Challenges and opportunities of collaborative robots for quality control in manufacturing: evidences from research and industry

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STRUCTURED ABSTRACT

Purpose - In the context of Industry 4.0, collaborative robots - which might be equipped with different types of sensors - have been gaining ground, used to cooperate with humans in quality control of finished or semi-finished products. Compared to the various applications of collaborative robotics in manufacturing (e.g., material handling, assembly, pick and place, and positioning), widely studied and adopted in industry, quality control and testing have not yet reached their full potential. This paper aims to study the state-of-the-art collaborative robotics used for quality control purposes in both academia and industry.

Design/methodology/approach – This paper analyses in a structured way the scientific literature and some prominent real industrial case studies regarding the state-of-the-art of quality control using collaborative robotic systems in manufacturing.

Findings - The analysis enables the identification and definition of the main challenges and opportunities that the manufacturing sector is facing for the large-scale use of the new quality control paradigm. Results show that collaborative robotics in quality still plays a marginal role and is mainly adopted for in-process visual inspections to increase system efficiency. Some barriers still hamper the full adoption of this paradigm, but there is plenty of opportunity for research and economic growth.

Originality/value - The innovative aspect of this research is the combined analysis of scientific articles and real-life case studies that provide a comprehensive overview of the research and actual use in industry of this emerging paradigm of quality control.

Keywords: Quality control, Manufacturing, Collaborative robots.

Paper type: Research paper.

INTRODUCTION

The application of Human-Robot Collaboration (HRC) in manufacturing systems has increased in the last years and goes hand-in-hand with the growing importance of Industry 4.0 related technologies. Collaborative robots (also called cobots) are defined as complex machines that support and relieve the human operator in a shared work process (Hentout *et al.*, 2019). Accordingly, in a simplified way, cobots are robots that collaborate with humans, sharing a workspace to alleviate human efforts. Drawing a parallel with the software context, cobots are the hardware version of augmented intelligence. Thus, instead of replacing humans with autonomous counterparts, cobots augment and enhance human performance with strength, precision and data capabilities to provide additional value to organisations.

The application fields of HRC are manifold and, as above mentioned, the main task is to relieve human workers from tedious and repetitive tasks, integrating the automation, repetitiveness, precision and flexibility that characterise collaborative robots while, at the same time, maintaining the cognitive and soft skills of human workers.

Product quality control is widely recognised as a key and indispensable factor in a production process that may reduce the number of defective parts reaching end-users (Montgomery, 2012). Considering the high customer demands in today's market, a constant search for new control systems and technologies to make quality control processes as efficient and effective as possible is one of the main challenges facing academia and industry.

In the context of Industry 4.0, cobots - which might be equipped with different types of sensors - have been gaining ground, used to cooperate with humans in quality control of finished or semi-finished products. Cobots are one of the key technologies of Quality 4.0, *i.e.* a new paradigm of quality management, which emphasises the need to adapt to recent technological innovations by updating traditional quality approaches in the modern era of Industry 4.0 (Antony *et al.*, 2021; Dias *et al.*, 2021). Quality 4.0 presents many benefits including real-time process monitoring, big-data collection and predictive maintenance supported by analytics (Küpper *et al.*, 2019). As a result, Quality 4.0 enables enterprise efficiencies, performance, innovation, and improved business models (Sony *et al.*, 2020). However, compared to the various uses and applications of collaborative robotics in manufacturing (e.g., material handling, assembly, pick and place, and positioning), widely studied and adopted in industry, quality control and testing still play a marginal role.

This paper aims to analyse the scientific literature and some prominent real case studies adopted by companies regarding the state of the art of quality control using collaborative robotics systems in manufacturing. The analysis enables the identification and definition of the challenges and opportunities that the manufacturing sector is facing for the large-scale use of the new quality control paradigm based on human-robot collaboration.

BACKGROUND FRAMEWORK

In recent years, the use of robotics has spread to almost every field and more specifically to the area of manufacturing, where the benefits that can be achieved are numerous. The underlying reason is that manufacturing today is facing the evolution towards Industry 4.0, which emphasises efficiency, cost reduction and productivity through automation and data analytics.

Industries, therefore, need to be faster, more flexible, proactive and respond quickly to market needs in a sustainable and efficient manner, ensuring excellent quality levels for customer satisfaction. The answer to these challenges has been partly found in the use of robotic automation within different production processes, playing a key role in the competitiveness of today's manufacturing industry. The main benefits of introducing robots into the production area include the ability to relieve workers of repetitive, heavy, and automatable tasks, as well as the resulting accuracy and repeatability, resulting in a higher quality product.

For high-volume manufacturing, a robot can maintain high efficiency and repeatability but lacks flexibility when it comes to problem solving and uncertainty. Human operators, on the other hand, know the way or can think of a possible way to solve these problems due to rationality, but they lack repeatability, speed and cannot lift heavy weights, which ends up in decreased efficiency and quality of the final product or service (El Zaatari *et al.*, 2019).

A balance between automation and flexibility is essential to achieve these overall manufacturing goals in mass customisation. This encourages researchers to look at combining the advantages of automation and manual labour. This research has culminated in Human-Robot Collaboration (HRC), a promising robotics discipline focused on enabling robots and humans to operate jointly to complete collaborative tasks (Zaatari, 2019).

This new area of research emerged during the fourth industrial revolution, or Industry 4.0, at the same time as the rise of the Internet of Things and the concept of collaborative systems. Shorter development times, customisation, adaptability and efficiency are all part of the Industry 4.0 paradigm. The smart factory is a concept introduced by the revolution, where everything is connected via sensors and computers, and large amounts of data are collected and evaluated for decision-making. Industry 4.0 and smart factories are two ideals that many industries are aiming for, and collaborative robots are a key aspect of both notions.

Collaborative robots make manufacturing lines more flexible and shift the status quo where robots and human operators are firmly separated; instead, they can now operate together and aim for the same goal. Collaborative robots can be integrated with numerous sensors and standardised interfaces and are designed to work together with humans and coexist in the same physical environment by enhancing, strengthening and assisting humans in increasing human well-being and production performance (Romero *et al.*, 2016). As a result, cobots were created and designed to work as pairs with humans in order to improve rather than replace their capabilities, thus representing a supporting technology towards Industry 5.0, where research and innovation are put at the service of the transition to a sustainable, human-centric and resilient European industry (European Commission, 2020; Maddikunta *et al.*, 2021).

Collaborative robots are increasingly preferred over traditional industrial robots as they can work in a variety of contexts and provide numerous advantages, including (*i*) ease of programming and program modification, making them more versatile and adaptable to various applications (*ii*) speed of setup (a few hours compared to weeks for traditional robots), (*iii*) flexibility, as they do not take up much space and can be deployed quickly, (*iv*) safety, being able to collaborate with humans without endangering them through the use of environmental cognition, and (*v*) equipped with sensors that detect various features. To summarise, collaborative robots are generally more profitable and productive than traditional industrial robots when used in the right situations. These robots are significantly lighter than industrial robots and, as a result, have greater mobility, making it easier to move them around the factory floor. The versatility of collaborative robots and their affordability make them a suitable choice for a wide range of industries and applications, including automotive, electronics, general manufacturing, metal fabrication, packaging and co-packing, plastics, food and agriculture, pharmaceutical and chemical, scientific research.

