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COMMISSIONING OF UNIVERSAL ROBOTS' COLLABORATIVE ROBOTS AND THEIR USAGE IN INDUSTRIAL APPLICATIONS

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ABSTRACT

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This thesis investigates the commissioning of industrial collaborative robots (cobots), focusing on models developed by Universal Robots (UR). The thesis has been implemented as a literature review. It explores the introduction of cobots in the context of industrial history and their emergence as a response to the advancing safety regulations and the limitations of traditional industrial robots. The study contrasts cobots with traditional industrial robots, highlighting the unique features of cobots, such as their smaller size, safety mechanisms, and ease of programming, which make them particularly suitable for small and medium-sized manufacturing companies.This paper discusses the detailed commissioning process of UR cobots, covering aspects like system design, integration with additional equipment, programming, testing, and optimization. The paper emphasizes the importance of proper training, troubleshooting, and maintenance to ensure effective and safe cobot operation. It is stated in the paper that cobots represent a significant advancement in industrial automation, offering versatility, safety, and cost-efficiency, and thus stand as a viable solution for enhancing productivity and safety in the manufacturing industry.

The paper also shows that commissioning of UR cobots is easy compared to traditional industrial robots, which is discussed to be particularly beneficial for small and medium-sized manufacturing companies due to their changing tasks. The paper states that cobots are adaptable and thus suitable for various tasks. The paper also emphasizes the possibilities of streamlined and rapid re-commissioning.

Keywords: Collaborative Robots, Universal Robots, Manufacturing, Commissioning, Deployment

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TIIVISTELMÄ

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Tämä kandidaatintutkielma käsittelee teollisten yhteistyörobottien (cobottien) käyttöönottoa ja teollisia käyttökohteita keskittyen etenkin Universal Robotsin (UR) kehittämiin ja valmistamiin malleihin. Tutkielma on suoritettu kirjallisuusselvitystyönä selvittääkseen cobottien käyttöönoton vaiheita ja haasteita, cobottien ja perinteisten teollisuusrobottien eroja sekä cobottien yleisimpiä käyttökohteita.

Tutkielma tarkastelee teollisuushistorian kautta teollisuudessa vaikuttaneita ilmiöitä ja vaatimuksia, joihin vastaamiseksi cobotit kehitettiin. Tutkimuksessa vertaillaan cobotteja perinteisiin teollisuusrobotteihin korostaen cobottien ainutlaatuisia ominaisuuksia kuten niiden pienempää kokoa, erilaisia turvamekanismeja sekä helpompaa ohjelmointia, mitkä tekevät niistä erityisen sopivia pienille ja keskisuurille tuotantoyrityksille.

Tämä tutkielma käsittelee myös yksityiskohtaisesti UR:n cobottien käyttöönottoa. Tämä tarkastelu kattaa asioita järjestelmän suunnittelusta ja itse käyttöönotosta sisältäen mekaanisen asennuksen, yhteyksien muodostamisen, ohjelmistoasennuksen, ohjelmoinnin, lisälaitteiden integroinnin, järjestelmän optimoinnin sekä koulutukseen liittyvät asiat.

Tämä kandidaatintutkielma myös osoittaa, että cobottien käyttöönotto on pääsääntöisesti helpompaa verrattuna perinteisiin teollisuusrobotteihin, minkä todetaan olevan erityisen hyödyllistä etenkin pienille ja keskisuurille tuotantoyrityksille. Tämä perustellaan esimerkiksi perinteisten robottien vaatimilla merkittävillä turvallisuustoimenpiteillä, kuten työskentelyalueen rajaamisella, jota ei cobottien kanssa yleensä tarvita. Myös esimerkiksi ohjelmoimisen vaativuudessa todetaan olevan merkittäviä eroja, jotka vaikuttavat suoraan käyttöönoton vaativuuteen. Cobottien myös näytetään olevan mukautuvampia sekä sopeutuvaisempia mikä mahdollistaa niille useita erilaisia käyttökohteita. Cobottien yleisimpiä käyttökohteita on esimerkiksi pakkaaminen, laaduntarkastus sekä kokoonpano. Tutkielma myös korostaa cobotin uudelleenkäyttöönoton helppouden ja nopeuden tarpeellisuutta sekä esittelee niiden luomia mahdollisuuksia.

Avainsanat: Yhteistyörobotit, Universal Robots, Tuotantoteollisuus, Käyttöönotto

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Cobot	Industrial collaborative robot
UR	Universal Robots
EU	European Union
ISO	International Organization for Standardization
ROI	Return on Investment
UML	Unified Modelling Language
UI	User Interface
TS	Technical Specification
CNC	Computer Numerical Control
I/O	Input/Output
GUI	Graphical User Interface

1. INTRODUCTION

This paper focuses on the commissioning of industrial collaborative robots. Collaborative robots are widely called cobots, and in this paper, the word cobot refers to an industrial collaborative robot.

