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Analysis of challenges and opportunities of collaborative robots for quality control in manufacturing

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ABSTRACT

The application of Human-Robot Collaboration on manufacturing systems has been increasing in the last years and comes hand-in-hand with growth of importance of Industry 4.0 related technologies.

The fields of applications of Human-Robot collaboration are vast and what is sought is to relief human operators of tedious and repetitive tasks, integrating the automation, repetitiveness, accuracy, and flexibility that characterizes the collaborative robots, and at the same time keeping the cognitive and soft skills of human workers.

The quality control and inspection of products is something that, considering the high customer requirements present on today's market, must be ensured and defective parts cannot arrive to the final users. That is why it is important to constantly search new technologies that makes this process the most efficient and accurate possible.

In specific, this thesis will focus on the analysis of the scientific literature and real case studies regarding the state of the art of quality control using collaborative robotics systems in manufacturing. The analysis will allow to identify and define the challenges and opportunities that the manufacturing sector will face for the large-scale use of the new quality control paradigm based on human-robot collaboration.

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1.INTRODUCTION

1.1 Background Information

1.1.1 General background information

In the last years, the employment of robotics has been spread in almost every field, and more specifically within the manufacturing area, where the advantages that may be obtained are numerous.

This is because of the very fact that nowadays the manufacturing is facing the evolution towards Industry 4.0 which emphasizes efficiency, reduction of costs and productivity through the usage of automation and data analysis.

In order to attain this, industries must be more rapid, flexible, proactive and to quick reply to the market needs, while still doing so in a sustainable and efficient manner, ensuring prime quality levels for customer satisfaction.

This is not an easy task for manufacturers, and the answer to those challenges has partly been found by the usage of robot automation within the different manufacturing processes, playing a pivotal role for today's manufacturing industry to be competitive. (Villani, 2021)

The main benefits of introducing robots into the manufacturing area include the capacity to relieve workers of repetitive, heavy, and automatable activities, as well as the precision and repeatability that comes with it, resulting in a higher quality product.

This in fact introduces a conflict considering that operators might imagine that they are going to be fully replaced by humans during a nearly future, but instead, the foremost advantageous point of this, is that robots will never replace humans, after all the thought is to seek out the proper complementation between them.

For high-volume production, a robot has the capability to maintain high efficiency and repeatability, but it lacks flexibility when it comes to problem-solving and uncertainty.

Human operators, on the other hand, know the way or they can think about a possible way to solve these problems due to rationality, but it lacks repeatability, speed, and they cannot lift heavy weights, and this ends up in a decrease in the efficiency and in the final product or service quality.

To achieve these overall manufacturing goals during mass customization, a balance between automation and flexibility is essential. 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 specializing in enabling robots and humans to control jointly to finish collaborative tasks. (Zaatari, 2019)

This new research area coincides with the fourth industrial revolution, or Industry 4.0, as well as the rise of the Internet of Things and the concept of collaborative objects.

Shorter development timeframes, customization, adaptability, and efficiency are all part of the Industrial 4.0 paradigm. The smart factory is a concept introduced by the revolution, in which 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 lines more flexible and shift the status quo where robots and human operators are firmly separated; instead, they can now operate together and point to the same goal.

1.1.2 Industry 4.0

Industry is one of the most important economic and social sectors in any region, and Europe is no exception. Industry provides the region with revenue, a future, stability, and the capacity to grow economically. That is why, in order to be more competitive on the global market, a region must reach high levels of industry efficiency and innovation.

Although the European Union is currently transitioning to Industry 5.0, the focus will be on Industry 4.0 because Industry 5.0 is based on Industry 4.0 and complements it by emphasizing research and innovation as drivers for a transition to a sustainable, human-centric, and resilient European industry. (European Commission, 2022)

This new type of industry 5 places the wellbeing of the worker at the centre of the production process and uses new technologies to provide prosperity beyond jobs and growth while respecting the production limits of the planet (European Commission, 2022), but this new paradigm does not make focus on the specific technologies or tools to achieve it, as they are actually the ones from Industry 4.0, but with a different focus. It could be interpreted or defined as a way of approaching instead of technologies itself.

As a result, digging and understanding the concepts and technologies that are part of Industry 4.0 are more exciting to comprehend

Therefore, the first thing to do is to analyse and understand the origin of the name “Industry 4.0” and where does it come from. Basically, since industrialization started, many technological developments and discoveries have led to various "industrial revolutions" that have radically altered the paradigms in place at the time. The earliest one was the First Industrial Revolution with great advances through the employment of steam power and mechanization of production, reducing therefore the production times leading an increase in human productivity. Following this one, came the Second industrial revolution with the arrival of electric energy and assembly line production, introduced by Henry Ford with the idea of mass production, which also allowed the reduction of times even more than the previous one and with this a big increase in the efficiency. After, during the last part of the 20th century the widespread digitalization, computers and the use of robots led to the beginning of the 3rd Industrial revolution. Later, following these three major revolutions, the 4th Industrial Revolution, often known as "Industry 4.0," began in Germany in 2011. It is characterized by the use of information and communication technology to industry. Basically, a network connection is used to expand what was accomplished during the third revolution. The concept of utilizing 4.0 instead of "4th revolution" references to software versioning, digitization, and the "smart" concept. (Desoutter Industrial Tools, 2022).

Given the difficulty of establishing a single definition of Industry 4.0, it is preferable to outline its key principles that better represent it (Lasi, H., 2014):

- **Smart Technology**: Industry 4.0 is sometimes used interchangeably with the term "smart factory." In fact, the Boston Consulting Group claims that Industry 4.0 uses sensors, actors, and autonomous systems to make factories "smart." We can find Internet of Things and artificial intelligence among these technologies, which are systems that are integrated in a way that allows them to interact and adjust continuously.

- **Cyber-physical Systems**: this is what happens when the physical and digital worlds collide. A clear example is given by Lasi, H: Process parameters (stress, productive time etc.) of mechanical components underlying a (physical) wear and tear are recorded digitally. The real condition of the system results from the physical object and its digital process parameters.
- **Self-organization**: The new paradigm of company structures is moving toward a decentralized system, which entails an increase in individualization and activities, as well as the disintegration of hierarchies.
- **New distribution and procurement systems**: in line with the previous point, distribution and procurement systems will become more individualized.
- **New systems in the development of products and services**: in order to be more receptive to innovation, this is necessary.
- **Adaptation to human needs**: contrary to popular belief, Industry 4.0 does not intend to replace human operators; rather, the new systems should place humans at the centre of processes and satisfy its needs.
- **Corporate Social Responsibility**: Resource efficiency and sustainability to safeguard resources for future generations.

Finally, industries who can truly grasp the benefits of Industry 4.0 and see it as a value rather than a cost will be more competitive and better prepared to face difficulties.

Now that the concept of Industry 4.0 has been established, the next stage is to identify concrete actions that will lead to Industry 4.0. It is driven by nine technologies, according to the Boston Consulting Group, as it can be seen on Figure 1:

Figure 1: Industry 4.0 technologies. Source: forbes.com

1. **Additive Manufacturing**. is defined as the manufacturing process to build up three dimensional objects by adding layer-upon-layer of material, a classic example is the 3D printing. Starts from a computer design file that includes digital 3D data about how the finished product should look. Plastic, metal, concrete, or even human tissue might be employed as the material. The benefits are numerous, including the ability to make small batches of customized products, relatively quick manufacturing processing times, the ability to produce intricate pieces that are impossible to do using conventional techniques, material efficiency, and lightweight designs.
2. **Augmented Reality**. is the perception of digital information synchronized with objects and places in the physical world around the user, in other words, a set of technologies that add digital images on the real world. In Industry 4.0, augmented reality can be used to visualize, instruct, and guide, as well as interact. BCG uses

the example of picking parts in a warehouse and sending repair instructions over mobile devices. Provide workers with real-time data to help them make better decisions and work more efficiently.

3. **Collaborative and Autonomous Robots** are integrated with numerous sensors and standardized interfaces and are designed to work together with humans in the same physical environment. It enhances, reinforces, and assists human talents, making the work less stressful and taking advantage of robots and humans at the same time.
4. **Big Data and Analytics.** Data analysis is a process of inspecting, cleaning, transforming, and modeling data with the goal of discovering knowledge of the problem that supports the decision-making. In the context of Industry 4.0, information is power: the power to make informed decisions, to identify areas for improvement, and to get a deeper understanding of operations.
5. **The Cloud.** Because more room is required to save all of the data discussed in the preceding paragraph, cloud technologies are becoming faster and more powerful.
6. **Cybersecurity.** As information is power, essential industrial systems and manufacturing lines must be protected from cybersecurity threats. For this reason, it is important to secure computer systems and networks from attacks to their hardware, software, or data.
7. **Horizontal and Vertical System Integration** to achieve more cohesion, with the creation of a network of data information between various systems and across all processes to provide more knowledge, insights and value creating actions.
8. **The Industrial Internet of Things** is a network of interconnected computing devices, mechanical and digital equipment, items, or people with unique identifiers and the ability to communicate data without requiring human-to-human or human-to-computer interaction. This encourages decision-making in real time.
9. **Simulation** is a tool that allows you to run a large number of tests. As a result, various circumstances and scenarios may be tested in real-time, without having to

invest a lot of money, and in a relatively short amount of time. This provides for increased productivity and improved end product quality.

1.1.3 Robot

The origin of the word Robot is derived from a Czech noun “robota”, that means “labor”. This leads us to consider and comprehend the primary goal and purpose of robots in our world: to execute a labor, a task, or to work.

But, since the word robot was first used in 1921, in Karel Capek’s play R.U.R., for Rossum's Universal Robots, plenty of different definitions to the word has been given. This is owing to the fact that today's robots come in a variety of applications, sizes, and functions, making it difficult to lump them all together in a single description. In fact, if someone asks different roboticists what a robot is, they will all provide different responses.

The following definitions of robot, organised on Table 1, have been compiled in order to gain a better grasp of the subject and to create a broad definition that attempts to encompass all of them.

Source	Definition
Collins dictionary, 2022	*A robot is a machine which is programmed to move and perform certain tasks automatically.*
	In British English: *Any automated machine programmed to perform specific mechanical functions in the manner of a human.*
Robot Institute of America, 1979	*A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of task.*
Webster's Dictionary, 2022	*An automatic device that performs functions normally ascribed to humans or a machine in the form of a human.*

British Department of Industry, 2022	*A reprogrammable manipulator device.*
Merriam-Webster, 2022	*A device that automatically performs complicated, often repetitive tasks (as in an industrial assembly line).*
Rodney Brooks Founder and CTO, Rethink Robotics, 2018	*A robot is an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world.*

Table 1: Robot definitions.

In order to summarize, a robot is any automatic mechanism programmed to execute function, primarily mechanical and repetitive, that are ordinarily performed by humans or in the style of a human, by detecting the environment, computing judgments, and acting on those decisions in the actual world.

The intelligence, the ability to sense the environment, and the autonomy to complete tasks distinguish the robot from any other programmable equipment and it gives it the value and importance it has today in the various industrial processes.

Isaac Asimov was the first using the term "robotics" his science fiction book "I, Robot", 1950, that inspired scientists and engineers in the developing of future robots. He was the leading promoter of the word "robot". In this book he wrote:

> *The three fundamental Rules of Robotics... One, a robot may not injure a human being, or, through inaction, allow a human being to come to harm... Two... a robot must obey the orders given it by human beings except where such orders would conflict with the First law... Three, a robot must protect its own existence as long as such protection does not conflict with the First or Second Laws*
>
> ***ISAAC ASIMOV** I, ROBOT*

At the end, Asimov articulated what is now the most fundamental premise when it comes to robot-human interaction, namely, safety. If safety is not guaranteed, any contact between them is possible, as the top concern is always to protect human integrity.

1.1.4 Cobots or Collaborative Robots

In manufacturing lines, robots are used to undertake activities that humans cannot physically accomplish, are unsafe to perform, or are not preferred by humans. Robots are used to perform the so-called 3D jobs, that means “Dirty, Dangerous or Dull jobs”.

However, in order to protect humans and avoid possible accidents, these industrial robots must work physically separate from human operators while doing this activity. This means that the robot must either have an operating zone that no humans can enter while it is functioning, or it must lower its power and capabilities to fit within this operating zone. Unfortunately, this is a disadvantage since it limits the activities that the robots can accomplish.

Anyway, the growing demand for automation, as well as the discovery of the benefits of human-robot interaction, led to the development of Collaborative Robots, which can work securely in the same environment as humans without endangering them.

The term "Cobot" comes from a contraction of the phrase "collaborative robot." The IFA (Institute for Occupational Safety and Health of the German Statutory Accident Insurance) defines the Cobots as “*complex machines which work hand in hand with human beings. In a shared work process, they support and relieve the human operator.*'' So, in a simplified way, it is a robot that collaborates with humans, sharing a workspace, in order to alleviate human efforts.

An interesting analysis of Cobots was done by the magazine Forbes, that states “In many ways, Cobots are the hardware version of augmented intelligence that we talk about in the software world. Instead of replacing humans with autonomous counterparts, Cobots augment and enhance human capabilities with super strength, precision, and data capabilities so that they can do more and provide more value to the organization.” (Forbes, 2019).

As a result, Cobots were created to work as pairs with humans in order to improve rather than replace their capabilities.

1.1.5 Difference between Robot and Cobots

There are two major differences between traditional industrial robots and Cobots. To begin with, as previously stated while discussing Cobots, the interaction between robot and human does not exist in traditional robots, where we may find them operating autonomously and without the presence of a human. On the other hand, unlike typical robots, which are trained by programming, Cobots are trained by humans manipulating the arms and by example through demonstration and reinforcement learning.

Robots that are autonomous and collaborate with humans in the same physical area and are equipped with a variety of sensors and standardized interfaces.

Autonomous and collaborative robots are one of the foundations of Industry 4.0, and they are increasingly being preferred over traditional industrial robots since they can function in a variety of contexts and provide numerous benefits, such as:

1. They are **easy to program**, making programming accessible to everyone, including workers with no prior programming knowledge. They are also quick to alter the program as needed, making it more versatile and adaptable for various applications.
2. **Fast to set up**; unlike traditional robots, which take weeks to set up, only a few hours are necessary.
3. **Flexible**, as they do not take up a lot of room and can be quickly deployed.
4. They are **safe**; they may collaborate with humans without endangering them through the use of environmental cognition. They are equipped with sensors that detect various characteristics.

To summarize, collaborative robots are typically a more profitable and productive option than traditional industrial robots when utilized in the correct situations. These robots are significantly lighter in weight than industrial robots, and as a result, they have greater mobility, making it easier to move them around the factory or industry where they are installed.

Collaborative robots' versatility, as well as their affordability, make them a suitable choice for a wide range of industries and applications. Today, collaborative robots are used in a variety of industries, including:

- Automotive
- Electronics
- General manufacturing
- Metal fabrication
- Packaging and co-packing
- Plastics
- Food and agriculture
- Pharmaceutical and chemical
- Scientific research

Collaborative robots can be used in a variety of scenarios. Sales volumes will increase as collaborative robot technology progresses and more companies see the productivity benefits of these sorts of robots.

1.1.6 Statistics of market

It is important to analyse and understand how the use of collaborative robots has been increasing through the years and also understand how widespread its use is, in order to be able to measure the impact that these new technologies can have.

For this purpose, the output of Statista's "Collaborative robots worldwide" research was used for the following statistical analysis.

As we can evidence in Figure 2, the market for collaborative robots has exploded in the past four years:

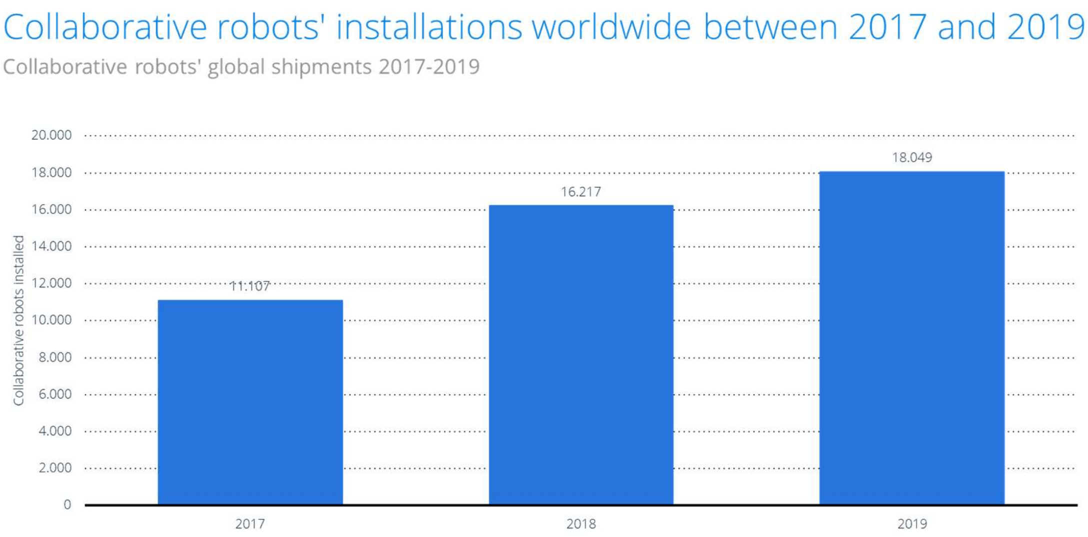

Figure 2: Cobots worldwide installation between the years 2017 and 2019. Source: statista.com

Every year between 2017 and 2019, the number of collaborative robots installed increased with a huge surge of 46 percent in 2018, from 11.107 collaborative robots deployed in 2017 to over 16,000 by the end of 2018.

However, the market for collaborative robots is currently a minor part of the overall market for industrial robots. These 16 thousand collaborative robots accounted for only 5% of the total market in 2018. In spite of these small proportion the future looks bright, as this percentage increased to 7% in 2019 and is predicted to rise in the following year, reaching a high of 13% in 2022, over three times the initial value, in just three years.

As a second parameter to analyse, the share of traditional and collaborative robot unit sales worldwide was considered.

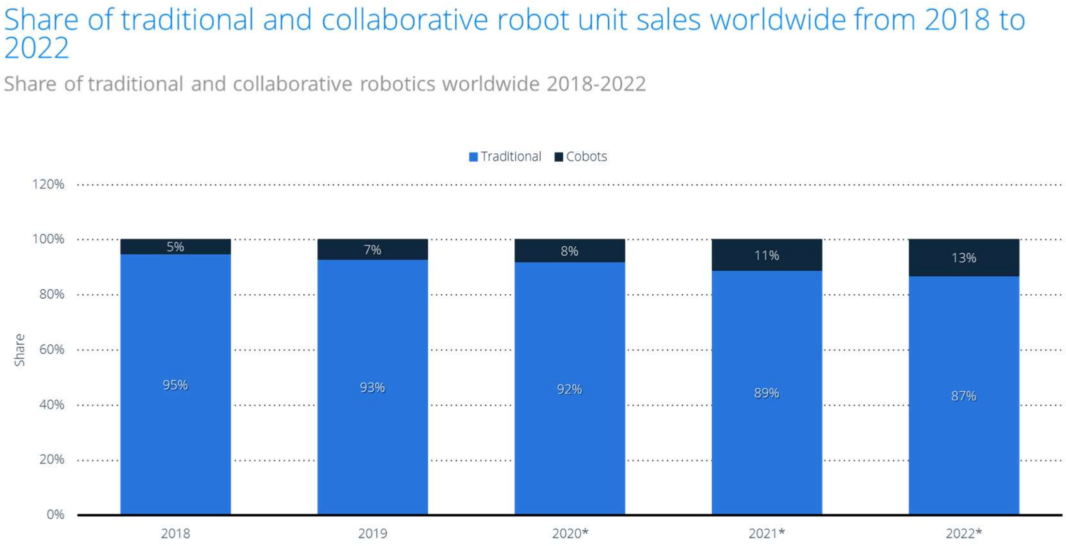

Figure 3: % of worldwide share of traditional robots and Cobots from 2018 to 2022. Source: statista.com

Figure 3 indicates that collaborative robots are gradually taking over the market share of traditional robots. In fact, a prediction of the worldwide market size for collaborative robots was conducted, with highly optimistic results, as we can see in Figure 4:

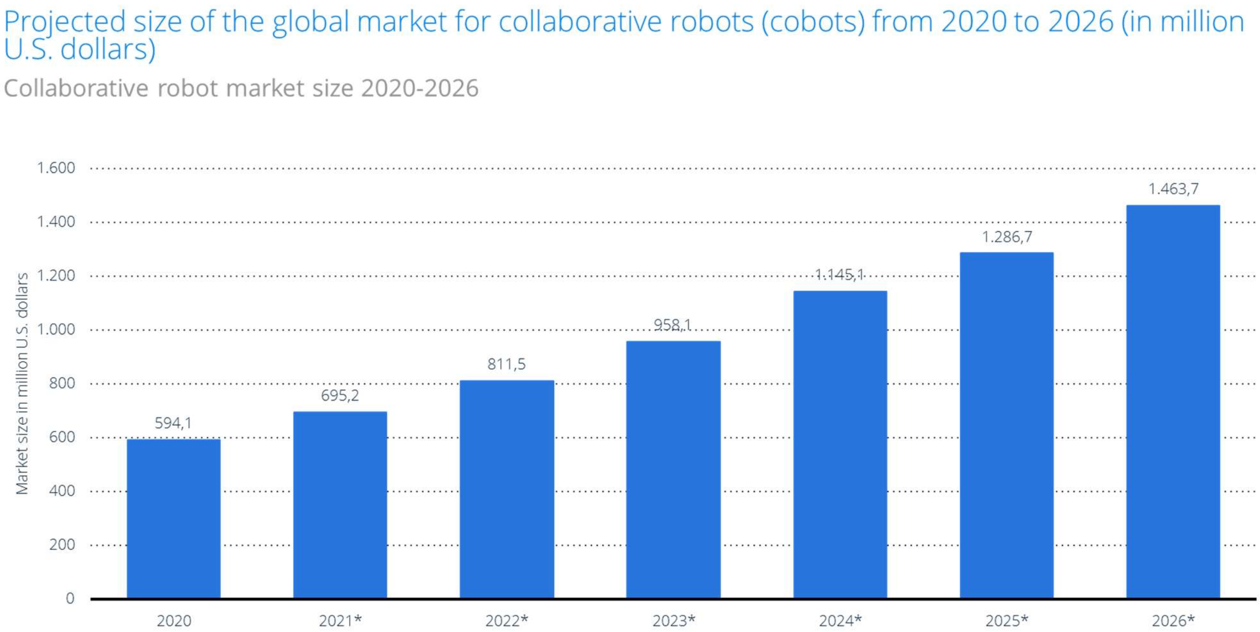

Figure 4: Forecast of Cobots market size between 2020 and 2026. Source: statista.com

This graph depicts the market for collaborative robots from 2020 to 2026, and it highlights the considerable growth that it will see in the next years, with no signs of slowing down. From 2020 to 2026, the Cobots market is expected to grow at a compound annual growth rate (CAGR) of 15 to 20%. While global Cobot revenue in 2020 was 594 million dollars, it is expected to reach about 1.5 billion dollars in 2026.

The following are some of the reasons behind this expansion:

- Lack of qualified workforce, leading to an increased need of automation.
- Increased labour costs, making robots cheaper than human operators.
- Demand is becoming more complex, requiring higher product mixes with shorter cycle times.
- Higher efficiency levels required.

Not least important is the wide range of applications for collaborative robots, which may be seen in Figure 5. It illustrates the revenue share of the collaborative robot market in 2019 by industry, indicating where robots are currently used.