According to Statista's "Collaborative robots worldwide" research (Statista, 2022), sales and installations of collaborative robots worldwide increased from 11 to 18 thousands over two years (2017 to 2019). However, the collaborative robot market is currently a small part of the overall industrial robot market. In 2018, only 5% of the total robot unit sales worldwide were collaborative robots. However, the percentage is expected to become 13% by 2022. The prospects for the cobots market are bright for the next few years, indeed it is expected that the size of the global market for collaborative robots will grow from 590 to 1990 million U.S. dollars from 2020 to 2030 (Statista, 2022). The following are some of the reasons behind this expansion:

- lack of skilled labour, leading to a greater need for automation;
- rising labour costs, making robots cheaper than human operators;
- demand is becoming more complex, requiring higher product mixes with shorter cycle times;
- higher levels of efficiency are required.

Another reason not to be underestimated is the wide range of applications in which collaborative robots may be employed. In 2019, the revenue share of collaborative robot market by industry was as follows (Statista, 2022): electronics (34.1%), automotive (16%), semiconductors and FPD (8.3%), plastics and rubber (7.8%), food and beverage (7.6%), chemicals and pharmaceuticals (5.5%), logistics (3.9%), and other (16.9%). In 2022, the expected global market size of cobots by applications will be material handling (31%), assembly (23%), pick and place (13%), testing (6%), welding (5%), sorting (4%), positioning (3%) and other (15%). If the first three categories are aggregated, as they all involve handling and managing parts, a 67% market share is achieved. Indeed, cobots offer significant advantages when dealing with picking up heavy objects and performing precise assembly work repeatedly and efficiently, without the stress that a human operator would experience.

Alongside the interest of the market and industries, cobots are also gaining considerable attention in academia worldwide, as demonstrated by the exponential increase in the number of articles published since 2015, after the publication of the paper "Industry 4.0" (Lasi *et al.*, 2014), a pillar article that has undoubtedly brought much more popularity to the topic.

The above has shown the relevance that collaborative robots are gaining in industry and academia, and how they have the scaffolding to surpass traditional robots due to features such as flexibility, safety and efficiency. In this sense, it is crucial to continue researching and identifying new applications to benefit from. In addition, it has to be considered that nowadays there are not many manufacturers of cobots and that a small number of companies dominates the market. Hence emerges the need to expand the market, bringing more competition and innovations at a lower price, making the purchase of these new collaborative robots more accessible to SMEs that still cannot afford them.

RESEARCH METHODOLOGY

Scientific literature search

The general objective of this research is to perform an analysis of the scientific literature regarding the state of the art of quality control using collaborative robotics systems in manufacturing. The analysis enables the identification of the challenges and opportunities that the manufacturing sector is facing for the large-scale use of the new quality control paradigm based on HRC.

Literature search was performed in Scopus, Web of Science and IEE Xplore databases. A fourth source was also consulted, the open-source Google Scholar. Concerning the keywords, the following ones were used for collaborative robot topic: "collaborative robot*", "human-robot interaction", "human-robot collaboration", "human-robot cooperation", "robot* application", "physical human-robot interaction", and the following ones for quality control topic: "quality control", "quality", "quality inspection".

Although the growing popularity of collaborative robotics, the subfield of quality control application plays a marginal role. Only 21 results were found, and some of them are outside the scope of this paper. This highlights a gap, creating a potential new research field to cover in the coming years, considering the advantages and benefits of this specific application.

The final set of inherent articles includes the 12 documents summarised in Table 1.

Table 1 – Examined literature on quality control with human-robot collaboration.

Ref.	**Title**	**Year**	**Type of publication**	**Country**
Müller et al. (2014)	Inspector Robot – A new collaborative testing system designed for the automotive final assembly line	2014	Journal Article	Germany
Rooker et al. (2014)	Quality Inspection performed by a Flexible Robot System	2014	Conference Proceedings	Austria
El Makrini et al. (2017)	Design of a Collaborative Architecture for Human-Robot Assembly Tasks	2017	Conference Proceedings	Belgium
Pichler et al. (2017)	Towards shared autonomy for robotic tasks in manufacturing	2017	Conference Proceedings	Austria
Bruker Alicona (2019)	Non-contact and highly accurate measurement of critical turbine engine components	2019	White paper	Austria
Lopez-Hawa et al. (2019)	Automated Scanning Techniques Using UR5	2019	Journal Article	United States
Papanastasiou et al. (2019)	Towards seamless human robot collaboration: integrating multimodal interaction	2019	Journal Article	Greece
Syberfeldt and Ekblom (2019)	Improved Automatic Quality Inspections through the Integration of State-of-the-Art Machine Vision and Collaborative Robots	2019	Conference Proceedings	Sweden
Doltsinis et al. (2020)	A Machine Learning Framework for Real Time Identification of Successful Snap-Fit Assemblies	2020	Journal Article	Greece
Brito et al. (2020)	A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems	2020	Conference Proceedings	Portugal
Karami et al. (2020)	A Task Allocation Approach for Human-Robot Collaboration in Product Defects Inspection Scenarios	2020	Conference Proceedings	Italy
Jian et al. (2021)	An image vision and automatic calibration system for universal robots	2021	Journal Article	Taiwan

The distribution of documents per year and per country is reported in Fig. 1.

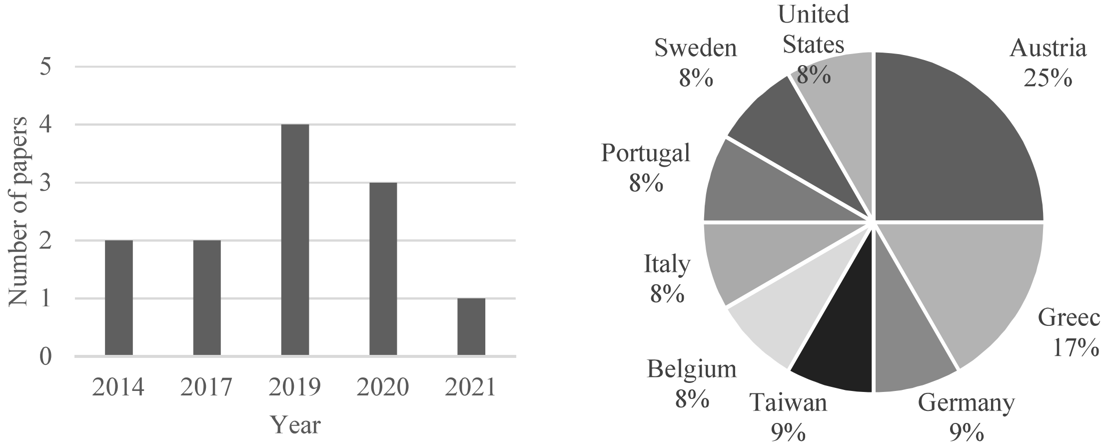

Figure 1 – Distribution of examined literature on quality control with human-robot collaboration per (a) year and (b) country.

Note that no papers are dated before 2014, while until 2021 the number of articles has remained nearly constant with a peak in 2019. This highlights how research regarding the use of HRC for quality control and inspection processes has increased with the emergence of Industry 4.0, but not exponentially as for HRC in general.

