso or head [15], [16]. Kinova has also worked on tactile sensors to provide information such as pressure and temperature during human-robot interactions [17].

Since 2012, the Robotic Industries Association hosts a technical committee to develop a set of guidelines for the safe deployment of autonomous mobile platforms in an industrial context. The RIA TR 15.606 and ISO/TS 15066 were published in 2016[18]. The standards paved the way to the safe deployment of cobots. According to the ISO/TS 15066, safety during collaborative operations can be guaranteed in mainly two ways: Speed and Separation Monitoring (SSM). Safety limitations are outlined in the standard ISO 10218 and have provided a speed limit of the Tool Centerpoint (TCP) as 250 mm/sec during operations when the operator can interface with the robot[19].

As summarized in Table. I, the industrial patents provide innovative solutions for enhancing the safety and efficiency

TABLE I

INDUSTRIAL PATENTS IN HUMAN-ROBOT INTERACTION OF COBOT

Assignee	**Patent**
ABB AG	Systems and methods for safe robot operation
Fanuc Corp	Laser welding apparatus with a multiple axis robot having an arm and a scanner attached to a tip end of the arm of the multiple axis robot
Guerin et al.	System and method for flexible human-machine collaboration
Kinova Inc.	Robotic arm with a plurality of motorized joints
Kinova Inc.	A method of operating a vision guided robotic arm system
Kinova Inc.	Dielectric geometry for capacitive-based tactile sensor
KUKA Systems GmbH	A method for controlling a human-robot collaboration (HRC) system wherein the HRC system includes at least one manipulator having an end effector
Laftchiev & Romeres	System for detecting anomalies during task execution in mixed human-robot process
Rethink Robotics	Method for teaching a robot movement
Robotiq Inc.	force/torque sensor
SMS Siemag AG	Robot interaction system
Tolgyessy	A collaborative robotic system that allows interaction through gestures
Universal Robot	Personal authentication method and device

TABLE II

RECENT YEARS PUBLICATIONS IN INDUSTRIAL HUMAN-ROBOT INTERACTION AND COLLABORATION

Type	**Authors**	**Topic**
Legible robots	Bozkus et al.	Fuzzy-based risk assessment methodology for HRI systems
	Breazeal et al.	Social robotics
	Brennan et al.	Shared gaze during collaborative search
	Duncan & Murphy	Human-aerial vehicle interactions
	Lidoris et al.	Mobile robot navigation
	Pupa et al.	Online framework for task scheduling
Worker-aware robots	Claret et al.	Robot kinematic redundancy
	Gervasi et al.	Applications of affective computing
	Gustavsson et al.	Trigger points of fear and distrust in HRI system
	Iqbal et al.	Real-time motion planning scheme
	Lauzier et al.	Force limiting device and method
	Secil & Ozkan	Framework for safe HRI
	Wang et al.	HRC system towards high accuracy
	Yu et al.	Adaptive human-robot collaboration control method
	Zhang et al.	Neural network for predicting collaboration request
Swarms	Dietz et al.	Human perception of swarm robot motion
	Levillain et al.	Expressivity with the control parameters for swarm's distributed behaviour

of human-robot interaction in the manufacturing industry.

B. Academic perspective

In academic publications, scholars often focus on developing innovative models and methodologies to analyze and optimize HRI systems. For instance, Bozkus et al. introduced a novel fuzzy-based risk assessment methodology for human-robot interaction systems in industrial settings, which offers a promising approach to identifying and mitigating risks associated with HRI [20]. Meanwhile, Gustavsson et al. delved into the root causes of fear and distrust in HRI systems during cooperative manufacturing, highlighting the need to understand and address these critical challenges [21]. Similarly, Secil and Ozkan presented a real-time distance calculation framework using skeletal tracking to promote safe HRI [22], while Pupa proposed a resilient online task scheduling framework for industrial HRI scenarios [23]. Moreover, Gervasi et al. explored the application of affective computing in HRI in the manufacturing industry, opening new possibilities for human-robot collaboration [24].

With better understanding of the operators' cognitive processes, researchers have conducted several studies to enhance the performance of human-robot collaboration (HRC) systems. For example, Zhang et al. have proposed a fusion-based spiking neural network approach to predict collaboration requests in HRC assembly systems, which can help to optimize the workflow [25]. Additionally, an adaptive control method based on optimal admittance parameters has been suggested to assist operators in completing tasks while optimizing task performance [26]. Furthermore, an HRI-based cost function was used in a real-time motion planning scheme to facilitate collaborative robots' operation, and an action recognition model for HRC assembly was developed by fusing the outputs of multiple binary classification networks, which can improve the precision of HRC systems [27]. Lauzier and Gosselin have also invented force limiting devices that can reduce the risks associated with manipulators colliding with humans. These devices work by maintaining the manipulator's stiffness until an external force exceeds a certain threshold, at which point the impacted robot link disengages, and its motion becomes mechanically disconnected from the rest of the manipulator, ensuring operator safety [28].