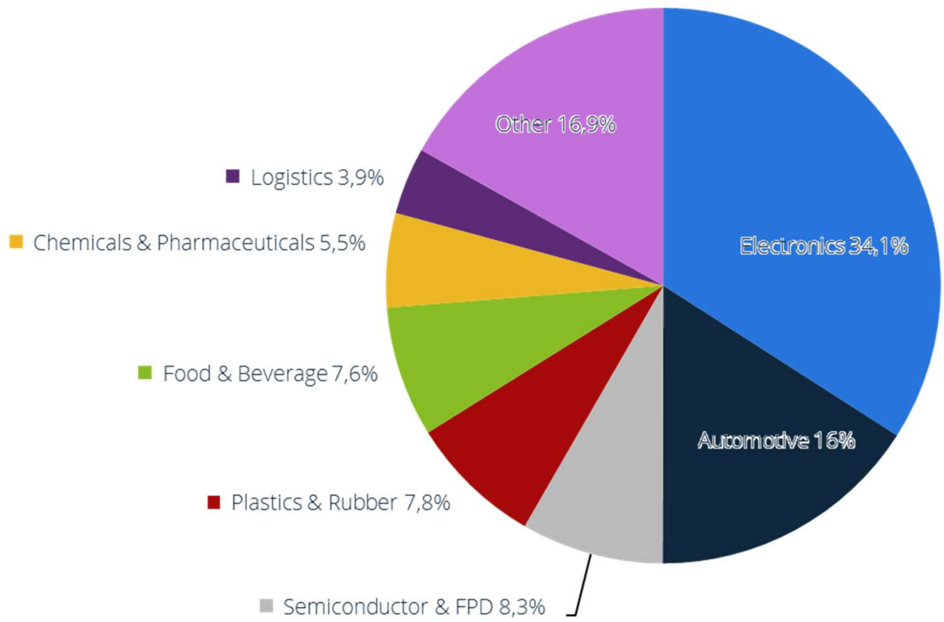

Figure 5: % of share in 2019 of Cobot's market by industry. Source: statista.com

Electronics, automotive, logistics, chemicals and pharmaceuticals, food and beverage, plastics and rubber, semiconductors, and so on are some of the industries that can be found. But the most relevant information we can obtain from this graph is that in 2019, two industries dominated the market share of applications for collaborative robots: electronics and automotive, with 34,1 percent and 16 percent of the market share, respectively.

Another approach to look at how Collaborative robots are used now is to divide the market into different types of applications for what the robot is employed for, as can be seen in Figure 6:

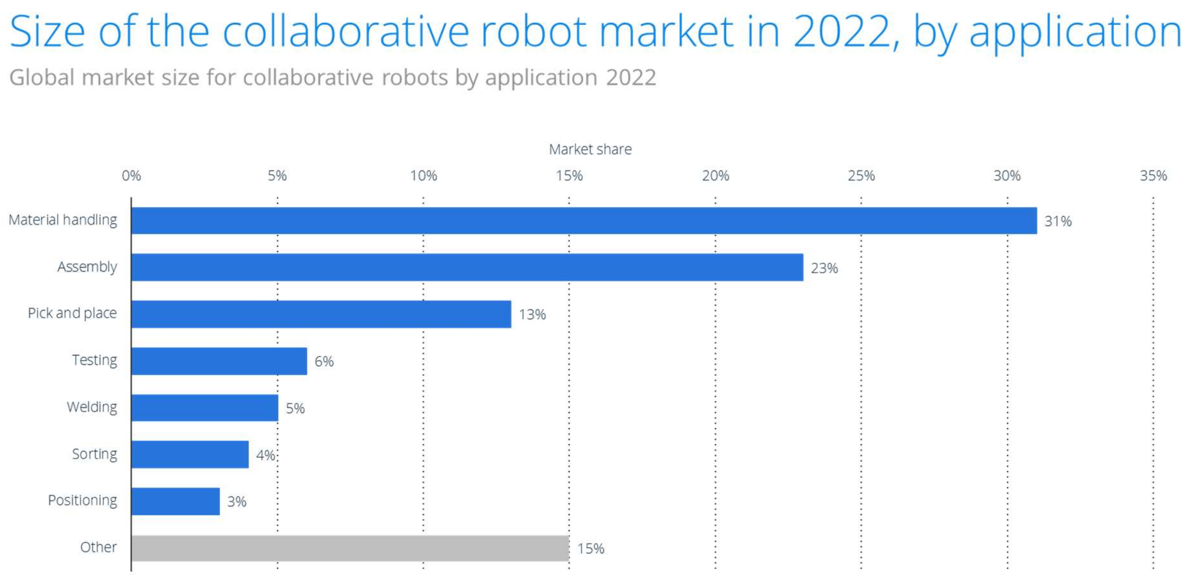

Figure 6: Expected global market size of Cobots by application for 2022. Source: statista.com

Material handling will be the most popular application for collaborative robots in 2022, with 31% of the market share, followed by assembly jobs and pick and place. Finally, if we add all three categories together since they all pertain to a material handle, we get a market share of 67 percent. The reason behind this situation is obvious: robots offer significant advantages when it comes to lifting heavy objects and performing precise assembly jobs in a repeated and efficient manner, without the stress that a human operator would experience.

Very far from this big material handle category, testing application follows with a 6% of market share, but that will be later analysed, because is one of the applications that is growing year-by-year, considering the good results than can be obtained by the usage of collaborative robots for testing, inspection, and control activities.

In conclusion, the preceding figures demonstrate the importance that collaborative robots are gaining in the business, and how they will eventually outnumber traditional robots due to features such as flexibility, safety, and efficiency. That is why it is critical to continue researching this topic and identifying new applications from which to benefit.

Another important fact to consider is that there are not many collaborative robot producers these days, and the market is dominated by a small number of them. So, the next necessary step is for the market to expand, bringing more competition, innovations, and a lower price, making it more accessible to small businesses that currently cannot afford them.

1.2 Research Objectives

1.2.1 General Objective

The general objective of this research is to perform an analysis of the scientific literature and real case studies regarding the state of the art of quality control using collaborative robotics systems in manufacturing. The analysis will allow to identify and define the challenges and opportunities that the manufacturing sector will face for the large-scale use of the new quality control paradigm based on human-robot collaboration.

1.2.2 Specific objectives

Based on the general objective, specific objectives of this study were identified and formulated as follows:

a) Explore and get familiar with the term “Cobot” and its origin.
b) Investigate the concepts of Industry 4.0
c) Make use of the literature review and past studies related to the corresponding concepts mentioned above to understand the current state of the art in terms of published literature.
d) Recognise the current situation regarding the implementation of Cobots
e) Analyse concrete applications of Cobots in various industries
f) Systematize the information collected to be able to make a comparison of the existing applications
g) Identify opportunities for implementing this type of technology
h) Identify challenges that may be encountered in carrying out “Cobot” implementation and application plans.
i) Recognize possible future fields of research in this area

j) Identify strengths in terms of application of Cobot applications and provide feedback, suggestions, and opportunities for improvement as well as possible future applications.

2. METHODOLOGY OF INVESTIGATION

In order to perform a proper literature review and a better analyse of the state of the art of the topics touched on this thesis, an organized investigation and research of documents was done.

The main sources and procedures applied on this investigation are further described on this chapter.

The main objectives of this investigation are the following ones:

- To obtain general data of the search results in order to perform analysis and derive to conclusions, in order words to understand general parameters of the topic investigated, such as documents per year, country of origin, and so on.
- To select the most accurate documents that allow to make a fair literature review and to obtain a good understanding on the topic.
- To provide a useful output that allows to future researcher to cover the gaps found.

The main added value of a literature review is to expose gaps and encourage to fill them in.

2.1 Databases

To be able to carry out this investigation and to gather valuable information to understand the state of art of human robot collaboration and quality control thorough collaborative robotic systems in manufacturing, in order to analyse the possible challenges and opportunities present in a current scenario, the literature research was done using the available databases that the Politecnico di Torino provides.

After a quick analysis of all available sources and considering advantages and disadvantages of each one, three of them were specifically selected for consultation during this research:

- Scopus
- Web of Science
- IEEW Xplore

A fourth source was also consulted, the open-source Google Scholar.

2.2 Search Engine

A search engine is an algorithm, moreover a system composed of numerous algorithms, that in a quick way, returns results by indexing all the pages it finds.

In more simpler words, what the search engine allows, is that when a user enters a term on the search box, the algorithm looks on all the webpages, or in this case documents, titles, authors, keywords, etc and returns the ones that fit with the search and sorts them putting first the most relevant ones.

The way users write the words and phrases on the box defines entirely what will be returned as output. In the databases used for this investigation, some codes operators and even using an asterisk, can be applied and it will help that the output is more accurate and adjusted on the needs of the user.

The databases used on the investigation have a search engine that helps user to find what they are looking for. They all work on a similar way, and for that reason the functioning of only Scopus will be explained.

Scopus is equipped with a search engine that allows to search publications by providing specific information of them, such as title, author, keywords, ISSN (International Standard Serial Number), and as users provide more and more information about it, more easily the finding will be. This of course when the main objective of the search is to find a specific publication; instead, if the user wants to search the publications done on a topic, it is important to define the specific words of interest and to define an approximate scope.

For this last kind of searching, Scopus have the option to set the data range, subject area, and the kind of document (article, paper, journal, etc.) to limit the results. This is called "advanced document search" because users do not only provide with the words of interest, but also limits the result by giving more information of the scope. This was used for the investigation in order to obtain better and "cleaner" results.

Figure 7 is an image that shows the initial page of Scopus where users can start the search:

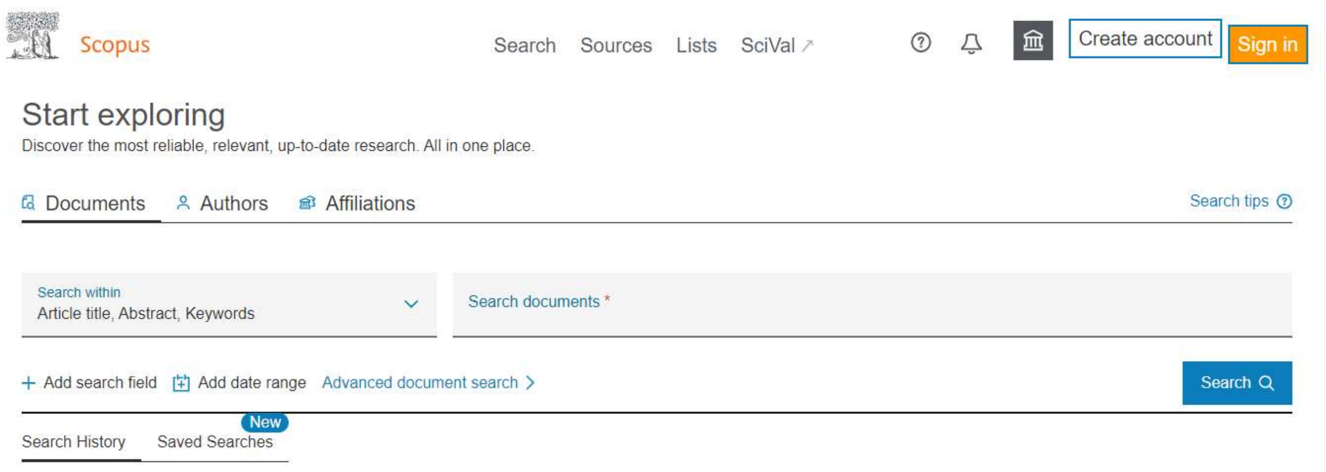

Figure 7: Scopus website initial page.

As it was mentioned before, for a more specific investigation, "Advanced document search" was used.

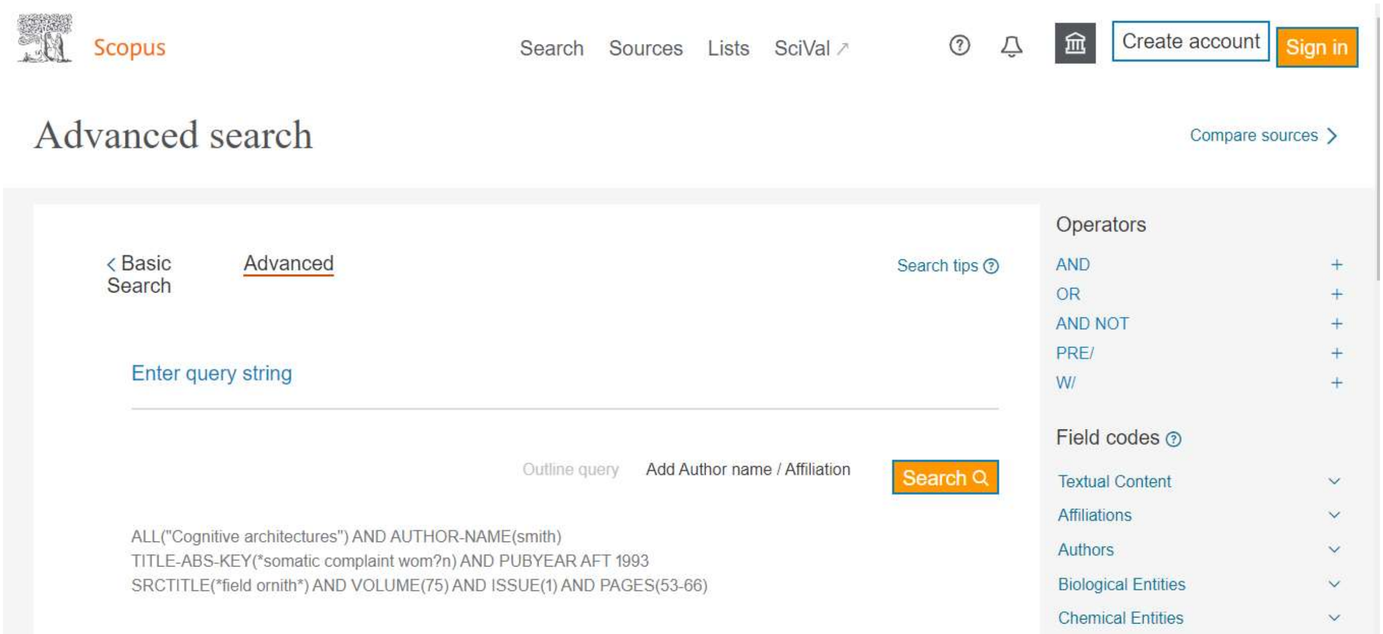

Figure 8: Scopus advanced search page.

As it can be seen on the right part of the screenshot of Figure 8, the two main ways to customize the searching are:

- Operators
- Field codes

2.2.1 Boolean operators

Operators can be divided in two main groups, Boolean operators, and proximity operators that their main function is to help users to limit the search results. In the research done for this thesis only Boolean operators were used.

The Boolean operators are the following ones:

- AND,
- OR, and
- NOT

Boolean operators are used to combine more than one term with a logic in order to for example search for documents that contain the word robot AND collaboration, or another example the word Cobots OR collaborative robots. Instead, the last Boolean operators NOT was not used as there were not searches that required to do so.

The operator AND helps to limit the number and results and to clear them in order to reach the more valuable ones for the purpose of the investigation, by making the search more specific. On the other hand, the operator OR, expands the number of results as it allows to show results that include 1 or both of the terms.

On Table 2, the operators and description are summarized:

Code	Name	Description	Note
AND	And	When you want your results to include all terms and the terms may be far apart.	When you use AND only documents that contain all of the terms will be found. If you are searching for a phrase which contains the word "and," omit the word "and" from your search string. For example, "profit loss" will find the phrase "profit and loss".
OR	Or	Use OR when your results must include one or more of the terms (such as synonyms, alternate spellings, or abbreviations). Documents that contain any of the words will be found.	
AND NOT	(And) Not	Use AND NOT to exclude specific terms.	When you use more than one Boolean connector, AND NOT must be at the end of the search string or contained within parenthesis.

Table 2: Boolean operators. Source: Scopus

There are some rules for a correct use of Boolean operators:

1. Advanced searches with multiple operators are processed using the following order of precedence:
    - OR
    - AND
    - NOT
2. AND NOT should always be used at the end of the query.
3. To search for a specific phrase, enclose the terms in double quotes (" ") or for an exact match use bracket ({}).

2.2.2 Field codes

The field codes are also called search filters. It is useful to search a term on a specific field. The format is: *field_code(search term).*

For example, it is useful when the user wants to have only the results that contains the term in the title, abstract and key words.

- TITLE-ABS-KEY(cobot*) will return documents where the terms cobot, cobots, or cobotics appear in the title, abstract or keywords.

It is important to highlight that it may occur that a document does not contain all fields, therefore searching for specific fields could prevent some articles from appearing in your search results.

The field codes that are more commonly used are presented on Table 3:

Name	Code	Category	Description	Example
Doc Title	TITLE	Textual Content	The title of a document.	Entering TITLE("neuropsychological evidence") will return documents with the phrase "neuropsychological evidence" in their title.
Doc Title, Abstract, Keyword	TITLE-ABS-KEY	Textual Content	A combined field that searches abstracts, keywords, and document titles.	Entering TITLE-ABS-KEY("heart attack") will return documents with "heart attack" in their abstracts, article titles, or keyword fields.

Affiliation ID	AF-ID	Affiliations	A unique identification number assigned to organizations affiliation with Scopus authors.	Entering AF-ID(Harvard Medical School 3000604) or AF-ID(3000604) will return documents written by authors affiliated with Harvard Medical School and variants of that name store in Scopus.
Author ID	AU-ID	Affiliations	The Scopus Author Identifier distinguishes between ambiguous names by assigning each author in Scopus a unique number and grouping together all of the documents written by that author.	Entering AU-ID(Sato, A. 100038831) or AU-ID(100038831) will return documents authored by Sato, A. and variants of that name stored in Scopus.
ORCID	ORCID	Affiliations	An ORCID is a 16-digit number and is used by editors, funding agencies, publishers, and institutions to reliably identify individuals in the same was that ISBNs and DOIs identify books and articles.	An ORCID ID must be entered as a 16 digit number (hyphens are not counted). ORCID("0000-0002-1108-3360")
Funding Information	FUND-ALL	Funding	A combined field that searches the Funding acknowledgement text as well as the following Funding fields: FUND-NO, FUND-ACR, FUND-SPONSOR.	FUND-ALL(NIH 5RO1AI091972-3)
Keywords	KEY	Keywords	A combined field that searches the AUTHKEY, INDEXTERMS, TRADENAME, and CHEMNAME fields.	Entering KEY(oscillator) will return documents where "oscillator" is a keyword.

ISSN	ISSN	Publication	A unique identification number assigned to all serial publications.	Entering ISSN(0-7623-106) or (07623106) will return documents containing "0762310669" as well as any other document containing single or multiple hyphens in any possible combination within "0-7623-106".
Reference	REF	References	REF is a combined field that searches the REFAUTH, REFTITLE, REFSRCTITLE, REFPUBYEAR, REFPAGE and WEBSITE fields.	To find documents where your search terms occur in the same reference, use: REF(darwin 1859).
			When searching the REF field, you can specify if you want all of your search terms to be found in the same reference.	To find documents where both terms appear in a document, but not necessarily in the same reference, use: REF(darwin) AND REF(1859).
Subject Areas	SUBJAREA	Subject Areas	Returns documents classified under specific subject areas in the four sub-categories Health Sciences, Life Sciences, Physical Sciences, and Social Sciences.	

Table 3. Top 10 field codes. Source: Scopus

2.2.3 Find exact or approximate phrases and words

The results returned by the engine will be different based on the way the term is written.

- Loose phrase: TITLE-ABS-KEY("collaborative robots") searches for documents where collaborative robots appear together in the title, abstract, or keywords.
- Not a loose phrase: TITLE-ABS-KEY(collaborative robots) searches for documents where collaborative and robots appear together or separately in the title, abstract, or keywords. Therefore, more results will be returned, and if the objective of the

search was to find specific collaborative robots documents, it would be more difficult to identify the useful documents.

2.3 Working with document search results

There are some other strategies to find more accurate documents within the results of the first search.

An option is the examination of keywords and subjects occurring in relevant articles and using these in subsequent searches.

Another way of working with the search results is to the something called “Limit to” or “Exclude” results. Is the possibility to filter the results by certain categories. For example, limiting the search results to the ones that have as a keyword a term of interest.

It is always possible to restore the original settings if while working with the search results its realised that is necessary to go back to the original set of documents.

2.4 Statistics of literature

2.4.1 How statistics are obtained

A remarkable feature is that these websites offer the possibility to perform customized search results analysis. For example, it is possible to analyse the distribution of the number of documents over the years, by source, by author, and the list can go on.

Normally the analysis of search result of the different websites used for this thesis, allows to show the documents broken down by:

- Year of publication
- Source
- Author
- Affiliation
- Country/territory
- Document type
- Subject area
- Source type
- Funding sponsor

This is a very useful tool as it allows to understand the investigation done on a certain field and the gaps to be filled in future research.

An analysis done to the search results is presented below, from which some conclusions will be drawn.

3. HUMAN-ROBOT COLLABORATION SYSTEMS IN MANUFACTURING

In the following chapter the different searches done will be presented in order to analyse the results obtained, and to draw conclusions from the statistics of the literature.

The searches will be presented in order, from the broadest to the more specific one, where more of the tools explained in Chapter 2 were applied in order to obtain the specific documents of interest.

Once all the searches are done, it is important to select the documents that are useful for the investigation, as clearly it is impossible to analyse all the papers that are found. The selected literature will be presented, and conclusions will be driven.

Finally, a brief summary of the concepts and applications found on the selected literature is given, in order to introduce the main definitions and topic of interest to the further analysis done in Chapter 4.

3.1 First level search

ALL ("collaborative robot") AND (LIMIT-TO (EXACTKEYWORD , "Collaborative Robots") OR LIMIT-TO (EXACTKEYWORD , "Human Robot Interaction") OR LIMIT-TO (EXACTKEYWORD , "Human-robot Collaboration") OR LIMIT-TO (EXACTKEYWORD , "Collaborative Robotics") OR LIMIT-TO (EXACTKEYWORD , "Collaborative Robot") OR LIMIT-TO (EXACTKEYWORD , "Robot Applications") OR LIMIT-TO (EXACTKEYWORD , "Human-Robot Collaboration") OR LIMIT-TO (EXACTKEYWORD , "Human-robot Cooperation") OR LIMIT-TO (EXACTKEYWORD , "Physical Human-robot Interaction"))*

This first search was carried out using much of the tools that were explained on Chapter 2. The main objective was to collect as much as documents as possible that refer to Human-Robot Collaboration Systems.

The main restrictions that were added to the search was to give the results that also contained the following terms as keywords:

- Collaborative Robots
- Human Robot Interaction
- Human-robot Collaboration
- Collaborative Robotics
- Collaborative Robot

- Robot Applications
- Human-Robot Collaboration
- Human-robot Cooperation
- Physical Human-robot Interaction

These measures helped to improve the search, and the number of documents reached was 2196.

Analysing the results obtained, it can be noticed an interesting trend, represented in Figure 9 which shows the number of documents published per year for this search.

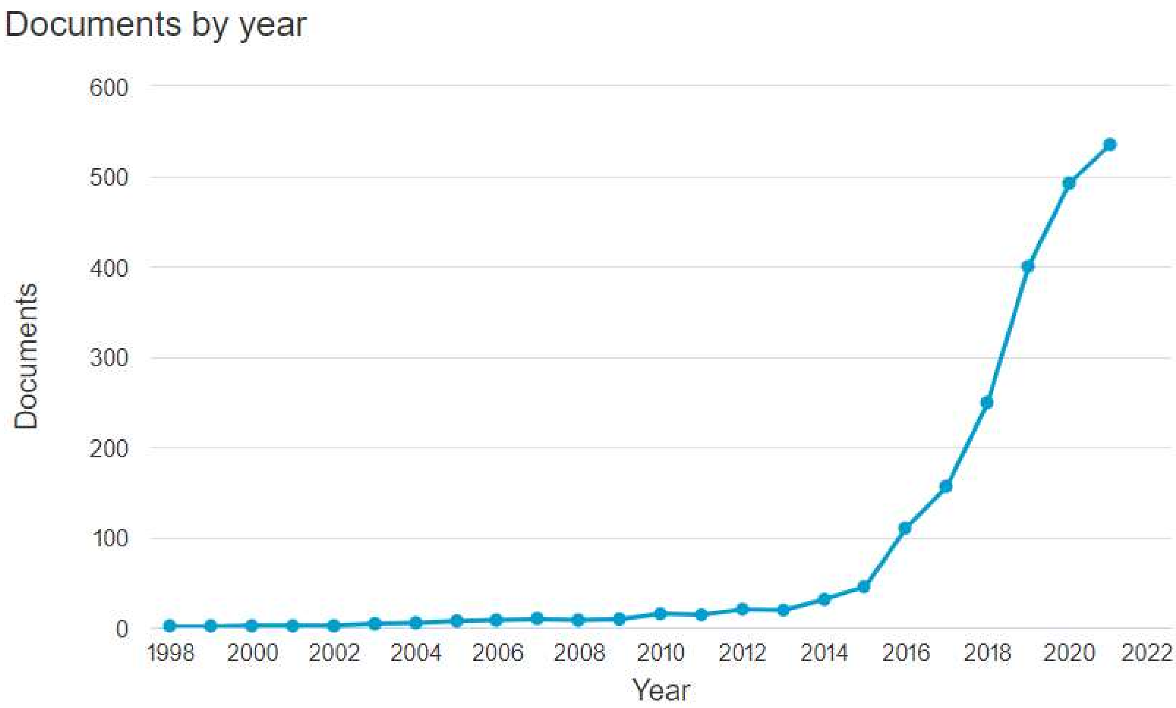

Figure 99: First level search results per year. Source: Scopus.