Regarding the country, the country-of-origin of the examined literature was attributed according to the country of affiliation of the first author of each paper.

Although the number of articles is very small, it can be noted that the origin is diversified and not concentrated in a few countries, as is the case for general research on cobots, where United States, Germany, Italy and China have the primacy (source Scopus). Finally, half of the articles have been published in conference proceedings, showing how research in this area is still in its early stages, and the results are not yet fully mature for publication in peer-reviewed journals.

Real case studies search

In order to provide a broader understanding of the topic, other sources of information were sought, considering real case studies. To this end, the web pages of collaborative robot manufacturers were analysed. In particular, the webpage of Universal Robots™ (UR) was primarily used for the wide range of case studies available, only considering case studies within the scope of this paper, *i.e.* concerning quality control (Universal Robots, 2022). Universal Robots™ is a pioneering company that has been working in the collaborative robot industry since 2005, but only in 2008 their first collaborative robot was launched into the market.

Table 2 summarises the examined case studies regarding quality control using HRC in which cobots by UR were employed. For each case study, Table 2 reports the primary information about the company (country, industry and company size), the description of the quality control process before the adoption of HRC, the challenges and requirements of adopting the new control paradigm.

Table 2 – Real case studies on quality control using HRC - general framework (Universal Robots, 2022).

Company	Country	Industry	Company size	Process before HRC	Challenge
BÖCO BÖDDECKER	Germany	Automotive and subcontractors	400	Each part is individually marked with a code and quality control is done manually	Increase efficiency by identifying repetitive tasks. Each part must be individually marked with a code
BW INDUSTRIE	France	Metal and machining	45	Manual inspection	Save from relocation. Increase competitiveness and reduce strenuous works tasks
COMPREHENSIVE LOGISTICS	USA	Automotive and subcontractors	190	Manual inspection, 80% efficient. The company's stationary multi-camera system could not position cameras into tight spots and was not as repeatable as the manufacturer needed. The data gathered by the camera system were not as pure	Life-threatening failure mode components, important to make sure that the clips are locked into place with 100% confidence
CRAFT AND TECHNIK INDUSTRIES (CATI)	India	Automotive	80	Most manufacturing tasks were handled manually	No availability of qualified manual labour, need to reduce the customer rejections for faulty components. No space
EVCO PLASTICS	USA	Plastics and polymers	300	Manning cells with repetitive and tedious tasks, handling parts assembly, machine tending, and packaging was especially hard. Operators prone to forget steps in the assembly process	Fast-changing processes. Low unemployment and trouble staffing the third shift in the company's 24/7 production
FERDINAND WAGNER	Germany	Metal and machining	90	Between 500 and 600 thousand components were manually soldered and welded each year, no longer cost-effective. Fluctuating manual production	Need of a robust and dependable automation solution that could consistently deliver high-quality welding and soldering of fragile parts
FORD MOTOR COMPANY	Romania	Automotive	5000+	-	Solutions to enhance their manual workforce generating added value to the manufacturing process
GKN DRIVELINE	Japan	Automotive and subcontractors	1400	Old machines, called front and back discriminators, were insufficient, so line workers were asked to manually perform such inspection tasks after a long workday	Chronic labour shortage issue. Difficulty of automating the experience and sense the operators as well as the safety issue with the traditional machinery

IZOELEKTRO D.O.O.	Slovenia	Electronics and technology	8	Manual time-consuming process	Increase production and improve quality assurance. Fulfil customers' demands in a cost-efficient manner
KOYO ELECTRONICS INDUSTRIES	Japan	Automotive	343	Manual product assembly and visual inspection, and in the post-process, operators apply styluses to the touch panels to confirm the devices react as intended	Increase productivity according to increase in demand in the production of products that require strict quality
NORDIC SUGAR	Sweden	Food and agriculture	1430	During the production season, the testing department analyses 80 thousand sugar beet samples. Robots have performed the task of weighing in containers with pureed beet since 1993. Expensive specialists to make a change. Too costly	Technological advances within robotic arms meant that it was time to replace the old ones
OPTIPRO SYSTEMS	USA	Metal & machining	70+	-	Automated solution that could measure in-process the products. Quality control is crucial since most OptiPro customers manufacture parts for the medical and military sectors requiring 100% inspection
STELLANTIS	Italy	Automotive and subcontractors	407500	No previous state because it is new assembly line	Assembly processes and quality controls required introducing specific automation technologies to ensure the quality and repeatability needed to meet product standards
THYSSENKRUPP BILTEIN	USA	Automotive	700+	Manual check of two parts every one or two hours	Increase in customer demands combined with fast-changing product requirements. Keep its manufacturing processes lean and flexible and could not grow at the desired rate by simply hiring more people

RESULTS

Analysis of the examined literature

In this section the examined literature is analysed focusing on the quality control performed. Especially, two different quality control paradigms are considered: in-process controls and offline controls. The main difference is that in-process controls are performed during production, while offline controls are performed at the end of production once the product is finished. As a result, in-process quality controls may enable that non-conforming parts do not reach the end of the line and, accordingly, defects can be reworked/scrapped directly during the manufacturing process, with possible consequent reductions in waste compared to offline controls (Genta *et al.*, 2020). Both in-process and offline quality controls are carried out using different types of inspections, *e.g.* visual or manual inspections, dimensional measurements, conformity tests, etc.

In Table 3, each examined document is classified according to the following analysis dimensions, defined by the authors:

- Industry: if available, industry field of the research.
- Process: typology of manufacturing process.
- Objective: aim of the quality control.
- Paradigm of quality control: general framework, in-process or offline controls.
- Type of inspection: typology of inspection (manual, visual, dimensional measurement, etc.)
- Methodology: research methodology/approach used.
- Technology: technology used for the control.
- Communication channel: kind of communication between human and cobot.
- Pros/Novelty: innovative aspects of the research.
- Research insights: possible research next steps.

For fields not specified, the symbol "-" is used.

Table 3 – Classification of examined literature on quality control with human-robot collaboration.

Ref.	Industry	Process	Objective	Paradigm of quality control	Type of inspection	Methodology	Technology	Communication channel	Pros/Novelty	Research insights
Müller et al. (2014)	Automotive	End-of-line car final inspection	Water leak test on a final assembly line inspection	Offline	Visual	-	Thermographic camera	-	The robot is mounted on a linear track and guided alongside the assembly object	Integrate this process into a real industry case. Apply it to other kinds of inspection processes.
Rooker et al. (2014)	Automotive	-	Examine the interlocking of plugs	In-process	Visual	Structured light principle	RGB-D sensor, ReconstructMe ShapeDrive® Sensor	Hand-guided	3D-sensor for the data acquisition is independent of the surrounding light conditions.	Introduce a more complex inspection process
El Makrini et al. (2017)	-	Assembly of a box	Put the assembly components in the correct order and perform quality control afterwards	In-process	Visual	Hough transform	Kinect v2 camera. Middleware NiTE 2.2, IAI Kinect2 ROS package. Hough transform provided by the OpenCV library	Face and gesture	Quality control during the assembly process. Gesture recognition and face recognition. Human-robot behaviour by providing social cues such as head nodding/shaking and eye gaze	Integrate this process into a real industry case. Introduce a more complex inspection process
Pichler et al. (2017)	Automotive (Engines)	Engine assembly	Quality inspection process for generator-plug connectors in car engines	In-process	3D Object Recognition	Random Sampling Algorithm	XRob software, 3D sensors, software ReconstructMe	Skeleton tracking (Gestures)	Environment reconstruction	Introduce a more complex inspection process. Test a collaboration environment
Lopez-Hawa et al. (2019)	-	Line scanner for scanning inspection	Generate surface geometry for further inspection	Offline	Surface characterisation	Test Object Grabbed by Robot (TOGR)	Keyence line scanner, combination of Ethernet socket communication and USB connections	-	MATLAB user interface to simulate the process	Integrate this process into a real industry case. Introduce a real inspection process. More cloud points and calibrations are required for the full construction of the object
Papanastasiou et al. (2019)	White goods	Pre-assembly of the refrigerator's cabinet	Improve sealing operation	General framework	-	-	Force/torque sensors, microphones, cameras, smartwatches, AR glasses, vision system, force sensors or joysticks attached to the robot, air press sensor	Speech, Gestures, Force measurement and mechanical	Top-level communication technologies	Integrate this process into a real industry case. Speed up the robot motion in safety mode. Test the network for an inspection process