Recent academic and industrial contributions in the domain of swarm robotics show the potential of such systems. [29], [30] present a very comprehensive overview of different research and commercial swarm robotic platforms. The inherent advantages of swarm robotics over single-robot systems - robustness, flexibility, and stability - can improve the overall efficiency of manufacturing processes. The ability of the swarms to efficiently utilize resources by coordinating with other robots to do multiple tasks, and its ability to adapt to changing production demands while allowing the system to scale up are some of the properties that can revolutionize the manufacturing industry. However, there are certainly some open issues in the field that require attention in order to accelerate the research in this domain and make these robot systems deployable in real-world scenarios. [31] discusses the future of swarm robotics while listing down the open challenges, some of which are: improving the robot hardware of individual robots to enhance the capabilities and robustness of the swarm, developing tools that can enable robotics researchers and share results easily, and addressing the issue of reality gap [32].

As manufacturing facilities become increasingly complex, the deployment of robotic systems has shifted from static, fixed collaboration (cobot) stations to dynamic collaboration across the entire plant. In this context, swarm robots offer an advantage over single-robot systems, as can cover larger areas and are less prone to critical single points of failure for the mission. While centralized multi-robot management is one solution, decentralized swarm control algorithms have been shown to be more efficient [33]. Swarm control algorithms, often referred to as behaviors, are generally distributed, leveraging the processing power of all units combined, which greatly decreases the load on each robot. Furthermore, swarm robots rely on local interactions, with neighbors and with their surroundings; a strategy that makes them more robust to dynamic mission contexts.

In the context of industrial scenarios, Jones et al. present a swarm robot platform testbed for prototyping and evaluating swarm algorithms in industrial scenarios [34]. The authors also introduce a case study on the effectiveness of a decentralized multi-robot system for a warehouse automation scenario. In a similar context, the work presented in [35] provides a framework for testing and evaluating collaborative swarm systems while focusing on safety and security of the human co-workers. Draganjac et al. [36] demonstrate an effective decentralized control strategy for a multi-AGV system for efficient warehouse management tasks. The simulation demonstrates the implementation of a prioritizing scheme to avoid conflicts, though certain aspects of the control remain centralized. LoadRunner [37] is a new, modular, and scalable platform that has been developed to automate logistics services in various environments (airports etc.), leveraging concepts of swarm intelligence. A case study has been presented to exemplify its effectiveness, with reduced delivery times and improved resource utilization.

Researchers have started to look into the *perception of safety* rather than solely the safety features and performance in industrial setups [38]. To enable smooth human-robot interaction, interactive robotic systems use non-verbal expressions such as dashboard indicators, sound or light signals, and deictic gestures to indicate a direction [39]. They also use visual cues to create a shared attention space and coordinate collaborative tasks [40], as well as emblematic gestures to communicate intentions and affective states [41], [42]. A repertoire of non-verbal expressions that is natural and intuitive to humans is essential for effective communication. The popularity of non-humanoid robots such as aircraft and rovers has motivated the exploration of other signaling channels and movement patterns [43]. However, for robot swarms, the use of these common non-verbal expressions is hindered by the abstractness of the 'group' entity and the possibility for the swarm to reconfigure itself at will.

The academic study of HRI focuses on formulating models and analytical techniques for use in a range of industrial situations, as summarized in Table II.

III. Kinova's use case

Kinova Robotics is a Canadian robotics company that specializes in designing and manufacturing serial manipulators for assistive, academic, medical and industrial applications. At the early stage of Kinova's business, its modular robotic systems include the robots JACO2 and MICO2, actuators and grippers. Kinova designs and manufactures robotics platforms and components that are simple and safe under two business units: Assistive Robotics empowers people living with disabilities to push beyond their current boundaries [44]. In recent years, Kinova's robot designs focuses more on working in close proximity with humans, from the assistive Jaco for users with upper-body limitations to the Gen3 and Gen3 lite for industrial and research applications.

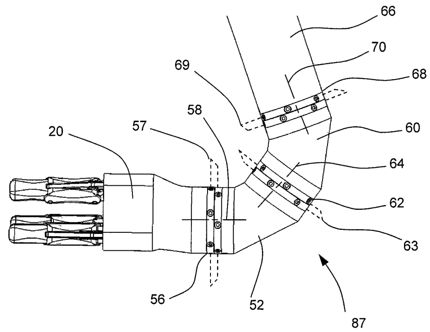

Fig. 1. Wrist for the assistive Kinova Jaco, extracted from associated patent

Over the years, several technologies related to HRI were developed and patented by the company and integrated into their products, and several features were designed and leverage for safe and efficient interactions with any human inside the workspace of the arm. Clearly, these technologies were developed to satisfy requirements for the intended market, capabilities and applications, which depend on the device.

