Collaborative robots for quality control: an overview of recent studies and emerging trends

Journal of Intelligent Manufacturing
https://doi.org/10.1007/s10845-025-02600-w

Collaborative robots for quality control: an overview of recent studies and emerging trends

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Received: 15 November 2024 / Accepted: 21 March 2025

Abstract

Over the past few decades, collaborative robots (cobots) have emerged as a key element in the advancement of smart industries and the transition to Industry 5.0, facilitating operations alongside human workers to reduce both cognitive and physical strain. Cobots have primarily been used for tasks such as material handling, assembly and precise positioning, but their integration into quality control and inspection remains underexplored. Using a mixed-methods approach, this paper conducts a thorough investigation of current applications of cobots in quality assurance, both in academic research and in industrial practice. Through a systematic review of the academic literature and analysis of real-world industrial case studies, the paper examines the current state and potential advances in manufacturing quality control facilitated by cobots. The findings suggest that while cobots are currently being used primarily to improve efficiency through in-process visual inspection, there are significant barriers to their widespread adoption in quality control. These barriers include high initial costs, lack of technical expertise among workers, integration challenges with existing systems, data security concerns and regulatory compliance issues. Nevertheless, the potential for research and industrial growth through the use of cobots in quality control is considerable. By drawing on insights from academic research and practical implementations, this study provides researchers, practitioners and policy makers with a comprehensive perspective on the innovative use of cobots to improve quality control in manufacturing.

Keywords Quality control · Manufacturing · Collaborative robots · Industry 5.0

Introduction

The product manufacturing landscape has changed significantly in recent years, driven by rapid technological advances and the trend towards mass customisation (Piller & Müller, 2004). This evolution has led to a continuous stream of new products entering the market, while sales volumes remain highly unpredictable due to market fluctuations. Such dynamics require production systems that are adaptable and flexible to meet changing customer demands. This need for flexibility has led to a shift from traditional automated production lines to collaborative setups.

Cobots have become a crucial aspect of Industry 4.0, and are evolving into Industry 5.0's vision of a human-centred manufacturing environment (Gervasi et al., 2022). While Industry 4.0 focused on automating manufacturing through cyber-physical systems, Internet of Things (IoT), and cloud computing, Industry 5.0 emphasises human creativity and manual skills in manufacturing and aims to balance economic performance with social and environmental goals (Xu et al., 2021). Cobots bridge the gap between these industrial phases by enabling direct interaction between humans and machines, increasing productivity and reducing worker fatigue by offloading repetitive tasks to robots (Gladysz et al., 2023). Unlike traditional robots, which often work in isolated environments and require extensive safety measures, cobots are designed to work safely and efficiently with human operators (Hentout et al., 2019). Moreover, traditional robots tend to be larger, faster and designed for high-volume, repetitive tasks, often working behind safety cages. In contrast, cobots are smaller, more flexible and equipped with sensors and software that allow them to safely sense and respond to human

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movements and actions (Villani et al., 2018). This difference highlights their ability to adapt to human presence and work in shared spaces without the need for physical barriers, reflecting a shift from purely technological optimisation to the integration of human creativity and problem-solving skills into manufacturing processes.

The integration of cobots into production lines has also had a revolutionary impact on assembly and quality control (Verna et al., 2022). Despite their widespread use in manufacturing, cobots are relatively under-utilised in quality assurance (Verna et al., 2023a). Quality control remains a critical success factor for companies in competitive markets, preventing defective products from reaching customers and protecting the company's reputation (Montgomery et al., 2010). Increasing consumer demand for high quality products has led academia and industry to explore innovative solutions, such as cobots, to improve quality control processes.

The emergence of Quality 4.0 represents a significant shift in quality management, integrating Industry 4.0 technologies to improve product quality and maintain competitiveness (Antony et al., 2021; Sony et al., 2020). This paradigm emphasises the role of cobots in ensuring defect-free products that meet customer expectations, a critical factor in consumer decision-making (Küpper et al., 2019). The adoption of Quality 4.0 practices, such as real-time monitoring and predictive maintenance through big data analytics, provides strategic advantages by preventing production problems and defective output. In addition, the concept of Zero Defect Manufacturing (ZDM) is gaining ground, with the aim of minimising defects to near zero while improving production efficiency and sustainability (Azamfirei et al., 2023; Psarommatis et al., 2020). This evolution in quality management drives innovation and optimises business models through improved management of production processes (Antony et al., 2021; Psarommatis & Azamfirei, 2024). Backed by scientific research and case studies, the integration of cobots into quality control processes has proven effective in meeting the growing demand for high quality products. Cobots provide the high precision and consistency required to maintain stringent quality standards and minimise waste, ultimately improving customer satisfaction and strengthening competitive positioning in the marketplace (Antony et al., 2021; Cohen et al., 2022).

However, despite the potential benefits, cobots are not yet widely used in quality control and are more commonly used in assembly processes (Keshvarparast et al., 2024). The aim of this article is to provide a comprehensive review of the use of cobots in quality control. By analysing scientific literature and real-world case studies through a mixed-methods approach, this article provides an overview of the current state of the art in this field. Specifically, it seeks to identify the factors limiting the adoption of cobots in quality control and to propose solutions to overcome these barriers. The main challenges include high initial cost, limited application in real industrial cases, light sensitivity, limited collaboration, lack of consideration for safety, lack of technical skills among operators, low human acceptance and lack of support tools for cobot deployment (see Sect. "Results analysis"). Addressing these barriers and clearly demonstrating the key benefits could facilitate the wider adoption of cobots in quality control.

Collaborative robots in manufacturing

The novelty of collaborative robots

The recent surge in the integration of robotics in various sectors, particularly manufacturing, is aimed at increasing efficiency, reducing costs and improving productivity. This trend is in line with the Industry 4.0, which calls for rapid adaptation to market changes, adherence to high quality standards and sustainable practices. Robots have been instrumental in improving product quality by performing repetitive and physically demanding tasks with precision and consistency. However, their effectiveness is limited in high-volume production environments that require problem-solving skills, an area where human operators outperform robots in terms of flexibility, despite lacking the consistency, speed and the ability to handle heavy loads (El Zaatari et al., 2019).

The emergence of cobots marks a decisive step forward in combining the efficiency of automation with the flexibility required for mass customisation. Born out of Industry 4.0, cobots enable the creation of a synergistic workplace where humans and robots work together to complete tasks. Cobots are an integral part of Internet of Things (IoT)-enabled smart factories, equipped with sophisticated sensors and standardised interfaces to facilitate human work in this collaborative environment (El Zaatari et al., 2019; Romero et al., 2016). They differ from traditional robots in their adaptability, ease of setup and enhanced safety features, and their lightweight and compact design allows for exceptional mobility in various sectors, including automotive, electronics, food processing and pharmaceuticals (Peshkin & Colgate, 1999). This shift towards cobots establishes a significant transformation in manufacturing towards a more adaptable, efficient and human-centred industry, underpinning the move towards Industry 5.0. This transition underlines the commitment to promoting a sustainable and resilient industry, where cobots are key to addressing today's industrial challenges and heralds a future of harmonious human–robot partnership in manufacturing (Maddikunta et al., 2021).

Collaborative robots' market

Cobots have become increasingly popular in manufacturing, warehousing and logistics, where they can perform repetitive and physically demanding tasks, such as picking and packing, without risking injury to human workers. Cobots have also proven to be highly flexible and adaptable, with the ability to be quickly reprogrammed to perform different tasks, making them a valuable tool for companies looking to increase their operational efficiency. As a result, the global cobot market has grown rapidly in recent years and industry analysts predict rapid growth in the future.

Figure 1 illustrates the value of the cobot market in millions of U.S. dollars (Statista, 2024). Since 2020, the market has grown by approximately \$350 million, and this upward trajectory is expected to continue into the future, as indicated by the grey area in the graph. However, despite this encouraging growth, the cobot sector remains a relatively small part of the larger industrial robot market.

In terms of applications, Fig. 2 shows that, in 2023, almost a third of the cobots purchased are used for material handling, followed by assembly and pick and place. This highlights that cobots are now mainly used for handling and assembling parts in order to reduce the physical and cognitive workload of the operator. However, very few applications today involve the use of cobots in quality control, despite the global recognition of the importance of quality as one of the success factors of a business (Galetto et al., 2020). In particular, small and medium-sized enterprises (SMEs) still prefer to use traditional methods of quality control, as they cannot afford to purchase of new cobots.

In addition to the market and industrial interest, cobots are also attracting considerable attention in academia worldwide (Statista, 2024), as evidenced by the exponential increase in the number of papers published since 2015, after the publication of the pillar paper "Industry 4.0" (Lasi et al., 2014), which undoubtedly brought much more popularity to the topic. However, as in the application domain, the literature on cobot applications in the quality control domain is still scarce and lacks real-world applications.

As a result, cobots are becoming increasingly important in both industry and academia, outperforming traditional robots in terms of flexibility, safety and efficiency (Hentout et al., 2019). This growing importance highlights the need for further research of new applications, particularly in quality control. The current cobot market is dominated by a few key manufacturers, emphasising the need for expansion to increase competition, drive innovation and reduce production costs. To facilitate cobot adoption across industries, manufacturers have implemented strategies such as developing comprehensive training programmes to increase user familiarity, customising cobots to meet specific industry needs, and streamlining integration through user-friendly, modular designs (Aaltonen & Salmi, 2019). These initiatives help to remove financial and technical barriers, particularly for SMEs, thereby enabling wider use of cobots across different sectors.

Collaborative robots and emerging technologies for quality control

In recent years, digital twins (DTs) have been widely applied for collaborative systems. According to Grieves et al. (2017), a DT is a digital representation of the physical world in the virtual world using bi-directional data connections. These connections enable the transfer of data collected in the physical world to the virtual world (P2V, i.e. Physical-to-Virtual connections), and the transfer of processed information from the virtual world to the physical world (V2P, i.e. Virtual-to-Physical connections). DTs differ from traditional simulation and modelling activities, where analysis is typically performed offline, by maintaining a constant connection between the physical and virtual worlds (Jones et al., 2020). As a result, DTs technology can create a real-time communication path between the physical and digital worlds, which is one of the main challenges to be solved in the Industry 4.0 (Guo & Lv, 2022).

DTs represent a transformative approach to quality control, using real-time data acquisition and mapping to continuously update and accurately reflect the conditions on the shop floor (Yao et al., 2024). This innovation provides a dynamic alternative to traditional quality control methods by maintaining a real-time awareness of process and equipment conditions, enabling prediction of final product quality. DTs facilitate the collection of comprehensive quality data through P2V links, including process information and quality control procedures (Verna et al., 2023b). This data is integrated with experimental models to simulate potential defects and process outcomes. V2P links enable these virtual models to inform real-world processes, improving overall quality prediction. The synergy of simulation with real-time sensor data refines these models and optimises physical production components. With advances in sensor technology and computing power, DTs have evolved from purely offline monitoring tools to in-line solutions, significantly enriching quality control in a wide range of industries. This shift highlights the potential of DTs to drive continuous improvement and provide comprehensive insight into manufacturing processes, ushering in a new era of quality management and control (Guo & Lv, 2022; Ma et al., 2019).