Syberfeldt and Ekblom (2019)	Volvo Group Truck Operations (Engines)	Apply two strings of glue on a frame to mount the engine cover	Determine if the glue strings are correct or not	In-process	Visual	Machine learning	Machine vision system, wrist camera	-	Machine learning	Evaluate the precision of the automatic quality control system developed and compare its performance with the manual inspection process
Bruker Alicona (2019)	Aeronautic components	Measurement process	Measurement of critical components of turbine engines	In-process	Surface characterisation	Fire Variation	Visual sensors	-	Measurement technology is directly integrated into production. Sensors detect defective components, and this information is automatically fed into the production cycle.	-
Brito et al. (2020)	-	Quality inspection tasks	Carry a product to be inspected in a given position	Offline	-	Reinforcement Learning	Force-Torque sensor FT-300, cone-shaped 3D printed tool	Operators apply force to a Force-Torque sensor that sends information to the system	Machine learning for reinforcement learning	Integrate this process into a real industry case
Doltsinis et al. (2020)	-	Snap-fit assembly	Characterisation and inspection of snap-fits	In-process	Force signal characterisation	SNAP-FIT FORCE SIGNATURE and Machine learning	A 7-DOF KUKA LWR 4+ manipulator with the three-finger gripper Barret BH-8. KUKA force estimation mechanism without using an external force sensor	Through Force measurement	Machine learning	Integrate this process into a real industry case. Apply it to other kinds of assembly processes
Karami et al. (2020)	-	Defect inspection on a product	Inspection of product defects	Offline	Visual	AND/OR graphs	Dual-arm Baxter manipulator from Rethink Robotics and a Kuka youBot mobile manipulator. LG G Watch R (W110) smartwatch	Gesture	AND/OR graphs for activity programming	Integrate this process into a real industry case. Introduce a real inspection process
Jian et al. (2021)	-	Grab and place	-	General framework	-	Hough transformation	Image vision and automatic calibration system. 2 CCD camera, computer and a robotic arm	-	Find an object on an image. Accurately locate the mass point of the workpiece to be gripped	Integrate this process into a real industry case

Analysis of examined real case studies

The previous section presented the state of the art of published papers on quality control with human-robot collaboration systems. However, the set of papers that suit the purpose of this article is scarce and half of these lack a real case application in industries. The plausible reason could be that being a topic of recent research interest, the approaches and methodologies developed have not yet been fully adopted or validated in real industrial applications of quality control processes with collaborative robots.

In Table 4, the descriptions of the main features of the solution adopted by each company are summarised. In particular, the analysis dimensions for each company, identified by the authors, are the following:

- Solution: description of the adopted solution.
- Main benefit: description of the main advantages achieved by the new solution.
- Technology used for control.
- Paradigm of quality control: in-process or offline paradigm of control.
- Type of inspection: typology of inspection (manual, visual, dimensional measurement, etc.).
- # Robots: number of robots adopted in the solution (single or multiple, see Wang *et al.* (2019)).
- # Humans: number of humans/operators involved (single or none, see Wang *et al.* (2019)).
- Robot role and Human role. Roles may be (*i*) active, meaning leading the task, or (*ii*) supportive, performing auxiliary tasks and assisting the other agent, or (*iii*) inactive, with no responsibility on the task, and meaning an obstacle to the other agent (Wang *et al.*, 2019).

For fields not specified, the symbol "-" is used.

Table 4 – Real case studies on quality control using HRC - collaborative solution features (Universal Robots, 2022).

Company	HRC Solution	Main benefit	Technology used for control	Paradigm of quality control	Type of inspection	# Robots	# Humans
BÖCO BÖDDECKER	The UR robot marks and label items to the strict requirements while doing quality control checks. The robot also identifies and discards faulty parts with camera control system. The camera can objectively determine the quality of the part.	Reduces likelihood of faulty parts being sent to customers.	6-axis robot arm with five kg lifting capacity. Advanced camera control system	In-process	Visual	Single	-
BW INDUSTRIE	Cobot presents metal tubes in front of two high-definition cameras which inspects the dimensional characteristics of the extruded tubes. If the inspection fails, the cobot places the part in a reject box.	Keep production in France. Maintain competitiveness and increase its workforce by 50%. Revenues increased by 70%. Reduction of the risk of musculoskeletal disorders (MSDs) among employees, Ensuring a healthier working environment. ROI less than 12 months.	High-definition cameras	In-process	Dimensional measurement	Single	Single
COMPREHENSIVE LOGISTICS	Cobot moves a vision camera safely and repeatably between inspection points, snapping a picture of each connection. If the inspection fails, operator can go in and re- inspect just the failed portion of the cycle. Each image processed and inspection results shown on a screen next to the cobot.	ROI of 7 months.100% quality in the assembly of automotive engines. Zero maintenance with no downtime or interruptions of the line.	Vision camera	Offline	Visual	Single	None

CRAFT AND TECHNIK INDUSTRIES (CATI)	Cobot places a component on a weighing machine, takes feedback via digital input to decide whether the part meets its weight requirement or not, and then proceeds to sort the component accordingly.	Efficiency has increased with production volume going up 15–20% with no defects or customer rejections.	Weighing machine	Offline	Weight measurement	Single	None
EVCO PLASTICS	After the cap is successfully inserted, the UR5 places the gearbox on a scale to make sure the grease has been added. If the gearbox does not weigh the correct amount, the UR5 places it in a reject box Like the UR5 in the assembly cell, the UR10 on the packaging line also uses force/torque sensing: first to check that all four corners of the box are where they're supposed to be, and second to place cardboard sheets between each layer of parts in the box.	Total costs allocated over several customers, so that makes them cost-competitive.	-	Offline	Weight measurement	Single	None
FERDINAND WAGNER	Robot takes the piece to a high-frequency soldering station to be fused together. The robot then holds the pieces up to a camera system that automatically and objectively checks the quality of the welding and soldering work. They are used in two-shift intervals followed by a blind shift. At the end of the working day the robots continue working on an unmanned shift until the material is exhausted.	Employees now mainly focus on the processing of smaller batch quantities. Improved the operational efficiency of the production line. This robot duo is designed to process around 160 parts/hour.	Camera system. Robots and the gripping tools are fine-tuned to carefully move the parts as they have fragile decorative surfaces, and any damage renders them unusable	In-process	Visual	Single	None