There are various types of collaborative robots in the world. To narrow the scope of this paper the focus will be only on cobots designed for manufacturing (industrial collaborative robots), so for example nursing collaborative robots are out of the scope. The scope of this paper is also narrowed by focusing on the cobots manufactured by Universal Robots (UR) but cobots in general are mentioned in various parts of the paper. And to be even more precise, most focus will be put on UR's e-Series, which is their most recent line of cobots. UR also has an older line of cobots, the CB3 series, but they are not manufactured anymore, and thus focusing on the e-Series is reasonable. Universal Robots' cobots were a clear choice for the focus of this paper as they are seen as an innovative frontrunner in the market [1, 2, 3]. UR cobots are also considered flexible and easy to use, which has led to them being increasingly used in manufacturing but also in other industries [4]. To give their success some numbers, in 2020 UR sold their 50 000th cobot unit [2].

This paper answers the following research-questions: where the demand for cobots comes from, how is the cobot commissioning done, how do cobots differ from traditional industrial robots, what are the typical cobot applications, and what are the challenges and requirements related to the commissioning? This paper also includes aspects about the cost of the commissioning, considers the need for programming skills, explains the cobot's communication options, and explains why and where the communication is needed. This is all related to the commissioning process, which is an important part of ensuring the cobot's proper functioning.

It is easier to introduce cobots by introducing robots first. In fact, cobots can be seen as a sub-class of robots. The Cambridge University's dictionary describes a robot as "a machine controlled by a computer that is used to perform jobs automatically" [5]. More specifically, an industrial robot is a machine that can complete manufacturing tasks through programmed motions on it [6]. The programmed motions can also be reprogrammed to achieve the completion of different tasks [6]. The robot is equipped with a tool that suits the needed task.

A recent advancement in robotics, the cobots, have altered the automation industry. They are like robots but can more safely collaborate with people and are thus considered collaborative [7]. Unlike traditional robots, the cobots are from the beginning primarily designed to work safely alongside human operators [7, 8, 9, 10 p. 85]. This is achieved through features such as collision detection and the ability to stop operations when encountering a fixed object or human [7]. If the cobot is stopped by an obstacle it will enter a safety mode and stop its movement [7]. Regular industrial robots would just keep moving forward, possibly hurting humans, or damaging themselves or other structures or materials. Because of this, collaborative robots do not usually require cages or other safety measures, which can be costly and require valuable space [7].

The second section “2. Industrial History” briefly introduces the reasons for cobots’ success starting from industrialization. The third section “3. Industrial Robots and Cobots” focuses on the similarities and differences between cobots and traditional robots. The fourth section “4. Cobot Manufacturers and Models in 2023” introduces the companies that nowadays manufacture the most renowned cobots on the market. The fifth section “5. Applications of Cobots” introduces some of the most used cobot applications and takes a closer look at some of them. The sixth section “6. System Design for Cobot implementation” introduces the needed design tasks that must be done before the actual commissioning. The seventh section “7. Commissioning of the Cobots” gives a detailed view of the commissioning process of cobots. The eighth section “8. Training, Troubleshooting, and Maintenance of Cobots” presents the training and maintenance requirements and possibilities related to cobots. The final body text section “9. Conclusion” briefly introduces the research-question related findings of this paper. The last section “10. Sources” includes the works cited in this paper.

2. INDUSTRIAL HISTORY

Industrial history gives a view of why robots and later cobots were developed. Industrialization can be considered to have begun in the mid-eighteenth century when the first manufacturing processes were invented [11 pp. 4–6; 12 pp. 12–13]. This era was called the first industrial revolution or shortly Industry 1.0 [11 pp. 4–6; 12 pp. 12–13]. By time, industries have developed and undergone several changes, where major technical leaps are called industrial revolutions [11 pp. 4–6; 12 pp. 12–13]. The second industrial revolution (Industry 2.0) began in the late 19th century when electricity and assembly lines were invented, whereas the third industrial revolution (Industry 3.0) can be seen to begin in the 1970s when computers were getting more popular in manufacturing and the first industrial robots were invented [11 pp. 4–6; 12 pp. 12–13; 13 p. 41]. We are currently experiencing the fourth industrial revolution (Industry 4.0) [11 pp. 4–6; 12 pp. 12–13; 13 p. 41]. Its characteristics are production processes integrated into the internet, with sensors and artificial intelligence applied to the machines creating information that can be shared and/or used to control the machine itself [11 pp. 4–6; 12 pp. 12–13]. This is what automation, including robots and cobots, is about.