Beyond DTs, the integration of Artificial Intelligence (AI) and blockchain technology significantly enhances the capabilities of quality control systems in collaborative robotic environments (Sharma, 2024; Verma et al., 2022). AI algorithms are particularly suitable at processing the vast amounts of data generated by DTs. By applying machine learning and

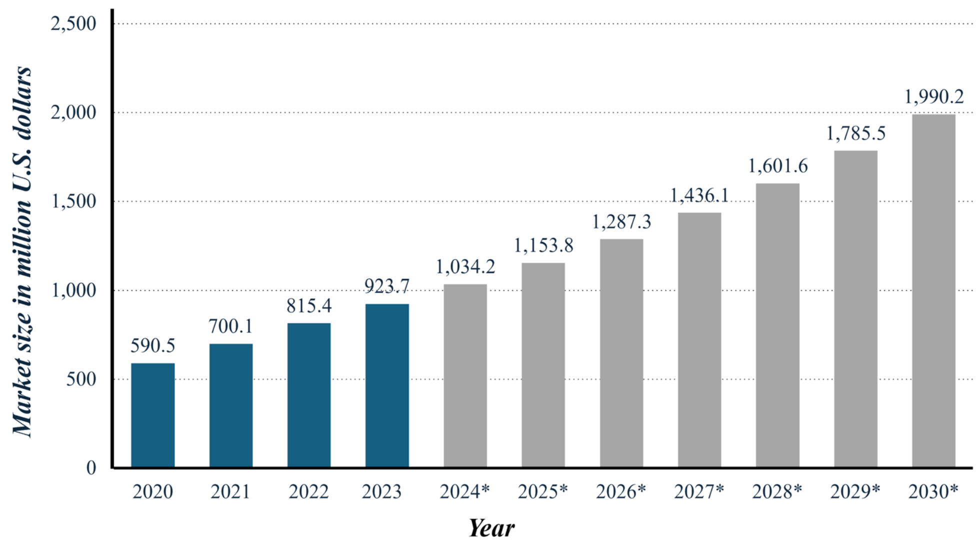


Fig. 1 Size of the collaborative robot market worldwide from 2020 to 2030 (expected). Adapted from Statista (2024)

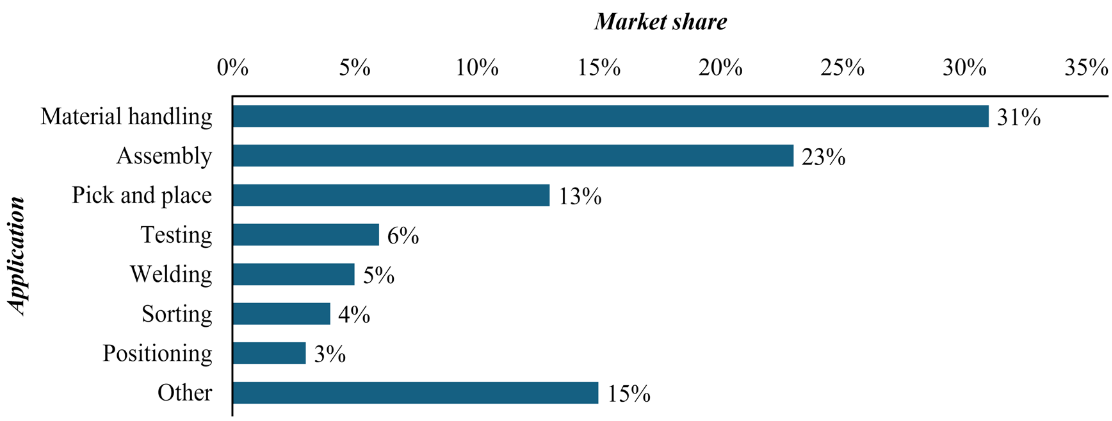


Fig. 2 Percentage size of the collaborative robot market by application. Adapted from Statista (2024)

deep learning techniques, AI can identify complex patterns and anomalies that may indicate potential defects or inefficiencies. This predictive capability allows for pre-emptive adjustments to manufacturing processes, helping to mitigate risk and reduce downtime. AI also facilitates adaptive learning, where the system continually refines its algorithms based on new data, improving the accuracy and effectiveness of quality control measures over time (Mahesh, 2020).

Blockchain technology complements this by adding a layer of security and traceability to the data exchange within the cobot ecosystem (Nofer et al., 2017). Every transaction, from data collection via P2V links to adjustments made via V2P links, can be recorded on a blockchain, creating an immutable ledger of all actions and changes. This ensures data integrity and provides a verifiable audit trail for quality control processes, which is critical in industries that require strict compliance and transparency standards.

Integrating these technologies with DTs creates a powerful synergy for quality control. The DT serves as a central framework that reflects the current state of the physical system and simulates future states based on input from AI-driven analytics (Sharma, 2024). In addition, blockchain can secure all related data exchanges, ensuring that every decision and action taken based on the DT's simulations is recorded and traceable (Verma et al., 2022). As a result, each of these technologies—DTs, AI and blockchain—addresses different aspects of quality control in collaborative robotics. Individually, these technologies contribute significantly to the efficiency, accuracy and reliability of quality control systems. When integrated, they enable more sophisticated, automated and intelligent manufacturing operations, driving the evolution of industry practices.

Survey on literature and case studies

This section aims to provide an in-depth review of current practice and research on cobot technology in manufacturing quality control systems. Using a mixed-methods approach (both literature analysis and real case studies) (Creswell & Clark, 2017), the section seeks to assess the benefits and challenges of implementing cobots in quality management, including cost, training and system integration considerations. By analysing the scientific literature and real case studies, the study aims to identify the potential impact of adopting cobot technology for quality control. The findings are expected to provide researchers, industry professionals and policy makers with critical insights into the effectiveness and impact of cobot-based quality control in the manufacturing sector.

Scientific literature survey

Literature searches were carried out in Scopus, Web of Science and the open-source Google Scholar. In terms of keywords, the following were used for the cobot topic: "collaborative robot*", "cobot*", "human–robot coexistence", "human–robot interaction", "human–robot collaboration", "human–robot cooperation", "robot* application", "physical human–robot interaction", and for the quality control topic the following: "quality control", "quality", "quality inspection", "quality assurance". An asterisk at the end of a word acts as a wildcard in search systems, indicating that results should include all variations of the word's root. For example, a search for "robot*" return records containing "robot", "robots", "robotic" etc.

Despite the growing popularity of cobots, the subfield of quality control applications plays a marginal role. In fact, only 92 results were found on this topic. The literature search included only academic literature published in English. After eliminating duplicate articles and those outside the scope of this paper, the final set of inherent articles includes only 26 documents (see Table 1). This highlights a gap and a potential new area of research to be addressed in the coming years, taking into account the advantages and benefits of this specific application. Moreover, research on the use of cobots in quality control and inspection processes has increased with the advent of Industry 5.0, but not as exponentially as for cobots in general.

As shown in Fig. 3, the number of publications on cobot applications has followed an interesting trend. Publications increased significantly until 2020, reflecting a surge in interest and the perceived potential of cobots in various fields. However, after peaking in 2020, the publication rate declined slightly before stabilising. This pattern suggests that while the initial enthusiasm for cobots has quited down, the technology remains a promising and evolving area of research. In addition, the integration of cobots with advanced AI solutions is driving the development of hybrid systems.

Despite the limited number of relevant articles, it is important to highlight that a considerable proportion are published in conference proceedings. As shown in Fig. 4, 46% of the articles analysed are from conference proceedings, while the remaining 54% are journal articles. This partition suggests that the field is still at an early stage of development, with a considerable amount of research being presented at conferences. Nevertheless, the observed increase in journal articles in recent years indicates a growing recognition and wider dissemination of research within the field, reflecting its increasing academic and practical importance.

A further significant element of this preliminary literature analysis pertains to the geographical distribution of research papers. The bar chart in Fig. 5 shows the distribution of publications on cobot applications across different countries. The United States and Italy lead the field with the highest number of publications, highlighting their strong commitment to cobot in quality control. This trend may reflect their robust industrial base and focus on improving production processes through automation. Germany and Finland also show significant research activity, with three publications each, in line with their well-established focus on engineering and industrial automation. These geographical trends are also confirmed by the citation network shown in Fig. 8, which will be discussed later.

In the context of the preceding discourse on global research trends, it is beneficial to undertake a detailed examination of the specific applications of cobots in the domain of quality control across diverse sectors. The pie chart in Fig. 6 highlights the main sectors using cobots for quality control.

The largest segment is the robotics industry, which accounts for 27% of these specialised applications, reflecting the significant role of cobots in increasing automation and efficiency within the industry itself. The automotive industry follows with 19% of applications, highlighting the critical role of cobots in ensuring quality and productivity in automotive production. Other key sectors include electronics and construction, each with 8% of applications, where cobots are used for their precision and adaptability in tasks ranging from assembly to quality control. Aerospace and metrology are also important sectors, with 7% each, where high standards of precision and quality are critical.

To deepen the understanding of the impact of these applications, a preliminary analysis of the keywords used in the articles was carried out. Figure 7 shows a word cloud generated from these keywords using the online software WordsClouds (2024).

The size of each word in the cloud corresponds to its frequency of occurrence within the keywords. Predictably, terms such as "human–robot", "collaborative", "interaction", "robot" and "quality" appear most frequently. This prevalence is due to the criteria used to select articles relevant to the topic under study.

Another preliminary analysis was to examine the authors who published the selected articles. Using the VOSviewer software (2024), the map shown in Fig. 8 was generated.

Table 1 Literature reviewed on quality control using collaborative robots in chronological order

References	Title	Year	Country	Industry	Publication type
Koskinen et al. (2009)	Monitoring of co-operative assembly tasks: functional, safety and quality aspects	2009	Finland	Automotive	Conference proceedings
Müller et al. (2014)	Inspector Robot—A new collaborative testing system designed for the automotive final assembly line	2014	Germany	Automotive	Journal article
Rooker et al. (2014)	Quality Inspection performed by a Flexible Robot System	2014	Austria	Automotive	Conference proceedings
El Makrini et al. (2017)	Design of a Collaborative Architecture for Human–Robot Assembly Tasks	2017	Belgium	University	Conference proceedings
Pichler et al. (2017)	Towards shared autonomy for robotic tasks in manufacturing	2017	Austria	Automotive	Conference proceedings
Liau and Ryu (2018)	Visual inspection based on machine vision system for smart injection molding	2018	South Corea	Molding	Journal article
Wahrburg et al. (2018)	Motor-Current-Based Estimation of Cartesian Contact Forces and Torques for Robotic Manipulators and Its Application to Force Control	2018	Germany	Metrology	Journal article
Cramer et al. (2019)	The application of line scan thermography using multiple collaborative robots	2019	USA	Aerospace	Conference proceedings
Lopez-Hawa et al. (2019)	Automated Scanning Techniques Using UR5	2019	USA	Metrology	Journal article
Papanastasiou et al. (2019)	Towards seamless human robot collaboration: integrating multimodal interaction	2019	Greece	Electronic and technology	Journal article
Syberfeldt and Ekblom (2019)	Improved Automatic Quality Inspections through the Integration of State-of-the-Art Machine Vision and Collaborative Robots	2019	Sweden	Automotive	Conference proceedings
Brito et al. (2020)	A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems	2020	Brazil	Robotics	Conference proceedings
Doltsinis et al. (2020)	A Machine Learning Framework for Real Time Identification of Successful Snap-Fit Assemblies	2020	Greece	Construction	Journal article
Islam et al. (2020)	Fast Underwater Image Enhancement for Improved Visual Perception	2020	USA	Marine	Journal article

Table 1 (continued)

References	Title	Year	Country	Industry	Publication type
Karami et al. (2020)	A Task Allocation Approach for Human–Robot Collaboration in Product Defects Inspection Scenarios	2020	Italy	Robotics	Conference proceedings
Kroeger et al. (2020)	Low-Cost Embedded Vision for Industrial Robots: A Modular End-of-Arm Concept	2020	Germany	Robotics	Conference proceedings
Magrini et al. (2020)	Human–robot coexistence and interaction in open industrial cells	2020	Italy	Polishing	Journal article
Jian et al. (2021)	An image vision and automatic calibration system for universal robots	2021	Taiwan	Robotics	Journal article
Khatib et al. (2021)	Human–robot contactless collaboration with mixed reality interface	2021	Italy	Robotics	Journal article
Xiao et al. (2021)	Visual Optimization of Ultrasound-Guided Robot-Assisted Procedures Using Variable Impedance Control	2021	China	Pharma and chemistry	Conference proceedings
Burke and Gurocak (2022)	Automatic Inspection of Green Concrete Quality Using Machine Learning and Cobot	2022	USA	Construction	Journal article
Magalhaes and Ferreira (2022)	Inspection Application in an Industrial Environment with Collaborative Robots	2022	Portugal	Robotics	Journal article
Queirós et al. (2022)	Human–Robot Collaboration (HRC) with Vision Inspection for PCB Assembly	2022	Portugal	Electronic and technology	Conference proceedings
Messeri (2023)	Enhancing the Quality of Human–Robot Cooperation Through the Optimization of Human Well-Being and Productivity	2023	Italy	Robotics	Journal article
Negri et al. (2023)	An Integrated Tool for Semi-Automatic repair of CFRP laminates and non-destructive quality control	2023	Italy	Aerospace	Conference proceedings
Yang et al. (2023)	Automation of SME production with a Cobot system powered by learning-based vision	2023	Denmark	Printing	Journal article

In this map, authors are represented as nodes, with larger nodes indicating more frequent occurrences of the respective authors in the articles. These nodes are connected by links representing citations between authors, with thicker links indicating a higher number of citations. The map also shows clusters of authors based on similarities such as shared research topics or affiliations, with proximity between clusters indicating greater thematic similarity. This VOSviewer-generated map is a powerful tool for visualising and analysing citation networks, facilitating the identification of influential authors, understanding research trends and