FORD MOTOR COMPANY	Checking the engine with a UV light and a camera for leakage after it has been filled with oil.	Faster production throughput while also relieving employees of repetitive tasks. Cobots do not require human/operator's intervention unless a change occur in the usual processes.	Cognex camera vision, a UR+product, communicating with the cobot through Ethernet	In-process	Visual	Multiple	-
GKN DRIVELINE	Two UR5 were introduced to the front and back inspection process of a thin iron plat. An external high precision camera judges if the plate is in the right side or not.	Manufacturing under a full 24-hour operation. Safe space-saving. No more risk of worker fatigue.	External high precision camera. Zone sensors are set in 4 different directions, which sets the robot in slower motion when people are around	Offline	Visual	Multiple	Single
IZOELEKTRO D.O.O.	The first project included two operation tasks as product routine testing processes for low voltage surge arresters and medium voltage surge arresters where the robot was applied. A future application is to include product routine testing of tensile load for tension composite insulators and post line composite insulators.	A robot can work for eight hours straight in one shift with consistent efficiency. The production and testing time of each product is much faster, reducing the overall production cost as human errors are eliminated. ROI between 18 and 24 months.	-	Offline	Conformity/ functionality test	Single	None
KOYO ELECTRONICS INDUSTRIES	UR3 touches the touch panel with a stylus, "OK" is displayed if there is no quality error, and the green signal of a signal tower lights up. When an abnormality is detected, "NG" is displayed on the display, the red signal tower lights up, and the buzzer sounds continuously. As a result, the person in charge immediately notices the abnormality and can respond.	Quality of the work improved. No interruptions in production. Reduced the daily work time from an average of 10 hours to 8 hours. 31% increase in productivity. ROI of just 1 year. Allocating human resources to another process.	Stylus	Offline	Conformity/ functionality test	Single	Single

NORDIC SUGAR	The UR5 robots scan barcodes and pick up containers with sugar for analysis from scales to filters and back again.	No longer have to call expensive experts when they need to change a robot's task. Payback period: 124 days.	Barcodes scanner	In-process	Weight measurement	Multiple	None
OPTIPRO SYSTEMS	When parts come out of an OptiPro grinding machine, Q-Span® Workstation immediately measures the parts in a pass/fail scenario. If parts pass, they move on to the CMM machine for further measurement.	Catch out-of-tolerance issues right away and change drills or feed rate if need be. Avoid brittle material breaking and sharp edges getting fractured or chipping from manual handling reduced in-house workforce.	-	In-process	Dimensional measurement	Single	Single
STELLANTIS	Visual inspection to ensure the correct extrusion of the adhesive band around the perimeter. Check on soft-top frame dimensions. Vision system checks the geometric continuity and dimensions of the adhesive band. UR cobot runs a size check (through a vision system) on the soft-top frame to ensure the conformity of the dimensions. Once conformity has been ascertained, the soft-top is removed from the line by the anthropomorphic robot.	Operating precision and quality, and also improved the ergonomics of a series of operations previously performed manually.	-	In-process	Dimensional measurement	Multiple	-
THYSSENKRUPP BILTEIN	Gauge inspection and check the post-fill crimp and final parts assembly. The cobot deployed in the final assembly is equipped with a Cognex camera and moves swiftly between inspection points to make sure that all components are in the right position and that the label is applied correctly and is readable.	10-14 months ROI. Product quality increase as a result of 100% inspection. Zero maintenance with no downtime or interruptions of the line. Elimination of repetitive and ergonomically unfriendly workflows. Employees alleviated from ergonomically unfavourable tasks.	-	Offline	Visual	Single	None

CHALLENGES AND OPPORTUNITIES

In this section, the challenges and the opportunities that the manufacturing sector will face for the large-scale use of the new quality control paradigm based on human-robot collaboration are be presented, based on the analysis results discussed in the previous section. In this study, challenges and opportunities refer to a specific *i*-th dimension, and are labelled as follows:

- C*i.j*: challenge corresponding to dimension *i*, order *j*.
- O*i.j*: opportunity corresponding to dimension *i*, order *j*.

Six dimensions were identified and considered, as follows:

- Dimension 1: Type of quality control.
- Dimension 2: Visual inspection.
- Dimension 3: Safety and trust in the collaborative system.
- Dimension 4: Efficiency of the collaborative system.
- Dimension 5: Fear of human job replacement.
- Dimension 6: Economic growth.

Dimension 1: Type of quality control

O1.1: Towards in-process controls

The pie chart in Fig. 2 shows the distribution of examined literature and actual case studies between in-process and offline quality control paradigms.

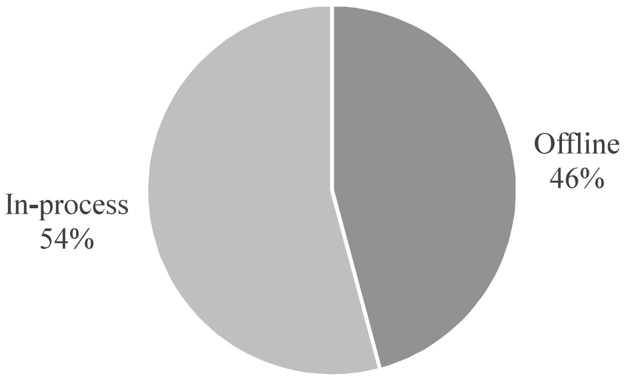

Figure 2 - Distribution of type of quality control of examined literature and case studies.

These two categories appear to be almost equal, with a slight predominance of in-process controls. As abovementioned, in-process controls are quality control performed during production to prevent defective parts from reaching the end of the line (Genta *et al.*, 2020). In this view, researchers and industries need to continue on the path towards in-process inspections. Collaborative robots support this policy by being small, lightweight, and flexible. Cobots require little space and are suitable for embedding into existing production lines. As a result, the space required for offline controls is not needed, and the resources that these extra stations would require are also saved. This implies an opportunity to make production systems more efficient in terms of cost and time savings and, more in general, to bring significant advantage for today's competitive market.

O1.2: Expanding the fields of application

Fig. 3 shows the types of inspections mentioned in the examined literature and in the real case studies analysed.