The country of origin of the publications has United States at the head of the list, followed closely by Italy and Germany.

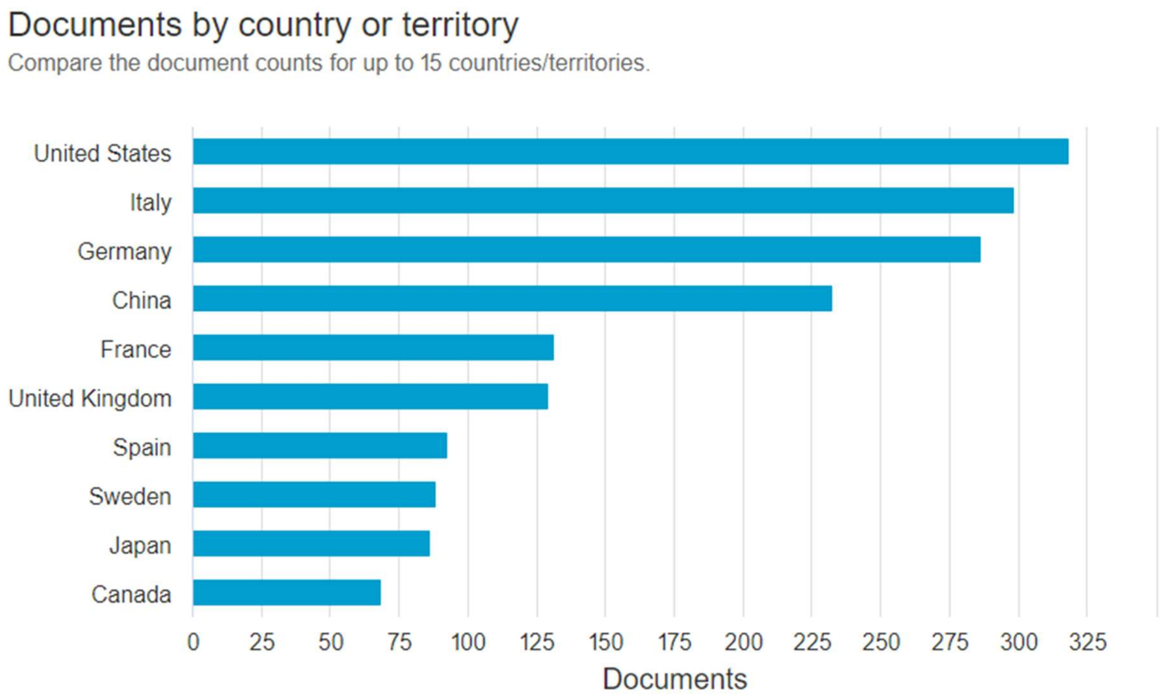

Figure 10: First level search results per country. Source: Scopus.

As the number of results obtained is high, it is also interesting to analyse the different subject areas to which they refer. Not surprisingly, engineering and computer science together englobe around the 70% of the publications.

A more detailed view of the different areas is presented on Figure 15:

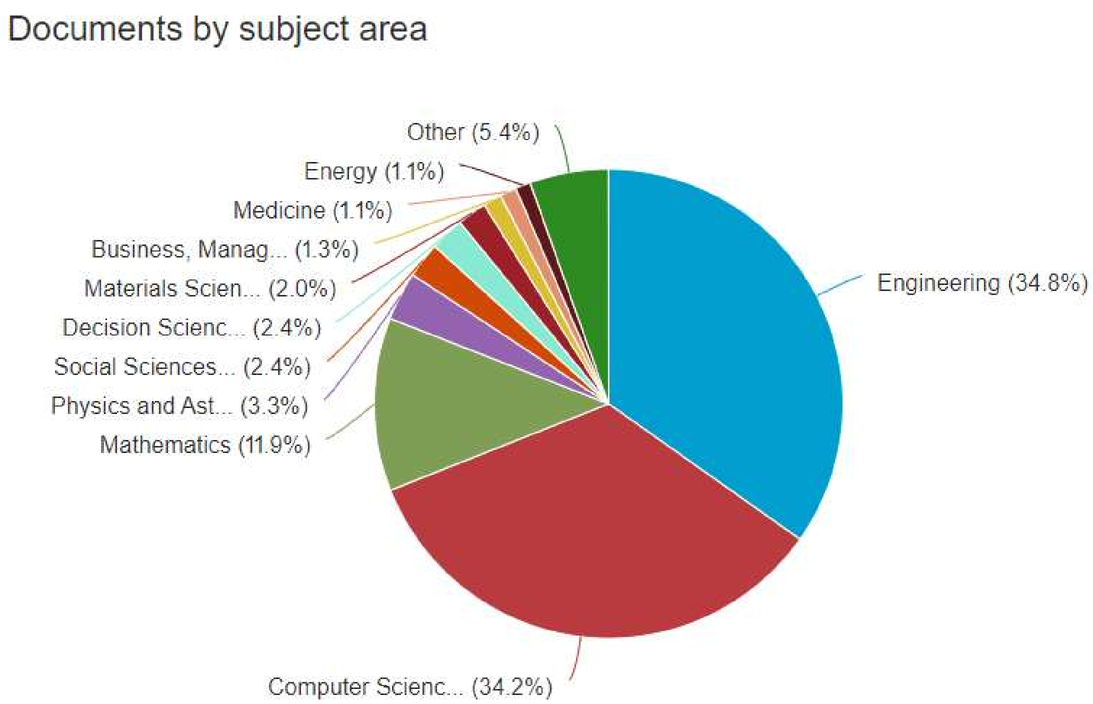

Figure 101: First level search results per subject area. Source: Scopus.

3.2 Second level search

TITLE-ABS-KEY (cobot)*

The definition of Cobot was given at the beginning of the research, and for a proper investigation and data collection, documents with the word Cobot included in their title, abstract or as a keyword were searched on Scopus. The results obtained were 656 documents.

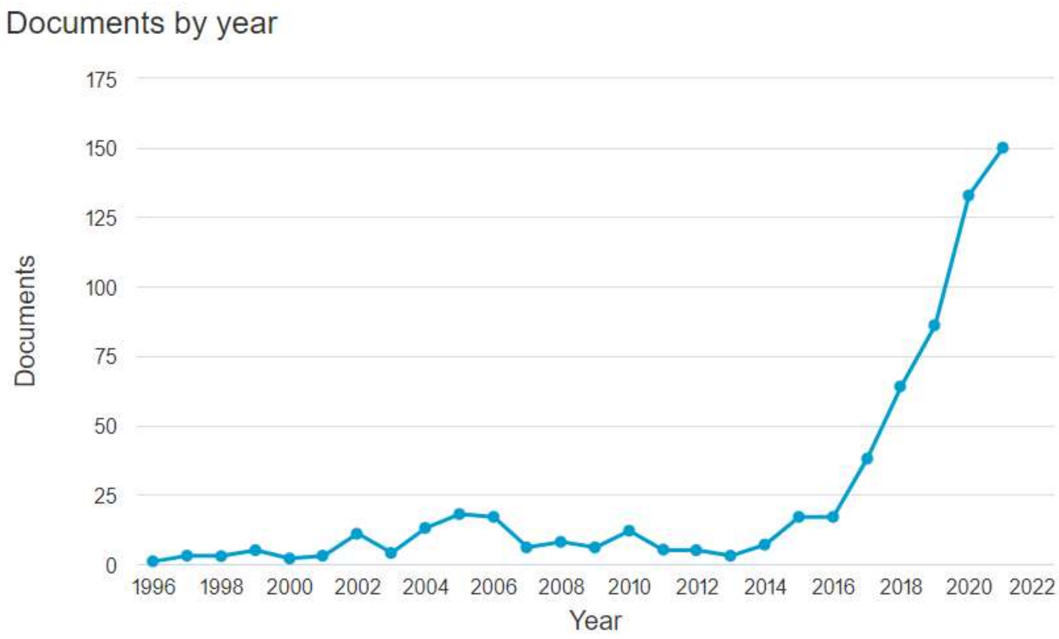

Figure 12: Second level search results per year. Source: Scopus.

From Figure 9 it can be read that, the term Cobot was first used in an article in the year 1996, growing enormously during the last years.

During the first years, from 1996 to 2003, the number of documents published that talked exclusively about Cobots or dedicated to Cobot-related topics remained low and constant. Around 3 or 5 articles were published per year, with the exception of 2002, when there were 11 publications. Between the years 2004 and 2007, the topic gained more popularity, with a peak of 18 publications being observed during the year 2005. However, after the increase in interest received during this period, a depression period was faced from 2008 to 2014 were the publications made scarcely reached the number of 8. Eventually, this situation changed drastically in 2015, surely closely related to the expansion of Industry 4.0.

In fact, in the middle of 2014, the paper “Industry 4.0” by German Dr. Heiner Lasi was published, which certainly brought much more popularity to the topic.

The exponential growth of publications about collaborative systems made since 2015 to the present, is intrinsically related to this fact, considering that paper is one of the pillars of Industry 4.0.

Most of these publications were authored by American authors, accounting for about 20% of the total number of publications. But this can be explained considering the fact that 95% of the results are written in English.

Continuing with the analysis of the countries with the highest number of publications, the ones that lead the list are United States, followed by France and Italy.

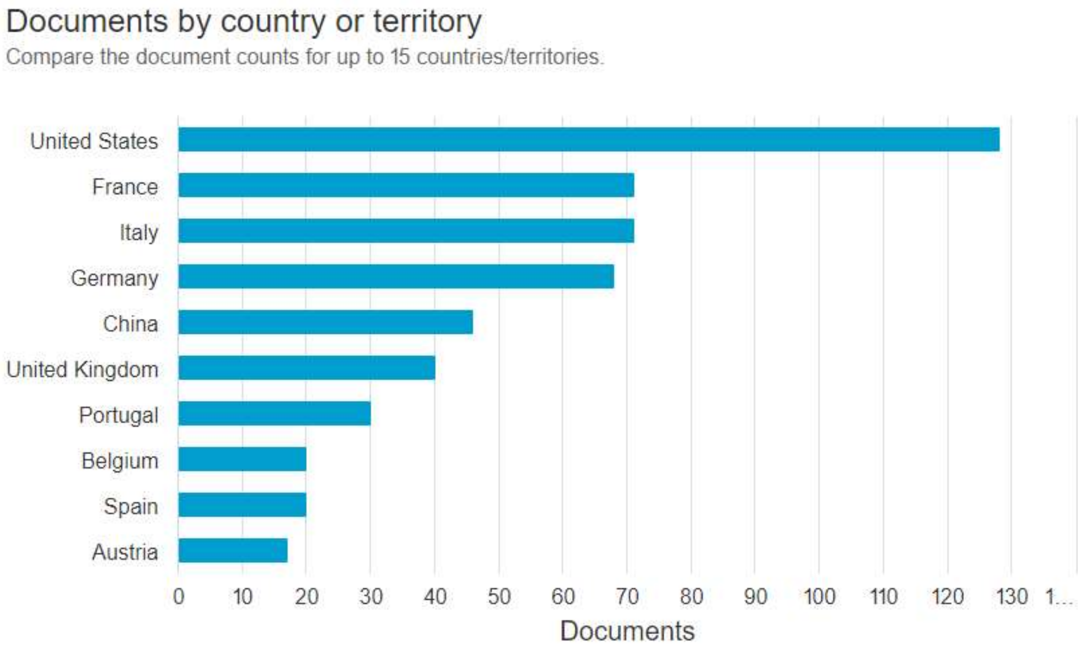

Figure 13: Second level search results per country. Source: Scopus.

If we make an insight and a more detailed reading about the origin of the italian publications, the result given is the one presented on Figure 11:

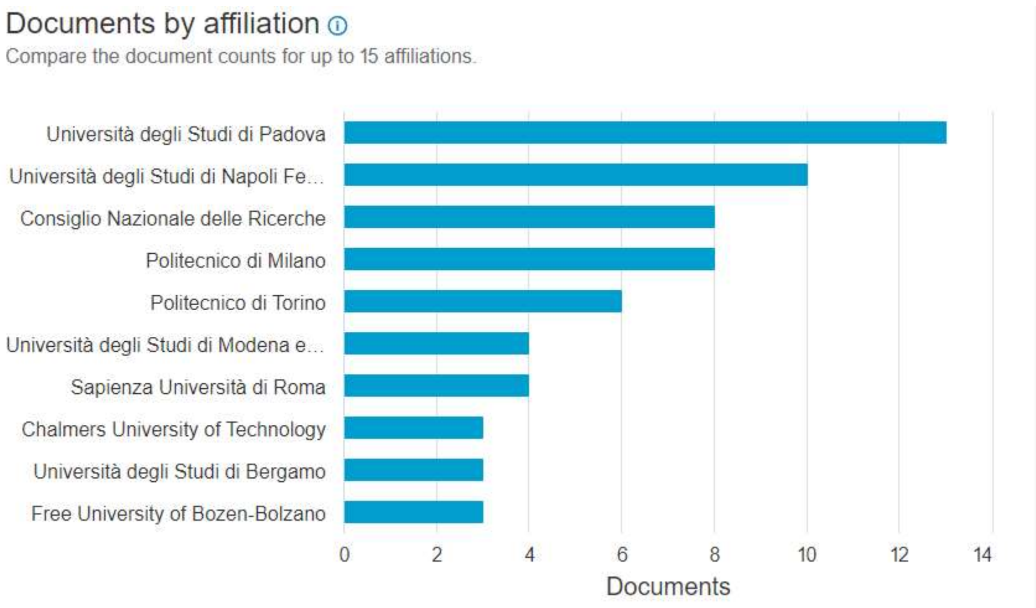

Figure 14: Second level search results per affiliation. Source: Scopus.

All the affiliates that are currently studying and conducting research on this topic are universities and research entities, which means that even though research in the field is growing, it is mostly in an academic and theoretical environment. Considering this reality, the next big challenge is to move all this academic research to an industrial environment, i.e., that this begins to be put into practice and to have it more applied in the field.

One particular reason why many publications have not appeared under the keyword search "Cobot" in comparison to the First Level Search, may be that the term Cobot, as the abbreviation of collaborative robots is not that well known or sufficiently diffused, and researchers may not have used it at their publication, so it was more convenient to perform a search for the complete term "collaborative robot*", with an *, making it possible to also find in the search articles containing for example "collaborative robotics", "collaborative robots" as results.

3.3 Third level search

ALL ("collaborative robots applications")

Following the same logic and carrying out the same procedure previously applied, through the Scopus site, the scope of this new search was to gain a better understanding about the different types of fields of applications in which collaborative robots can and are being used nowadays.

Analysing the country of publication of these documents, the results obtained were a little bit different to the ones of the first search. The leader country on the application of collaborative robots is Germany with 20 documents, country in which the development and research of Industry 4.0 were born.

However, not so far from Germany, Italy with 17 publications follows the list. This information, together with the results from the first and second search, allows to conclude that in Italy collaborative robots are a field in which not only researchers are interested in but also those who will eventually make use of them in the industries.

Still the percentage of articles specifically related to collaborative robots' applications is really small compared to the ones from collaborative robots in general. While the outcome of the first search was 656 documents, the one from the application only reached just 90 documents.

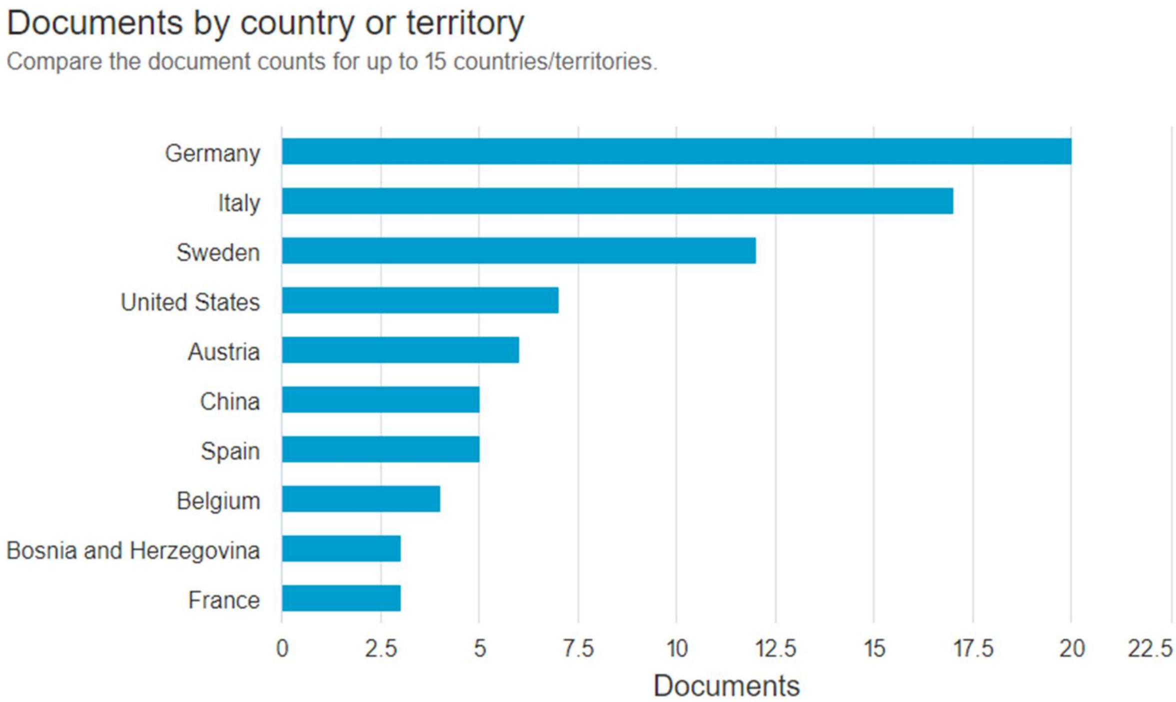

Figure 115: Third level search results per country. Source: Scopus.

3.4 Fourth level search

ALL ("collaborative robot") AND (LIMIT-TO (EXACTKEYWORD , "Collaborative Robots") OR LIMIT-TO (EXACTKEYWORD , "Human Robot Interaction") OR LIMIT-TO (EXACTKEYWORD , "Human-robot Collaboration") OR LIMIT-TO (EXACTKEYWORD , "Collaborative Robotics") OR LIMIT-TO (EXACTKEYWORD , "Collaborative Robot") OR LIMIT-TO (EXACTKEYWORD , "Robot Applications") OR LIMIT-TO (EXACTKEYWORD , "Human-Robot Collaboration") OR LIMIT-TO (EXACTKEYWORD , "Human-robot Cooperation") OR LIMIT-TO (EXACTKEYWORD , "Physical Human-robot Interaction")) AND (LIMIT-TO (EXACTKEYWORD , "Quality Control") OR LIMIT-TO (EXACTKEYWORD , "Quality Inspection")).*

This last search was performed with the objective of finding the specific articles of interest for this thesis, which is the application of collaborative robots in quality inspection in manufacturing industries.

Even though collaborative robotics is a field with a lot and growing popularity nowadays, it is not the same for the subfield of quality inspection application.

Only 21 results were found, and most of them were out of the scope of this thesis. Moreover, it is not a field really covered by Italian researchers, since it has only one of these 21 publications, being at the bottom of the list, this is visible at the below graph.
This leaves a gap, creating a potential new research field to be covered in the coming years, considering the advantages and benefits of this specific application.

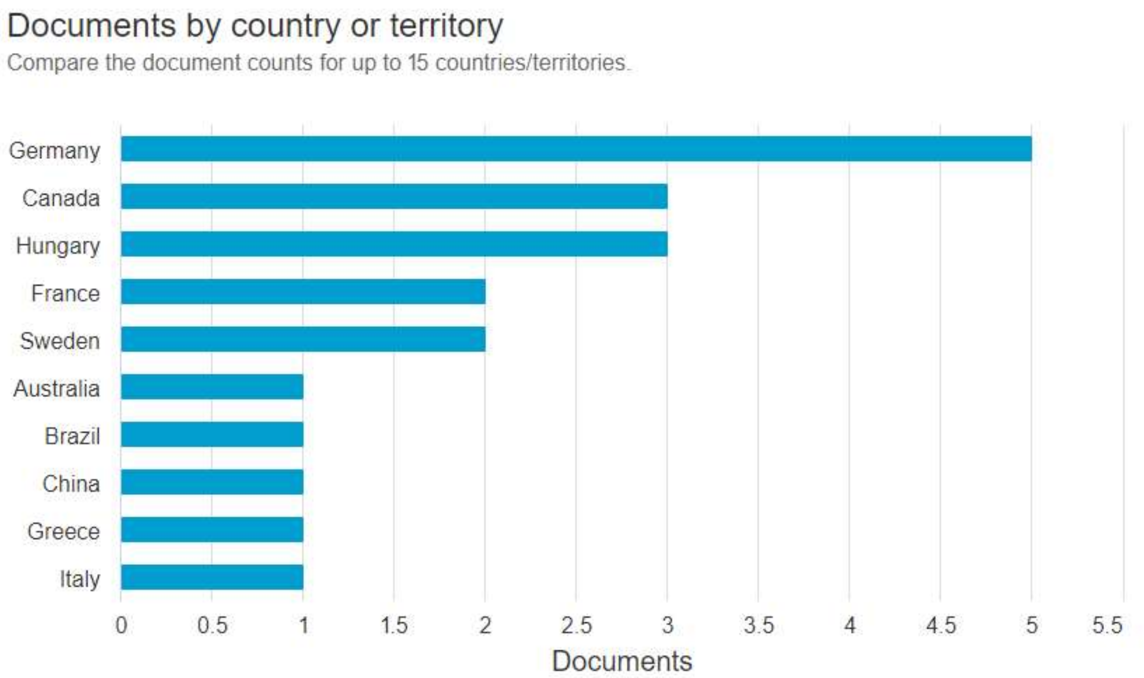

Figure 12: Fourth level search results per country. Source: Scopus.

3.5 Selected literature

Once all the searches where done, and as it was stated at the beginning of the chapter, it is meaningful to select the specific documents of interest, that provides the most valuable content for the investigation, for the Human-Robot Collaboration Systems in Manufacturing topic only. The specific articles for the Quality Control in Human-Robot Collaboration found on the fourth level search will be analysed in Chapter 4.
At the Table 4 the selected literature is presented, with some specific information such as authors, year of publication, country; through which it is possible to perform an analysis of the sample.

