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An overview of cobots for advanced manufacturing: human-robot interactions and research trends

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Abstract. Advanced manufacturing is currently undergoing a significant transition towards human-robot collaboration. This shift has attracted considerable attention from researchers seeking to harness the synergistic potential of human and robotic capabilities across a range of applications and tasks. This paper presents a comprehensive review of the classification of robots, considering key aspects like architecture, mobility, function, size, autonomy, and human contact. The study goes deeper into collaborative robots by emphasizing the levels of interaction between robots and humans. To provide a comprehensive overview, a meticulous analysis of scientific publications spanning a two-decade period is conducted, with a focus on data collected over the past decade. Furthermore, the analysis extrapolates main trends and developments to offer insights for the next decade, thereby facilitating a comparative assessment of publication rates about both collaborative and industrial robots during this timeframe.

1 Introduction

Human-robot collaboration (HRC) represents a paradigm shift in advanced manufacturing, a field characterized by its emphasis on human well-being, safety, and optimal economic outcomes [1]. HRC refers to the symbiotic relationship between humans and robots, designed to leverage the unique capabilities of each entity to achieve specific tasks [2]. This collaborative approach aims to create a harmonious and efficient work environment, enabling the accomplishment of complex tasks that would be challenging for either humans or robots to perform independently [2].

In the context of advanced manufacturing, HRC emerges as an ideal solution to address the dual objectives of worker safety and productivity optimization [3]. By delegating monotonous, repetitive, physically demanding, and hazardous tasks to robots, the safety and comfort of human workers are significantly enhanced. Consequently, the integration of robots in such capacities not only improves the overall working environment but also contributes to maximizing productivity [3].

The increasing utility of Collaborative Robots (Cobots) in advanced manufacturing has gained substantial attention from researchers in recent years [4]. To elucidate this trend, we

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conducted a comprehensive analysis of the research landscape, comparing industrial robots and Cobots using the data obtained from authoritative literature sources such as ScienceDirect and Scopus. Figure 1 presents an analysis of publications in both fields from 2013 to 2023.

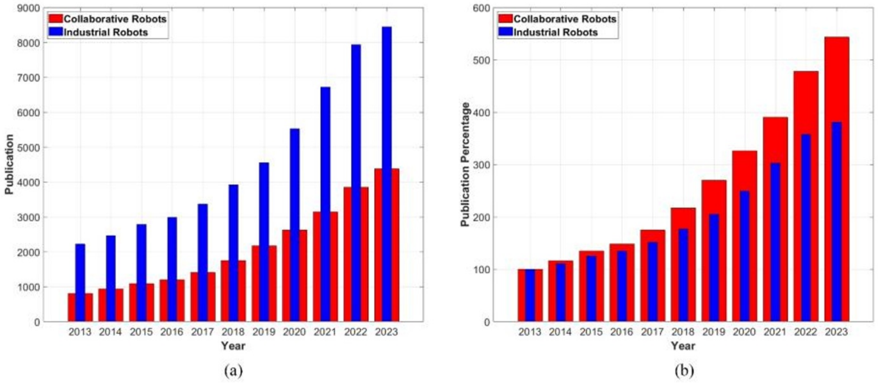

Fig. 1. Comparison between Industrial and Collaborative Robots in terms of Scientific Publication from 2013 to 2023.

Figure 1(a) reveals a notable disparity in the volume of publications, with industrial robots attracting a greater number of research articles compared to Cobots. However, Figure 1(b) highlights an intriguing trend: while the publication rate for industrial robots experienced a growth rate of 3.8 times that of 2013, Cobots exhibited a substantially higher growth rate of 5.43 times during the same period. This indicates a burgeoning focus on Cobots, despite the overall greater number of annual articles published on industrial robots.

This analysis underscores a significant and rapid increase in research emphasis on Cobots, highlighting their growing relevance within the realm of advanced manufacturing. Consequently, there exists a pressing need for a comprehensive understanding of Cobots. The present study aims to address this need by providing a thorough overview of robot and Cobot classification, as well as an estimation of future research directions, thereby facilitating the informed anticipation of forthcoming developments in this domain.

2 Understanding robots

The origin of the term "robot" can be attributed to the Czech brothers Josef and Karel Ōapek, who adopted the word "robota" from Czech, meaning "forceful employment" or "servitude" [5]. In 1942, Isaac Asimov introduced his seminal laws of robotics, which have become widely recognized. Asimov's laws state that a robot must adhere to human commands while ensuring its safety and the safety of humans [6]. Numerous authors, besides Asimov, have contributed to the establishment of definitions and laws pertaining to robotics. These classifications vary, with some categorizing robots based on their shapes, while others focus on their type of locomotion. Consequently, a multitude of classifications has emerged. To facilitate the categorization of Cobots within this framework, a comprehensive analysis of diverse robot classifications has been conducted.