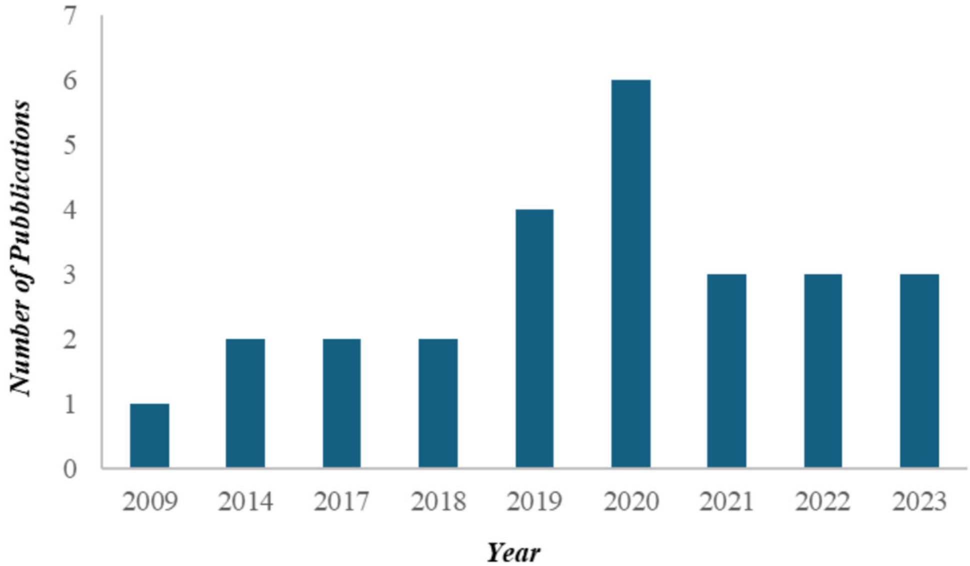


Fig. 3 Number of papers published over the years

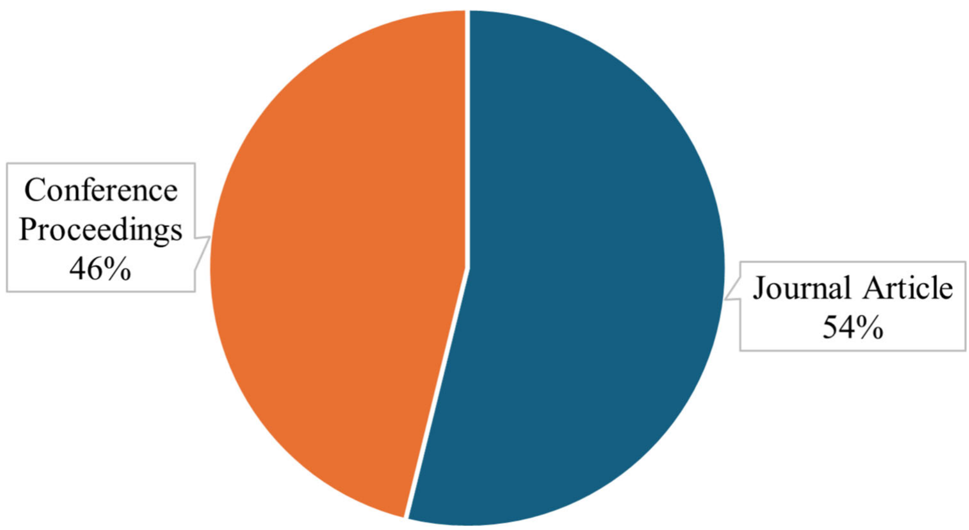


Fig. 4 Partition of analysed literature between journal articles and conference proceedings

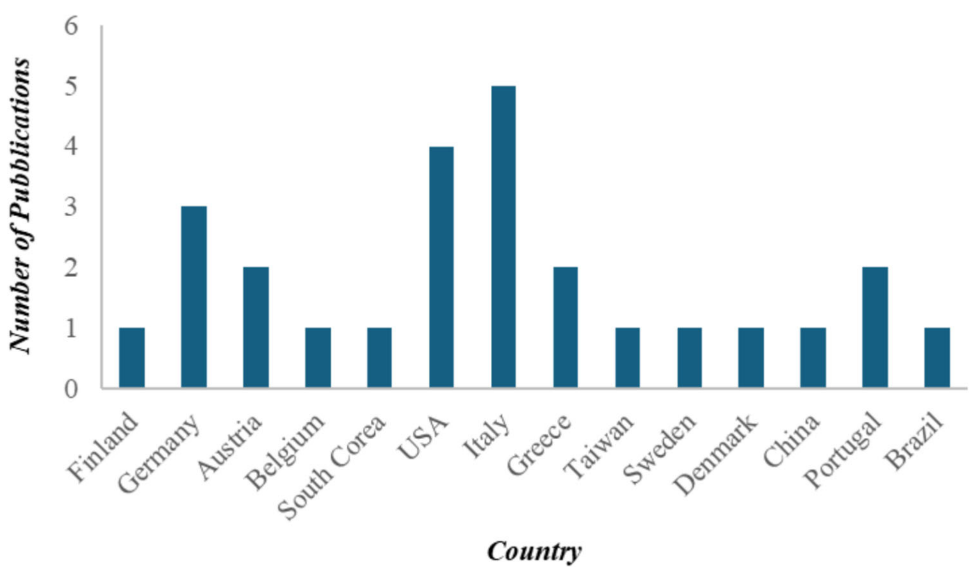


Fig. 5 Number of papers published by country

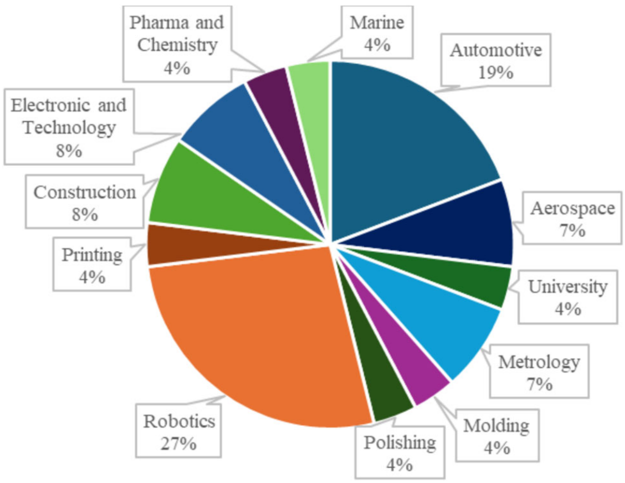


Fig. 6 Partition of analysed literature between industrial applications

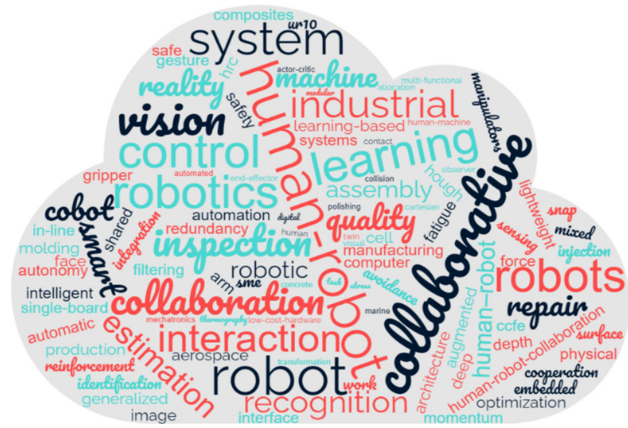
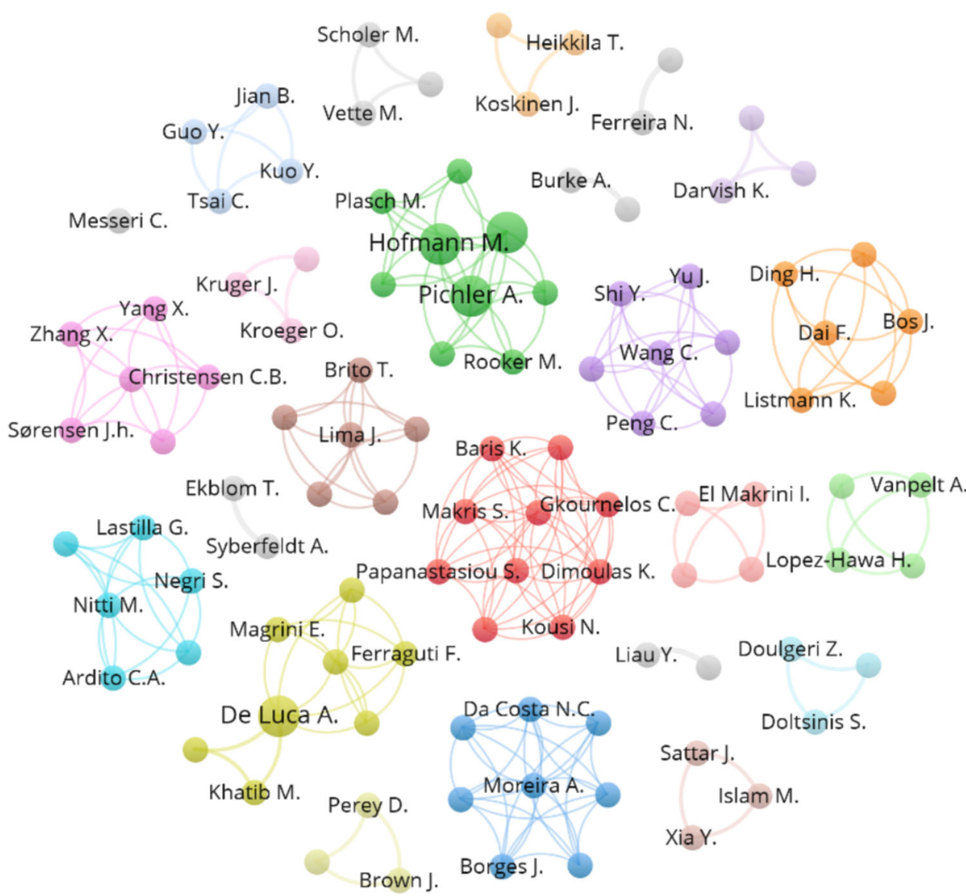


Fig. 7 Overview of keywords used in the selected articles

exploring the collaborative landscape in the field. Specifically, the citation network shown in Fig. 8 reveals distinct research clusters within the literature that specifically focus on the application of cobots in quality control. The close proximity of the different clusters within the network indicates a high degree of thematic overlap between the topics addressed by these research groups. This suggests a common focus in their research agendas and potential avenues for collaboration and interdisciplinary study within the field. For example, the analysis shows that Papanastosiou's group mainly explores topics related to seamless collaboration. A closely related theme is pursued by the Magrini's group, which investigates strategies to improve collaboration in manufacturing cells. Despite the lack of direct publications

Fig. 8 Citation network of analysed articles



linking these groups, their proximity on the map highlights their engagement with similar research themes, suggesting a potential for synergy. This type of analysis can be extended to all groups and sub-groups to explore the various connections between theme-focused authors and to understand the themes of greatest interest.

Real case studies survey

Additional sources were consulted to broaden the scope of the research, with an emphasis on real-world case studies. This included a systematic review of the websites of various cobot manufacturers. The analysis did not focus on specific cobot brands or sub-groups with particular technical characteristics but rather provided a comprehensive view of the use of all types of cobots in quality control by using the websites of different suppliers (Universal Robots, 2024). Examining these case studies provides an in-depth perspective on the use and market dynamics of cobots. Table 2 summarises the quality control case studies reviewed. Each case study in Table 2 shows:

- Primary information about the company (name, country, industry and company size in terms of number of employees);
- Description of the quality control process before the adoption of cobots, highlighting the pros and cons of the previous process;
- Challenges and opportunities of adopting the new quality control paradigm;
- Description of the quality control process after the adoption of cobots, highlighting the pros and cons of the current process.

From the data presented in Table 2, it is possible to perform preliminary analyses similar to those in the literature review, revealing significant trends in the use of cobots for quality control in real-world case studies. The bar chart in Fig. 9 illustrates the annual number of applications involving cobots in quality control from 2017 to 2023, showing a declining trend with a peak in 2017. Despite this decline, cobots remain highly valued for their flexibility and ability to work alongside human operators. They are particularly effective in environments that require adaptability and nuanced human judgement, making them an excellent alternative for complex quality control tasks, as highlighted in recent literature (Hentout et al., 2019). However, the wider shift towards traditional automation has been significantly influenced by advances in AI, which have enhanced the capabilities of fully automated systems. These technologies offer speed and consistency, which are highly valued in high-volume and repetitive tasks, making them increasingly preferred in many industries for their ability to reduce errors and increase

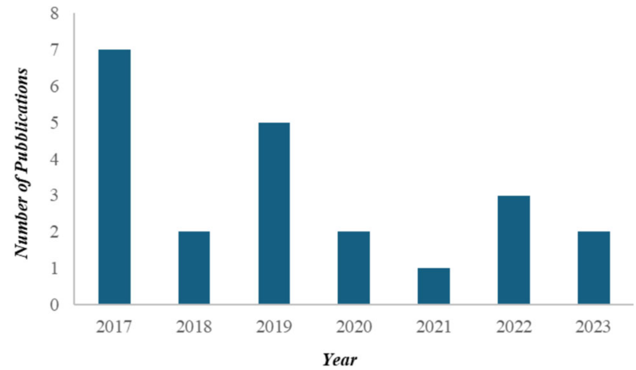


Fig. 9 Number of real case studies over the years

throughput (Mahesh, 2020). While traditional automation systems may appear more advantageous in certain scenarios, cobots remain a compelling option due to their unique collaborative capabilities. Their ability to work safely and efficiently alongside humans ensures that they remain a relevant and powerful tool in the evolving landscape of industrial quality control.

Despite this downward trend, it remains valuable to analyse the sectors in which cobots are used for quality control, following the approach used in the literature review. Figure 10 shows the distribution of the use of cobots in different industrial sectors and shows that the automotive industry is the main user, accounting for 45% of total applications. This is followed by the metals and metalworking industry with 23%. These figures highlight the strategic use of cobots in sectors where precision and repeatability are essential. In addition, the electronics and engineering sector accounts for 14% of cobot applications, while the pharmaceutical and chemical sector contributes 5%, reflecting the wider integration of cobot technology in industries requiring stringent quality control measures.