Short name	Title	Year	Author(s)	Country
Goodrich, 2008	Human–Robot Interaction: A Survey	2008	Michael A. Goodrich and Alan C. Schultz	United States

Bauer, 2008	Human-Robot Collaboration: A Survey	2008	Andrea Bauer, Dirk Wollherr, Martin Buss	Germany
Villani, 2018	Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications	2018	Valeria Villani, Fabio Pini, Francesco Leali, Cristian Secchia	Italy
Wang, 2019	Symbiotic human-robot collaborative assembly	2019	L. Wang, R. Gao, J. Váncza, J. Krüger, X.V. Wang, S. Makris, G. Chryssolouris	Sweden,
Hentout, 2019	Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017	2019	Abdelfetah Hentout, Mustapha Aouache, Abderraouf Maoudj & Isma Akli	Algeria
Knudsen, 2020	Collaborative Robots: Frontiers of Current Literature	2020	Mikkel Knudsen and Jari Kaivo-Oja	Finland
Vicentini, 2021	Collaborative Robotics: A Survey	2021	Federico Vicentini	Italy
Gervasi, 2020	A conceptual framework to evaluate human-robot collaboration	2020	Riccardo Gervasi, Luca Mastrogiacomo, Fiorenzo Franceschini	Italy
Gualtieri, 2021	Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review	2021	Luca Gualtieri, Erwin Rauch, Renato Vidoni	Italy
Berglund,2019	Strategies for Implementing Collaborative Robot Applications for the Operator 4.0	2019	Åsa Fast-Berglund and David Romero	Sweden
Cherubini,2016	Collaborative manufacturing with physical human–robot interaction	2016	Andrea Cherubini, Robin Passama, André Crosnier, Antoine Lasnier, Philippe Fraisse	France
De Luca, 2012	Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration	2012	Alessandro De Luca and Fabrizio Flacco	Italy
Gienger, 2018	Human-Robot Cooperative Object Manipulation with Contact Changes	2018	Michael Gienger, Dirk Ruiken, Tamas Bates, Mohamed Regaieg, Michael Meißner, Jens Kober, Philipp Seiwald, Arne-Christoph Hildebrandt	Germany

Grau, 2021	Robots in Industry: The Past, Present, and Future of a Growing Collaboration With Human	2021	ANTONI GRAU, MARINA INDRI, LUCIA LO BELLO, and THILO SAUTER	Spain
Kadir, 2018	DESIGNING HUMAN-ROBOT COLLABORATIONS IN INDUSTRY 4.0: EXPLORATIVE CASE STUDIES	2018	B. A. Kadir, O. Broberg and C. Souza da Conceição	Denmark
Kosuge, 1997	Control of a Robot Handling and Object in Cooperation with a Human	1997	Kazuhiro KOSUGE and Norihide KAZAMURA	Japan
Krieger, 2021	The Future of Human-Robot Interaction	2021	Benedikt Krieger	Sweden
Krüger, 2009	Cooperation of human and machines in assembly lines	2009	J. Kru¨ ger, T.K. Lien, A. Verl	Germany
Levratti, 2016	TIREBOT: a Novel Tire Workshop Assistant Robot	2016	Alessio Levratti and Antonio De Vuono and Cesare Fantuzzi and Cristian Secchi	Canada
Li, 2005	Hierarchical Modeling and Recognition of Manipulative Gesture	2005	Zhe Li, Nils Hofemann, Jannik Fritsch, and Gerhard Sagerer	Germany
Magrini, 2020	Human-robot coexistence and interaction in open industrial cells	2020	Emanuele Magrinia, Federica Ferraguti, Andrea Jacopo Ronga, Fabio Pini, Alessandro De Luca, Francesco Leali	Italy
Michalos, 2014	ROBO-PARTNER: Seamless Human-Robot Cooperation for Intelligent, Flexible and Safe Operations in the Assembly Factories of the Future	2014	George Michalos, Sotiris Makris, Jason Spiliotopoulos, Ioannis Misios, Panagiota Tsarouchi, George Chryssolouris	Greece
Pavlovic, 1997	Visual Interpretation of Hand Gestures for Human-Computer Interaction: A Review	1997	Vladimir I. Pavlovic, Rajeev Sharma and Thomas S. Huang	United States
Pfeiffer, 2016	Robots, Industry 4.0 and Humans, or Why Assembly Work Is More than Routine Work	2016	Sabine Pfeiffe	Germany
Sherwani, 2020	Collaborative Robots and Industrial Revolution 4.0	2020	F. Sherwani, Muhammad Mujtaba Asad and B.S.K.K. Ibrahim	Pakistan

Shi, 2012	Levels of Human and Robot Collaboration for Automotive Manufacturing	2012	Jane Shi, Glenn Jimmerson, Tom Pearson and Roland Menassa	United States
Tsarouchi, 2017	On a human-robot collaboration in an assembly cell	2017	Panagiota Tsarouchi, Alexandros-Stereos Matthaiakis, Sotiris Makris & George Chryssolouris	Greece
Unhelkar, 2015	Challenges in Developing a Collaborative Robotic Assistant for Automotive Assembly Lines	2015	Vaibhav V. Unhelkar and Julie A. Shah	United States
Vojic, 2020	Applications of collaborative industrial robots	2020	Samir Vojić	Bosnia and Herzegovina
Yanco, 2004	Classifying Human-Robot Interaction: An Updated Taxonomy	2004	Holly A. Yanco and Jill Drury	United States
Zaatari, 2019	Cobot programming for collaborative industrial tasks: An overview	2019	Shirine El Zaatari, Mohamed Marei, Weidong Li and Dr Zahid Usman	United Kingdom
Zentay, 2021	Aspects of Industrial Applications of Collaborative Robots	2021	Peter Zentay, Lajos Kutrovacz, Mark Ottlakan, and Tibor Szalay	Hungary

Table 4: Human-Robot Collaboration on manufacturing systems selected literature.

The final sample is made up of 32 documents from different countries.

In order to compare these selected results with the general statistics presented first, the same graphs will be constructed. Making possible to infer if the sample behaves similar or not to the whole literature results.

3.5.1 Documents per year

The below bar chart on Figure 17 shows the distribution of quantity of documents selected per year.

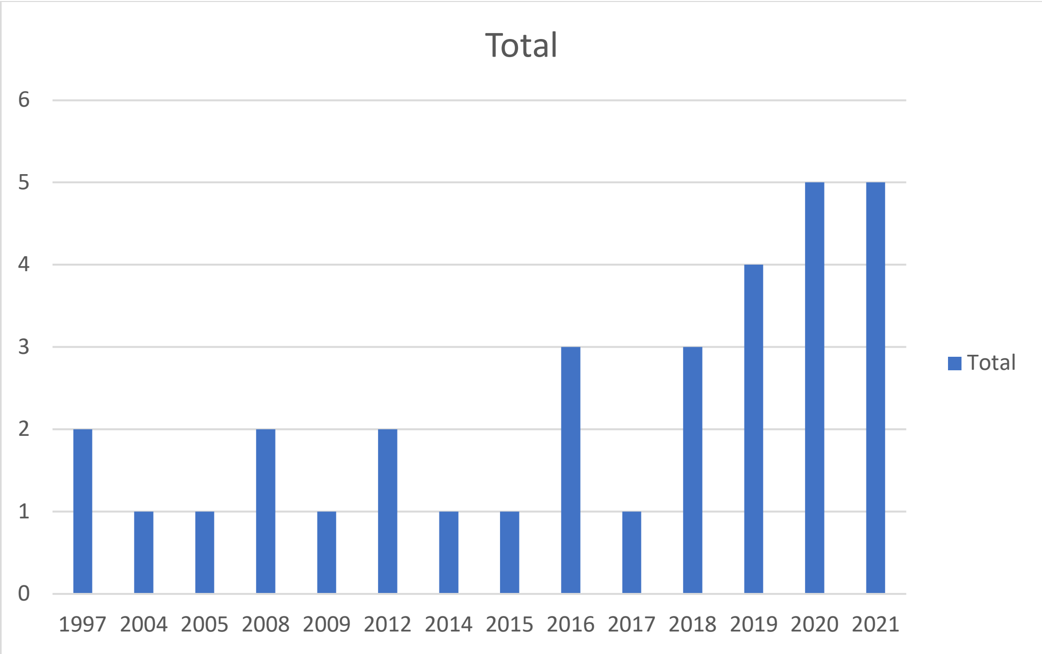

Figure 13: Selected literature per year.

Comparing this graph with the one present in the section 3.1 First level search referred to all the results, it can be deduced that the behaviour resembles, with articles starting at the end of last century, up to 2021.

The trend is repeated, with a considerable growth of articles during the last years. The only difference is that the starting point of the rise, when referring to all the documents is clearly marked with the expansion of Industry 4.0 at the year 2014. Instead, the sample of selected literature has the point of rise short time later, on the year 2016.

This could be clearly explained by the fact that the documents of interest are more likely to be the most up-to-date ones, using the oldest ones to understand the origin of the topic and the basis.

3.5.2 Country of Origin

For a second analysis and contrasting of the selected literature, the distribution of the country of origin of the documents is showed in the following pie chart.

The selection of countries was based on the country of affiliation of the first author of each paper.

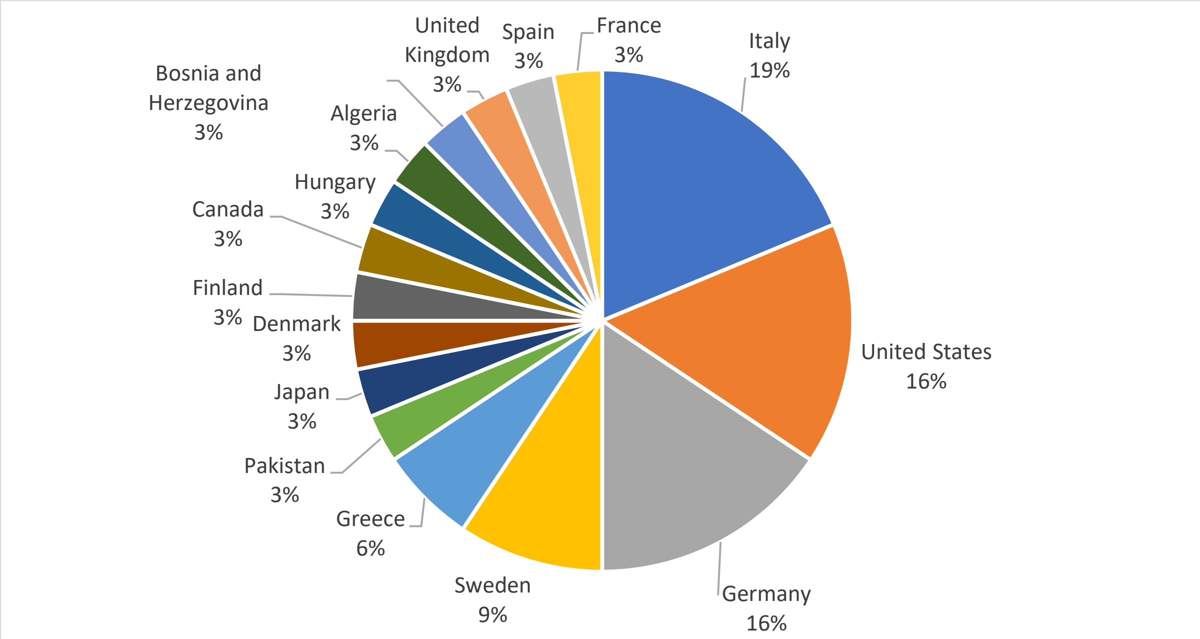

Figure 14: Selected literature per country.

There are three countries that are clearly leading the list. They are Italy (19%), Germany (16%) and United States (16%), and together englobe the 47% of the documents analysed. This top 3 countries were also leading the graphs of the country origin in the sections 3.1 to 3.3. The only difference is that countries such as France and Sweden that were also in the top 3 in the general results, when analysing the selected literature, they are not.

Germany is a country were Industry 4.0 was practically born, so it is not surprising that collaborative robots being one of the concepts of interested is also well diffused. The United Stated is well-known about all the investigation done in the technological field. And Italy clearly highlights having such high percentage in comparison with other countries.

3.6 Analysis and summary of the selected literature

A detailed reading and analysis of the selected literature was done in order to understand the state-of-the art of the Human-Robot Collaboration Systems in the Manufacturing field. Most recent documents, introduce the topic highlighting the necessity of rapid, proactive responses to ever-changing consumers' demands, in the industry 4.0 era. (Zaatari, 2019). This implies shorter development times, increased individualized customization, higher flexibility, and resource efficiency. Introducing the concept of smart factory where everything is interconnected, equipped with sensors, and functions as an autonomous and self-organising system that requires minimal human intervention with the capability of adapting to human needs. (Lasi, 2014; Kadir, 2018), and how collaborative robots play an important role in realizing this. (Zentay, 2021), and being pivotal role for today's manufacturing industry to be competitive. (Villani, 2018).

A common affirmation that most of authors state is that the main benefit of Human-Robot Collaboration systems is the fact of combining the advantages of automation, repetitiveness, accuracy of robots with the flexibility and cognitive and soft skills of human workers. (Villani, 2018). The main objective of the robot is to assist the human in tedious, repetitive, and stressful tasks, reliving from non-value-adding job the operator, and allowing to focus on more skilled tasks.

Another advantage of using collaborative robots in manufacturing is that they are really adaptable to achieve mass customisation, they do not require much floor space, while increasing the product quality and production efficiency and improve working conditions for humans. (Zaatari, 2019), in contrast with traditional industrial robots mainly present in the factories, are fixed for a specific application, and as they are not safe for workers, fencing is required.

The fact that the operator and the collaborative robot can coexist on the same physical space, being safe for the human, and behaving as an equal partner, has completely changed the paradigm of what it was known as production lines, becoming more flexible manufacturing/assembly cells, and positioning the robot as an organic part of the production instead of playing a central role. (Zentay, 2021).

The safety assurance is not a minor topic, and in fact is something that all authors include in their work. Safety is the inherent and most important feature of a robot that has to work close to human beings. (De Luca, 2021). No Human-Robot Collaboration can exist or even be considered if the framework is not developed and thought on a way that it is not dangerous for the human operator. The Cobot must adapt to the human, help him, and not to entail a risk to its health and safety. One of the ways to achieve this is that Cobots are equipped with sensors and are highly responsive to the detection of any unexpected force, granting them the ability to stop immediately when encountering human workers or any misplaced objects in their path. This makes them highly reliable colleagues when it comes to workplace safety. (Kadir, 2018).

(Sherwani, 2020; Zaatari, 2019; Magrini, 2020), just to mention some of them, summarize how safety is commonly achieved through different features when it comes to Human-Robot collaboration, based on the ISO 10218-1/2.

- **Safety rated stop monitoring**, is the inherent capacity of the collaborative robot to stop the action being performed if it is detected that the human operator is interfering the workspace where the robot must pass through. The robot is equipped with sensors in order to detect the operator. This explicitly consists of no motion of the robot if the operator is inside the robot's meaning that the robot and the operator can work together, but not at the same time.
- **Hand guiding feature**, mostly used on the training phase of the robot, the operator teaches the robot the trajectory that must follow in a safely manner. This provides the possibility to perform complex tasks without the necessity of explicit programming. The safety on this case is assured because the robot is being guided manually and controlled at an appropriately reduced speed.
- **Speed and Separation Monitoring**, this is designed to make the robots movements change with respect of the position of the operator. This means that the robot will perform the movements in a lower speed when the human is nearby. This results that the process is a bit slower when it is done on a collaborative way, in comparison to a full automated one, where no human intervention exists. Basically, the variable of speed depends on the distance between operator and robot, and this is usually measured by scanners or vision systems.
- **Power and Force Limitation** consists of reducing the force applied when the human is nearby, in order that if some contact occurs, the robot will not harm the operator. The methods to achieve this are: monitoring, force-torque sensors, compliant joints or intrinsically safe design through low-power actuators.

After this short introduction of the topic, in the following three sections, the main topics of interested regarding the Human-Robot Collaboration will be developed, as they are of high importance for the future analysis of the specific case studies in Quality Control and Inspection processes on Human-Robot Collaboration environments.

3.6.1 Different Human-Robot relationships

One of the starting points on most of the literature is the analysis of the different kind of relationships between human and robot that can be found. From a simple coexistence till, what is highly desired, a full collaboration.

In L. Wang's paper the different relationships and their characteristics are well summarized as follows:

Features of different human-robot relationships.

		Coexistence	Interaction	Cooperation	Collaboration
Shared	Workspace		✓	✓	✓
	Direct contact		✓		✓
	Working task		✓		✓
	Resource			✓	✓
	Simultaneous process	✓		✓	✓
	Sequential process		✓	✓	

Figure 15: Human-Robot types of relationships. Source: Wang, 2019.

These categories are presented from the broadest to the tighter one, meaning that as it goes forward the interaction also grows.

- **Coexistence** occurs when humans and robots share the physical space, but not a common task. It is the least form of human-robot relationship. An example of coexistence that also may be called coaction is when a robot and a human operator work together on the same object, without ever requiring mutual contact or coordination of actions and intentions (De Luca, 2012). Neither coordination nor direct contact between them exist, the work object might be exchanged between them, but the process is performed independently and simultaneously. The main concern is to avoid collisions. This first kind of relationship does not bring much benefit and interest for the study, considering that the situation is almost as the one present in traditional industrial robots, with the only difference that the operator and the machine share physically the workspace while performing simultaneously their processes, but without any interesting and advantageous interaction.
- **Interaction** between human and a robot exists when apart from sharing the workspace, they also communicate with each other in a physical or different way, by

contact, guiding or commanding. The process is done in a sequential way, where the human and the robot can work on the same task but complete the task step by step. It is a robotic system to be used by or with humans. It mainly refers to human activities that requires a robot intervention, or vice versa, a robot activity that uses a human intervention. One of the main differences with the following ones, is the fact that the interaction does not necessarily need a direct contact between human and robot, in fact for example in teleoperation, the human constantly guides the robot, but may not be in the same room or physical space. This is called “remote interaction”, and the human and the robot are not co-located. “Proximate interaction”, instead, is called when they are physically sharing the workspace.

- **Cooperation** is a step froward from interaction, because here the robot and the operator are working together for mutual benefits, but still each own has its one objective. The workspace and resources are shared, in a sequential and also simultaneous process. The work is divided in sub activities, that are then assigned respectively to operators and robots, and each one is responsible for their part of the job.
- **Collaboration**, the last kind of relationship defines, and the most important for this analysis. Here the robot is performing a complex task with direct human interaction and coordination (De Luca, 2012). Of course, when human and robots are collaborating, they share the same workspace, but they also share tasks, for a common objective. collaboration assumes a joint, focused goal-oriented activity from the parties who share their different capabilities, competences, and resources. The operator performs task parts requiring dexterity or decision-making, while the robot realizes parts that are not well suited to direct human involvement (repetitive or high-force applications, chemical deposition, precision placement, etc.). As it can be seen on the table above, the sequential process is not ticked, considering that those tasks are performed together and not step by step.

In Figure 20 the difference between the previous categories can be visually explained:

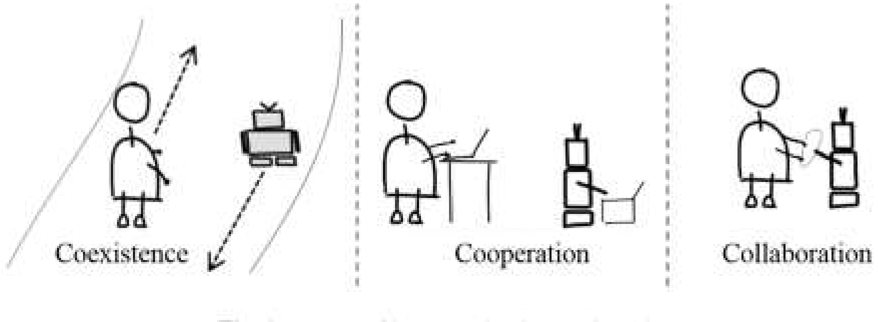

Figure 16: Forms of human-robot interaction. Source: Müller-Abdelrazeq, 2017.

With the only difference that it considers coexistence, cooperation, and collaboration as forms of human-robot interaction, as a major category that includes them.

Also, the classification can be found sometimes done in just two of those categories: Human-Robot Interaction (HRI) and Human-Robot Collaboration (HRC). Where basically the first one includes the latter one, englobing it. HRC shares many aspects with HRI and can be considered a sub-field of HRI.

HRI is more global and is a general field of study that is focus on understanding, designing and evaluating robotic systems to be used by or with humans.

HRC is specifically focused on the implementation of collaborative robots, that share space and tasks with people on a safe co-existence and a natural interaction with humans. This implies that collaborative robots need to have at least a minimum form of autonomy and possibly show initiative.

Once that the kind of relationship between the robot and the operator is defined, two key properties can be furthered described based on the combinations of single or multiple humans and robots. They define the distinct classes of HRC instances across all applications and are multiplicity and autonomy. (Wang, 2019)

(Wang, 2019) uses the agent multiplicity to distinguish single, multiple, and team settings, the latter being a group acting together by consensus or coordination and interacting with the environment and other agents in a specified. Figure 21 shows on a matrixial way all the possible cases of Agents Multiplicity between human and robots. Of course, in terms of simplification, when talking about multiple or team is does not mean that they can just be 2 agents, but also more.

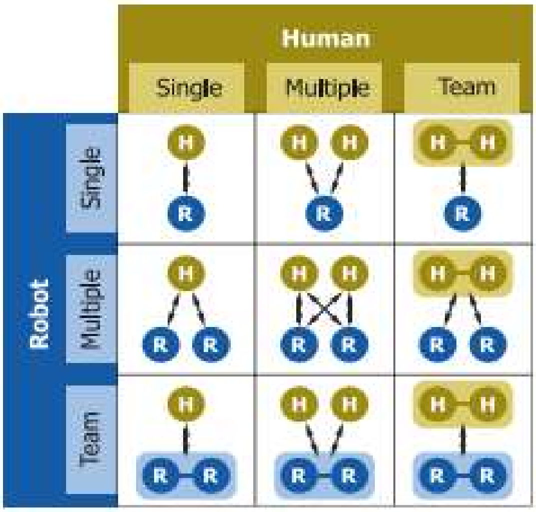

Figure 17: Possible cases of human and robots' agents' multiplicity. Source: Wang, 2019.

The origin of this graphic is found at (Yanco,2004), where he raises to questions that are important to answer when it comes to collaboration systems with more than one agent. The questions that need to be asked according to the author are:

- if there are multiple human controllers, are these humans agreeing on commands prior to providing the robot(s) direction, or are they independently issuing commands that robot(s) need to prioritize and or deconflict?
- Also, if there are multiple robots, are they each receiving and acting on commands independently, or are all robots receiving all commands and coordinating among themselves to determine which robot(s) should respond to which commands?

The second key property is the one called Agent autonomy and it basically expresses how much of robot action is directly determined by human agents, and vice versa (Wang, 2019). Different scenarios can be found, where the human or the robot may assume an active role, meaning the one leading the task, or to be a support, performing auxiliary tasks, and assisting the other agent. Or it is also possible to barely be involved and have an inactive role, with no responsibility on the task, and meaning an obstacle to the other agent. The role assignment is usually and most of the times done before the task is performed, in order to guarantee more coordination and correct functioning of the system.

The possible combinations of the agents' roles are showed on the Figure 22 matrixial image.

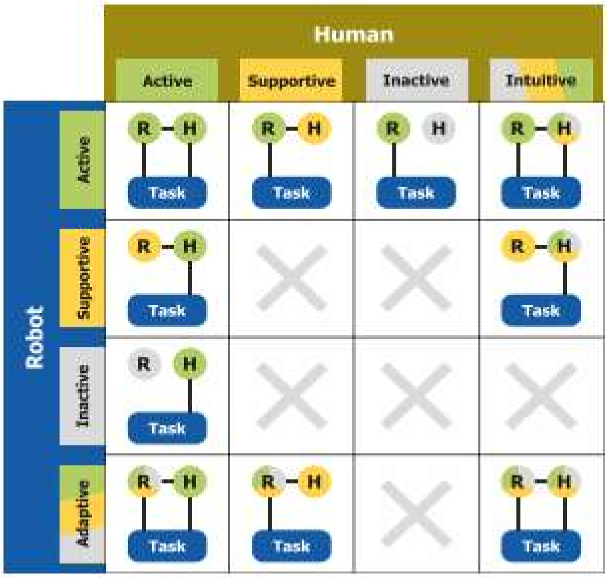

Figure 18: Possible combinations of the human and robots' agent's roles. Source: Wang, 2019.

All these concepts will be further used on Chapter 4 for the characterization of specific case studies of Quality Control and Inspection processes on Human-Robot Collaboration systems.