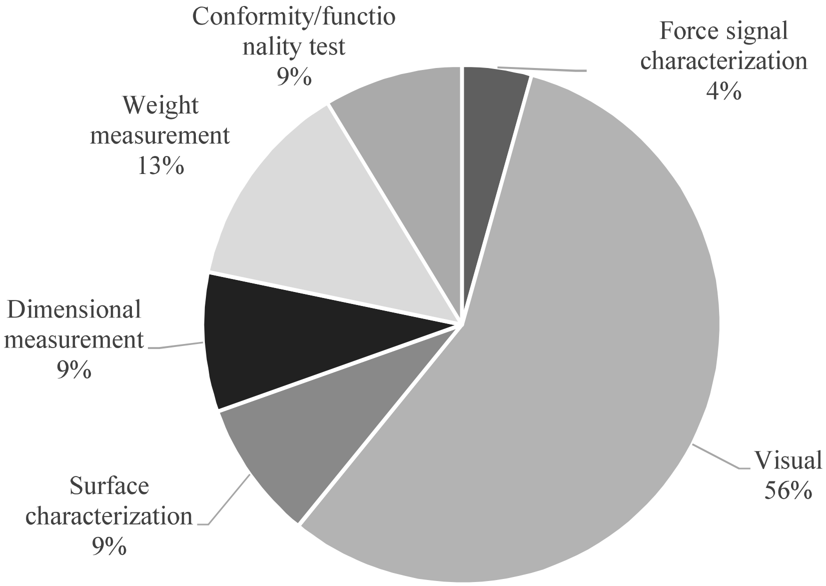

Figure 3 – Distribution of type of inspections performed on examined literature and case studies.

Visual inspections are the most frequently addressed type of inspection in both industry and academia (56%). Indeed, visual inspections previously performed by operators can be easily replaced by mounting a camera on the arm of the cobot, whose learning capability may be improved by using machine learning techniques. As Fig. 3 shows, there is plenty of scope for development and research into other types of inspection performed by cobots, including dimensional and weight measurements, topographical and mechanical characterisation and conformity or functionality testing.

C1.1: Application on real industrial cases

As the literature review showed, there is often a lack of real application of the quality inspection methods developed in the studies. The challenge for researchers is to test the functioning of the developed systems in real applications. Thus, in the future, comparisons can be made between manual and collaborative quality control, testing in which cases and conditions the collaborative scenario is more advantageous.

Dimension 2: Visual Inspection

A specific dimension is dedicated to visual inspection, as it is the most widespread application of cobots in the field of quality control.

C2.1: Ensuring accurate visual inspection

Although equipping the cobot with a camera may seem straightforward, visual inspection is not trivial to implement in industrial environments. For example, Lopez-Hawa et al. (2019) state that a problem encountered during scanning was an error in the data generated due to the reflection of the laser beam. This error increases with an increase in the reflectivity of the object being used, thus methods to eradicate or minimise this problem require further research. Syberfeldt and Ekblom (2019) claimed that even on low-quality images, object detection becomes complex. It is difficult in an industrial environment because the content of the image could vary greatly depending on the product variant or the angle from which the image is taken. When there are randomness and disturbances in the images, it becomes difficult to achieve accurate feature recognition for object location. How to handle this challenge efficiently is an open question that requires further study (Syberfeldt and Ekblom, 2019). Therefore, the challenge is to ensure similar conditions throughout the inspection process so that the system conditions may be considered stable and provide accurate information. However, this is not straightforward considering the intrinsic variability of industrial environment. The above-mentioned issues related to visual inspection represent a barrier to the flexibility that characterises cobots.

C2.2: Training the visual system

Many of the authors applying visual inspection have also equipped their systems with machine learning algorithms as they make the system able to learn and refine itself as more inspections are performed. This results in a more accurate and precise inspection system. However, the performance is dependent on rigorous training and appropriate training data, which in this case are images (Syberfeldt and Ekblom, 2019). The challenge is to provide the system with as many images as possible. Two categories of images must be provided for training the system:

1. Images that correspond to a conforming part.
2. Images that correspond to nonconformities.

The more complex the inspection task, the more training data is needed. In particular, the system needs as many images as possible related to nonconformities to recognise all possible cases in which parts should be rejected. However, it is not possible to provide the system with 100% of the possible non-conformities due to high process and product variability. Therefore, inevitably a small percentage of cases will always occur wherein the system will not be accurate in recognizing and acting accordingly.

O2.1: Overcoming light issues

One solution presented by Rooker et al. (2014) to solve the surrounding light challenge is using a blue-light LED projector and a suitable blue light bandpass filter. Incorporating the cobot with own light that provides the right conditions to perform an accurate visual inspection allows a portion of the challenges presented in C2.1 to be overcome. As a result, this is also an opportunity to expand visual inspection applications using cobots in manufacturing systems.

Dimension 3: Safety and trust in collaborative system

C3.1: Safety assessment

Safety is a vital topic when dealing with human-robot collaboration. In order for the operator to trust the robot, the operator safety must be ensured. However, the authors of the analysed papers do not pay particular attention to system safety evaluation. The underlying reason may be that some research is in a preliminary study phase, and the application has not yet been thoroughly implemented and tested in a real-world scenario. However, as Andersson et al. (2020) affirmed, if safety is not assessed in the pre-study, it may propagate into the following stages of implementation. Thus, the manufacturer needs to adapt the collaborative robot application in subsequent stages to ensure safety, which may impact the application's design (Andersson *et al.*, 2020). The challenge for future research is to implement safety assessment from the early stages as, if this is not incorporated, it can be a barrier to later-stage implementation.

C3.2: Collaboration instead of Cooperation

As shown in Fig. 3, in none of the case studies analysed, the human operator plays an active role.

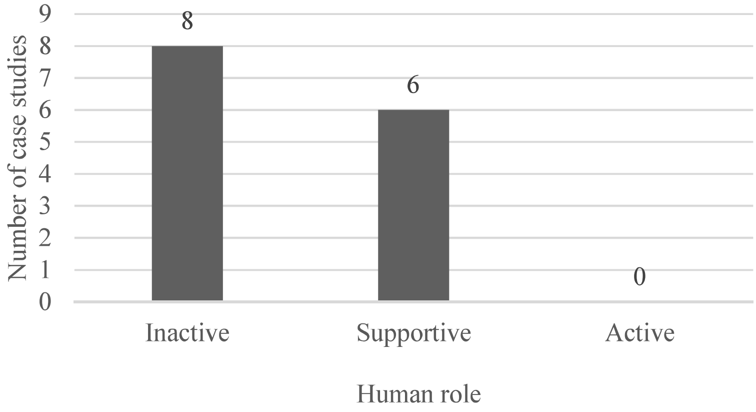

Figure 4 - Human role in the collaborative system in the analysed case studies.

Therefore, no real collaborative scenario has been identified in today's production processes, but rather cooperation, where cobot and operator work together for mutual benefits, albeit each one has its own goal. The workspace and resources are shared in a sequential and even simultaneous process. The work is divided into subtasks, which are then assigned to operators and robots respectively, and each is responsible for its part of the work. Analysing real case studies, the role of the operators is only to control or support the robot, assist it when a problem arises, or provide material to work with. No tasks are shared between the human and the robot. Certainly, cooperative systems also imply benefits for the quality control process, yet the challenge is to increase collaborative applications in which effective collaboration occurs.

O3.1: Human-Robot Communication

The opportunity to develop more human-robot collaborative systems is closely related to how humans can communicate and interact with the cobot. As presented in the previous section, several channels can be used to enable communication between the human and the cobot. In Fig. 5, the communication channels in the examined literature on quality control in human-robot collaborative systems are represented with the corresponding number of papers.