One central technology patented early by Kinova is the design of a portable robotic arm with a plurality of motorized joints, which is basically the assistive Jaco arm [45]. The small mass, low power and limited joint achievable speed make it safe for HRI. Moreover, its particular wrist joint design, depicted in Fig. 1, gives it a form factor minimizing potential pinch points that could represent a potential hazard.

A. The Link 6

The market need for cobots capable of lifting heavier payloads led Kinova to Link 6, shown in Fig. 2, launched in 2022. Several earlier features from previous robotic arms were integrated into the Link 6, but the increase mass, the higher velocity and the longer reach of the robot required the development of additional safety features to reduce the risk for anyone within the workspace of the robot.

Fig. 2. Kinova Link 6 cobot, with a rated payload capability of 6 kg

Therefore, along with the hardware, software was crucial for the development of a safe robotic system for human-robot interactions and collaboration. For instance, like other robotic arms sold by Kinova and other manufacturers, admittance control (a method of controlling the robotic arm's movements based on external forces) can be used on the Link 6 to teach the system a trajectory manually. This allows it to be more responsive, not having to apply large forces to move the arm with hand-guiding. Moreover, with the Link 6, when hand-guiding is not used, a feature named *Contact Force Reduction* allows the detection of collisions between the arm and anything in its environment, which included a person. In parallel, still with the aim of reducing the severity of potential injuries after a collision occurring while the robot conducts a trajectory, kinetic energy limitations (at the tool center point and the elbow) can be configured by the user.

However, in the case of robots interacting and collaborating with humans within their workspace, having some safety features is not enough, as a bug or any other unexpected behavior could result in serious injuries. Therefore, software quality, redundancy and stability are also crucial in the development process in order to provide a safe robotic system. Related to this point, Kinova and other robot manufacturers have to consider several industrial standards and technical specifications during the product development process. Some cover industrial robots (cobots or not), others medical devices, and some software development in general. Among them, we can name the ISO TS 15066 on cobots, defining notably pain thresholds regarding contact between a robot and different body parts, ISO 9283, which describes performance criteria to assess industrial robots, and ISO 13485 on the quality management of medical devices. They all give crucial guidelines to manufacture safe and reliable devices for HRI and HRC, describing processes required to handle documents and records related to the product to meet regulations, criteria on accuracy, repeatability, deviation, overshoot and stabilization, as well as guidelines on protective measures, stopping functions and well-defined collaborative operative modes. To ensure the reliability and functionality of these

Fig. 3. *Image on the left:* An assembly setup simulated in Isaac Sim with workstations, storage areas and multiple mobile manipulators. *Images on the right:* Camera images captured by 2 robots of the same scene to find the spatial and temporal relations in the scene to predict the intention of the subject.

safety features and functions, several processes are in place, from software unit verification protocols, regression tests, functional tests, software-hardware integration verification protocols (including automated tests) to quantitative characterization/tuning and system validation protocols.

In the end, the complete design and manufacturing process of any robot for HRI and HRC applications, whether it is the Link 6 or any similar robot on the market, involves different elements to consider, some of them dependent on the application (certifications required for medical devices for example). Larger capabilities of the robot (mass, payload, velocity, reach) to meet the market demands also lead to a greater need of safety features and functions, as the severity of potential injuries and the exposure to hazards also increase. The rising prevalence of cobots in environments and situations to meet ever increasing needs, such as using them on mobile platforms, will therefore need to be address by from both academic and industrial perspectives, as will be discussed in the next section.

B. Cobot swarms

A group of academic researchers, supported by Kinova Robotics, have embarked on a new research path that aims to incorporate swarm intelligence into a worker-centric robotic solution for the manufacturing industry. The objective of this research is to equip the manufacturing industry with the necessary tools and processes to safely deploy swarms of cobots (mobile manipulators). While the successful deployment of a cobot swarm is certainly a major goal, this project places a particular emphasis on the operator-centric aspects of cobot swarms. The project focuses on developing algorithms for operator awareness for mobile cobots, including operator pose detection, smart motion control for operator avoidance, explainable behavior from motion control, and testing and validation of safety standards compliance. On the actual cobot swarm deployment side, the research focuses on developing algorithms for collision-free motion planning, multi-robot communication, multi-objective optimization, and distributed decision-making. Two instances of the research objectives is discussed below.