3.6.2 Human-Robot Communication

It is important for an efficient collaborative system to establish a good communication protocol among the human and the robot. (Makrini, 2017). This is a consequence of the high reliance of humans on communication to work in teams and complete tasks fluently and efficiently. (Zaatari, 2019). Through communication, it is possible to transmit information, command the robot, exchange of intentions, beliefs, desires, and goals in order to ensure shared beliefs between the agents and allow the execution of a shared plan. (Krieger, 2021) The communication between human and robot is crucial not only for the functioning of the system, but also for the safety assurance.

What many authors highlight is the idea of making robots and allowing them to behave as humans, in order that the communication is performed in a more natural way for the operator, allowing the ones with not much experience to interact with the robot with no previous knowledge required resulting an easy and efficient human-robot interaction.

In order to facilitate the communication, and to make it the most naturally possible, the main way of communication between robot and human consist of the typical channels such as speech, gestures, actions, that are the ones found and the normal and daily kinds of interaction between humans too.

The main challenge that can be found to guarantee a natural language system is that the language use differs drastically as the operator progresses with work, making the standardization of the communication difficult. (Zaatari, 2019)

The authors of many of the documents dedicate a section to talk about this, and all the ways of communication that they present are described on the following list:

- Speech or voice commanding: In general, voice commands channel remains the most preferred method to communicate with another agent, human or robot, thanks to many factors, such as the velocity and simplicity. (Hentout, 2019). It is also applied when the hands-free interaction is required, this means when the human operator's hands are occupied or basically gesture recognition is not feasible. (Villani, 2018). The main challenges regarding voice commanding is the industrial environment where the human-robot collaboration takes place, considering the surrounding noises and that the range where the voice can be detected by the robot is not unlimited. Also is important to consider when it comes to voice commanding is the fact that different operators have different type, tones, accents when talking.

  Therefore, what (Villani, 2018) presents as a solution to this is the idea to inform operators about the outcome of speech recognition, in order to prevent that any misrecognition is further processed by the system. (Villani, 2018)
- Vision based communication is a general classification that englobes different kind of communications that are based on a vision framework. Generally speaking, vision systems are used for object and environment recognition, and to recognize the human body gestures and the facial expressions. Thus, they can be used for recognizing the demonstrator's actions and transferring them to the robot for motion imitation. (Villani, 2018)

- Gestures, such as facial expressions, eye gaze, hand, and body gestures. Humans are used to communicate through gestures and use them to social interact with other humans. Also considering the intensive use of hands when it comes to industrial processes and activities, gestures is an important information source. (Li, 2005). If the robot is able to recognize and consequently act after the gesture's recognition, the communication is done on a natural and fluent way.
- Actions, for example, the execution of a task. The robot is able to understand what the human has done and know how to intervene consequently. It is very related to the gesture recognition, but instead of recognizing just one gesture, the goal is to understand a complete action that the human performs, that could be considered as a combination of many and different gestures.
- Face recognition: Overall, faces recognition along with fingerprint scanning are mainly used for identifying human operators inside factories that are allowed and have required skills to work side-by-side with Cobots. Also, it is useful to endow the robotic system with face recognition capacities to personalize the robot for each operator, whereby the user is identified and greeted. (Hentout, 2019)

- Touch, the robots have integrated sensors, for example a button, that behaves as the channel that allows the interaction between the human and the robot. More complex, distributed, and expensive sensors can be used to detect also punctual interactions, similarly to an artificial skin. (Cheng, 2019)
- Haptic signals, for exploring less humanlike but more reliable communication modes, such as haptics and Graphical User Interfaces (GUIs), might be more suitable for industrial scenarios. (Zaatari, 2019). Haptic communication can occur also through applied forces and torques or joint angles and orientations. (Bauer, 2008)

Figure 23, done by (Bauer, 2008), summarizes the ways of communicating that can be found on human-robot collaboration systems explained before.

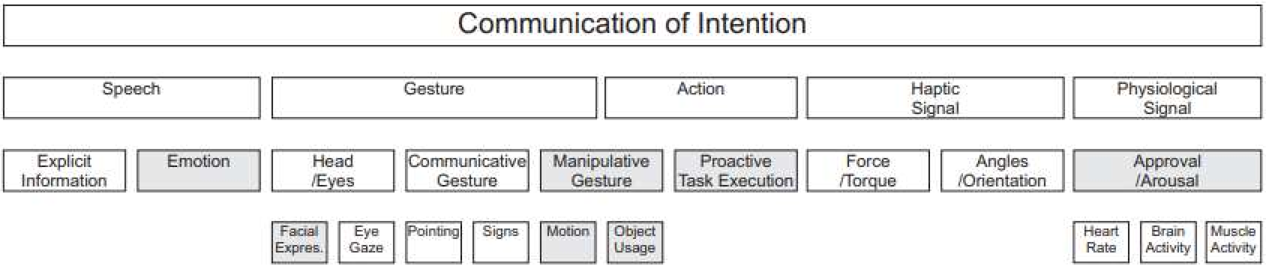

Figure 19: Main Human-Robot Communication channels. Source: Bauer, 2008.

No matter what kind of communication is used, what must be sought is to do it as much natural as possible, and that the detection and recognition by the robot is done as accurate as possible. The naturality is connected to the fact that the human must feel that it is communicating with another human operator, and not a robot, and to make the communication the comfiest.

3.6.3 Applications of Human-Robot Collaboration Systems in manufacturing

Now a days application of collaborative robots in manufacturing systems are countless and are continuously being developed.

Manufacturing industry shares the most part in terms of applications of collaborative robots, especially automotive manufacturing industries and assembly lines employ Cobots to carry out numerous tasks ranging from picking, packing, and palletizing, welding, assembling items, handling materials, product inspection and much more. (Sherwani, 2020).

The changing market and customers high requirements introduce to the industry the challenge to be more efficient and flexible. Therefore, collaborative robots due to all benefits mentioned on Chapter 1, are being installed on factories not only for assembly and simple tasks, but instead to work along with humans in almost all production and not production processes.

Within the selected literature, vast fields of applications were found, which will be summarised as follows:

- Welding
- Material handling
- Machinery
- Assembly

- Quality inspection
- Picking, packing, and palletizing
- Automotive

In order to describe them on an organized way, table 5 contains a brief explanation of each application, a summary of the main benefits that characterize each application and the reference of the documents where the information or the previous two points was found.

Application	Brief definition	Benefits	Documents
Welding	Welding co-bots can carry out welding with high precision and speed on their own and can also be used to facilitate the human co-workers in welding as required. The Cobot allows to have a vision sensing, automatic programming, guiding, and tracking, and real-time intelligent control of welding process. As we are talking about a collaboration system, it allows to tackle such complexity and uncertainty by relying on human skills. The robot is under a robot-as-tool approach and little autonomy, or cognitive capabilities are provided to the robot	• Precision • Repetitiveness	Villani, 2018 Sherwani, 2020 Vojic, 2020
Material handling	Now a days is the largest application. Moving materials inside a manufacturing unit, around a factory floor, is a tedious process for humans. Using robots for material handling is advantageous to reduce the worker efforts in lifting and moving materials or when material cannot be handled by a human for hygiene, or because of danger, or because of weight. But is important to highlight that it does not prescribe collaboration between the human worker, but instead a cooperation. The robot has a robot-as-tool approach, most of the cognitive effort, which depends on the application, is left to the user. There exists a huge variety of palletizing and material-handling robots available in the market, with very different payloads and tools, like bag grippers, suction, and magnetic grippers.	• Move materials to the desired location at faster speeds • Increased worker health and safety • Reduced costs • Faster production cycles • Reduced downtime	Villani, 2018 Grau, 2021 Sherwani, 2020 Vojic, 2020
Machinery	Application of robots as machinery, again means a robot-as-tool approach. But as in welding application, they can perform these tasks with high precision and speed on their own and can also be used to facilitate the human co-workers Cutting, deburring, drilling, foundry, grinding, material removal, milling, polishing, refuelling, routing, sanding, spindle, and waterjet	• Precision • Repetitiveness	Grau, 2021

Assembly	Cobots are used for lean industrial processes and have expanded production capabilities in the manufacturing world. It conforms what are called the hybrid assembly robotic cells. Cobots use their part handling, high-speed picking, and assembly capabilities to assemble parts and components into sub-assemblies, freeing up the operators to do other more value-added tasks at the assembly line, relieving workers from tedious jobs and increases productivity for simple assembly tasks. Specifically, cooperative assembly work stations are suited for sequential assembly, that is when the robot first performs the simple tasks and the complex frequently varied tasks that give the assembled products their individual features are performed at the end of the line by human operators Timing and coordination between the human and the robot are critical factors that might severely affect the acceptability and effectiveness of HRC.	• Increases the efficiency and precision of parts assembly • Ensuring the ergonomic safety • Increased quality, consistency, and production speed • Easy programming for fast redeployment to new assembly configurations • Space-saving, lightweight and manufacturing flexibility • Ability to adapt assembly output to meet peak seasons and changing consumer demands • Fast payback	Villani, 2018 Berglund, 2019 Sherwani, 2020 Vojic, 2020
Quality inspection	A robot arm consistently and repeatedly follows precise processes with minimal deviations, much more precise than a human. It is able to perform this dull task with high accuracy without any exhaustion or boredom as compared to human operators. The most common application is the use a vision system together with a Cobot, and it is possible to check products for quality and immediately remove defective products from the production line. With the camera, main objective is to identify and remove defective parts before they are packaged or shipped. The use of human-robot collaboration systems for quality inspections allows to reduce human errors and opens a new paradigm of quality control and assurance for final customers.	• Precision and consistency • Reduce operating costs • Consistent quality	Berglund, 2019 Sherwani, 2020 Vojic, 2020
Picking, packing, and palletizing	Today's industries have an ever-increasing need for packaging. Nine out of ten packaging companies are now using robots. Manually performing these tasks can be mind-numbing, labour-intensive, and also time-consuming Cobots capabilities are used for shrink-wrapping, box assembly and loading, and box collating or placing onto a pallet for shipping.	• Speed • Robots can work for long hours and even days	Berglund, 2019 Sherwani, 2020 Vojic, 2020

Automotive	A separate cathegory is done for automotive, considering the great interest that has been put in this application domain both by industries and academia. It is important to say that most of the applications are devoted to assembly tasks, where collaborative robots are inserted in producing lines High-precision tasks are done in a more accurate way thatnks to the help of collaborative robots, something really sought on this industry on particular.	• Efficiency and precision of parts assembly • Increased quality, consistency, and production speed • Easy programming for fast redeployment to new assembly configurations • Space-saving, lightweight and manufacturing flexibility	Villani, 2018

Table 5: Human-Robot collaboration applications in manufacturing systems.

These are some of the most general fields of application, and now a days industries are adapting the use of collaborative robots in different scenarios due to their flexibility and wide usage that can be given.

The following Chapter 4 will analyse the specific application of Human-Robot Collaboration systems for Quality Control and Inspection processes on manufacturing system.

4. QUALITY CONTROL IN HUMAN- ROBOT COLLABORATION

Quality is a central aspect of today's market. Organizations must ensure that the final customer will receive products that are according to the respective quality parameters. No matter the type of industry, the sector, the product, all need to ensure the conformity of the product regarding the specifications.

The ISO:9000 defines the concept of quality as follows: "The quality of an organization's products and services is determined by the ability to satisfy customers and the intended and unintended impact on relevant interested parties. The quality of products and services includes not only their intended function and performance, but also their perceived value and benefit to the customer."

In order to be sure that the product is conforming, quality control and inspection processes must be defined along the manufacturing cycle. As more standardized these controls are, more effective and faster the process will be.

On today's manufacturing lines, two main general types of inspections are present: online and offline. They are defined as follows:

- Online inspections are the ones that are performed while the product is processed, that means, during the manufacturing process. This kind of inspection is mostly used when the products to be controlled are on continuous production, the requirements are very strict, and it is important to detect the deviations as soon as possible. In this way it I possible to intervene and solve the problem and reducing the delays and rework of parts, if possible. If not, all products will not be conforming to the requirements, not reworkable, meaning a huge loss. On this way is feasible to confirm that quality and the conformity to specifications is being maintained throughout the production process. These characteristics make online inspections the ones that are more convenient in an economical and efficiency point of view but is not applicable in all kinds of manufacturing process, and that is why a second type of inspection can be done, the offline one. (Genta, 2020)

- Offline inspections are performed once the product is finished or can also be done in between of the different stages of manufacturing, therefore, an inspection of the semifinished product. The advantage of this type of control is that it does not intervene the production process, but the non-conformity will only be detected at the end of the process, meaning that if the product cannot be reworked, all the value-added activities and material that the product has, will be scraped, and consequently meaning a loss for the organization. (Genta, 2020)

The type of inspection selected, the way the process is take into practice, how is controlled, and revised will define if the whole production process is efficient, or instead, if failures and non-conformities lead to an expensive and inefficient manufacturing process.

The high requirements of the markets now a days, challenges industries to be more flexible, and to make different kind of products in very little time, the so-called mass-customization. Consequently, this complicates the task of defining a standardized, unique, and error-proof inspection process.

The introduction of collaborative robots into quality control process is an application that is growing in importance the last years, considering the solutions that brings to the challenges mentioned before. Collaborative robots are flexible, are rapid, are lightweight, and can perfectly work along with human operators.

One important characteristic of collaborative robot for inspection processes, is the repeatability and accuracy. They can repeat the inspection procedure many times, without need to stop, 24 hours a day, and will do it on the same way, making the process more capable of detecting non-conformities. This kind of control activities are really prone to errors when performed by humans, that is why is really interesting the introduction of collaborative robots. Also implies the increasing of human operators' motivation, considering that repetitive and automatable tasks, will be done by the robot, and they can focus on more interesting tasks, that need the human reasoning to be performed.

For example, most of application found, consist of a collaborative robot with vision sensors or cameras and in that way are capable of inspecting several visual aspects, such as dimensions, shape, presence of an object, etc., with accuracy and precision.

In order to analyse on a more detailed way the applications of collaborative robots for quality control in manufacturing systems, specific literature regarding this topic was searched, and developed in the following section.

4.1 Selected literature

For this chapter, the specific documents that treats the topic of interest of this thesis are analysed, this means the documents that address the specific application of Human-Robot Collaboration for Quality control and inspection processes.

It was not easy to find articles that would be useful, as it is a novel topic. The literature was selected by the results of the fourth level search, section 3.4, also by the articles cited on this ones, and other ones provided by the supervisors of this thesis.

With all this sources, the final sample of articles is composed by the following 12 documents organized on the Table 6, that provides general information about them for further analysis.

Short name	Title	Year	Author(s)	Country
Jian, 2021	An image vision and automatic calibration system for universal robots	2021	Bo-Lin Jian, Chi-Shiuan Tsai, Ying-Che Kuo and Yu-Sying Guo	Taiwan
Brito, 2020	A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems	2020	Thadeu Brito, Jonas Queiroz, Luis Piardi, Lucas A. Fernandes, Jose Lima, Paulo Leitao	Portugal
Doltsinis, 2020	A Machine Learning Framework for Real-Time Identification of Successful Snap-Fit Assemblies	2020	Stefanos Doltsinis, Marios Krestenitis, and Zoe Doulgeri	Greece
Karami, 2020	A Task Allocation Approach for Human-Robot Collaboration in Product Defects Inspection Scenarios	2020	Hossein Karami, Kourosh Darvish, Fulvio Mastrogiovanni	Italy
Lopez-Hawa, 2019	Automated Scanning Techniques Using UR5	2019	Homar Lopez-Hawa, Alexander VanPelt, Suveen Emmanuel, and Yimesker Yihun	United States
Makrini, 2017	Design of a Collaborative Architecture for Human-Robot Assembly Tasks	2017	Ilias El Makrini, Kelly Merckaert, Dirk Lefeber and Bram Vanderborght	Belgium

Müller, 2014	Inspector Robot – A new collaborative testing system designed for the automotive final assembly line	2014	Rainer Müller, Matthias Vette and Matthias Scholer	Germany
Papanastasiou, 2019	Towards seamless human robot collaboration: integrating multimodal interaction	2019	Stergios Papanastasiou, Niki Kousi, Panagiotis Karagiannis, Christos Gkournelos, Apostolis Papavasileiou, Konstantinos Dimoulas, Konstantinos Baris, Spyridon Koukas, George Michalos and Sotiris Makris	Greece
Pichler,2017	Towards shared autonomy for robotic tasks in manufacturing	2017	Andreas Pichler, Sharath Chandra Akkaladevi, Markus Ikeda, Michael Hofmann, Matthias Plasch, Christian Wögerer, Gerald Fritz	Austria
Rooker, 2014	Quality Inspection performed by a Flexible Robot System	2014	Martijn Rooker, Michael Hofmann, Jürgen Minichberger, Markus Ikeda, Gerhard Ebenhofer, Gerald Fritz, Andreas Pichler	Austria
Syberfeldt, 2019	Improved Automatic Quality Inspections through the Integration of State-of-the-Art Machine Vision and Collaborative Robots	2019	Anna SYBERFELDT and Tom EKBLOM	Sweden
Alicona, 2019	Misurazione senza contatto ad alta accuratezza di componenti critici dei motori a turbina	2019	Bruker Alicona	Austria

Table 6: Selected literature of Quality control with Human-Robot Collaboration.

As it was done for the selected literature of Chapter 3, and in order to perform a third comparison, the distribution of documents per year and per country will be showed here below.

4.1.1 Documents per year

The number of documents published per year is summarized in Figure 24 as follows.

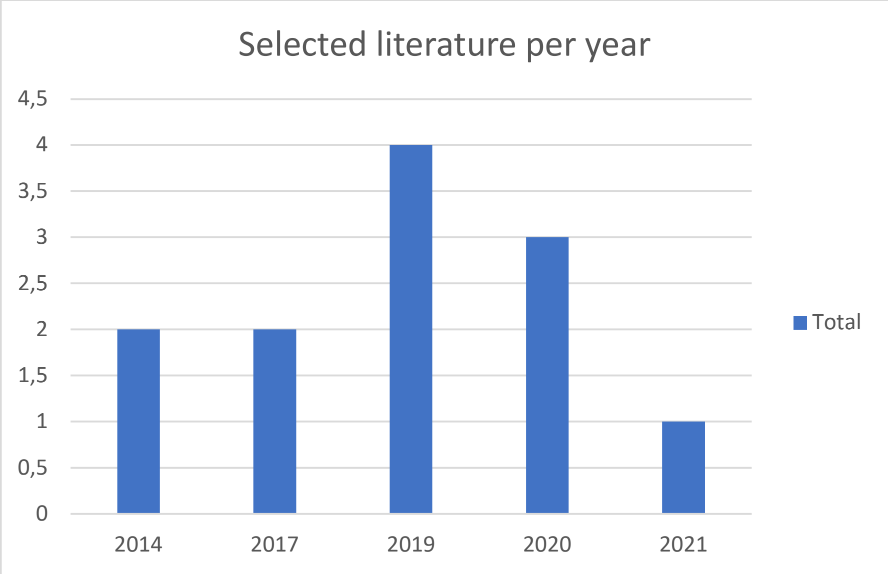

Figure 20: Selected literature of Quality control with Human-Robot Collaboration per year.

Even though the graphic may seem very different from the distribution per year of the previous chapters, one similarity can be highlighted. This is that in this case no articles of interest are dated before 2014, matching with the rise of articles published regarding Human-Robot Collaboration in general. This can mean that also the research regarding the use of Human-Robot Collaboration for quality control and inspection processes is boosted with the birth of Industry 4.0, but with less impulse than Human-Robot Collaboration in general, where plenty of articles were published in the last years.

4.1.2 Country of origin

In order to judge if similarities or differences regarding the origin of the documents for the different searches, this last pie chart shows the country-of-origin distribution of the selected literature.

As for the section 3.5.2 Country of Origin, the selection of countries was based on the country of affiliation of the first author of each paper.

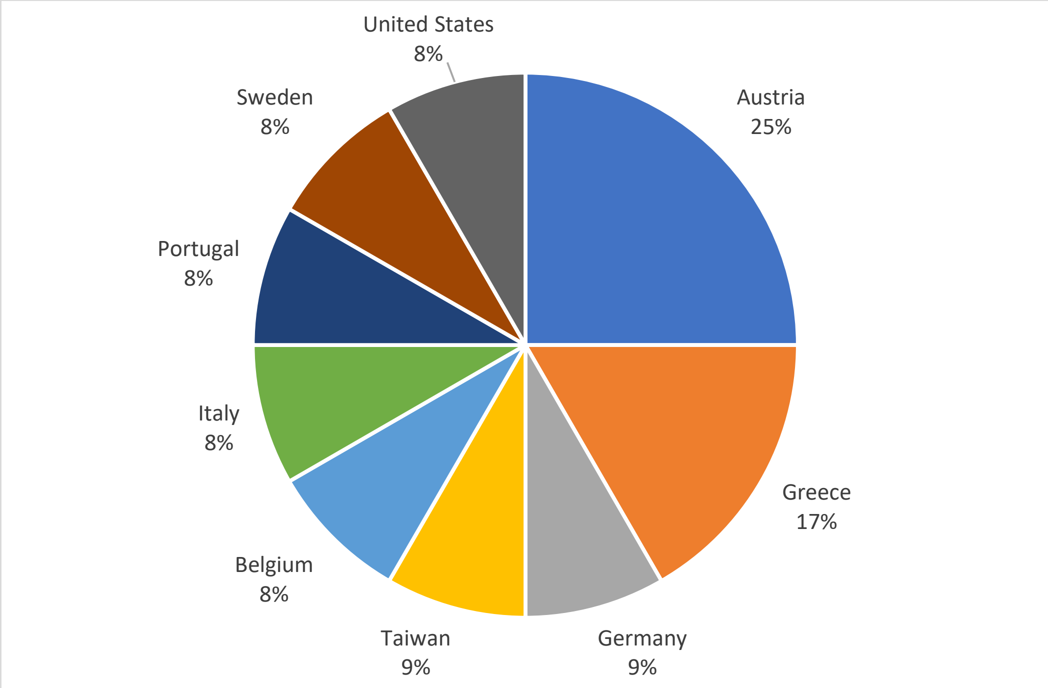

Figure 21: Selected literature of Quality control with Human-Robot Collaboration per country.

In this case as the number of articles is much lower than before, 12 in contrast with 32 and before more than 600, is more difficult to understand if the results clearly show the behaviour of the overall investigation of the topic.

Nevertheless, is interesting to say that Italy, Germany, and United States still appear as country of origin of some documents, but on this case the leaders of the list are Austria and Greece, that before were at the bottom of countries of origin.

This anyway cannot say much, as the sample contains 12 documents, and the countries of origin are 11, meaning that the origin is very diversified and not crowed in few countries.

4.2 Analysis of the literature

As it was mentioned before, the number of documents of interest for this specific application are only 12, being feasible to make an individual analysis of each one. A brief summary of each document will be given, highlighting the benefits and next steps.

At the end a table comparing all the documents is presented, in order to draw conclusions from it.

4.2.1 Jian et al., 2019

Title: An image vision and automatic calibration system for universal robots

This document published in the year 2019 done by Taiwanese researchers aims to combine image identification with robotic arms. This is because many simple and repetitive tasks done by humans as for example recognizing one object, shape, etc., in other words a visual recognition, could be replaced by robots in order to relieve humans of tedious tasks, and to reduce human errors, commonly found at quality inspections.

This article was chosen because, in spite it does not talk about a specific application case of quality control using collaborative robots, it explains very well the background and the foundational and theoretical base of the image recognition, that is the most common one used while doing quality inspection with Cobots. Therefore, understanding the background of how image vision works when using collaborative robots, will allow to establish challenges and opportunities, as well as the existing limitations on the applications that can be done.

The foundational basis behind image detection explained on this article is the one called Hough transformation that, as the paper says, is commonly used for computer vision, graphic analysis, and digital image processing. It is used in order to find the object on the image taken by a CCD camera, in order to communicate it to the robot arm and serve as instructions of where it should go.

As the author explain: "*The thinking behind the Hough circular transformation is that each non-zero-pixel point is likely to be a point on a circle, and an accumulated coordinate plane is generated by voting. The position of the circle is determined by setting up an accumulated weight. On the line coordinate, the circular equations of all points on the same circle are the same. Therefore, when mapping to the 3D space Cartesian coordinate system, also known as the abr-coordinate system, they will be the same point. Therefore, by judging the accumulated intersections of each point in the abr-coordinate system, the points greater than a certain threshold value are circles. Any straight line that passes and holds a right angle to the circumference will intersect and be perpendicular to a point. The intersection of the points is the centre of the circle*"

Summarizing, the Hough transformation method analyses and compute the information contained on the image until the object of interest is found, it serves as a GPS to the robot to indicate where it should go.