The classification of robots encompasses various factors, including function, size, mobility, architecture, autonomy, and interaction with humans [5] as shown in Figure 2. This classification framework has been operationalized through a meticulous examination of research papers encompassing the field of robotics. This study enables a comprehensive understanding of the different dimensions along which robots can be classified.

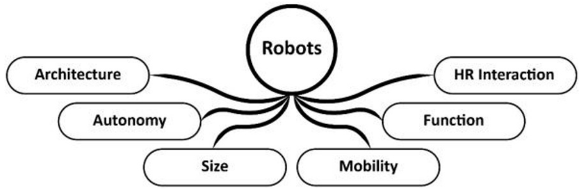

Fig. 2. General Classification of Robots.

Robots can be classified as follows:

- Function: Robots can be classified according to the type of mission they are involved in. They can be classified into industry, military and defence, service, exploration, education, and social robots [7].
- Size: Robots can be classified into many sizes such as micro, small, medium, large, and extra-large robots [8].
- Mobility: Robots are categorized as either stationary or mobile, reflecting their ability to navigate and traverse different environments [5].
- Architecture: Robots can be classified into distinct types based on their architectural features, including legged, wheeled, tracked, aerial, underwater, and hybrid [7].
- Autonomy: Vagia, et al. [9] discussed many levels of autonomy through their survey. It can be concluded that as a general concept, there are six levels of autonomy starting from no autonomy to full autonomy level, Table 1.
- Interaction with humans: There are several ways for interaction between humans and robots such as direct control, speech, gesture, touch-based, augmented reality, and collaborative interaction [10].

Table 1. Levels of Autonomy for Robots.

Level	Name	Description
0	No Autonomy	Robot lacks autonomy and needs continuous human control and operation.
1	Direct Control	Robot has limited autonomy and performs pre-programmed tasks under human control and guidance.
2	Assisted Autonomy	Robot can make basic decisions but relies on human intervention for complex tasks.
3	Conditional Autonomy	Robot operates independently in predefined conditions but still requires human oversight in uncertain situations.
4	High Autonomy	Robot operates independently in most situations, with minimal human intervention.
5	Full Autonomy	Robot possesses complete autonomy and can operate independently without any human intervention.

3 Understanding cobots

Cobots represent a distinct category of robots that exhibit notable distinctions from conventional industrial robots, primarily in terms of their interactions and operations alongside humans. Unlike traditional industrial robots that are primarily designed for autonomous operation, Cobots are specifically designed to work near humans within shared workspaces [2]. These robots are equipped with advanced sensor systems, vision capabilities, and safety features, enabling them to detect and respond to the presence of humans, thereby ensuring secure and efficient collaboration [3]. Furthermore, Cobots are characterized by their user-friendly, adaptable designs, facilitating easy programming, and enabling precise collaboration with human counterparts [1, 3]. Consequently, the key distinguishing factor between Cobots and industrial robots lies in their intended function and the extent of their interactions with humans.

3.1 Identifying HRI levels

The extent of collaborations between humans and robots can be classified into five levels, providing a framework for assessing the degree of interaction and cooperation in joint tasks [11]. Figure 3 illustrates this categorization, which evaluates the potential for task sharing, workspace sharing, and object sharing.

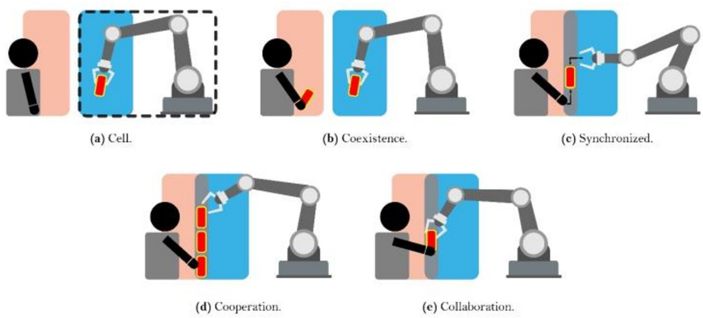

Fig. 3. Levels of Interaction between Human and Robot.