On the other hand, Fig. 11 shows the geographical distribution of cobot application in quality control. The United States leads with a significant 32% share, followed by Germany with 18%. Italy and Japan also make significant contributions with 9% each. The regional data are consistent with sectoral trends, suggesting a concentrated use of cobots in areas with a strong industrial manufacturing base.

Key cobot and quality control concepts for classification

Fundamental paradigms regarding cobots and quality control were used to systematically classify both scientific articles and real-world case studies. Specifically, the analysis introduced key concepts such as the human–robot relationship (Sect. "Human–robot relationships"), the communication channels between these two entities (Sect. "Human–robot communication"), and the types of quality control (Sect. "Quality inspections and quality control paradigms"). These paradigms provided a structured framework that facilitated a comprehensive and organised examination of the current applications and potential of cobots in quality control, ensuring that the analysis was both thorough and coherent.

Table 2 Real case studies on quality control using collaborative robots

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
3D Infotech (2022)	USA	Electronic and Technology	40	Automated metrology machines performed parts measurement	Overcome the use of automated metrology machines that require a prominent level of customisation and integration	Several programmable cobots are used to operate a wide range of sophisticated quality control sensors for part measurement
Böco Böddecker (2017)	Germany	Automotive	400	Each piece was individually marked with a code and manually checked by operators	Increase efficiency by identifying repetitive tasks in order to remain competitive. Each part must be individually marked with a code	A cobot arm marks and labels items to exacting standards, while a camera mounted on the arm performs quality control checks
BW Industrie (2020)	France	Metal and machining	45	An outdated, traditional robot was used to move light-weight parts, which were then inspected by an operator	Improve competitiveness by reducing strenuous work and avoiding displacement	Four camera-equipped cobots are used to load and unload a lathe, while simultaneously checking the quality of the parts
Comprehensive Logistics (2017)	USA	Automotive	190	A completely manual inspection process that only allows for 80% of the production to be inspected	Reduce components with life-threatening failure modes (important to ensure clips are 100% secure)	A ceiling-mounted cobot equipped with a camera moves quickly between inspection points, taking an image of each joint
Craft and Technik Industries (2018)	India	Automotive	80	Most manufacturing tasks handled manually	Reduce customer waste due to lack of skilled labour and resulting defective components	A cobot arm loads and unloads a vertical Computer Numerical Control (CNC) machine and also performs part inspection using a scale to provide feedback on whether the part meets weight requirements

Table 2 (continued)

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
DJH (2017)	Denmark	Scientific and Research	150	Manual sorting carried out by an industrial robot and quality controlled by students	Program the robot to collect items from the warehouse and place them in three different stacks	A camera equipped cobot picks up parts from a warehouse, places them in the correct position and simultaneously performs a quality check on the transported parts
EVCO Plastics (2019)	USA	Plastics and polymers	300	Manually manning cells with repetitive and tedious tasks	Increase employment and reduce staffing problems for the third shift of 24/7 enterprise production	Four different cobots, equipped with cameras and mounted on wheels, move around the factory floor to transport and inspect parts
Ferdinand Wagner (2017)	Germany	Metal and machining	90	Workers manually welded and inspected 500–600,000 parts per year	Define a robust and reliable automation solution that could consistently deliver high quality welding and brazing of fragile parts	Two cobots working together. The first cobot selects the parts to be welded, while the second robot holds the parts up to a camera system for quality control
Ford Motor Company (2019)	Romania	Automotive	5000+	Manual production and inspection	Define solutions that enable manual workers to create value and a quality production process	Three cobots are integrated into the work processes, while another camera-equipped cobot uses UV light to inspect the engine
Gentofte Hospital (2017)	Denmark	Pharma and Chemistry	1633	Manual sorting of blood samples	Optimise the handling and sorting of blood samples, with the aim of delivering more than 90% of results within an hour, despite a 20% increase in the number of samples arriving for analysis	A cobot arm optimises the handling and sorting of blood samples, while a camera checks the level of blood in the tube

Table 2 (continued)

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
GKN Driveline (2019)	Japan	Automotive	1400	Use of old machines called front and rear discriminators, which were manually guided by operators for inspection	Address the chronic problem of labour shortages and the difficulty of automation due to operator experience with traditional machines	Two cobots handle front and rear quality inspection
Koyo Electronics Industries (2019)	Japan	Automotive	343	Manual assembly and visual inspection of products, with post-processing by operators to confirm that equipment performs as expected	Increase productivity to meet the growing demand for high-quality products	A cobot is used in the touch panel quality inspection process. When the cobot touches the touch panel with a stylus, "OK" is displayed if there are no quality defects and a green signal tower light up. If an anomaly is detected, the display will show "NG", the red tower will light up and the buzzer will sound
Lear Corporation (2017)	Germany	Automotive	132,000	Fully manual seat frame bolting and quality control	Achieve just-in-time assembly with associated quality control in a consolidated supplier production model	The robotic arm is responsible for screwing in the seat frames by using a screwdriver. A camera mounted on the arm then checks the quality of the assembly
Nordic Sugar (2017)	Sweden	Food and agriculture	1430	Old robotic arms weighed the containers with pureed beets	Replace old robotic arms due to obsolescence in relation to new processes	Three cobots scan barcodes and pick up containers of sugar for analysis from scales to filters and back again. The process is carried out using a pneumatic gripper and a barcode scanner integrated into the robot's end-of-arm tool

Table 2 (continued)

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
Olympus (2022)	Singapore	Metal and machining	50–100	Manual inspection tasks performed over long periods of time in uncomfortable, unsafe positions that can lead to accidents	Enable customers to implement a comprehensive and efficient quality inspection solution, freeing operators from the potential health risks associated with working long hours in confined spaces	A cobot equipped with a non-destructive testing (NDT) device is used to detect cracks, defects and the elemental composition of materials without damaging them
Optipro Systems (2021)	USA	Metal and machining	70+	Manual inspection of 100% of production	Define an automated solution that can measure defects in work-in-process products	Use of the Q-Span® system for in-process quality control. This system includes a cobot, robotic grippers, sample parts and accessories on a versatile trolley that can be easily moved around the plant. As the parts leave the grinding facilities, the Q-Span® workstation measures them in a pass/fail scenario
Precisionform Inc (2020)	USA	Manufacturing	50	A robotic arm picked up the parts from deep bins and fed them into a CNC machine. An operator would then check the quality of the machined parts	Improve competitiveness, overcome labour challenges, empower your workforce and extend the life of older equipment	A cobot inserts and removes parts from the CNC machine. During both phases, it performs a quality check on the parts using a laser sensor mounted on the arm
Siemens Gerätewerk Erlangen (2023)	Germany	Electronics and Technology	1000+	Old manual assembly line completely different from the current one	Define a new production process to cope with labour shortages and increasing cost pressures. Integrate the new assembly line with a DT to monitor the production process	More than 70 cobots automate previously manual tasks. A DT of the processes is used to monitor product quality in real time

Table 2 (continued)

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
Stellantis (2022)	Italy	Automotive	407,500	Old manual assembly line completely different from the current one	Automate assembly and quality control processes to ensure the quality and repeatability required to meet product standards	Two cobots work on the car's soft top assembly line. The first cleans and prepares the primer track, while the second cobot, equipped with a vision system, checks the geometric continuity and dimensions of the adhesive tape
Thales Alenia Space (2023)	Italy	Electronics and Technology	2800	Manual inspection of 100% of satellite installation circuit boards. Operators had to simultaneously compare the image captured by the camera with the original CAD of the board and identify any discrepancies	Automating the quality control of printed circuit boards for satellite equipment is a task that requires precision and high repeatability, as well as a number of ergonomic challenges for the human operator	A cobot arm, equipped with a microscopic precision inspection camera, inspects printed circuit boards. The integrated software allows the camera to move over the features of the board and, via built-in augmented reality protocols, superimpose CAD images of the board on the screen, allowing the inspector to verify the actual correspondence between the board and the design
Thyssenkrupp Bil-tein (2019)	USA	Automotive	700+	Manual inspection of two selected parts every two hours of production	Keeping production processes lean and flexible despite increasing customer demands, rapidly changing product requirements and the inability to hire new staff	A cobot, equipped with a Cognex camera, moves quickly between inspection points to ensure that all components are in the correct position and that the label is correctly applied and legible

Table 2 (continued)

Company	Country	Industry	Size	Process before cobots	Challenge	Process after cobots
Zippertubing Company (2018)	USA	Automotive	50+	Manual inspections of each insertion	Define a new thorough inspection of the male and female spring pins to ensure proper insertion	A cobot takes a pre-cut piece of fabric and passes it through a machine that adds five male snaps, then passes it to a second machine that adds five female snaps. The 25-s cycle ends when the cobot presents the piece to a camera that checks that the snaps have been added correctly

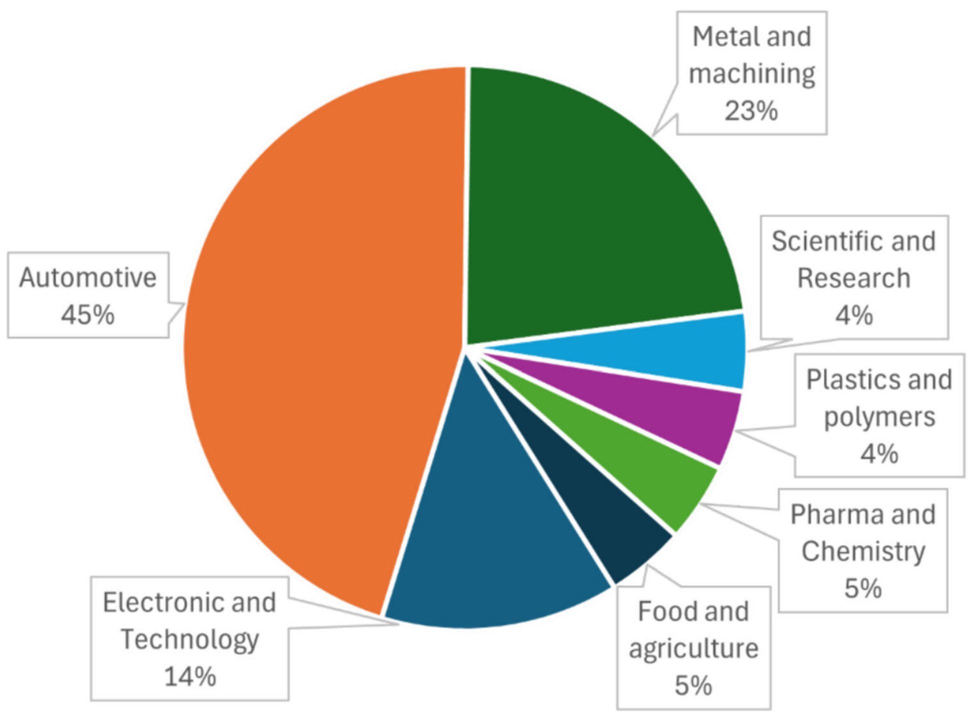


Fig. 10 Cobot application in quality control in various industrial sectors

Human–robot relationships

Several types of relationships between human and cobot can exist on the factory floor. According to Wang (2019), four categories can be identified (see Table 3). De Luca and Flacco (2012) introduced the concept of "coexistence", describing it as a fundamental level where humans and robots share a physical space without engaging in a common task. This form of interaction, sometimes referred to as coercion, includes scenarios where a robot and a human can work independently on the same object without coordination or direct contact, focusing only on avoiding collisions.

Expanding on coexistence, Human–Robot Interaction (HRI) includes scenarios where humans and robots not only share a workspace, but also communicate physically or otherwise, such as through contact, guidance or commands. This "interaction" can be sequential, where tasks are performed in steps that involve either direct contact or remote interaction, such as teleoperation, where the human guides the robot from a remote location.

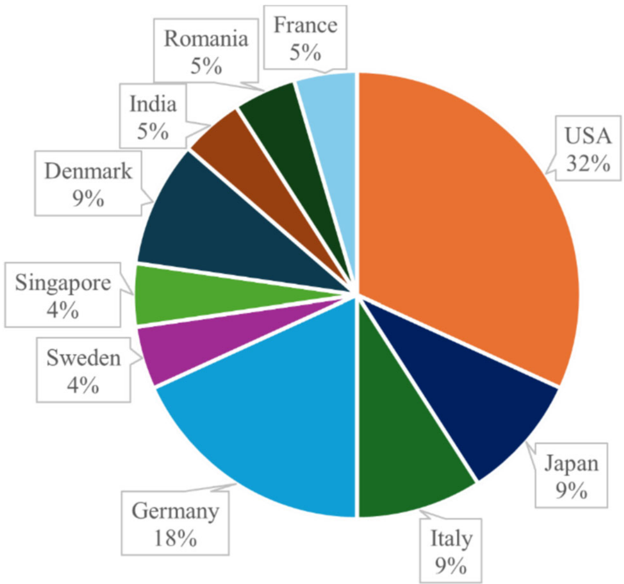


Fig. 11 Geographical distribution of cobots in quality control

Further along the spectrum of human–robot relationships is "cooperation", where humans and robots share a workspace and resources to achieve mutual benefits through divided subtasks, each responsible for different parts of the work (Váncza et al., 2011). This includes both sequential and simultaneous processes, indicating a higher level of integration between human and robot actions.