An experimental and simple case is shown on the paper, that consists of gripping a workpiece and then placing it on a fixture for future processing. For performing this activity one robot arm, two CCD cameras and a computer are used.

A flowchart provided by the authors is shown on Figure 26 in order to understand the order of the tasks and the logic applied.

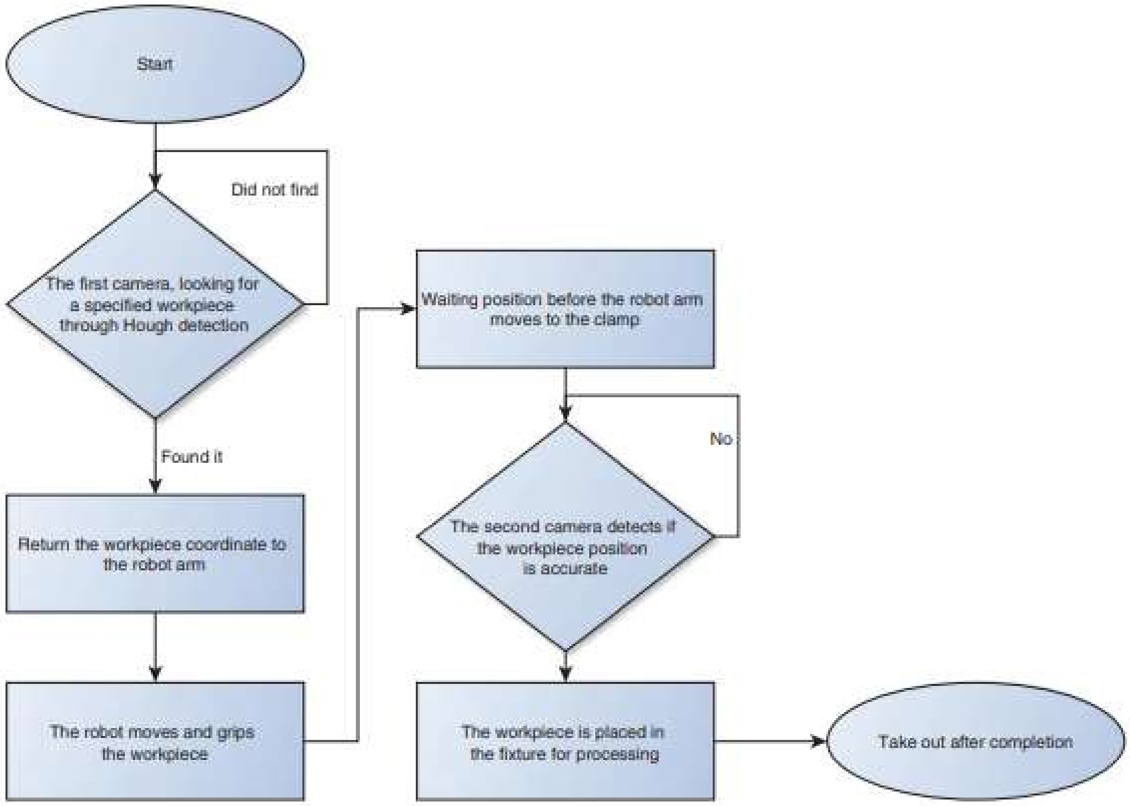

Figure 22: Experiment flowchart. Source: Bo-Lin, 2019.

This simple process can be also applied to a quality inspection station, imagining for example that the object to be controlled cannot be grabbed by the humans, due to surface characteristics, it a heavy part or because it implies a risk for the operator. So, on this hypothetic case, the robotic arm, thanks to the image identification, accurate locates the object, grabs it and, for example, position it on a specific way that allows inspection to be performed by a human and supported by an automatic image recognition, and after the evaluation the object is rejected or accepted.

This paper though, leaves many points without explanation that are fundamental when talking about human-robot collaboration, because its main focus was to only develop the algorithm behind the visual recognition.

No information regarding the communication between robot and humans is included, how the human communicates the robot that the process can start, how safety environments is ensured in order to make human, and robot safely coexist and collaborate.

Apart from that, this case as it is, does not represent a human-collaboration activity, as the human does not intervene in any part of the process, and not even considered on the analysis.

This leaves the door open on the investigation on how to integrate what has been developed on this paper that is the communication between the robotic arm and image identification into a real case present on industries, where more aspects, such as communication between operator and robot have to be defined, for ensuring safety.

4.2.2 Brito et al.,2021

Title: A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems

This early published article takes advantage of machine learning on a quality control system that inspects parts on a manufacturing process, so by the usage of machine learning the whole system learns and improves according to the previous inspections.

In this real case the collaborative robot arm has machine learning incorporated, and the human with whom shares the working space, teaches the path that the robot must follow for achieving task requirements. This article emphasis the benefit on how facilitated the task of programming is, considering that in the past, experts where the only ones able to program a robot, and with this example, just by moving the arm the robot learns, like a human operator.

The objective of the experiment is to train the robot to perform quality inspection tasks according to the points determined by the operator. For instance, an inspection task may consist in the robot to carry a product to be inspected in a given position, where there is an inspection equipment, then rotate this object to inspect different angles. The same object can be moved to another position, to another inspection equipment, and finally, show it to the operator for some final check. (Brito, 2021).

Comparing with the previous paper, Bo-Lin 2019, this article explains in the detail the way the robot and the operator communicate in order to perform the collaborative task.

A Force-Torque sensor FT-300 is incorporated on the manipulator that the human operator uses to move the robot, this sensor recognizes the forces done to the robot on all axes and sends this information to the system, receiving in this way the information about the desired trajectory to be done by the arm.

This incorporates a new flexibility to the collaborative system, "*by establishing a dynamic teaching and operation, where the user can interact and change the path on-the-fly. In this way, it allows the human to interact with the robot to guide it on a new path, as soon as unexpected situations arise during the quality inspection, using the force sensor attached to the robot"*, the authors remark.

On Figure 27 the sequence of control and dynamic learning developed to perform quality inspections is represented, and remarks how the robot can perform tasks already known and is also able to learn new ones and remember them for the future.

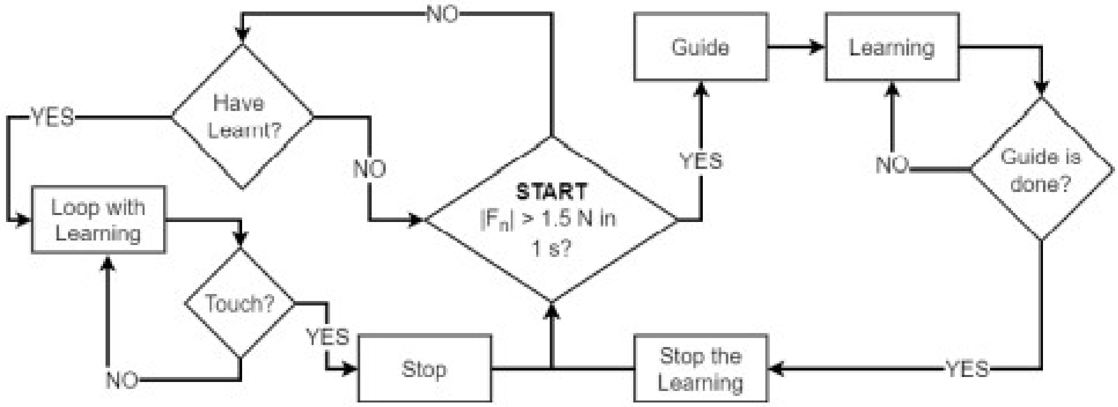

Figure 23: Logic sequence applied to perform the quality inspection. Source: Brito, 2021.

On a safety point of view, it is very advantageous that the human can control the collaborative task by the force application that is recognized by the robot by the Force-Torque sensor, ensuring safety and more reliability from the human towards the robot.

Finally, an implementation in a real environment factory should be implemented emphasizing the character of the problem.

4.2.3 Doltsinis et al., 2019

Title: A Machine Learning Framework for Real-Time Identification of Successful Snap-Fit Assemblies

This is the second paper that includes on its analysis the use of machine learning for a quality control using collaborative robots. Unlike the previous one (Brito, 2021), this paper presents a specific framework for a real-time inspection to check correct snap-fit assemblies.

A snap-fit is a kind of assembly widely used in different kind of industries. The main challenge is to identify is the snap-fit has been complete correctly. Is a difficult type of control, where visual inspection is most of the times not possible, so usually is done by sensing the developed forces or identifying the snapping sound during a manual assembly. (Doltsinis,2019)

The main objective of this paper is, as the authors say, to propose a framework that *"allows the real-time characterization of the snap-fit process with very high accuracy and is easily implemented with collaborative robots."*

Is a very specific application but it can also be used on future investigations as a starting point to develop further type of inspections where the force applied on the assembly is the main indicator.

As it was mentioned before, the snap-fit correct assembly is a very difficult process to inspect, and the most used way to do it up to the present, has been the human recognition by the snapping sound, as the indicator of success or not, the so called "clip". But in modern industries, human assembly is continuously being replaced by automatic and robotic one, making this kind of control impossible to do, and the snap-fit is only controlled at the end of the process on an off-line quality control station. Nevertheless, this involves a huge challenge, considering that visual inspection on snap-fit assemblies is most of the times impossible to do.

The authors then developed a framework that applies what has been described on the chapter of introduction, a framework that uses collaborative robots in order to integrate the benefits of human abilities in this case to recognize a good snap-fit assembly, and the capacity of robots of automation, repetitiveness, and accuracy, also incorporating machine learning. Resulting on a minimization of complexity, time, and cost.

The machine learning is introduced in order to overcome the problem of rigid planning and programming that usually robots involve, so in this way to making them more flexible and adaptable to different situations, by the learning of the process.

The author's remark: *"Combining intelligent methods with autonomous robot operation leads to more robust robotic assembly processes in terms of variability and fault tolerance."*

The reasoning behind this framework is that all snap-fit assemblies generate force profiles that are used as way of realizing if the final snap lock has been completely done.

The framework divides the process in two main phases:

1. Training phase: here the collaboration between human and robot takes place, where the human acts as the trainer and the robot the trainee. In order to do this, the robot holds one of the parts of the snap-fit assembly and the human the other one, performing a manual assembly. The force applied by the human is measured by a sensor on the robot. This process is repeated several times, and showing the robot successful and unsuccessful assemblies, in order to teach him different kind of scenarios that could happen on normal assembly, and to leave him prepared to know how to proceed.
2. Operational phase: once the robot has been trained, the assembly process is now done only by the robot on an autonomous way, and as it has learned on the previous phase, the measurement of the forces is used to identify successful or unsuccessful assemblies, without needing human intervention, and using the knowledge acquired on the training phase.

This document presents a very useful framework in order to perform an inspection while the assembly process is taking place, something that is very important on industries now a days, considering all the costs involved on detecting scrap parts only at the end of the process, being also inefficient as a quality dedicated inspection station must be added at the end of line.

The collaborative way of teaching the robot by human demonstration makes the framework easy to use, and performable by operators without programming experience.

Once more, the article does not present a real case on an existing industry, and present the framework on an experimental way, leaving the door open to do it on a real assembly line, in order to be able to specify and elaborate on a more detailed manner the communication between human and robot, safety issues related on the training phase and defining how intervention of human can be done on the operational phase if needed.

4.2.4 Karami et al., 2020

Title: A Task Allocation Approach for Human-Robot Collaboration in Product Defects Inspection Scenarios

The authors of this documents propose a framework called CONCHRC that allows the allocation of tasks either to human operators or robots on a collaborative process, with concurrent and multi human-robot collaboration. They apply and explain how this framework work on a general inspection of products process, by the interaction of one human and two collaborative robots.

In this work, authors claim that *"the collaboration between an experienced human operator and a robot may lead to higher rates in defects spotting, overall productivity, and safety."*

Robots will be used in order to bring relief to human operators on tasks that require repeatability, stress, ergonomic issues, and simple and automatable tasks, while humans' expertise will be exploited for tasks that are not modellable, or that require awareness impossible or difficult to assign to a robot.

In order to summarize the process explained on the document, the following flowchart on Figure 28 was done, showing on a simplified way the assignment of activities to the two robots and the human operator.

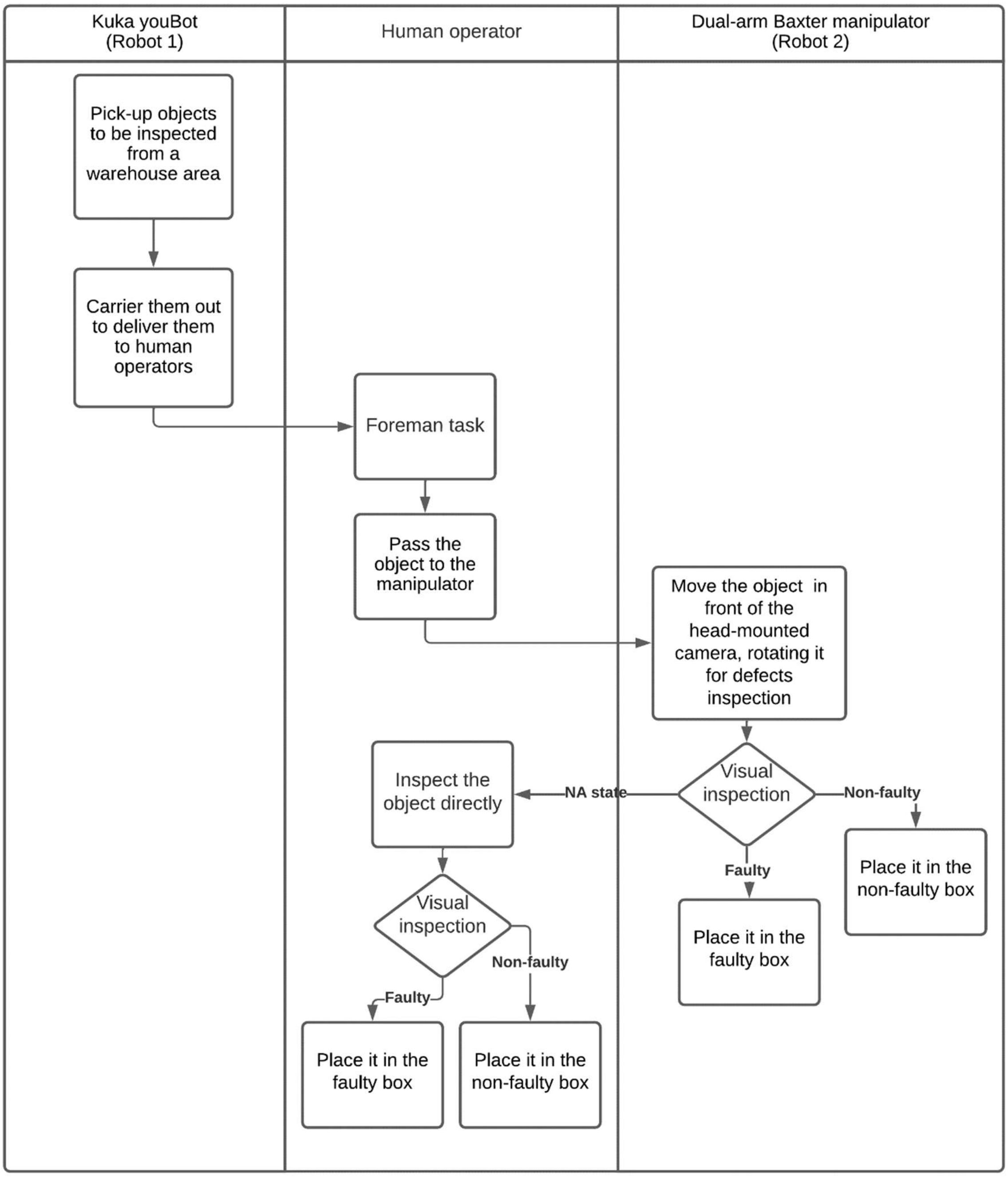

Figure 24: Process flowchart.

This graph clearly shows how this application case implies a real human robot collaboration case, where both parts have tasks assigned and interact to perform an inspection.

For a simplification purpose, it was not included on the flow-chart the way robots and human communicate to start, finish, and perform activities, but they are explained on the document. Essentially, the human communicates with the robot through gestures, ensuring this a safety environment for the operator, and a perfect synchronization between robots and human, resulting in a more efficient process.

The programming of the process is achieved through the adoption of AND/OR graphs. An AND/OR graph allows for representing procedures to follow, which can be decomposed in subproblems as parts of the graph, as well as the logic relationships among them, i.e., the graph interconnectivity. (Karami, 2020)

The quality inspection process was tested on a simplified experiment, where the inspection consisted of the lecture of a QR tag attached to the object, that being read by the camera, it would be possible to know if it is a faulty or non-faulty part.

For a more complete analysis, it would be interesting to experiment this framework with a real inspection process in order to analyse process efficiency and how accurate is the process to detect fault or non-fault objects.

An interesting next step would be to perform a trial on a real industrial quality control process, and to real determine an inspection process, more complicated than the QR tags reading.

4.2.5 Lopez-Hawa et al., 2018

Title: Automated Scanning Techniques Using UR5

This document focuses on scanning techniques for inspection processes. Authors propose an automatic scanning technique using laser line scanner, that is a non-contact-base kind of scanning that allows to obtain in a short time a fair quantity of data. Together with a collaborative robot, they propose to completely automate visual inspection process, that normal is a tedious task for human operators, and highly error prone.

One clear example the authors expose where this technique could be advantageous, is in the manufacturing industry in which certain inspection systems are required to inspect surfaces of components as manufactured parts become more complex and high quality of such parts are required.

Two sources of data are used on this technique. The first one is the collaborative robot position sensor; this info is sent to a computer through an Ethernet cable. The second source is the line scanner that is integrated in the arms robot, so it performs the same path, and the scanned raw data obtained from it is sent to the scanner controller where it will be processed. Once this data is processes, by an USB cable it is received by the computer. Combining both sources of data, the one from the collaborative robot, and the one from the scanner, it is possible to obtain the cloud point data of the scanned object. With this info about the object, different kind of inspections can be performed, about the surface, the shape, holes presence and so on.

A novelty developed by the authors is explained by them as follows: *"Another key objective is to generate a MATLAB user interface to simulate the process and to apply the correct transformation to the data gathered from the line scanner. This interface was successfully created, allowing a human operator to visualize the scanning process. To obtain a clear image and find to show the details of the object, more cloud points need to be taken. However, if the overall size is required, only few cloud points are needed, and hence the scanning process will be expedited."*

Further technical details, useful for a better understanding, are present on the document.

Some gaps are still left for future investigation, such as, more accuracy on the scanning by taking more cloud points. Authors also suggest changing the communication between the robot and computer, from Ethernet to a wireless connection, making the system more flexible.

It is a very interesting article to be used as starting point for inspection processes using scanning techniques, and a next step would be to really try it on a real quality control, and to test its efficiency on detecting a non-compliant part.

4.2.6 Makrini et al., 2017

Title: Design of a Collaborative Architecture for Human-Robot Assembly Tasks

This paper is really interesting because it introduces a collaborative architecture between human and robots on an assembly task, where the process consists of the assembly of a box and simultaneously the inspection of its correct completion.

This architecture is divided in four modules that together allow the perfect functioning of the system.

In contrast to the previous documents, this one explains in high detail how the communication is done between human operator and robot, allowing to future researchers, and interested industries to apply them on their work. This is developed in the first three modules: face recognition, gesture recognition and human-like robot behaviour modules.

Face recognition consists of the identification of the people, and to allow only the authorised operators to use the robot. This is done through a camera that recognises the operator by a real-time comparison between the picture and the database of authorised personnel.

The second module is the one that performs the gesture recognition, a really useful communication channel considering that often on factories shop floor noise is present, therefore communication through speech is not possible. Making the collaborative robot able to understand the human gestures provides a safer environment for the collaboration to take place. The gestures used on this specific case are waving hand and thumbs up/down.

The third module is very particular, and it has not been discussed in any other article. It is the introduction of the robot human-like behaviour, providing to the operator through a screen, social cues typical from a human being such as head nodding/shaking and eye gaze. This helps the acceptance of the robot by operators as they feel they are working with another person instead of a robot that they do not know how it works.

The assembly and quality check are summarized and represented on the following flow chart on Figure 29, where activities performed by the robot and by the human are distinguished.

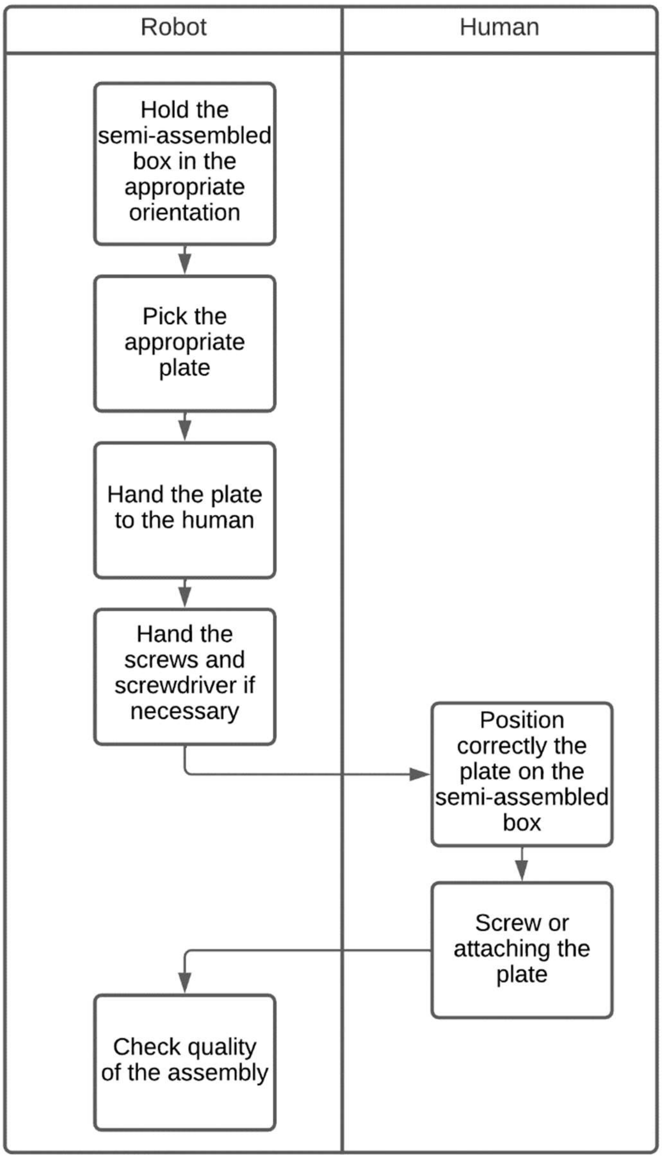

Figure 25: Process flowchart.

Tasks performed by the human for the communication with the robot, such as waving hands, thumbs up/down, were not represented for simplification.

What it interesting about this kind of graph is that it clearly shows that the case study presents a real collaboration environment, as the task is performed by both, human and robot, and not a fully automated processes where operator acts only as a controller.

Being the first to talk about in such detail about the communication between human and robot, the authors propose future improvements that could be developed. For example, to allow the robot to adapt its behaviour in terms of speed and the height of the working zone, based on the way the operator works, improving on this way the collaboration tasks, and thus making the operator feel more comfortable.

As a next step, it would be interesting to apply this simply and very useful concepts on a more complex assembly and quality control process, more adapted to current industry needs.

4.2.7 Muller et al., 2014

Title: Inspector Robot – A new collaborative testing system designed for the automotive final assembly line

The authors, Muller et al., explain on this document a replicable and specific inspection control, where the main objective is to perform a water leak test on the final assembly of a car manufacturing line, highlighting the benefits of doing this on a human–robot collaboration environment.