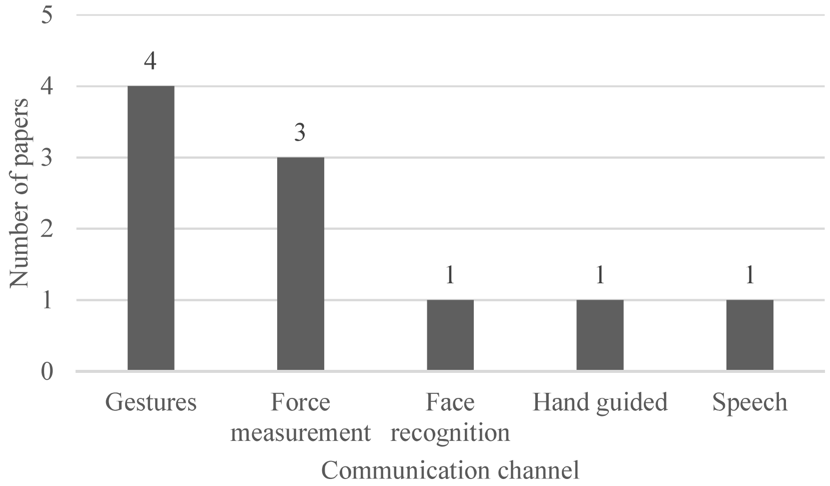

Figure 5 – Number of papers per communication channel used on examined literature.

In addition, communication helps to ensure a safe environment for humans. If the robot can understand human gestures and speech, collaboration tasks are performed more naturally, and the cobot is able to know how to respond accordingly to human movements, words and actions. Research related to human-robot collaboration also revolves around enhancing particular enabling functions such as visual perception and action recognition that enables human awareness and promotes flexible cobot behaviour (Knudsen and Kaivo-Oja, 2020; El Zaatari *et al.*, 2019). Many of the examined papers do not mention the communication between humans and cobots. However, if communication is not addressed in the early design stages, it can become a critical issue during the actual implementation of the quality control process. Researchers and manufacturers using cobots for quality control processes have an opportunity to equip the robots to make communication between agents as natural as possible for humans. Despite the increasing use of gestures and voice commands in HRC to control robots, they are less natural or practical in crowded and noisy work environments. Instead of defined gestures and voice commands, recognising and predicting human movements through deep learning provides better context awareness and fewer disruptions to typical performance induced by signalling gestures (Wang *et al.*, 2019).

O3.2: System parameters adaptation

If the system is already embedded with visual capabilities, e.g., with a camera, the system can be improved and made more personalised and safer for the operators by adapting the robot's behaviour to the user. Parameters adaptation can be quickly done after recognising the operator's face, and with a database provided to the cobot the height of the person can be extracted, and consequently, the speed and height at which the parts are given can be defined (El Makrini *et al.*, 2017). Although a vision system is not present, this feature can be added to the process by providing a username and password to each operator. If the system is customised for each operator, humans would have more confidence in it and environment safety would be more guaranteed as the speed of work adjusts to different operators.

Dimension 4: Efficiency of the collaborative system

O4.1: Overall efficiency and costs reduction

The adoption of collaborative robots to quality control processes has increased the efficiency and productivity of production lines and led to a reduction in costs, as experienced by companies reported in Tables 2 and 4. Moreover, the ROI of collaborative robots is very promising, as it ranges from months to a maximum of two years (Universal Robots, 2022).

O4.2: Reduce human error

Another benefit that industries have found by applying cobots to quality control processes is the reduction of human error, and thus improved defect detection, shorter production and testing time, and greater end-customer satisfaction. Reducing the incidence of errors and increasing the defect detection capability is crucial in the quality control processes of current manufacturing systems.

Accordingly, the opportunity to improve these aspects through collaborative systems must be considered to be competitive.

Dimension 5: Fear of human job replacement

C5.1: Human fear of losing job

Operators often associate the introduction of robotic technology with the fear of being replaced by machines (Kopp *et al.*, 2020). Therefore, the challenge is to let operators know that the introduction of cobots does not imply that they will be replaced, but instead that they will be reassigned to other tasks involving more cognitive and reasoning efforts, adding more value to the company. The goal is to make humans feel that the cobot is like a human colleague, that it is safe to work with, and that it relieves them of tedious tasks.

O5.1: New tasks for humans

As was explained in challenge C5.1, by incorporating collaborative robots into production lines, humans can be reassigned to more valuable tasks where they can apply reasoning and bring more value to the process. On automotive assembly lines, where many quality checks are performed, there is a clear opportunity to assign repetitive, automatable control to robots, and more skilled tasks to human operators (Müller *et al.*, 2014). This is possible by making human operators feel more useful and assigning them tasks that are not boring and stressful.

Dimension 6: Economic growth

O6.1: Cobot market growth worldwide

The development of the market in terms of both suppliers and demand can affect what will become the dominant type of cobots as well as the dominant cobot markets (Knudsen and Kaivo-Oja, 2020). As the cobot market expands, supply and demand will change, resulting in a price decrease. With a more affordable cost, applications of cobots on production lines will experience an increase and small companies will be able to afford the investment to purchase them.

CONCLUSIONS

The introduction of collaborative robots in the quality control process is growing in importance in recent years. Collaborative robots are flexible, fast, lightweight, and work flawlessly with human operators. A distinguishing feature of collaborative robots for inspection processes is repeatability and accuracy. They can repeat the inspection procedure many times, without needing to stop, 24 hours a day, and they will do it the same way, making the process more capable of detecting non-conformities. This type of inspection activity is often more prone to errors when performed by humans, which is why the introduction of collaborative robots is beneficial. The use of collaborative systems also implies increased motivation of human operators, being aware that the robot performs repetitive and automatable tasks and can focus on tasks that require human reasoning to perform. For example, most of the applications involving cobots are visual inspections, where vision sensors or cameras are integrated into the cobot to inspect different visual aspects, such as size, shape, presence of an object, etc., with accuracy and precision.

In the present article, the scientific literature dealing with HRC in industrial quality control was analysed. In addition, some real-world case studies were investigated to understand the state-of-the-art in the industrial domain. The analysis of the articles and case studies led to the definition of 6 dimensions of analysis. Each dimension was then divided in turn into challenges and opportunities that the manufacturing sector will face for the large-scale use of this new control paradigm, summarized in Fig. 6.

1. Type of quality control	**2. Visual Inspection**	**3. Safety and trust in collaborative system**	**4. Efficiency of the collaborative system**	**5. Fear of human job replacement**	**6. Economic growth**
• O1.1: Towards in-process controls • O1.2: Expanding the fields of application • C1.1: Application on real industrial cases	• C2.1: Ensuring accurate visual inspection • C2.2: Training the visual system • O2.1: Overcoming light issues	• C3.1: Safety assessment • C3.2: Collaboration instead of Cooperation • O3.1: Human-Robot Communication • O3.2: System parameters adaptation	• O4.1: Overall efficiency and costs reduction • O4.2: Reduce human error	• C5.1: Human fear of losing job • O5.1: New tasks for humans	• O6.1: Cobot market growth worldwide

Figure 6 – Schematic of analysis dimensions with related challenges (C) and opportunities (O) of HRC in quality control.

From the results of the analysis, it is clear that collaborative robotics in quality still plays a marginal role compared to the many industrial applications currently available. In order for this new paradigm of quality control to become widely used, the challenges listed in Fig. 6 must be faced and overcome, trying to take full advantage of the opportunities and benefits it can offer.