Human–Robot Collaboration (HRC) represents the most integrated form of relationship, where robots perform complex tasks with direct human interaction and coordination (De Luca & Flacco, 2012). Musić and Hirche (2017) emphasise that "collaboration" involves joint, goal-oriented activities that combine different skills, competencies and resources towards a common goal. This includes task sharing, where the operator may perform tasks that require dexterity or decision making, while the robot performs repetitive or precision tasks.

To move beyond traditional collaborative frameworks, the concept of human–robot symbiosis represents a new and more deeply integrated form of human–robot relationship. As outlined by Barravecchia et al. (2023), this bio-inspired approach to collaborative assembly embodies a profound fusion of human cognitive abilities and robotic precision. This symbiotic interaction goes beyond simple collaboration, fostering an environment in which both human intuition and robotic capabilities are seamlessly intertwined, improving the efficiency of production processes and the ergonomic safety and job satisfaction of human operators. Sylla et al. (2014) illustrate an example of this symbiosis through a wearable electromechanical device (exoskeleton) that supports human movement. Such exoskeletons are used in rehabilitation to help individuals regain limb functionality and in industrial settings to reduce physical strain. This shift highlights symbiosis as the ultimate form of human–robot integration aimed at fostering a more dynamic, interactive and efficient industrial environment.

Human–robot communication

Effective communication between humans and robots is critical to achieving common goals. Communication enables the exchange of information, commands to the robot, and intentions, beliefs, desires, and objectives to ensure that the operators share the same values and to carry out a common plan. As well known in the literature (Bauer et al., 2007; El Makrini et al., 2017; El Zaatari et al., 2019), several communication channels are available to facilitate human–robot communication, including speech, vision-based communication, touch, haptic signals, and physiological signals (see Fig. 12).

Communication between humans and robots is essential for collaboration, with speech or voice commands being a primary method due to its quick and easy nature (Bauer et al., 2007). However, speech recognition in industrial environments is challenged by background noise and varying accents, requiring feedback to the operator to avoid misinterpretation. As an alternative, vision-based communication methods are increasingly being used (El Makrini et al., 2017; El Zaatari et al., 2019). These approaches use cameras and sensors to interpret non-verbal cues such as gestures, facial expressions, gaze and pointing, which are particularly important in manual tasks. By recognising these cues, robots can respond dynamically to human actions, facilitating smoother interaction and enabling the recognition of complex tasks composed of multiple gestures.

Table 3 Human–robot relationships and features. Adapted from (Wang et al., 2019)

	Shared workspace	Direct contact	Working task	Resource	Simultaneous process	Sequential process
Coexistence					x	
Interaction	x	x	x			x
Cooperation	x			x	x	x
Collaboration	x	x	x	x	x	

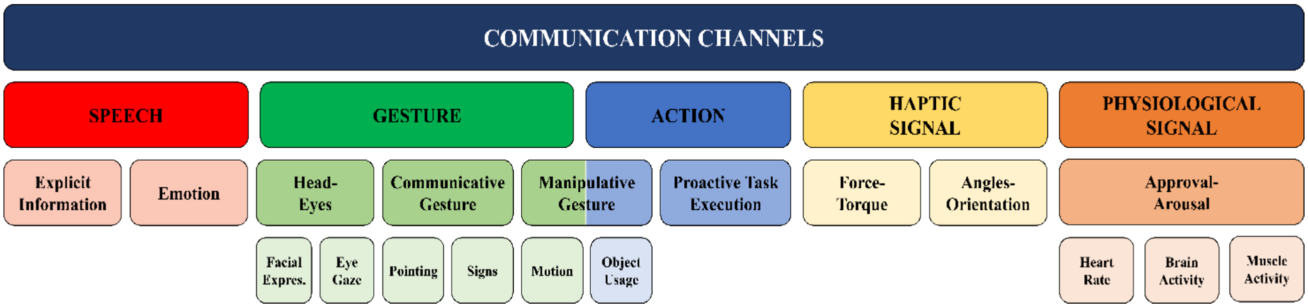


Fig. 12 Human–robot communication channels. Adapted from (Bauer et al., 2007)

Touch interaction, facilitated by cobots equipped with sensors such as buttons or more advanced technology that mimics artificial skin, provides another layer of communication. Haptic feedback, which includes forces, torques and angles of orientation, is particularly relevant in industrial environments, where physical cues enhance integration (Bauer et al., 2007). Graphical user interfaces (GUIs) also support haptic communication. In addition, physiological signals, including brain activity, heart rate and skin response, provide insight into an operator's agreement, arousal and intentions, helping to plan joint actions towards common goals (Peshkin & Colgate, 1999).

The integration of natural communication methods such as speech and gestures with touch, haptic signals and physiological measurements can significantly improve the interaction in industrial environments. Advances in machine learning and natural language processing further enhance the understanding and responsiveness of robots, making interactions more intuitive and user-friendly. This multifaceted approach to communication is critical for effective and safe human–robot collaboration, using a range of channels to accommodate the complexity of human expression and intent.

Quality inspections and quality control paradigms

In today's marketplace, quality is an essential consideration for industries across all sectors. Regardless of the type of product, organisations need to ensure that their end customers receive high quality products that meet industry standards and specifications. In particular, the ISO 9000 standard (ISO 9000 2015, 2015) defines quality as the ability to satisfy customers while taking into account the impact on stakeholders, including intended and unintended effects.

To ensure product conformity, quality control procedures must be defined throughout the production cycle. In general, there are two main paradigms of quality controls that are commonly used in production lines: in-process and offline inspections (Genta et al., 2020; Verna et al., 2021). In-process inspections are carried out during product processing and allow timely corrective action to be taken in the event of nonconformities. This approach is particularly useful when products are in continuous production and requirements are stringent. In-process control systems typically involve sensors and automated inspection equipment that monitor critical parameters such as temperature, pressure and dimensions during the manufacturing process. The benefits of in-process control include the ability to detect and correct deviations immediately, helping to maintain product quality and reduce scrap rates. However, it requires a significant investment in advanced technology and integration and must be carefully designed to avoid disruption to the production flow (Genta et al., 2020; Verna et al., 2021).

In contrast, offline inspections are performed after the production process has been completed and are usually more suitable for non-continuous production processes. These inspections are more thorough and can include both visual inspection by human operators and automated testing using specialised equipment. Offline inspection allows detailed inspection of each item or batch, which can be critical for industries with high safety or compliance standards. However, this method can be slower and less efficient as it can delay the identification of defects until after the production process has been completed, potentially leading to higher reject rates and increased waste (Genta et al., 2020; Verna et al., 2021).

In-process and off-line controls are critical to an effective quality management system, tailored to specific production needs and constraints. The choice of these quality control strategies has a significant impact on production efficiency and the ability to meet modern market demands, such as mass customisation (Krüger et al., 2009). Cobots play a key role in this scenario, enhancing quality control processes by combining robotic precision with human creativity and problem-solving skills. This synergy can improve the adaptability and efficiency of quality control processes, ensuring that products meet precise specifications without compromising production throughput. Integrating cobots into quality control systems allows companies to leverage advanced automation technologies while maintaining flexibility in production and inspection tasks. These systems can be programmed to adapt to varying product designs and changing quality criteria, making them ideal for industries facing rapid product evolution and customisation requirements. In addition, cobots can reduce the cognitive and physical workload of human inspectors, which can lead to a reduction in human error and an increase in overall job satisfaction.

Literature and case studies classification

In line with the paradigms defined in Sect. "Key cobot and quality control concepts for classification", this section presents a systematic classification of relevant literature (Sect. "Literature classification"), and real-world case studies (Sect. "Case studies classification") related to the use of cobots in quality control.

Literature classification

This section reviews the scientific literature identified on the use of cobots in quality control (see Table 1). Following the concepts presented in Sect. "Key cobot and quality control concepts for classification", Table 4 classifies each paper according to the following dimensions defined by the authors:

- Industry: the industry sector that the article analyses in its research.
- Process objective: objective of the quality control.
- Quality control paradigm: in-process or offline quality controls (Galetto et al., 2020).
- Human–robot relationship: type of relationship between human operators and cobot. According to Wang et al. (2019), these human–robot relationships can be: coexistence, interaction, cooperation and collaboration.
- Communication channel: type of communication between human and cobot. According to Bauer et al. (2007), these communication channels can be: action, haptic, gesture, speech and physiological signal.
- Type of inspection: typology of inspection (manual, visual, dimensional measurement, etc.);
- Methodological approach: the approach used to achieve the process objective (deep learning, heuristic etc.).
- Technology: technology used for the control (type of cobot, type of sensor, type of camera etc.).
- Pros/Novelty: innovative aspects of the research in relation to solutions already implemented.

It is important to emphasise that the existing literature on the use of cobots in quality control is limited, with about half of the studies lacking empirical validation in industrial settings. The most plausible explanation for this is that, as a relatively new area of research, the approaches and methodologies developed have not yet been widely adopted or validated in actual industrial quality control processes using cobots.

Case studies classification

As detailed in the previous section, the paucity of scientific literature on the use of cobots in quality control, together with their limited implementation in industrial contexts, necessitated a shift towards the analysis of real-world case studies. Consequently, case studies were analysed using the same methodological framework as the literature review.

Table 5 summarises the descriptions of the main characteristics of the quality control approaches using cobots adopted by the selected companies. Similar to the classification of the papers, the analysis dimensions identified by the authors for each company are as follows:

- Process objective: objective of the quality control.
- Quality control paradigm: in-process or offline quality controls (Galetto et al., 2020).
- Human–robot relationship: type of relationship between human operators and cobot. According to Wang et al. (2019), these human–robot relationships can be: coexistence, interaction, cooperation and collaboration.
- Communication channel: type of communication between human and cobot. According to Bauer et al. (2007), these communication channels can be: action, haptic, gesture, speech and physiological signal.
- Type of inspection: typology of inspection (manual, visual, dimensional measurement, etc.);
- Technology: technology used for the control (type of cobot, type of sensor, type of camera etc.).
- Pros/Novelty: innovative aspects of the research in relation to solutions already implemented.

Results analysis

Using a mixed methods approach (Creswell & Clark, 2017), which combines an extensive literature review with a detailed analysis of case studies, several advantages and disadvantages were identified. This section systematically outlines these advantages and disadvantages associated with the large-scale implementation of a new cobot-based quality control paradigm in the manufacturing sector. A clear definition of these advantages and disadvantages is essential to promote the wider adoption of cobots for quality control by companies. In detail, benefits and drawbacks referring to a specific i-th analysis criterion are labelled as follows:

Table 4 Classification of the literature examined on collaborative robots in quality control (see Table 1)

References	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Methodology approach	Technology	Pros/novelty
Koskinen et al. (2009)	Examine the correct position of a car rear screen	In-process	Collaboration	Haptic	Visual	Algorithm implemented in C++ for cell control	Industrial robotic arm, high-definition cameras, safety mats	Radio positioning technology used to locate the human operator in the cobot cell
Müller et al. (2014)	Water leak test inspection	Offline	Coexistence	Action	Visual	Blob detection algorithm	Universal Robot 10 (UR10) cobot, Thermographic camera	Cobot mounted on a linear track and guided alongside the continuous assembly process
Rooker et al. (2014)	Examine the interlocking of plugs	In-process	Interaction	Action	Visual	Structured light principle	UR10 cobot, RGB-D from ShapeDrive® Sensor, CMOS camera	The 3D-sensor for the data acquisition is independent of the surrounding light conditions, offline setup and teach-in procedure
El Makrini et al. (2017)	Assembly and quality control of the assembled box	In-process	Collaboration	Gesture	Visual	Hough transformation	Baxter cobot, Kinect v2 camera, middleware MiTE 2.2	Cobot capable of understanding operator intent by analysing head nod/shake and gaze
Pichler et al. (2017)	Quality inspection for generator-plug connectors	In-process	Collaboration	Gesture	Visual	Random Sampling Algorithm	UR3 cobot, 3D sensors and software ReconstructMe	Environment reconstruction with XRob platform
Liau and Ryu (2018)	Quality inspection for mold assembly	In-process	Collaboration	Gesture	Visual	Machine vision algorithm	Cobot, Machine vision system	Integration of machine vision systems into smart injection molding

Table 4 (continued)