A water leak test is an expensive test that is performed on every car before it leaves the assembly line. The high cost is due to the fact that first the car must be watered approximately six minutes and after that was it commonly done is a manual inspection of the inside of the vehicle in order to find, if present, leakages. It is common that when infiltrations are very small, human eye cannot detect them, resulting this on a lower efficiency of the control.

Motivated to improve this, Muller et al., designed a system that incorporates collaborative robots to perform the tedious and error-prone task of water leakage control inside the car.

Instead of using an operator that performs the unergonomic task of bend over inside the car for inspection, they incorporate a thermographic camera to the robotic arm. From the images taken with the camera from the inside of the car, water leakages can be detected with a much higher precision than the one obtained with human eyes. In fact, by the experiment done by the authors, it was discovered that even drops of a diameter 1 mm can be detected using the thermographic camera. A complete explanation of how water drops are detected by the use of the thermographic camera is given in the article, and it could be applied in other kind of inspection, where a fluid wants to be detected, as oil for example.

All the possible benefits to take advantage of by establishing this human-robot collaboration environment are summarized on the following table on Figure 30 present on the article.

	State of the Art	Human-Robot Collaboration
Quality Level	↓	↑
Process Capability	↓	↑
Necessary Rework	↑	↓
Customer Satisfaction	↓	↑
Investment	-	↗
Maintenance	-	No intensive maintenance
Worker Capacity	↑	Adjustable to necessary level of quality control
Flexibility	-	↑
Cycle Time	-	-
Floor space required	-	-
Efficiency	↓	↑
Work station ergonomics	↓	↑

Figure 26: Comparison between manual assembly and a collaborative workstation. Source: Muller, 2014.

The division of tasks between human and robot is summarized on the following flowchart on Figure 31. The main objective of the authors while dividing the activities, was as they state on the document “the definition of the specific skills and key characteristics of human and robot to combine their strengths and reach an optimal efficiency of the process.” Therefore, to allocate the more suitable task that each one could perform better. For example, the inspection of the trunk, requiring complex movement, was assigned to human rather than to the robot. Instead, the inside inspection of the vehicle, as it is easy to be automated, is performed by the robot.

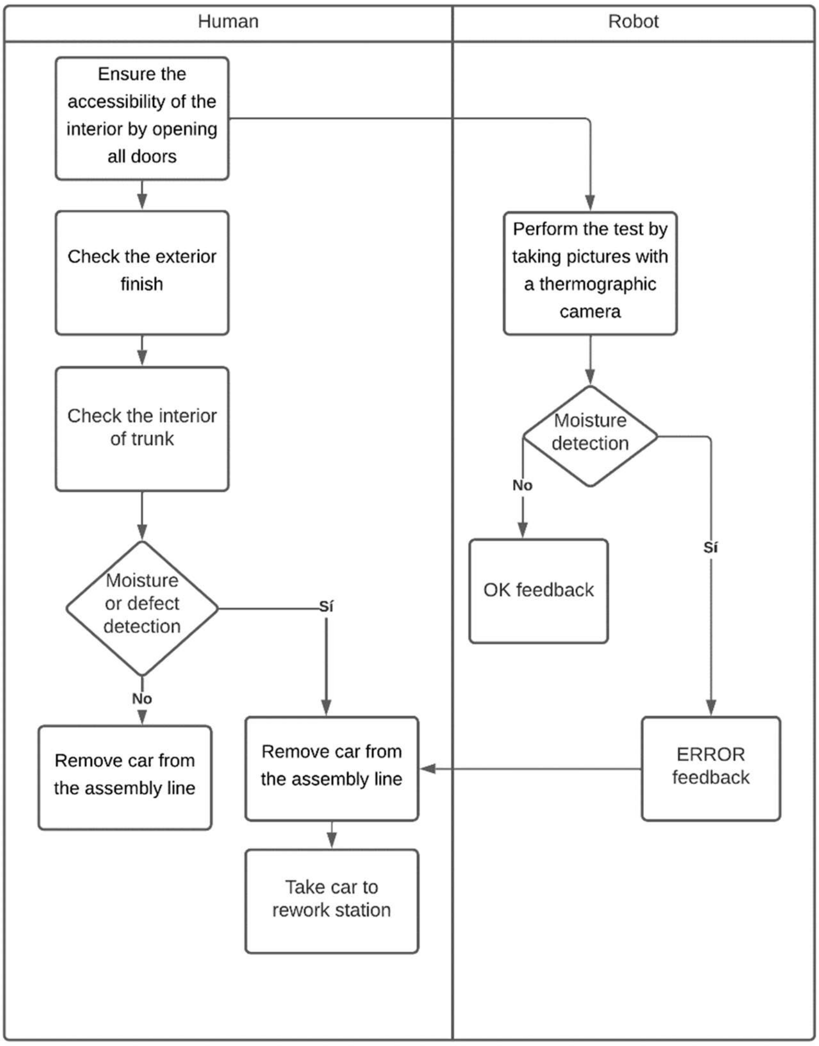

Figure 27: Process flowchart.

Before the application of the new system, the inspection of the car was done sequentially, controlling first the interior, and then going to the exterior and trunk. With the robot incorporation these tasks can be done in parallel, resulting a shorter inspection time, and lower inspection overall costs.

This particular article does not present a collaboration system where human and robot share the same task and perform it together, instead the collaboration system is used for the division of tasks of a general inspection process, in order to increase efficiency and reduce human errors. Following the definition presented previously, instead of collaboration, it should be called cooperation system, and in case the robot finds an error, the human can rapidly intervene to solve the problem.

The next step by the authors is*" the implementation of a conveyor tracking system to achieve the synchronization of the robot and the conveyor with the car moving in a continuous line. In this scenario, the complete validation and risk assessment for the process is performed, and the process will be optimized to a pilot production stage."*

The results presented on this document are very useful for car manufacturers that want to apply it on their assembly lines, also because spite it was not tested on a real manufacturing line, it was done on the ZeMA research facility that has available for experiments a Model Factory and specifically a process station for water leak tests.

The only missing points that are strictly needed to be developed is the communication between robot and human for the creation of a safe environment, a priority point on industries.

4.2.8 Papanastasiou et al., 2018

Title: Towards seamless human robot collaboration: integrating multimodal interaction

This paper proposes a simple but very complete interaction network between robot and human. Using sensorial technologies, the communication between human and robot is done more fluently.

The interaction between the robot and the human is done through different wearable devices such as sensors, microphones, cameras, smartwatches, and AR glasses. A novel communication framework that it is not present in any other document analysed. The interaction is done in a way that it is very simple for the human operator to communicate and command the robot, as if it were another human operator. The human operator can talk to the robot, the robot recognizes parts through a camera that acts as vision, and even command the robot's movements by a joystick.

Every time the operator finishes a task, send a confirmation through its smartwatch, informing on this way the system and allowing the next operation to start, regardless the responsible of it.

The following image on Figure 32 provided by the authors, clearly shows the level of technology used in this communication framework, and how are all connected in order to facilitate tasks.

Figure 28: Communication framework. Source: Papanastasiou, 2018.

Specific information regarding the different devices is present in the document for further understanding.

Although this article does not present a quality control case, it was chosen to be analysed and included in the table of analysis because it is bringing an important added value argument that in other articles is not even present and discuss, the communication.

The communication system the authors present is very interesting to apply not only in assembly task, but also in a quality control process, leaving this point open to be further investigated and applied by future researchers.

4.2.9 Pichler et al., 2017

Title: Towards shared autonomy for robotic tasks in manufacturing

The following article explains in a general way a platform developed by the authors that can be used in different industrial ambits. After the general explanation, three cases are presented, being the first one of interest for this thesis as it is used for a quality control process.

The platform is called XRob and authors explain that among the benefits, the most important ones are, first of all the rapidity of application, creating complex applications in less than an hour. It is also so simple to use that makes the robot more flexible and efficient when it comes to changing the task assigned to it.

The components of the platform are showed on the following graph on Figure 33 done by the authors, being the Cognitive Reasoning System, Perception System, the Planning and Execution System and the Application Development, the ones that together make possible the communication of the whole system and allowing the proper functioning of it. More details about each component are given in the document.

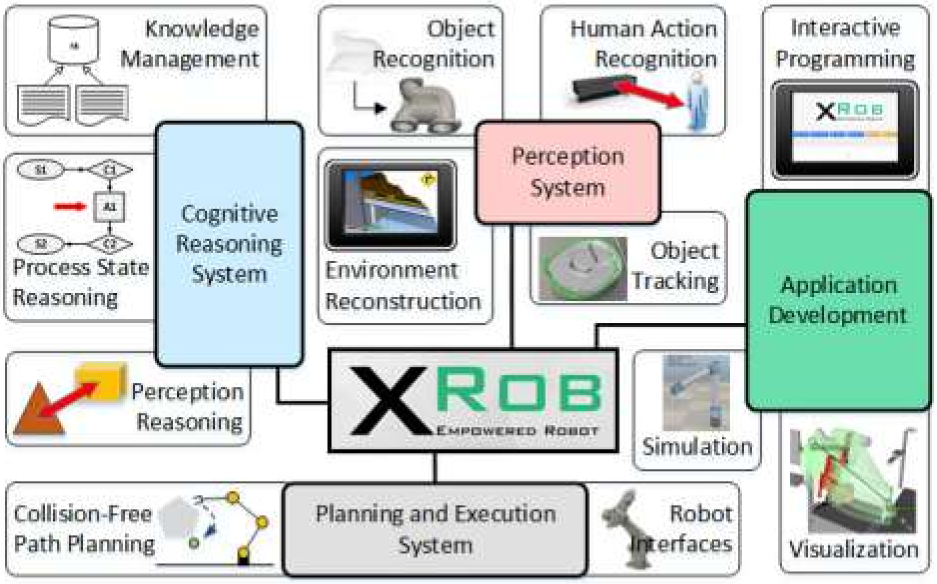

Figure 29: XRob platform components. Source: Pichler, 2017.

The specific case of interest, the one of quality control is done on a coexistence application, where the robot and the human operator share the workspace but will not perform an activity together.

In few words, the robot's first task is to take a picture for each reference position given, that will serve as a reference for a well-connected operable generator-plug. After having this reference image, the inspection during the process is done by the simple comparison of reference images, and actual ones, in order to determine if the connection has successfully been done.

For a further investigation, it would be interesting to apply this already done framework that allows to start not from scratch, but with a system that is already functional, on a collaboration type quality inspection process.

4.2.10 Rooker et al., 2014

Title: Quality Inspection performed by a Flexible Robot System

This paper presents a quality inspection process using a collaborative robot. The main objective is to control the correct assembly, therefore the interlocking, of plugs. For achieving this, the robot is equipped with a vision sensor that will be guided through the part.

Is a very adaptable quality control process that can be applied to different geometries and assembly processes.

As in other documents, the authors define two main stages, first of all the set-up or programming, followed by the real inspection process.

For the first one, the training of the robot can be done by hand-guiding the robot to the different positions where images must be taken. In order to ensure that the camera's field view is the desired one, a user interface is present in order to corroborate what is the data processed by the sensor.

After the programming step is completed, is possible to perform the inspection task completely by the robot.

The principle is explained by the authors as follows, *"The sensor uses the structured light principle utilizing a blue light LED projector in combination with a suitable band pass filter in front of the integrated CMOS camera. The sensor provides point cloud data for a measurement volume of 120x70x50 mm and allows acquisition of regular high-resolution images. To reach the independence of the surrounding light a blue light LED projector and a suitable blue light band pass filter is used."* This means that the system is very robust for the recognition of the object and applicable to different kind of shapes.

The results of the experimental case the authors did, show that the performance of the system on the inspection process is really good, obtaining 99,2% of precision and less that 7% of false positives.

Future development can be done on the inspection of different shapes, to verify if precision is maintained.

4.2.11 Syberfeldt et al., 2019

Title: Improved Automatic Quality Inspections through the Integration of State-of-the-Art Machine Vision and Collaborative Robots

The following document presents a case study where a Quality Inspection through machine vision is performed.

Authors highlight the benefits that can be obtained by the usage of machine vision for quality inspection instead of a manual one. The machine vision system main task is to control if the product has been processed according to the specification and reject products that has not. The authors also analyse the possibility of using machine learning.

The quality inspection that must be carried out is the determination if the glue strings are correct or not on a frame to mount an engine cover. A task that if done manually is subject to many human errors, and that is why the paper proposes a novel machine vision system to overcome this drawback.

The technology used for the control is a robotic arm that comes with a wrist camera mounted and integrated to the robot's control system. Also, a machine learning library called TensorFlow is employed.

The documents explain how the machine learning algorithm must be trained in order to achieve a high performance. Fundamentally, the algorithm must be feed with accurate training data, that in this case are images of a correct quality, therefore images of proper glue strings, and not correct quality, meaning incorrect glue strings. Consequently, when more training data is given to the algorithm, more accurate will be in the quality control process. Accordingly, images from different angles, with different lights and so on must be provided, if not the algorithm will not be able to recognize all the situations present on the real process.

Apart from training data, the document treats two main challenges to deal with when it comes to machine vision system for quality detection.

First, the object location, a complex task when it comes to work on an industrial setting since the background and characteristics of the image it vastly varies. Therefore, authors emphasise that when there are randomness and disturbances in the images, it becomes hard to accomplish an accurate feature recognition for the object location.

Apart from that, the other main challenge is the recognition of the object. On production lines is difficult to ensure stable reference points, complicating the task to recognize the object of interest. Authors suggest as a solution to this, the standardization of the position of the image, therefore, to leave fix the position where the image is taken. But doing so, it eliminates one of the main benefits of using machine vision with collaborative robots, that is the flexibility.

As authors also remark, no experimental evaluation to compare the precision of using this automatic machine vision quality control with manual inspection has been done, and it would be interesting to analyse if it is really improved or not.

Apart from that it would be interesting to develop the whole framework of the case study, also studying the collaboration between human and robot, and how the latter one is inserted on a human workspace. Considering also on this study the communication between robot and human.

4.2.12 Alicona Aerospace application

Title: Highly accurate non-contact measurement of critical components of turbine engines

This white paper included in the analysis is not a document found on the data bases, instead it is a publication done by Bruker Alicona, an Austrian company of measuring systems.

The case study presented on this white paper talks about the quality control of aerospace components which have to meet high security requirements. We are talking about components with complex geometries and tolerances in the range of a few micrometres, making the task not only of production, but also of quality control very hard.

The company proposes to achieve this task the accurate as possible, the use of high-resolution 3D optical metrology. A detailed explanation of how the different characteristics is controlled by the system are present on the publication.

The novelty presented on this white paper is the combination of the 3D optical metrology with collaborative robots for the automation of the quality control process. The starting point of this are the current Smart Manufacturing, Industry 4.0 concepts that, among other things, requires that measurement technology is integrated directly into production and is part of a networked and communicated production chain. In few words, the idea is that when measuring sensors detect defective components, this information is automatically sent to the production cycle and is then used to control the production process.

4.3 Articles classification

Tittle	Industry	Process	Objetive	Type of Quality Control	Type of inspection	Methodology	Technology used	Communication	PROs - Novelty	Research insights
An image vision and automatic calibration system for universal robots	-	Grab and place	-	General framework	-	Hough transformation	Image vision and automatic calibration system. 2 CCD camera, computer, and 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
A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems	-	Quality inspection tasks	Carry a product to be inspected in a given position	Off-line	-	Reinforcement Learning	Force-Torque sensor FT-300, cone-shaped 3D printed tool	Humans 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
A Machine Learning Framework for Real-Time Identification of Successful Snap-Fit Assemblies	-	Snap-fit assembly	Characterization and inspection of snap-fits	On-line	Force signal characterization	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 on other kind of assembly processes
A Task Allocation Approach for Human-Robot Collaboration in Product Defects Inspection Scenarios	-	Defect inspection on a product	inspection of product defects	Off-line	Visual	AND/OR graphs	Dual-arm Baxter manipulator from Rethink Robotics and a Kuka youBot mobile manipulator. LG G Watch R (W110) smart watch	Gesture	AND/OR graphs for activity programming	Integrate this process into a real industry case Introduce a real inspection process
Automated Scanning Techniques Using UR5	-	Line scanner for scanning inspection	generate surface geometry for further inspection	Off-line	Surface geometry characterization	Test Object Grabbed by Robot (TOGR).	Keyence line scanner a 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.

Design of a Collaborative Architecture for Human-Robot Assembly Tasks	-	Assembly of a box	Offering the components of the assembly in the correct order and performing afterwards the quality check.	On-line	Visual	Hough transform	Kinect v2 camera. Middleware NiTE 2.2 [18] IAI Kinect2 ROS package [19]. Hough transform provided by the OpenCV library	Face and gesture	Quality control during the assembly process. Gesture recognition and face recognition Human robot behavior 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
Inspector Robot – A new collaborative testing system designed for the automotive final assembly line	Automotive	End-of-line Car final inspection	water leak test on a final assembly line inspection	Off-line	Visual	No info	Thermographic camera	-	The robot is mounted on a linear track and guided alongside the assembly object robot is mounted on a specially designed linear track which guides it alongside the car	Integrate this process into a real industry case Apply it on other kind of inspection processes
Towards seamless human robot collaboration: integrating multimodal interaction	White goods	pre-assembly of the refrigerator's cabinet	improve sealing operation	General framework	-	No info	Force/torque sensors, microphones, cameras, smartwatches, and AR glasses, vision system, force sensors or joysticks attached tothe 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
Towards shared autonomy for robotic tasks in manufacturing	Automotive (Engines)	Engine assembly	Quality inspection process for generator-plug connectors in car engines	On-line	Visual	Random Sampling Algorithm	XRob software, 3D sensors, software ReconstructMe	Skeleton tracking (Gestures)	Environment Reconstruction:	Introduce a more complex inspection process Test a collaboration environment
Quality Inspection performed by a Flexible Robot System	Automotive	No info	Examine the interlocking of plugs	On-line	Visual	structured light principle	RGB-D sensor, ReconstructMe ShapeDrive® Sensor	Hand guided	3D-sensor for the data acquisition is very independent on the surrounding light conditions.	Introduce a more complex inspection process

Improved Automatic Quality Inspections through the Integration of State-of-the-Art Machine Vision and Collaborative Robots	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	On-line	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
Highly accurate non-contact measurement of critical components of turbine engines	Aeronautic components	Measurement process	Measurement of critical components of turbine engines	On-line	Surface characterization	Fire Variation	Visual sensors	-	Measurement technology directly integrated into production. Sensors detect defective components, and this information is automatically fed into the production cycle.	-

Table 7: Selected literature main information

5. REAL CASE STUDIES ANALYSIS

The Chapter 4 presented the state-of-the art of documents published about the Quality Control and Inspection process with Human-Robot collaboration systems. But as in the table present on section 4.4 Articles classification, not only the number of documents found is scarce, but also many of them lack a real case application on industries.

This may occur due to the fact that as it is a novel topic, most of the real industrial applications of quality control processes with collaborative robots are not being published.

In order to have a better understanding of the topic, and also to have more information for the drawing of conclusions, further sources of information were sought.

As the main objective was to find real case studies, the solution was to enter to the collaborative robots' manufacturers webpages. Through this investigation, Universal Robots official page discovered.

Universal Robots is working since 2005 in the collaborative robot's industry and are the pioneers of this field, but it was not until 2008 that they sold their first collaborative robot.

Their webpage is very complete, and in contrast to its competitors, they have a full section of case stories where many of the real applications of the robots that they offer are explained, most of the times with videos included.

What it is useful inside this case stories section, is the possibility to filter them based on different categories, as shown in Figure 34.

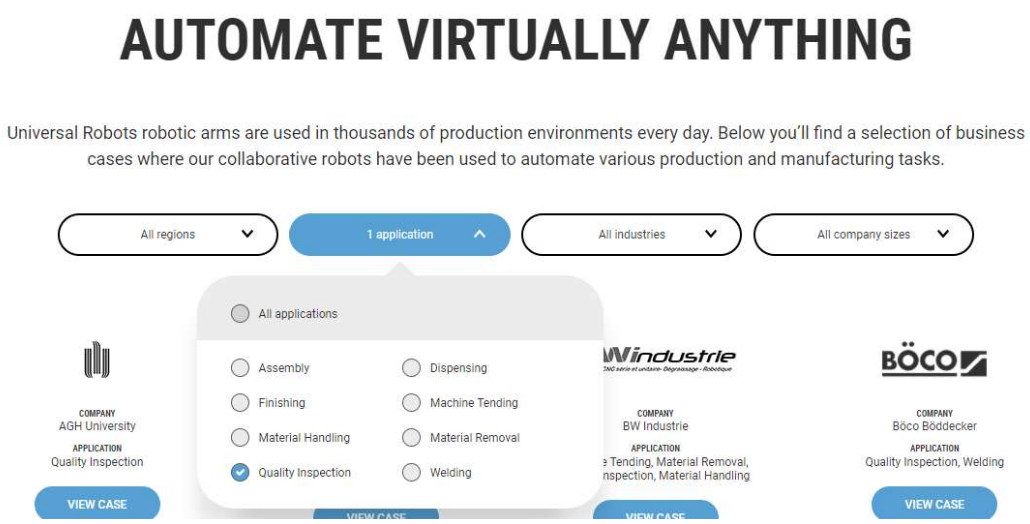

Figure 30: Universal Robots website applications section.

It was possible with this to find on a fast and easy way the case studies of interest, therefore the applications for quality inspection.

The selected case studies are summarized and presented on the following table, that will allow to perform comparisons and derive conclusions.

Company	Country	Industry	Company size	Challenge	Before	Requirements
BWINDUSTRIE	France	METAL AND MACHINING	45	Save from relocation. Increase competitiveness and reduce strenuous works tasks	Manual inspection	Intuitive and simple. Easy-to-use Cobot, Quick training and simple care of day-to-day maintenance.
BÖCO BÖDDECKER	Germany	AUTOMOTIVE AND SUBCONTRACTORS	400	Increase efficiency by identifying repetitive tasks Each part must be individually marked with a code.	Each part be individually marked with a code and quality control done manually	Easily integrated into existing system. No take up too much space.
COMPREHENSIVE LOGISTICS	USA	AUTOMOTIVE AND SUBCONTRACTORS	190	Life-threatening failure mode components, so important to make sure that those clips are locked into place with 100 percent confidence	Manual inspection, 80 percent efficient. A stationary multi-camera system the company implemented could not position cameras into tight spots and was not as repeatable as the manufacturer needed. The data gathered by the camera system was not aspure.	Respect up-time requirements Be simple to use, integrate easily with actual process and operators.
CRAFT AND TECHNIK INDUSTRIES (CATI)	India	AUTOMOTIVE	80	No availability of manual qualified labor, need to reduce the customer rejections for faulty components. No space	Most manufacturing tasks at CATI were handled manually	Easy to work on the shop floor with workforce
EVCO PLASTICS	USA	PLASTICS AND POLYMERS	300	Fast-changing processes. Low unemployment and trouble staffing the third shift in the company's 24/7 production	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.	Versatile automation solution in order to spread out costs between different customers
FERDINAND WAGNER PROFILE	Germany	METAL AND MACHINING	90	Need of a robust and dependable automation solution that could consistently deliver high quality welding and soldering of fragile parts.	Between 500,000 and 600,000 components being manually soldered and welded each year, no longer cost-effective. Fluctuating manual production	Flexible and reprogrammable to effectively meet the needs of the company's production.
FORD MOTOR COMPANY	Romania	AUTOMOTIVE	5000+	Solutions to enhance their manual workforce generating added value to the manufacturing process	-	Space savings, easy to move around, high degree of safety and a fast return of investment (ROI).
GKN DRIVELINE	Japan	AUTOMOTIVE AND SUBCONTRACTORS	1400	Chronic labor shortage issue. Difficulty of automating the experience and sense the operators as well as the safety issue with the traditional machineries.	Old machines, called front and back discriminators, insufficient, so line workers were asked to manually carry out such inspection tasks after a long day of work.	Automate the high-level experience and sense of operators and at the same time of allowing humans and robots to safely coexist
IZOELEKTRO D.O.O.	Slovenia	ELECTRONICS AND TECHNOLOGY	8	Increase production and improve quality assurance. Fulfil customers' demands in a cost efficient manner	Manual time-consuming process	Good quality for a very good price
KOYO ELECTRONICS INDUSTRIES	Japan	AUTOMOTIVE	343	Increase productivity according to increase in demand in the production of products that require strict quality	Manual product assembly and visual inspection, and in the post-process the operators apply styluses to the touch panels to confirm the devices react as intended.	Installed without a safety fence.