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REFERENCES

Andersson, S.K.L., Granlund, A., Hedelind, M. and Bruch, J. (2020), "Exploring the Capabilities of Industrial Collaborative Robot Applications", available at:https://doi.org/10.3233/ATDE200148 (accessed April 6th, 2022).

Antony, J., McDermott, O. and Sony, M. (2021), "Quality 4.0 conceptualisation and theoretical understanding: a global exploratory qualitative study", *The TQM Journal*, ahead of print, available at:https://doi.org/10.1108/TQM-08-2021-0242.

Brito, T., Queiroz, J., Piardi, L., Fernandes, L.A., Lima, J. and Leitão, P. (2020), "A machine learning approach for collaborative robot smart manufacturing inspection for quality control systems", *30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)*, Vol. 51, Procedia Manufacturing, 15-18 June 2021, Athens, Greece, pp. 11–18.

Bruker Alicona. (2019), *Non-Contact and Highly Accurate Measurement of Critical Turbine Engine Components*.

Dias, A.M., Carvalho, A.M. and Sampaio, P. (2021), "Quality 4.0: literature review analysis, definition and impacts of the digital transformation process on quality", *International Journal of Quality & Reliability Management*, ahead of print, available at:https://doi.org/10.1108/IJQRM-07-2021-0247/FULL/XML.

Doltsinis, S., Krestenitis, M. and Doulgeri, Z. (2020), "A machine learning framework for real-time identification of successful snap-fit assemblies", *IEEE Transactions on Automation Science and Engineering*, IEEE, Vol. 17 No. 1, pp. 513–523.

European Commission. (2020), "Industry 5.0", available at: https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en (accessed April 6th, 2022).

Genta, G., Galetto, M. and Franceschini, F. (2020), "Inspection procedures in manufacturing processes: recent studies and research perspectives", *International Journal of Production Research*, Taylor & Francis, Vol. 58 No. 15, pp. 4767–4788.

Hentout, A., Aouache, M., Maoudj, A. and Akli, I. (2019), "Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017", *Advanced Robotics*, Taylor & Francis, Vol. 33 No. 15–16, pp. 764–799.

Jian, B.-L., Tsai, C.-S., Kuo, Y.-C. and Guo, Y.-S. (2021), "An image vision and automatic calibration system for universal robots", *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 40 No. 1, pp. 347–366.

Karami, H., Darvish, K. and Mastrogiovanni, F. (2020), "A task allocation approach for human-robot collaboration in product defects inspection scenarios", *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, IEEE, August 31 - September 4, 2020 - Virtual Conference, pp. 1127–1134.

Knudsen, M. and Kaivo-Oja, J. (2020), "Collaborative Robots: Frontiers of Current Literature", *Journal of Intelligent Systems: Theory and Applications*, No. June, pp. 13–20.

Kopp, T., Baumgartner, M. and Kinkel, S. (2020), "Success factors for introducing industrial human-robot interaction in practice: an empirically driven framework", *International Journal of Advanced Manufacturing Technology*, Springer Science and Business Media Deutschland GmbH, Vol. 112 No. 3, pp. 685–704.

Küpper, D., Knizek, C., Ryeson, D. and Noecker, J. (2019), "Quality 4.0 takes more than technology", *Boston Consulting Group (BCG)*, pp. 1–14, available at https://www.bcg.com/publications/2019/quality-4.0-takes-more-than-technology (accessed May 4th, 2022).

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T. and Hoffmann, M. (2014), "Industry 4.0", *Business & Information Systems Engineering*, Springer, Vol. 6 No. 4, pp. 239–242.

Lopez-Hawa, H., VanPelt, A., Emmanuel, S. and Yihun, Y. (2019), "Automated Scanning Techniques Using UR5", *Journal of Robotics*, Vol. 2019 No. ID 5304267, p. 8.

Maddikunta, P.K.R., Pham, Q.-V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T.R., Ruby, R., *et al.* (2021), "Industry 5.0: A survey on enabling technologies and potential applications", *Journal of Industrial Information Integration*, Elsevier, p. 100257.

El Makrini, I., Merckaert, K., Lefeber, D. and Vanderborght, B. (2017), "Design of a collaborative architecture for human-robot assembly tasks", *IROS 2017 - IEEE/RSJ International Conference on Intelligent Robots and Systems*, IEEE, 24-28 September 2017, Vancouver, British Columbia, Canada, pp. 1624–1629.

Montgomery, D.C. (2012), *Statistical Quality Control*, 7th Ed., John Wiley & Sons, New York.

Müller, R., Vette, M. and Scholer, M. (2014), "Inspector robot - A new collaborative testing system designed for the automotive final assembly line", *Assembly Automation*, Vol. 34 No. 4, pp. 370–378.

Papanastasiou, S., Kousi, N., Karagiannis, P., Gkournelos, C., Papavasileiou, A., Dimoulas, K., Baris, K., *et al.* (2019), "Towards seamless human robot collaboration: integrating multimodal interaction", *International Journal of Advanced Manufacturing Technology*, Vol. 105 No. 9, pp. 3881–3897.

Pichler, A., Akkaladevi, S.C., Ikeda, M., Hofmann, M., Plasch, M., Wögerer, C. and Fritz, G. (2017), "Towards shared autonomy for robotic tasks in manufacturing", *27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017*, Vol. 11, Procedia

Manufacturing, 27-30 June 2017, Modena, Italy, pp. 72–82.

Romero, D., Bernus, P., Noran, O., Stahre, J. and Fast-Berglund, Å. (2016), "The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems", *IFIP International Conference on Advances in Production Management Systems*, Springer, pp. 677–686.

Rooker, M., Hofmann, M., Minichberger, J., Ikeda, M., Ebenhofer, G. and Pichler, A. (2014), "Quality Inspection performed by a Flexible Robot System", *Proceedings of the Austrian Robotics Workshop 2014*, 22-23 May, Linz, Austria, pp. 47–51.

Sony, M., Antony, J. and Douglas, J.A. (2020), "Essential ingredients for the implementation of Quality 4.0: a narrative review of literature and future directions for research", *The TQM Journal*, Vol. 32 No. 4, pp. 779–793.

Statista. (2022), "Collaborative robots worldwide", available at: https://www.statista.com/topics/8062/collaborative-robots-worldwide/ (accessed April 6th, 2022).

Syberfeldt, A. and Ekblom, T. (2019), "Improved automatic quality inspections through the integration of state-of-the-art machine vision and collaborative robots", in Yan, J. and Price, M. (Eds.), *Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research*, IOS Press Advances in Transdisciplinary Engineering, 10–12 September, Belfast, UK, pp. 107–112.

Universal Robots. (2022), "Universal Robots: case stories", available at: https://www.universal-robots.com/case-stories/quality-inspection/ (accessed April 6th, 2022).

Wang, L., Gao, R., Váncza, J., Krüger, J., Wang, X. V., Makris, S. and Chryssolouris, G. (2019), "Symbiotic human-robot collaborative assembly", *CIRP Annals*, CIRP, Vol. 68 No. 2, pp. 701–726.

El Zaatari, S., Marei, M., Li, W. and Usman, Z. (2019), "Cobot programming for collaborative industrial tasks: An overview", *Robotics and Autonomous Systems*, Elsevier B.V., Vol. 116, pp. 162–180.