The levels of human-robot collaborations are as follows:

- No interaction (Level 0): The robot operates within an isolated cell, with no sharing of workspace between humans and robots. Physical separation is maintained as a strict barrier.
- Coexistence (Level 1): Physical barriers are eliminated, allowing humans and robots to occupy separate workspaces without direct interaction. Their workspaces remain insulated, ensuring a degree of spatial segregation.
- Synchronization (Level 2): Humans and robots can occupy the same workplace and perform tasks simultaneously. However, real-time collaboration does not occur at this level.
- Cooperation (Level 3): This level permits shared workspace and workpieces between humans and robots, but physical contact is still restricted. It allows for coordination and cooperation in task execution while maintaining a certain level of separation.
- Collaboration (Level 4): This represents the highest form of interaction, where human-robot interaction reaches its peak. Physical contact and shared tasks are permitted, enabling the close cooperation and joint execution of tasks, fostering seamless integration between humans and robots.

This classification framework provides a valuable tool for assessing and designing human-robot collaboration systems, particularly in the context of advanced manufacturing environments.

3.2 Estimating the future of cobots' research

To provide some insights into the future trajectory of cobot research in advanced manufacturing, we conducted an analysis of publication rates, projecting trends until 2032 of next decade. This estimation is based on the observed annual increase rate from last years, as illustrated in Figure 1(b).

We employed a second-order polynomial curve fitting approach to model the publication trends for both cobots and industrial robots. The general form of the equation used is:

$$Y=aX^2+bX+c \quad (1)$$

Where Y represents the normalized publication rate, X represents the year, and a, b, and c are coefficients that determine the shape and position of the curve.

The coefficients for both collaborative and industrial robots were calculated using a least-squares regression method and are given in Table 2.

Table 2. Coefficients for Both Collaborative and Industrial Robots.

Robot	a	b	C
Cobot	0.042831	-0.070235	1.086189
Industrial	0.026960	-0.032088	1.039279

By applying the coefficients specific to each robot type in (1), we obtained the estimates for both cobots and industrial robots, as demonstrated in Figure 4.

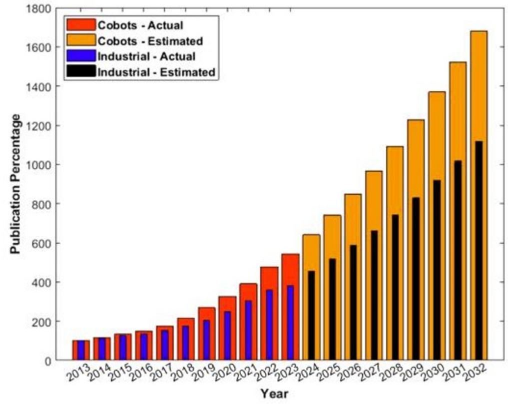

Fig. 4. Estimation for Both Cobots and Industrial Robots' Publication until 2032.

The analysis reveals several key findings: The publication rate for cobots is projected to be 16.8 times higher in 2032 compared to 2013; the publication rate for industrial robots is estimated to increase by a factor of 11.18 during the same period. The disparity in growth rates between cobots and industrial robots, which was 1.63 in 2023, is anticipated to reach 5.62 in 2032.

These projections indicate that the research focus on cobots will experience rapid and substantial growth, surpassing that of industrial robots. The difference in the rate of increase between cobots and industrial robots is expected to be approximately 3.5 times greater in 2032 than it was in 2023.

This estimation suggests a significant shift in research priorities within the field of robotics, with a growing emphasis on collaborative systems that can be seamlessly integrated with human workers in advanced manufacturing environments.

The accelerated growth in Cobot-related publications reflects the increasing recognition of their potential to revolutionize manufacturing processes by combining the strengths of human workers with the precision and efficiency of robotic systems.

4 Conclusion and future work

In conclusion, this study has provided a comprehensive overview of robot classification, with a specific focus on positioning Cobots within the broader realm of robotics. We have explored the levels of collaborations between humans and robots, highlighting the unique features that distinguish Cobots from traditional industrial robots.

Our analysis of publication trends reveals a significant and growing academic focus on human-robot collaboration, particularly in the domain of Cobots. The projected growth in Cobot-related research substantially outpaces that of traditional industrial robotics, reflecting the increasing importance of collaborative systems in advanced manufacturing.

Based on these findings, we anticipate some key areas for future research and development: enhanced sensing and perception, adaptive learning algorithms, intuitive human-robot communication, advanced safety protocols, expanded task flexibility, and ethical considerations for human-robot collaboration in manufacturing and society.

These research directions will be critical in realising the full potential of human-robot collaboration in advanced manufacturing and beyond. As the field continues to evolve rapidly, interdisciplinary approaches combining robotics, human factors, and manufacturing engineering will be crucial in addressing the complex challenges and opportunities presented by this transformative technology.

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