References	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Methodology approach	Technology	Pros/novelty
Wahrburg et al. (2018)	Improve the Cartesian contact force and torque estimation	In-process	Interaction	Haptic	Force training	Kalman filter calibration and tuning	ABB YuMi cobot station	Improvement of accuracy and response time of CCFE
Cramer et al. (2019)	Inspection of aircraft fuselage of complex geometry	In-process	Interaction	Action	Surface characterisation	Principal Component Analysis (PCA)	UR10 cobot, Line scanning thermography (LST)	Ten times the inspection process speed
Lopez-Hawa et al. (2019)	Generate surface geometry for further inspection	Offline	Interaction	Haptic	Surface characterisation	Test Object Grabbed by Robot (TOGR)	UR5 cobot, Keyence line scanner	Greater flexibility in positioning the line scanner around and inside the parts to be scanned
Papanastasiou et al. (2019)	Quality control of sealing operation	In-process	Collaboration	Haptic	Visual	Deep Learning	COMAU Open C5G controller (LPC), Force/torque sensors, microphones, cameras, smartwatches, AR glasses, vision system, air press sensor	Human–robot collaborative welding interaction simplified
Syberfeldt and Ekblom (2019)	Inspection of glue strings	In-process	Interaction	Action	Visual	Convolutional Neural Network (CNN) with ReLU function	UR3 cobot, wrist camera	Automated quality inspection improvement in the glue string industry
Brito et al. (2020)	Transport of a product to be inspected in a certain location	Offline	Collaboration	Haptic	Force training	LSTM Neural Network	UR3 cobot, Force-Torque sensor FT-300, cone-shaped 3D printed tool	Dynamic teaching and operation for real-time path modification
Doltsinis et al. (2020)	Characterisation and inspection of snap-fits assembly	In-process	Collaboration	Haptic	Force training	Support vector machine (SVM) classifier	KUKA LWR 4 cobot, three-finger gripper Barret BH-8	External force sensor free force estimation mechanism
Islam et al. (2020)	Underwater visual inspections	In-process	Interaction	Action	Visual	Generative Adversarial Networks (GANs)	GoPros cameras, Aqua AUV's uEye cameras, low-light USB Cameras, Trident ROV's HD camera	Improved perceived image quality

Table 4 (continued)

References	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Methodology approach	Technology	Pros/novelty
Karami et al. (2020)	Inspection of product defects	Offline	Collaboration	Gesture	Visual	AND/OR graphs	Dual-arm Baxter cobot, Kuka youBot mobile manipulator, LG G Watch R (W110) smartwatch, OptiTrack-Flex cameras, RGB-D camera	AND/OR graphs for activity programming
Kroeger et al. (2020)	Inspection of circular shaped objects	In-process	Interaction	Action	Visual	Object detection module	UR5 cobot, Co-act JL1 two finger gripper, Robotiq wrist camera	Greater speed and flexibility than current industrial solutions for circular objects
Magrini et al. (2020)	Polishing defects inspection	In-process	Collaboration	Gesture	Visual	Depth-space monitoring algorithm	ABB IRB 4600 cobot, KEYENCE SZ-V32n scanners, Kinect V2 sensor	Allow human–robot physical contact during polishing activities
Jian et al. (2021)	Error's location	In-process	Interaction	Action	Visual	Sobel computation, Denavit-Hartenberg transformation matrix, Hough transformation	UR5 cobot, CCD camera	Accurately locate the mass point of the workpiece to be gripped
Khatib et al. (2021)	Mixed reality interface inspection	In-process	Collaboration	Gesture	Visual	Saturation in the Null Space (SNS) algorithm	KUKA LWR4 cobot, Oculus Rift HMD + ZED Mini stereo camera, RGB-D depth sensor	Introducing augmented reality to help inspect HRC
Xiao et al. (2021)	Control system for intraoperative ultrasound imaging	In-process	Interaction	Haptic	Visual	HRI mode, HREI mode and REI mode	OpenMANIPULATOR-P robot arm with two SBT650 force sensors at the end-effector, M8 Diagnostic Ultrasound System	Reducing surgeon effort and improved ultrasound stability for percutaneous interventional procedures

Table 4 (continued)

References	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Methodology approach	Technology	Pros/novelty
Burke and Gurocak (2022)	Concrete quality inspection	In-process	Interaction	Action	Surface characterisation	K-Nearest Neighbor model (KNN), Ultrasonic Pulse Velocity (UPV), Artificial Neural Network (ANN) models, Support Vector Machine (SVM)	UR10 cobot, end-effector with microswitch, FUTEK LCM 100 load cell	Use of non-destructive techniques on uncured concrete for prediction of cured strength
Magalhaes and Ferreira (2022)	Geometric parameterisation of inspection places	In-process	Interaction	Action	Visual	Time-of-Flight (ToF)	UR5 cobot, SOPAS Engineering Tool, NANS3-CAAZ30AN1 laser scanner, Doosan M0617 camera, TriSpector1000 sensor	Easy parameterisation of the system, allowing new parts to be added for inspection
Queirós et al. (2022)	PCB inspection	In-process	Interaction	Action	Visual	Programmable Logic Control (PLC) System	TM5-700 cobot, NX102-9020 Omron PLC, FH-1050 Omron vision system	Autonomous work cell capable of assembling PCBs with PTH components
Messeri (2023)	Quality inspection of collaboration	In-process	Collaboration	Gesture	Visual	LF/HF, RMSSD, OpenSim Static Optimization system	ABB IRB 14000 YuMi cobot, disposable electrodes, camera vision system	Innovative dynamic task allocation strategy
Negri et al. (2023)	Inspection of CFRP laminates	In-process	Interaction	Action	Visual	Deep learning algorithm	UR10e cobot, 3140-C-DBL-P-ER20-PR-AC-RH electro-spindle, LMI Gocator 3210 optical profilometer	Innovative collaborative cell for scarf repairing of CFRP
Yang et al. (2023)	Quality control of hockey puck printing	In-process	Interaction	Action	Visual	YOLOv5, CNN-SVM, DT	UR3e cobot, See3Cam cameras, Robotiq multi-functional gripper	Easy expansion to a new collaborative production line

Table 5 Real case studies on quality control using collaborative robots (see Table 2)

Company	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Technology	Pros/novelty
3D Infotech (2022)	Product line standardisation with the use of UR cobots	In-process	Collaboration	Action	Dimensional measurement	Aruna Vision, 5 kg payload cobot	Easy integration of cobots with different types of sensors around a wide range of part geometries
Böco Böddecker (2017)	Quality control of closure, locking and latching systems	In-process	Interaction	Action	Visual	Advanced camera control, 5 kg payload cobot	Massive cost savings by automating repetitive tasks and reducing the likelihood of sending faulty parts to customers
BW Industrie (2020)	Inspection of extruded tubes	In-process	Interaction	Action	Dimensional measurement	High-definition cameras, 10 kg payload cobot, 16 kg payload cobot	Maintained production in France without compromising competitiveness and increased the workforce by 50%, resulting in a 70% increase in sales. Reduced the risk of musculoskeletal disorders (MSDs) among employees
Comprehensive Logistics (2017)	Inspection of automotive engine sub-assemblies	In-process	Collaboration	Action	Vision	Vision camera, 10 kg payload cobot	Reduce maintenance, downtime and line stoppages with 100% inspection in automotive engine assembly
Craft and Technik Industries (2018)	Automatic inspection and CNC machine tending	In-process	Interaction	Action	Weight measurement	Weighting machine, 10 kg payload cobot	Increased production volume by 15–20% with no defects or customer rejects
DJH (2017)	Introducing students to the world of automatic inspections	In-process	Collaboration	Action	Vision	Vision system, 5 kg payload cobot	Preparing students for industrial reality

Table 5 (continued)

Company	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Technology	Pros/novelty
EVCO Plastics (2019)	Quality inspection of a gearbox assembly	In-process	Interaction	Action	Weight measurement	Force-torque sensor, Cognex camera, 5 kg payload cobot, 10 kg payload cobot	Redistributing the savings from integrating cobots across all departments
Ferdinand Wagner (2017)	Automatic inspection of welding and soldering work	In-process	Interaction	Action	Visual	Camera system, 2 cobots with a payload of 5 kg	Improved operational efficiency of the production line (160 pieces/hour)
Ford Motor Company (2019)	Checking the engine with a UV light and a camera for leakage	In-process	Collaboration	Haptic	Visual	Cognex camera vision, UV light, 4 cobots with a payload of 10 kg	Faster production throughput while also relieving employees of repetitive tasks
Gentofte Hospital (2017)	Checking the blood samples level and sorting the tubes	In-process	Interaction	Action	Visual	Barcode scanner, vision camera, 5 kg payload cobot	Increased process speed despite increased orders
GKN Driveline (2019)	Front and back inspection of thin iron plats	In-process	Collaboration	Action	Visual	2 cobots with a payload of 5 kg, camera system	Keeps production running 24/7, increasing safety and reducing worker fatigue
Koyo Electronics Industries (2019)	Review of the touch panel computer inspection process	In-process	Interaction	Action	Force training	3 kg payload cobot, stylus	Improved quality of work with a reduction in daily working time from an average of 10 h to 8 h and a 31% increase in productivity
Lear Corporation (2017)	Checking the presence and correct tightening of car seat bolts	In-process	Interaction	Action	Visual	Vision camera, 5 kg payload cobot, screwdriver end effector	Easy programming of the robotic arm for different applications
Nordic Sugar (2017)	Inspection of the weight of containers with pureed beets	In-process	Interaction	Action	Visual	Barcode scanner, pneumatic gripper, 5 kg payload cobot	Increased system flexibility

Table 5 (continued)

Company	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Technology	Pros/novelty
Olympus (2022)	Inspection of aircraft to verify the absence of inclusions	Offline	Interaction	Action	Dimensional measurement	Olympus NDT devices, 5 kg payload cobot	Avoid potential health risks to operators from working in confined spaces for long periods of time
Optipro systems (2021)	In-process measurement of small parts produced on precision optical machines	In-process	Collaboration	Action	Dimensional measurement	Robotic gripper-calipers, 3 kg payload cobot	100% in-process inspection of parts without operator intervention, which is less accurate and can be prone to chipping or damage of fragile parts
Precisionform Inc (2020)	Sampling and inspection of small mechanical components from deep bins	In-process	Collaboration	Action	Visual	3 kg payload cobot, 5 kg payload cobot, laser sensor	Picking from containers without the problem of piece presentation
Siemens Gerätewerk Erlangen (2023)	Industrial controls for machine tools and production machinery	In-process	Interaction	Action	Visual	Optical camera, 10 kg payload cobot	Increased flexibility for low to medium volume production and improved management for in-house application development using Process Simulate software
Stellantis (2022)	Visual inspection to ensure the geometric continuity of the adhesive band around the perimeter	In-process	Interaction	Action	Dimensional measurement	Vision system, 10 kg payload cobot	Improved ergonomic accuracy in a range of operations previously performed manually
Thales Alenia Space (2023)	Automated quality control of satellite installation PCBs	Offline	Interaction	Action	Visual	Microscopic vision camera, augmented reality system, 10 kg payload cobot	Remote inspection of PCBs without risking human contact and handling
Thyssenkrupp Biltein (2019)	Gauge inspection and control of post-fill crimping	In-process	Interaction	Action	Visual	Cognex camera, 10 kg payload cobot	Improved product quality through 100% inspection with reduced maintenance, downtime and line stoppages

Table 5 (continued)

Company	Process objective	Quality control paradigm	Human–robot relationship	Communication channel	Type of inspection	Technology	Pros/novelty
Zippertubing Company (2018)	Verification of the correct addition of the snap fasteners	In-process	Interaction	Action	Visual	Vision camera, 5 kg payload cobot	Reduced cycle time and increased number of parts inspected at the end of the day

- *Bi.j*: benefit corresponding to dimension *i*, order *j*.
- *Di.j*: drawback corresponding to dimension *i*, order *j*.

Five analysis criteria were identified and considered, as follows:

- Criterion 1: Type of quality control.
- Criterion 2: Visual inspection insights.
- Criterion 3: Safety and trust in the collaborative system.
- Criterion 4: Human Factor vs. Cobot Efficiency.
- Criterion 5: Economic growth.

These criteria are described in Subsects. "Criterion 1: Quality control paradigm and inspection type" to "Criterion 5: Growing economy", while Subsection 6.6 summarises their advantages and disadvantages and makes some observations.

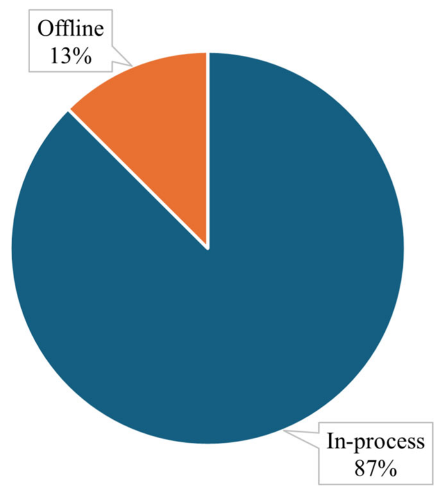


Fig. 13 Partition of the literature and case studies reviewed by quality control paradigm

Criterion 1: Quality control paradigm and inspection type

B1.1: On the way to in-process controls

Figure 13 shows the partition of the reviewed literature and real case studies between in-process and offline quality control paradigms. The data shows a significant preference for in-process quality control using cobots, which accounts for 87% of the cases, compared to a smaller 13% still using offline methods. Further analysis of the data in Tables 1, 2, 3, 4 shows a clear progression: in 2014 there was a split between offline and in-process inspections, but by 2023 the ratio had shifted to 90/10 in favour of in-process inspections. This shift highlights the industry's increasing reliance on in-process quality control methods in order to increasingly pursue the ZDM concept (Psarommatis et al., 2024).