NORDIC SUGAR	SWEDEN	FOOD AND AGRICULTURE	1430	Technological advances within robotic arms meant that it was time to replace the old ones.	During the production season the testing department analyses a total of 80,000 sugar beet samples. Task of weighing in the containers with pureed beet had been performed by robots since 1993. Expensive specialists to make a change. Too costly.	Flexibility, user-friendliness, and a reasonable price tag. A robot that employees could program for other tasks and place in production by themselves.
OPTIPRO SYSTEMS	USA	METAL & MACHINING	70+	Automated solution that could measure – in-process – the products. Quality control is crucial since a majority of OptiPro customers manufacture parts for the medical and military sectors requiring 100% inspection.	-	safe, user-friendly solution
STELLANTIS	Italy	AUTOMOTIVE AND SUBCONTRACTORS	407500	Assembly processes and quality controls required the introduction of specific automation technologies to ensure the quality and repeatability needed to meet product standards.	No previous state because it is new assembly line	Given the fairly high average age of the factory workers, the question of ergonomic well-being was a keenly felt issue.
THYSSENKRUPP BILSTEIN	USA	AUTOMOTIVE	700+	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.	Manual check of two parts every one or two hours	Decrease ergonomically unfavorable tasks.

Table 8a: Real case studies main information. Source: https://www.universal-robots.com/case-stories/

Company	Solution	Main benefit	Technology used for control	Type of Quality control	Type of inspection	Robots	Humans	Robot	Human
BWINDUSTRIE	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 thepart in a reject box.	Keep its 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	On-line	Dimensional Measurement	Single	Single	Active	Suppotive
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	On-line	Visual	Single	-	Active	Supportive
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	Off-line	Visual	Single	0	Active	Inactive: robot arm automatically stops operatingif it encounters objects or people within its route.
CRAFT AND TECHNIK INDUSTRIES (CATI)	Cobot places a component on a weighting 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. 40,000 parts, with zero defects or customer rejections.	Weighting machine	Off-line	Weight Measurement	Single	0	Active	Inactive
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 are 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 really cost-competitive	-	Off-line	Weight Measurement	Single	0	Active	Inactive

FERDINAND WAGNER PROFILE	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 per 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.	On-line	Visual	Single	0	Active	Inactive
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	On-line	Visual	Multiple	-	Active	Supportive: Cobots do not require human/operator's intervention unless a
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 four different directions, whichsets the robot in slower motion when people are around.	Off-line	Visual	Multiple	Single	Active	Supportive
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.	-	Off-line	Conformity/ functionality test	Single	0	Active	Inactive
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	Off-line	Conformity/ functionality test	Single	Single	Active	Supportive
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	On-line	Weight Measurement	Multiple	0	Active	Inactive

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 necessary. Avoid brittle material breaking and sharp edges getting fractured or chipping from manual handling reduced in-house workforce	-	On-line	Dimensional Measurement	Single	Single	Active	Supportive
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.	-	On-line	Dimensional Measurement	Multiple	-	Active	Inactive
THYSSENKRUPP BILSTEIN	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 unfavorable tasks	-	Off-line	Visual	Single	0	Active	Inactive

Table 8b: Real case studies main information. Source: https://www.universal-robots.com/case-stories/

6. CHALLENGES AND OPPORTUNITIES

In this last and concluding chapter the challenges and opportunities that the manufacturing sector will face for the large-scale use of the new quality control paradigm based on human-robot collaboration will be presented. These conclusions will be based on what has been presented on Chapter 4 and Chapter 5.

The chapter will be organized as follows; it will be divided in general dimensions, and inside of each, its challenges and opportunities will be developed. The nomenclature to be applied will be:

- C i.j: challenge corresponding to dimension i, order j (if more than one present)
- O i.j: opportunity corresponding to dimension i, order j (if more than one present)

Dimension 1: Type of quality control

O1.1: Towards On-Line controls

The first graph constructed it shows the distribution of the cases from the selected literature and the real case studies, between On-line and Off-line quality control, based on when the inspection is done. As it was explained at the beginning of Chapter 4, On-line controls are the ones performed during the production, and Off-line, the ones that are instead done at the end of the production once the product is finished.

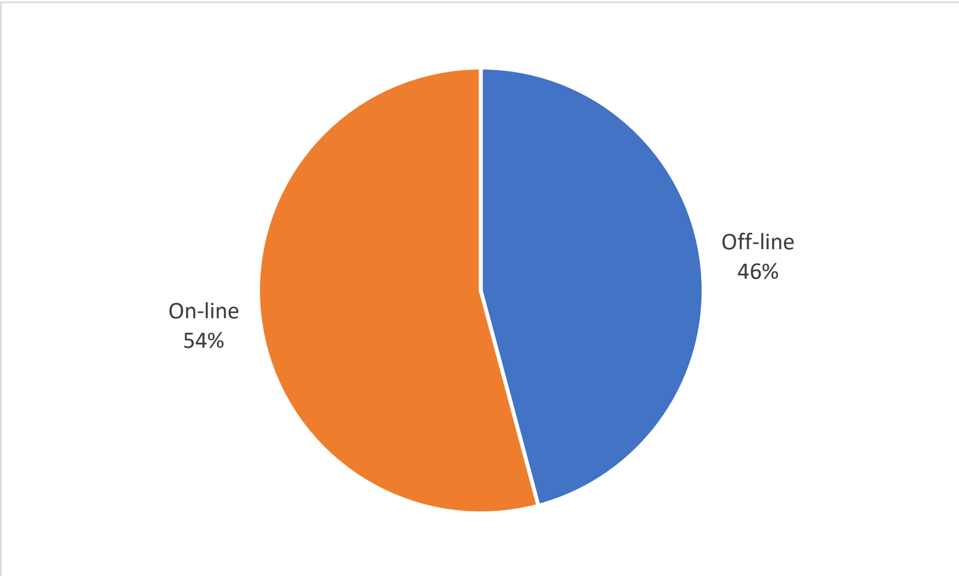

Figure 31: Distribution of cases based on type of quality control of the selected literature.

The distribution between these two categories results to be almost equal, with just a bit more of predominance of On-line controls. This could be due to the fact that On-line quality control process guarantees that the non-conform parts do not arrive at the end of the line, and to make possible to correct them.

Apart from that, if the quality control is delayed to the end of the process, therefore an Off-line control, it means that finished parts rejected cannot be sold, resulting on a waste of resources. That is why it is important for researchers and industries to continue on the way to make all possible quality controls while the product is being processed, considering that collaborative robots help to do this due to its characteristics: small, light, and flexible.

The online controls mean a saving of time and money, and considering that Cobots take up little space, they are adaptable to be incorporated on existing manufacturing lines. Consequently, the space needed for an offline control is not further necessary and the resources that this extra station would use are also saved. This implies an opportunity to make manufacturing systems more effective and a cost reduction on the final product, a significant advantage to actual competitive market.

O1.2: Expanding the fields of application

To understand the type of inspection are done by the collaborative robots on the selected literature and on the real case studies, the following pie chart on Figure 36 shows the type of inspection performed by the collaborative system.

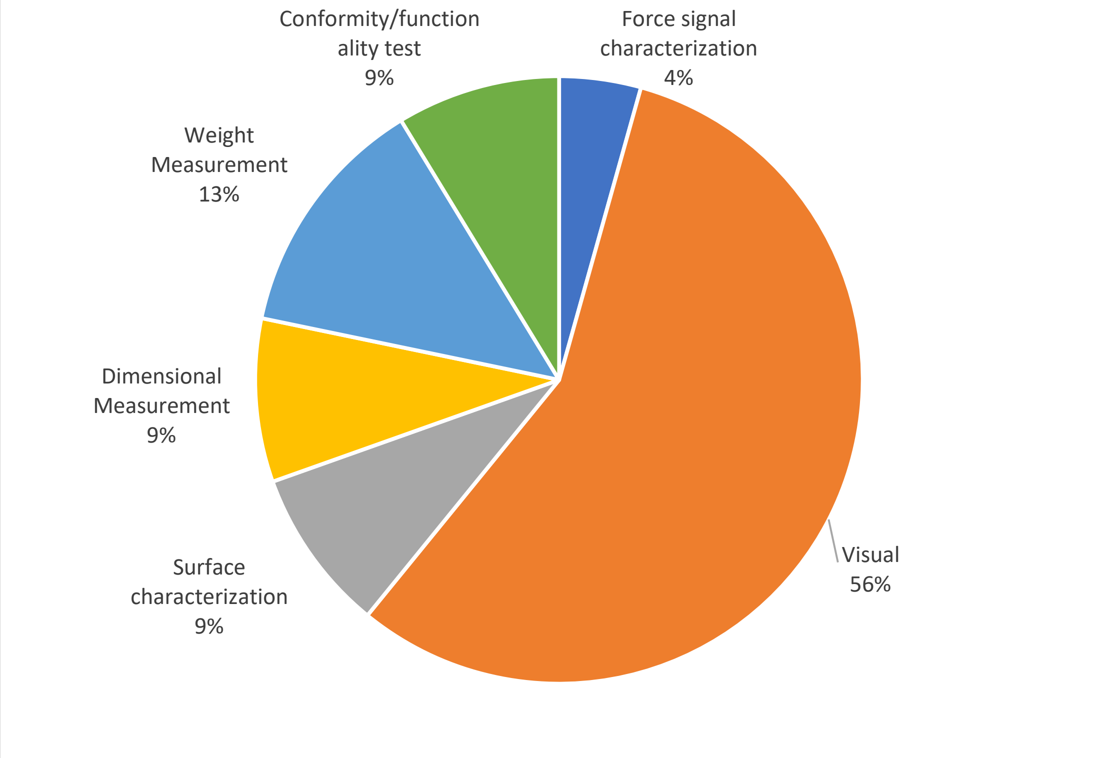

Figure 32: Types of inspections performed on selected literature.

A high predominance of visual inspections is present, with almost 60% of the cases fitting on this category. This can be explained considering that visual inspections previously performed by humans, can easily be replaced by mounting a camera on the robot arm, and can be even improved by using machine learning to train the system.

The type of inspection that follows is the Measurement one with 21%, 9% for Dimensional Measurement, with a very similar methodology than visual inspection, through the usage of camera vision systems, and 13% for Weight Measurement, a very easy type of inspection to be done with collaborative robots, as the only task is to feed the weight machine and based on the output to scrap or not the part.

Even though a 56% of the applications are using visual inspections, is important to highlight that is not the only one that exists, there are other kind of inspections that can be advantaged by the use of Cobots, being a great opportunity to further developed them and not stating as the only inspection applicable the visual ones.

The further development and research on quality controls performed by Cobots, apart from visual inspections, will result on an increase of manufacturers that will see it as an opportunity to apply it on their industries.

C1.1: Application on real industrial cases

Something missing on almost every document of Chapter 4, and also the reason why Chapter 5 was developed, is the fact of the real application of the quality inspection processes developed on the selected literature.

The challenge for researchers is to put them on practice and test the real functioning of the system developed. Therefore, comparisons between manual quality controls and collaborative ones can be done, and it can be corroborated if definitely the collaborative scenario is more advantageous.

Dimension 2: Visual Inspections

A full section will be dedicated to this application, considering that, as it was shown in dimension 1, is the one with most importance now a days.

C2.1: Ensuring an accurate visual inspection

Although it seems to be a simple task to put a camera on the robot, the visual inspection is not something trivial to implement on industrial settings. What most of the authors of the papers analysed on Chapter 4 emphasise is that some important characteristics of the environments has to be assured in order to have an accurate visual inspection. Some of the challenges encountered by the authors are the ones mentioned below.

For example, Lopez-Hawa, et al., state that "a problem we encountered during the scan was an error in the generated data due to refection of the laser beam. This gave some inaccurate data for the scan at certain cloud points of the scan. This error increases with an increase in reflectivity of the object being used and therefore methods to eradicate or minimize this issue further research is required. More specifically, a correction needs to be made to account for the differences of reflectivity of the laser beam depending on the surface being scanned."

On their side, Syberfeltd et al, shares that "even on low quality images object detection becomes complex. It is hard in an industrial setting since the contents of the image might vary a lot depending on for example product variant or angle from which the image is taken. When there are randomness and disturbances in the images, it becomes hard to accomplish an accurate feature recognition for the object location. How to handle this challenge in in efficient way is an open question that needs to be further investigated."

These examples are just to mention some of the challenges regarding visual inspection. But adding what all authors claim, the most important challenges regarding this kind of inspection is the light present on the system, the quality of the image, the different angles, and shadows. (Andersson, 2021) also remarks the challenge with the colours of various components and the light factor.

Therefore, the challenge is to ensure more or less similar conditions during all the process, no matter the day, time, etc., so the system is stable and is able to make the visual inspection under the same conditions and making a correct judgement. This is not an easy task considering the industrial environment, and the variability enhanced. This results on an obstacle on the flexibility that characterizes Cobots.

C2.2: Training the visual system

Many of the authors that apply visual inspection, are also equipping their systems with Machine Learning algorithms, due to the fact that it makes the system able to learn and perfectionate as more controls are performed. A more accurate and precise inspection system is therefore obtained. But this performance is completely dependent on a rigorous training and that appropriate training data, that in this case are images. (Syberfeldt, 2019).

The challenge is to provide to the system as many images as possible. Two categories of images must be provided for the training of the system:

1. Images that correspond to a conforming part.
2. Images corresponding to non-conformities.

More difficult the inspection task is, more training data is needed. Especially, the system needs as much as images as possible regarding the non-conformities, in order that is able to recognize all the possible cases that it must reject the parts. But is not feasible provide to the system with a 100% of possible non-conformities due to the uncertainty present on every kind of process. Therefore, it will always remain a percentage of cases that the system will not be accurate to recognize and act on consequence.

O2.1: Overcoming light issues

One solution presented by (Rooker, 2014) to solve the challenge of the surrounding light, is using a blue light LED projector and a suitable blue light band pass filter.

Incorporating to the Cobot an own light that ensures the right conditions to perform an accurate visual inspection, allows to overcome a part of the challenges presented on C2.1, meaning an opportunity to expand the applications of Cobots visual inspection on manufacturing systems.

Dimension 3: Safety and trust on the collaborative system

C3.1: Safety assessment

Safety is a major topic when it comes to human-robot collaboration. In order to make the human operator trust on the robot, the safety of the person must be ensured.

As it was stated on Chapter 4, the authors of the selected literature do not pay the attention that it requires to the safety assessment of the system. This can be explained considering that most of the documents are on a study phase, and the application has not been developed on a real case yet. But the point is that, as (Andersson, 2021) explains, the unassessed safety in the pre-study propagates into later stages of the implementation. Thus, the manufacturer must adapt the ICR application in later stages to ensure safety, and this impacts the design of the application. The manufacturer needs to design a safe application while gaining the benefits of utilizing less floor space. (Andersson, 2021).

The challenge for future research is to implement the safety assessment from the beginning, because if this is not incorporated, it may be an obstacle on the future application on the implementation stage.

C3.2: Collaboration instead of Cooperation

Something to highlight regarding the type of role assigned to human operators on the real case studies, is that not even one case is using on an active way the human operator, as shown on Figure 37.

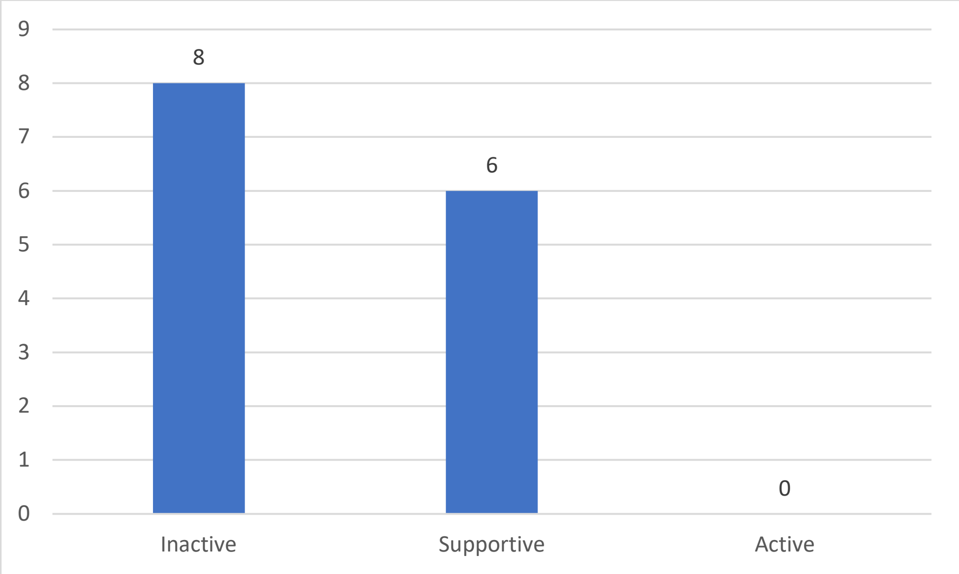

Figure 33: Human operator's role on the collaborative system

Meaning that they are not a real collaborative scenario, but instead, a cooperation one, were Cobot and the operator are working together for mutual benefits, but still each one has its own objective. The workspace and resources are shared, in a sequential and also simultaneous process. The work is divided in sub activities, that are then assigned respectively to operators and robots, and each one is responsible for their part of the job.

Analysing the real case studies, the role of the operators is just to control or support the robot, by assisting it when a problem comes up, or by providing material to work. No tasks are shared between the human and the robot.

Of course, cooperation systems also imply benefits to the quality control process, but the challenge is to increase the collaborative applications were the human and the Cobots advantages are more exploited.

O3.1: Human-Robot Communication

The opportunity to develop more human-robot collaborative systems is strictly related on how the human can communicate and interact with the Cobot. As it was presented on Chapter 4, there are different channels to be used for enabling the communication between human and the Cobot. In Figure 38 it can be seen the type and frequency of utilization of the channels of communication found on the selected literature of quality control in human-robot collaboration systems.

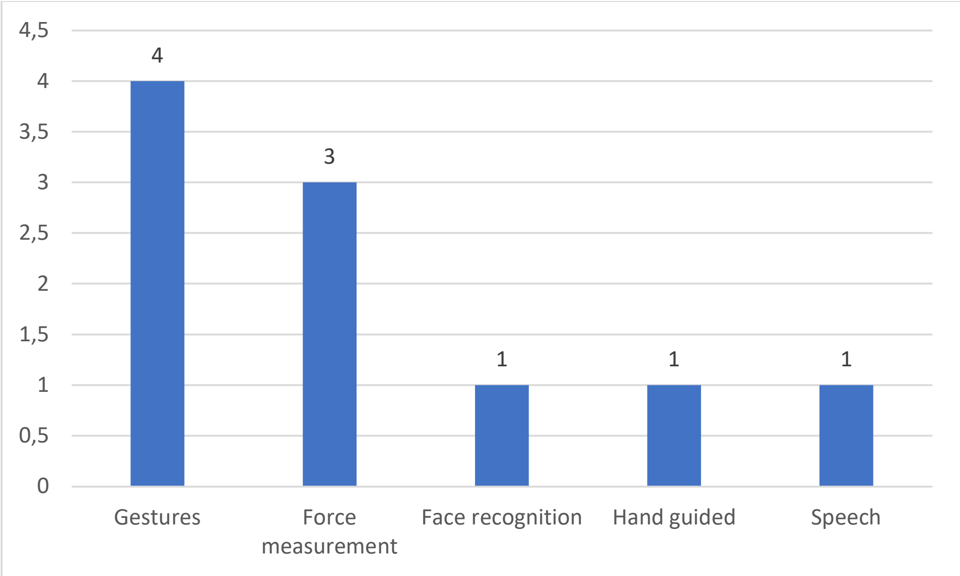

Figure 34: Communication channels used on selected literature.

Furthermore, the communication helps to ensure a safety environment for the human. If the robot is capable to understand human's gestures, speech, the collaborative tasks are done in a more natural way and the Cobot is able to know how to respond consequently to human's movements, words, and actions. Research related to human-robot collaboration also revolves around enhancing particular enabling functions like visual perception and action recognition which enables human awareness and promotes flexible Cobot behaviour (Zaatari, 2019; Knudsen, 2020).

Many of the documents do not even mention about the human and Cobot communication and that, as mentioned for the safety assessment, is a problem when it comes to the real implementation of the quality control process.

Researchers and manufacturers that are using Cobots for their quality control processes, have the opportunity to equip the robots in order to make the communication between the agents the more natural for the human as possible.

Despite the increasing use of gestures and voice commands in HRC for robot control, they are less natural or practical in busy and noisy work environments. Instead of defined gestures and voice commands, recognition, and prediction of human motions through deep learning provides better context awareness and less interruption to normal performance induced by signalling gestures. (Wang, 2019)

O3.2: Adaptation of system parameters

If the system is already embedded with visual capabilities, with a camera for example, there is the opportunity to improve the system and to make it more customized and safer for the operators by the adaptation of the robot behaviour to the user. This can be easily done after the face recognition of the operator, and with a database provided to the robot the height of the person can be extracted, and consequently the speed and the height at which the parts are given can be defined. (Makrini, 2017)

Even if no vision system is present, also this feature can be added to the process by proving a user and a password to each operator.

If the system is customized to each operator, they would have more trust on it and the safety environment would be more guaranteed, as the working speed will never be the same for different operators.

Dimension 4: Efficiency of the collaborative system

O4.1: Overall efficiency and costs reduction

The application of collaborative robots to quality control processes have increased the efficiency of the manufacturing lines and has implied a cost reduction, stated by the industries showed on Chapter 5. Also, the ROI of collaborative robots is very promising, as the range goes from months to maximum two years.

Some of the phrases that confirms what previous mentioned are on Universal Robot applications section:

- Thanks to the flexibility of the Cobot *“total costs allocated over several customers, so that makes them really cost-competitive.”*
- *“Manufacturing under a full 24-hour operation.”*
- *“31% increase in productivity.”*

O4.2: Reduce human error

Another benefit that all the industries encountered when applying Cobots to quality control processes is the reduction of human error, and therefore the increment of defect detection accuracy and customer rejections.

Some of the phrases that confirms what previous mentioned are on Universal Robot applications section:

- *"Reduces likelihood of faulty parts being sent to customers."*
- *"100% quality in the assembly of automotive engines"*
- *"Efficiency has increased with production volume going up 15–20% with no defects or customer rejections."*
- *"40,000 parts, with zero defects or customer rejections."*
- *"The production and testing time of each product is much faster, reducing the overall production cost as human errors are eliminated."*

Reducing error occurrence and increasing the capability of defects detection is something crucial when it comes to quality control processes on the actual manufacturing systems. The opportunity to improve it thanks to collaborative systems must be considered in order to be competitive.

Dimension 5: Fear of human's job replacement

C5.1: Fear of losing the job

Operators often associate the introduction of robotic technology with a fear of being replaced by machines. (Kopp, 2020).

Therefore, the challenge is to make them know that the introduction in this case of Cobots does not mean that they will be replaces, but instead they will be reassigned to other tasks that imply more cognitive and reasoning efforts, only assignable to humans, and that amore more value-adding for the organization. The objective is to make them feel that the Cobot is as a human colleague, that is safe to work with, and that will relieve them of tedious tasks.

O5.1: New tasks for humans

As it was explained on C5.1, thanks to the incorporation of collaborative robots to the manufacturing lines, humans can be reassigned to more valuable tasks where they can apply reasoning and apport more value to the process.

On automotive assembly lines, where many quality controls must be done, the opportunity to assign repetitive and automatable control to robots, and more skilled ones to human operators. (Muller, 2014).

This comes with a motivation to the human operators to feel more useful, and to assign them tasks that are not tedious and stressful.

Dimension 6: Economic expansion

O6.1: Cobot market grows 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 (Knuedsen, 2020)

With the expansion of Cobots market, the supply and demand will change, resulting in a decrease on the price. With more accessible cost, the applications of Cobots on manufacturing lines will experience an increase and it will be more available for smaller companies that cannot afford them right now.

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