While cobots are designed to handle collisions and often react to avoid significant injuries, avoiding them altogether in the first place to prevent the hazard is preferable. Vision systems with cameras can be leverage to achieve this goal. However, visual occlusion can decrease the efficiency of the system and create a safety hazard. Therefore, for applications involving cobots, considering their architecture give them intrinsically the ability to reach the same end-effector pose (position and orientation) with different feasible postures (joint configurations), an optimal posture with an optimal path can be found to minimize the risk of occlusion, as proposed by Montazer et al. [46]. Along the same lines, the camera pose could also be adjusted in real-time, again to minimize the potential visual occlusion.

More generally, deploying robots in an industrial setting requires highly reliable and robust robotic systems that can handle non-sequential and large displacement inputs, distributed information sharing, and local vision-based inference tasks [47]. To ensure reliable data acquisition, multiple robots can look at a scene from different angles and perspectives and then fuse the local information to improve the global understanding of the scene. Drawing inspiration from [48], a graph neural network (GNN) architecture can be deployed on a swarm of robots to implement shared perception and predict the intention of a human worker/operator. By representing relevant objects and human workers in the scene as nodes in the graph, a multilayered GNN can establish spatial relations in the scene. Combining it with GRUs can help develop temporal relations between successive frames in time, and thus can prove highly promising.

Isaac Sim [49], on the other hand, provides a powerful platform to accelerate research in deploying deep learning models in realistic industrial setups. It allows the development of realistic industrial environments, collection of realistic data for deep learning model training, and eventual deployment of a trained model in the simulation. A simulation environment example is shown in Fig. 3.

C. Advancement in swarm robotics

The field of swarm robotics has witnessed remarkable advancements in various industrial applications, revolutionizing the way factories operate. Swarm robots have excelled in inventory tracking, allowing for seamless monitoring of stock levels and real-time awareness of the whereabouts of commodities within the facility, like Geekplus[50]. These sophisticated robots explore the inventory shelves swiftly, scanning and updating the database to ensure accurate and up-to-date inventory management. Furthermore, in LoT companies, like Strong Force[51], swarm robots have transformed factory logistics by autonomously transporting parts and components to the appropriate workstations, optimising the production process and reducing human interference. Their combined efforts and advanced algorithms enable materials to be moved quickly and precisely, increasing total efficiency. Furthermore, swarm robots have demonstrated their worth in collective transport, effortlessly lifting and transporting huge and heavy goods that would otherwise be difficult for human employees[52]. With their synchronised activities, these robots undertake difficult tasks with ease, increasing production and lowering the danger of injury. Furthermore, swarm robots have made substantial advances in quality assurance, leveraging improved sensing capabilities to inspect parts and components for faults. These robots ensure that only high-quality items leave the assembly line, improving total product reliability, thanks to their exact analysis and prompt detection. Swarm robot industry development in these areas has not only altered manufacturing processes, but has also paved the road for safer, more efficient, and highly optimised production environments.

Swarm robotics has also made major advances in academic research, with many algorithms, swarm engineering methods and taxonomy proposed to categorise and understand the field. For instance, Parpinelli and Lopes [53] also address biological swarm behaviours from which several computing techniques were derived. Aspects of generic self-organization in biological systems are covered by Camazine et al. [54]. In addition, Garnier et al.'s [55] summary of the biological foundations of swarm intelligence is helpful. Swarm intelligence is discussed with evolutionary computation, artificial neural networks, and bio robots by Floreano and Mattiussi [56]. Swarm intelligence algorithms for optimisation are discussed by Krause et al. [57] and Binitha and Sathya [58]. Swarm intelligence-based optimisation algorithms' natural inspirations are shown by Hassanien and Alamry (2015)[59]. Yang et al. (2013)[60] analyse swarm intelligence-based optimisation algorithms, and Yang et al. [61] investigate the relationship between swarm intelligence-based optimisation algorithms and self-organization. According to their underlying mathematical structure, multi-agent algorithms that are currently in use are categorised by Rossi et al. [62].

These researches have provided useful frameworks for analysing and interpreting the vast swarm robotics literature, contributing to the academic advancement of the field.

IV. CONCLUSIONS

In summary, the study of human-robot interaction in both the academic and industrial communities is driven by a shared goal of improving collaboration between humans and robots in manufacturing and assembly tasks. While the industrial community prioritizes the development of specific systems and methods to improve physical safety, the academic community places more emphasis on proposing cognitive models of operators, natural interaction modalities, and integrating swarm intelligence.

This dual approach is exemplified by Kinova Robotics, who recently released a new cobot for manufacturing and is supporting innovative cobot swarm research. Through research and patents, academics and industry alike are working towards enhancing the efficiency, intuitiveness, accuracy, and safety of human-robot interaction and collaboration systems.

By developing new models and methodologies and integrating cutting-edge technologies, there is a collective effort to push the boundaries of human-robot interaction and enable more seamless and effective collaboration between humans and robots. These advancements have the potential to revolutionize (again) the manufacturing industry and transform the way humans and robots work together.

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