As noted by Genta et al. (2020), in-process inspection is critical because it allows real-time monitoring of production quality to catch and correct defects before products move further along the production line. This method is becoming increasingly important, leading both academia and industry to prioritise in-process inspection strategies. Cobots are at the heart of this shift as their inherently compact, lightweight and versatile design makes them ideal for integration into existing production lines without the significant space requirements typically associated with offline inspection setups (Peshkin & Colgate, 1999). This strategic application improves operational efficiency, reduces costs and speeds up production cycles (Cohen et al., 2022; Fager et al., 2021).

B1.2: Expanding inspection methods

Figure 14 shows the types of inspections discussed in the literature and in the case studies analysed. Visual inspections predominate, accounting for 71% of cases in both industry and academia.

These inspections, traditionally performed by human operators, are now being automated by equipping cobots with cameras enhanced by machine learning techniques. In addition, there is significant potential to extend cobot applications to other types of inspection. These include dimensional, and weight measurements, as well as surface characterisation (Chen & Yang, 2021; Chen et al., 2022; El Makrini et al., 2017). This diversity highlights the considerable potential for

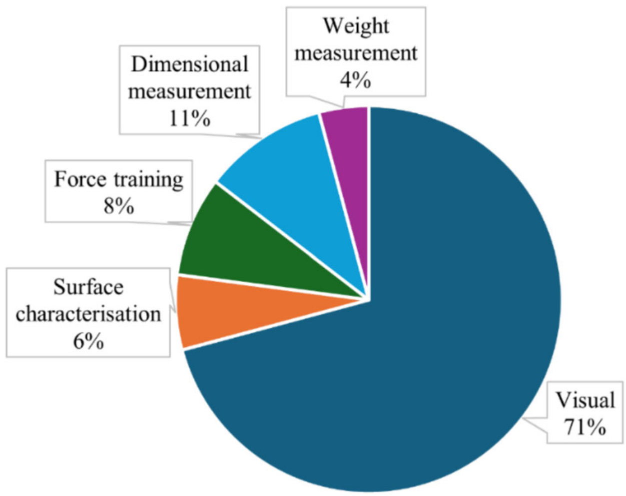


Fig. 14 Partition of literature and case studies reviewed by type of inspection performed

further development and research into cobot-based inspection systems, opening up avenues for more comprehensive quality control in manufacturing processes (Li et al., 2022).

D1.1: Limited application in real industrial cases

The study highlights a notable gap between the theoretical quality control methods developed in academic research and their practical application in real-world settings. This gap poses a significant challenge to researchers who need to validate the effectiveness of these systems in real-world settings (Simões et al., 2022). This problem is exacerbated by findings, such as those of Bauer et al. (2007), which suggest that collaboration is often limited to simple, singular actions. Such observations highlight the early stage of cobot integration in quality control processes. Looking ahead, it is essential to conduct detailed comparative studies between traditional manual quality control and those involving cobots. These studies should aim to determine under what circumstances and conditions collaborative approaches prove to be more beneficial. By exploring these facets, the field can move towards a more mature and effective implementation of cobot-assisted quality control.

Criterion 2: Visual inspection insights

As visual inspection is the predominant use of cobots in quality control, a specific criterion has been established to address this application.

B2.1: Accurate visual inspection

Visual inspection in collaborative environments offers significant advantages for quality control, particularly in improving the accuracy, efficiency and ergonomics of manufacturing operations. Cobots equipped with advanced vision systems can continuously monitor production lines with high accuracy and speed, identifying defects that might elude human observers (Peshkin & Colgate, 1999). These systems use sophisticated image processing algorithms and machine learning techniques to analyse visual data and detect minute inconsistencies and variations that indicate quality problems. This capability enables real-time feedback and immediate corrective action, minimising the incidence of faulty products passing through the production process (Pagani et al., 2021).

In addition, the integration of cobots in quality control can significantly improve the ergonomic experience for human operators. By automating repetitive and physically demanding tasks, cobots reduce the ergonomic burden on workers, decreasing the risk of injury associated with prolonged or repetitive activities. This shift increases productivity and promotes a safer and more satisfying work environment. The ability of cobots to adapt to different tasks and product specifications without extensive reprogramming adds further value, ensuring flexibility in dynamic manufacturing environments (Faccio et al., 2023; Peshkin & Colgate, 1999).

B2.2: Visual system automation

Numerous studies have integrated visual inspection systems enhanced with machine learning algorithms, enabling collaborative systems to autonomously learn and refine their performance based on continuous inspections (Castro et al., 2023). This advance significantly increases the accuracy and precision of inspection processes. However, the effectiveness of these machine learning systems depends on extensive training with a robust dataset that includes a wide range of relevant images. For complete training, the system must have access to images of parts with and without defects. The complexity of the inspection task determines the amount of training data required, particularly for defect detection. A wide range of defect scenarios must be presented to the system to ensure reliable identification of defective parts.

However, automating the cobot vision system brings additional challenges in terms of lighting and angle requirements, which are critical to ensuring system accuracy. As highlighted in Sect. "D2.1: Limitations due to lighting issues", these requirements can vary significantly depending on environmental conditions and the type of product being inspected. This variability makes the process highly complex and cognitively demanding, particularly when defects and inspection criteria are not clearly defined—a problem often encountered in the early stages of production.

Nevertheless, the automation of cobot vision systems offers additional benefits, such as freeing up operators to focus on other highly skilled tasks. For example, by automating routine inspections, operators can focus on programming complex automated systems, advanced troubleshooting and quality control analysis (El Makrini et al., 2018; Hentout et al., 2019). These tasks are essential in industries such as automotive, where precision is critical, and food and beverage, where maintaining product quality is essential for safety and compliance. Moreover, this reallocation of human expertise maximises operational efficiency and enhances the ability of human operators to engage in more complex and cognitive functions within the production environment, driving innovation and improvement across various processes (Universal Robots, 2024).

D2.1: Limitations due to lighting issues

While the integration of a camera into a cobot for visual inspection may seem straightforward, the practical implementation of this technology in industrial settings presents numerous challenges. Lopez-Hawa et al. (2019) report specific difficulties with data accuracy during scanning processes due to the reflection of laser beams. This problem is worsened as the reflectivity of the target object increases, suggesting the need for advanced methods to either eliminate or at least minimise this problem. Moreover, Syberfeldt and Ekblom (2019) highlight the challenges of object detection in low image quality scenarios. The variability inherent in industrial environments—such as different product variants or different imaging angles—can significantly alter the content of captured images, thus disrupting the consistent feature detection required for accurate object localisation (Puttero et al., 2024). The presence of random noise within images further complicates this task, raising critical questions about how to effectively deal with these inconsistencies.

Achieving a consistent inspection process that can adapt to the dynamic conditions of industrial environments remains a significant obstacle. Maintaining stable system conditions to ensure reliable data acquisition is critical, but difficult due to the inherent variability of such environments. These issues highlight a significant barrier to exploiting the inherent flexibility of cobots in automated quality control processes. One solution to solve the surrounding light drawback is using a blue-light LED projector and a suitable blue light bandpass filter (Rooker et al., 2014). Incorporating the cobot with own light that provides the right conditions to perform an accurate visual inspection.

Criterion 3: safety and trust in a collaborative environment

B3.1: Different communication channels

The advantage of developing collaborative systems is closely related to the way in which humans can communicate and interact with the cobot. Figure 15 shows the partition of the reviewed literature and case studies by type of communication channel.

As presented in Sect. "Human–robot communication", different channels can be used to enable communication between humans and the cobot (Bauer et al., 2007). Communication helps to ensure a safe environment for humans. If the robot can understand human gestures and speech, collaborative tasks can be performed more naturally, and the cobot will be able to know how to respond appropriately to human movements, words and actions. Recent research has also focused on improving specific functions such as visual perception and action recognition, enabling human awareness and promoting flexible cobot behaviour (El Zaatari et al., 2019; Knudsen & Kaivo-Oja, 2020).

The pie chart in Fig. 15 shows that physical interaction between humans and cobots, referred to as "Action", remains the primary mode of communication in industrial settings, even though it is the least collaborative. Scientific research is increasingly exploring more interactive technologies. For example, haptic systems enhance learning through force sensors and gesture-based communication (Guda et al., 2022), while advances are also being made in voice command systems. However, voice-based systems face challenges in achieving widespread adoption due to noisy production environments that affect the reliability of speech recognition

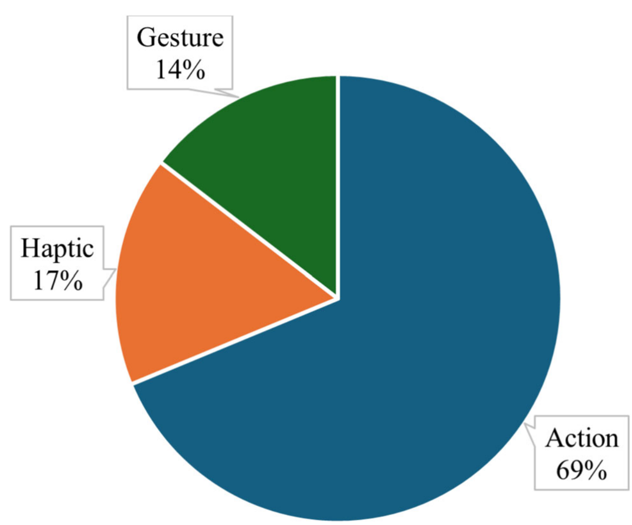


Fig. 15 Partition of literature and case studies reviewed by type of communication channel

(El Zaatari et al., 2019). The transition to these innovative methods is more pronounced in academic research than in industrial practice. As shown in Table 5, the industrial sector, especially the automotive industry, continues to prefer action-based methods, while gradually adopting haptic solutions (Universal Robots, 2024). Conversely, academic research explores a wider range of communication technologies, as shown in Table 4.

B3.2: System flexibility

Cobots are particularly versatile in their functionality. They often incorporate visual systems such as cameras that can identify parts or defects in a collaborative environment. These cameras also increase awareness of their surroundings and personalise interactions with operators. For example, by recognising an operator's face, a cobot can instantly change its operating settings. It can access the operator's height from a database and adjust the speed and height at which it handles materials accordingly. Such tailored adjustments increase the operator's safety and confidence in working with the cobot (El Makrini et al., 2017; Verna et al., 2023c). This flexibility ensures that the cobot's actions are specifically tailored to each operator's unique needs and physical dimensions, promoting a more effective and safer working environment.

D3.1: Safety not considered in the design phase

Safety is a critical issue when dealing with cobots. In order for the operator to trust the robot, the safety of the operator must be guaranteed. Ensuring the safety of the operator is essential to promote confidence in robotic systems. However, the literature reviewed indicates a lack of focus on rigorous evaluation of system safety, possibly because some studies are at an early stage and applications have not been fully implemented or tested in practical settings. As pointed out by Andersson et al. (2020), neglecting safety assessments in the early stages can lead to them being perpetuated in later stages of implementation. As a result, manufacturers may need to modify cobot applications at later stages to incorporate necessary safety measures, with potential design implications. Future research must prioritise the integration of safety assessments from the initial stages to prevent them from becoming an obstacle in later stages of implementation.

D3.2: Limited collaboration

Another limitation of collaborative quality control is the lack of an active role of the human operator. As can be seen in Fig. 16, both in case studies and in the scientific literature, interaction still predominates, but not direct collaboration. As a result, a true collaborative scenario does not exist in today's production environments. Instead, cobots and operators interact in a partnership where they share workspace and resources but perform distinctly separate tasks. This interaction is organised into a sequential process where specific subtasks are assigned to either human operators or robots, with each entity managing its assigned responsibilities independently (Wang et al., 2019). From an analysis of practical case studies, it is clear that the primary role of operators is limited to supervising or assisting the robot, intervening in case of malfunctions, or providing materials for operations. There is no real task sharing between human and robot. While these interaction systems offer advantages, particularly in improving quality control processes, a major challenge remains to extend the scope of collaborative applications to include true collaboration between humans and robots.

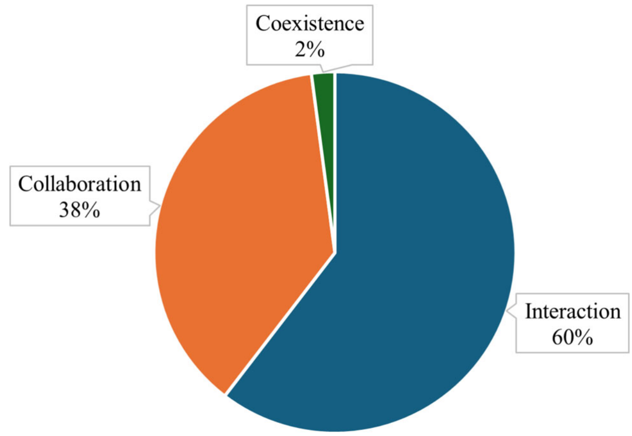


Fig. 16 Partition of literature and case studies reviewed by relationship type

Criterion 4: Human factor vs. cobot efficiency

B4.1: Process efficiency increase and costs reduction

As documented in Tables 5, the integration of cobots into quality control processes has significantly improved the efficiency and productivity of production lines and led to significant cost reductions. This integration has been associated with a promising return on investment (ROI), typically ranging from several months to a maximum of two years. This rapid ROI is due to the ability of cobots to streamline operations, minimise waste and reduce the need for intensive labour, which together reduce operating costs (Lefranc et al., 2022; Peruzzini & Pellicciari, 2017). In addition, cobots' precision and consistency contribute to improved product quality, further increasing their economic value to manufacturing companies.

Building on the economic impact of cobots discussed earlier, several companies have reported significant operational improvements after integrating them into quality control systems. For example, Koyo Electronics Industries reduced its daily work hours from 10 to 8 and increased productivity by 31% by integrating a cobot into its touch panel inspection process. Similarly, Ferdinand Wagner achieved an operational efficiency of 160 parts per hour by using two cobots—one to select parts for welding and the other to inspect quality using a camera system. In addition, Craft Und Technik Industrie (CATI) increased production volumes by 15–20% while maintaining zero-defect output by using a cobot to both load parts and check their weight on a vertical CNC machine. Likewise, BW Industrie has also used cobots to maintain its manufacturing competitiveness in France (Universal Robots, 2024). By using camera-equipped cobots to handle and inspect parts on a lathe, the company increased its workforce by 50% and increased sales by 70%.

B4.2: Human error reduction

Industries that have integrated cobots into their quality control processes have seen significant benefits, including a reduction in human error and improved defect detection capabilities. These improvements lead to shorter production and inspection cycles, which in turn increase end customer satisfaction. The ability to minimise errors while increasing the accuracy of defect detection is critical to the quality control operations of today's manufacturing systems in order to remain competitive in an increasingly demanding marketplace. The use of cobots provides a systematic approach to refining these aspects by exploiting the precision and repeatability that human operators may lack (Faccio et al., 2023). This technological advancement improves operational efficiency and ensures a higher standard of product quality in line with industry benchmarks and customer expectations.

B4.3: Human reallocation

Incorporating cobots into production lines allows human workers to be reassigned to more intellectually stimulating and valuable tasks (Faccio et al., 2023). Particularly in automotive assembly lines, where numerous quality checks are essential, there is a distinct advantage in delegating repetitive and automatable tasks to robots. This delegation allows human operators to focus on more skilled and critical functions. Such strategic reallocation of tasks maximises efficiency and increases job satisfaction. By engaging human workers in more challenging and less monotonous activities, their roles become more fulfilling and less stressful. This approach also harnesses human cognitive and creative problem-solving skills, adding value to the manufacturing process and promoting a more dynamic and supportive working environment.

D4.1: Human acceptance

Operators often perceive the introduction of cobots as a threat to their job security, associating it with potential replacement by machines (Kopp et al., 2020). This fear poses a significant challenge to the integration of cobots into the workplace. It is crucial to communicate to operators that the introduction of cobots is not a precursor to job loss, but rather a strategic reallocation to roles that require higher cognitive and analytical skills (benefit B4.3). These roles will involve more complex decision-making and problem-solving tasks, thereby adding more value to organisational processes. The aim is to promote the perception of cobots as useful colleagues rather than replacements, emphasising their role in improving safety and efficiency in the workplace. By automating routine and physically demanding tasks, cobots allow human workers to focus on more intellectually engaging and creative activities, improving job satisfaction and productivity.

Criterion 5: Growing economy

B5.1: Cobot market growth worldwide

The evolution of the market, influenced by both supply and demand dynamics, can significantly influence the dominant types of cobots and the dominant markets for their deployment (Knudsen & Kaivo-Oja, 2020). As the cobot market expands, the interaction between supply and demand is expected to lead to competitive pricing, thereby reducing costs. This price reduction will make cobots more accessible and encourage their wider use in various industrial applications. As a result, lower financial barriers will make it economically feasible for smaller companies to invest in cobot technology. This increased affordability is expected to lead to greater integration of cobots into production lines, increasing automation and efficiency in sectors traditionally less exposed to advanced robotic solutions, such as quality control. These developments should stimulate further market growth and create a cycle of increasing supply and demand, underpinning continued innovation and cost-effective deployment of cobots.

D5.1: Support tool for cobot deployment

Currently, the industry faces a significant lack of practical business decision support tools designed to assess the cost-effectiveness and efficiency of augmenting human labour with collaborative systems. The need to develop and disseminate specialised tools to help organisations make informed decisions about the use of collaborative systems highlights a significant research challenge. These tools should provide a robust framework for assessing the potential return on investment, operational impact and strategic benefits of integrating cobots into different workflows. Equipping companies with such analytical capabilities would enable a more strategic approach to the adoption of collaborative technologies, ensuring that investments are both prudent and beneficial to improving productivity and economic outcomes.

Discussion on cobot-based quality control

In the previous sections, an analytical framework based on five different criteria was used to analyse both scientific papers and real case studies on the use of cobots in quality control. The proposed study aimed to highlight the specific benefits and drawbacks associated with each criterion. The overall results of this comprehensive evaluation are summarised in Table 6.

The analysis shows that the integration of cobots in quality control presents a complex landscape of ethical, operational and technical challenges that must be carefully navigated to unlock their full potential. First of all, addressing the ethical concerns of job displacement is critical. By redefining cobots as partners rather than replacements, industries can mitigate this issue. Reskilling and upskilling initiatives are essential to turn potential job losses into opportunities, enabling workers to move into higher-skilled roles focused on monitoring and strategically deploying cobots (Dornelles et al., 2023). In addition, improving human–robot interaction through ergonomic and intuitive design will ensure that cobots remain assistive, improving job satisfaction and workplace safety (Kopp et al., 2022).

Table 6 Outline of analysis dimensions with associated benefits (B) and drawbacks (D) of collaborative quality control

Criterion	Benefits	Drawbacks
1. Quality control paradigm and inspection type	B1.1. On the way to in-process controls B1.2. Expanding inspection methods	D1.1. Limited application in real industrial cases
2. Visual inspection insights	B2.1. Accurate visual inspection B2.2. Visual system automation	D2.1. Limitations due to lighting issues
3. Safety and trust in a collaborative environment	B3.1. Different communication channels B3.2. System flexibility	D3.1. Safety not considered in the design phase D3.2. Limited collaboration
4. Human Factor vs. Cobot Efficiency	B4.1. Process efficiency increase and costs reduction B4.2. Human error reduction B4.3. Human reallocation	D4.1. Human acceptance
5. Growing economy	B5.1. Cobot market growth worldwide	D5.1. Support tool for cobot deployment

From a technical perspective, overcoming barriers such as limited real-world applicability is critical to the wider adoption of cobots. Implementing comprehensive pilot programmes that demonstrate the effectiveness and adaptability of cobots can provide actionable insights into their scalability and adaptability and adaptability and advantages over more automated solutions (Kopp et al., 2020; Simões et al., 2022). In addition, these pilot programs need to address differences in quality control requirements across industries and explore how cobots can be adapted to meet sector-specific standards and challenges (Hentout et al., 2019). This will require tailoring cobot technology to different operational requirements, from pharmaceuticals to electronics, where precision and regulatory compliance vary widely. Overcoming these customisation challenges in pilot implementations can increase understanding and confidence in cobots, demonstrating their flexibility and ability to meet a wide range of industry-specific needs.

Another significant technical challenge is the dependence of cobots on optimal lighting conditions for effective operation. Developing adaptive lighting systems or enhancing sensor technology to function in different lighting environments can significantly improve their operational versatility (Syberfeldt & Ekblom, 2019).

Safety must be a core component of cobot design, integrated from the earliest stages of development. Involving safety engineers and ergonomics experts early in the process can ensure that cobots are inherently safe and designed to augment human capabilities. Promoting effective human–robot collaboration is also essential (Andersson et al., 2020). Developing intuitive cobot interfaces and conducting joint human–robot training sessions can improve mutual understanding and operational efficiency, leveraging both human intuition and robotic precision.

Policy considerations also play a crucial role in the integration of cobots. Creating supportive regulatory frameworks that encourage innovation while maintaining safety and ethical standards can facilitate smoother adoption. Economic incentives, such as tax breaks and grants, can lower financial barriers and make cobot technology more accessible to a wider range of companies. In addition, educational campaigns aimed at both the public and industry stakeholders can demystify the role of cobots and raise awareness of their benefits and practical applications (Liu et al., 2024).

By addressing these challenges through comprehensive strategies, the functionality and acceptance of cobots in quality control can be significantly enhanced. This holistic approach will ensure that the integration of cobots enable industries to take full advantage of advances in robotics for improved quality control and increased competitiveness.

Conclusions and perspectives for future research

The integration of cobots into quality control processes is rapidly gaining momentum in various industrial sectors due to their flexibility, speed and ability to interact seamlessly with human operators. Cobots excel at repetitive and precision-critical tasks, such as inspections, which they can perform continuously without fatigue. This capability increases the effectiveness of quality control measures, ensuring that products consistently meet stringent standards and reducing human error in monotonous tasks. By automating routine tasks, cobots allow human operators to focus on more complex and cognitively demanding aspects of production, potentially increasing job satisfaction and fostering innovation.

This paper presents a comprehensive analysis of academic literature and practical case studies to evaluate cobot applications in quality control using a mixed methods approach. Through this analysis, five key criteria have been identified that highlight both the benefits and drawbacks associated with the large-scale implementation of cobots. The aim of the article is to provide criteria that will facilitate the adoption of cobots for quality control in manufacturing companies, clearly outlining the benefits of such adoption and the limitations that need to be addressed. Specifically, the findings indicate that while cobots can significantly improve operational efficiency and reduce errors, they also present drawbacks in terms of integration and require significant adjustments in terms of workforce training and system flexibility. Building on these established criteria, a key objective for future research is to develop a model for evaluating cobot integration in quality control. This model will be rigorously tested using experimental data collected from real-world environments.

The results of this research must be contextualised within the framework of contemporary production technologies. The merging of cybernetic and physical domains (Industry 4.0) and the prioritisation of human well-being in production processes (Industry 5.0) are driving the development of innovative inspection strategies. These technological advances are leading to an exponential increase in IoT-connected devices, including cobots. Equipped with embedded sensors and other IoT capabilities, cobots facilitate real-time data collection and online inspections, improving quality monitoring and enabling early defect detection and rapid root cause identification. The vision for Industry 5.0 is to achieve 100% inspection capabilities and move towards the concept of ZDM through the use of IoT sensors, which support continuous monitoring and are integrated into production processes in close collaboration with human operators. In addition, digitisation technologies such as IoT, cloud computing and AI are helping to develop DTs of physical systems, which will revolutionise quality control, preventive maintenance and reliability tasks.

Future advances in the integration of cobots into quality control processes are expected to significantly increase contributions to conference proceedings and peer-reviewed journals, enriching the academic discourse on this technology. This expansion will foster a deeper and broader understanding of the subject, leading to improved practical applications and greater societal benefits.

To overcome existing barriers to cobot adoption, it is essential to boost industry-academia collaboration, develop standardised regulations and implement targeted training programmes. In addition, the introduction of financial incentives—such as grants, subsidies and tax breaks—and the streamlining of regulations can help reduce economic barriers and promote integration. Public awareness campaigns and pilot programmes can further demonstrate the effectiveness of cobots and encourage wider adoption.

Based on the structured forecasting approach of the Delphi study (Mahajan et al., 1976), several potential scenarios for the future use of cobots in quality control can be identified. This methodology, which uses iterative rounds of expert interviews to reach consensus, will help shape subsequent research. Key areas of research will range from incremental improvements in accuracy and adaptability in different manufacturing environments, to transformative integrations with real-time data analytics that could redefine dynamic quality control processes. As research advances, these scenarios highlight the need for comprehensive policy frameworks and innovative financing strategies—such as innovation vouchers and public–private partnerships—to ensure the efficient adoption and safe use of cobots. Continued investment in technological advancement and rigorous testing will be essential to fully explore and realise the transformative potential of cobots to significantly improve quality control in manufacturing.

Author contributions SP: Conceptualisation; Methodology; Software; Validation; Investigation; Data Curation; Writing—Original Draft; Visualisation. EV: Conceptualisation; Methodology; Validation; Formal Analysis; Writing—Review & Editing; Visualisation; Supervision. GG: Conceptualisation; Methodology; Validation; Formal Analysis; Writing—Review & Editing; Supervision. MG: Conceptualisation; Methodology; Formal Analysis; Writing—Review & Editing; Supervision.

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement.

Data availability The author confirms that all data analysed during this study are included in this published article. Furthermore, the databases

supporting the findings of this study are all publicly available at the time of submission in WOS, Statista, Google Scholar and Scopus Databases. The list of all papers as a data set of the study can be found below.

Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose.

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