2.1 Promoters for Robotics

Industrialization created the need for occupational safety [14]. The employers oversaw the working conditions and thus employers' responsibility for accidents was emphasized. Great Britain, a precursor in industrialization, had their first labor inspectors appointed in 1802 and a labor inspection service was created in 1833 [15 p. 1]. These were some of the very first steps towards the occupational safety and health we have today.

Nowadays occupational safety and health are major factors in most countries. People do not want to do work where there is a risk of injury, at least not without adequate compensation. It is increasingly harder to hire manufacturing personnel, which is one of the many reasons manufacturers choose to automate their production. People also tend to make mistakes. These human errors can be caused by various reasons, such as a lack of precision or haste [16, table 1] and they can lead to equipment breakdowns, poor quality, loss of company earnings, or even personnel injuries [9]. Automating dangerous, numbing, and monotonous tasks can help the company to prevent the negative effects of human error [9, 17]. Robotics are a considerable solution for automation, especially in the manufacturing industry where you can find several monotonous tasks.

Today’s working conditions are generally regulated by laws. Some of these laws also apply to robotics. For example, in the EU, the European Union can set regulations or directives that all EU countries must achieve [18, 19]. One major act towards the working conditions in the modern-day EU was the Framework Directive (89/391/EEC) set by the Council of the European Union in 1989 [18, 19, 20]. The directive prescribes for example that “The employer shall have a duty to ensure the safety and health of workers in every aspect related to the work” [20]. This is a major rule to ensure safer working conditions for employees.

The most significant directive in terms of robotics in the EU is the Machinery Directive (2006/42/EC), which was set by the European Parliament and the Council of the European Union in 2006 [21, 22]. The directive states for example that “Machinery must be designed and constructed so that it is fitted for its function, and can be operated, adjusted and maintained without putting persons at risk when these operations are carried out under the conditions foreseen but also taking into account any reasonably foreseeable misuse thereof”, and “The moving parts of machinery must be designed and constructed in such a way as to prevent risks of contact which could lead to accidents or must, where risks persist, be fitted with guards or protective devices” [21 annexes 1: 1.1.2. and 1.3]. This kind of ensuring occupational safety and health through laws is widely used in more developed countries outside of the European Union too [23]. These laws can be seen as a promoter of automation. The laws have been a strong message for employers to make their production safe for the employees. Robots, including cobots, can do hazardous work that people are not allowed to do. In addition to the directives and laws, automation in industries is regulated by safety standards like ISO 10218 for industrial robots and ISO/TS 15066 for cobots, but they are not directly creating the demand for robotics [24, 25 pp. 1845–1847].

Still, probably the most important promoter for robots is the competitive advantage they bring. They can work around the clock to increase productivity and replace human workers from various monotonous tasks to achieve labor cost reductions [9, 26 p. 2147; 27, 28, 29]. Given the circumstances, even with high initial capital investment, robots are often more cost-effective in the long run compared to human workers [9, 28, 29]. This of course depends on the nature of the tasks the robot does. The more there are repetitive tasks in a manufacturing process, and the longer the period these tasks are executed, the better the investment.

To highlight the competitive advantage that robots and cobots bring, two investment-related terms are useful: the payback period and the return on investment (ROI). The payback period is the time it takes for the investment to pay itself back and the ROI measures the profitability of an investment relative to its cost. To calculate the payback period, you need to know the costs of the robot, but also how much value it brings [30 pp.94–95]. In most cases with robotics, the gained benefits are equal to the cost savings the robot investment brings. For example, a robot investment could cost 100 000€, the employee's costs could be 25€/hour, and the employee's task to be automatized could take 7,5 hours daily. In addition to these, we assume that the cobot is as efficient as a human worker would be. For a more accurate calculation, the cobot's cycle time should be calculated, but this example is kept simple just to show the principles of ROI calculations to justify expensive investments.

The universal formula for the payback period is shown in formula 1 [30 pp. 94–95]

$$\text{Payback period} = \frac{\text{Project costs}}{\text{Annual Project Benefits}} \tag{1}$$

According to formula 1, in our case, the payback period can be calculated as shown in formula 2:

$$\text{Payback period} = \frac{100\ 000€}{365\frac{\text{days}}{\text{year}} * 7{,}5\frac{\text{h}}{\text{day}} * 25\frac{€}{\text{hour}}} \approx 1{,}5 \text{ years} \tag{2}$$

So, in a case like this, the payback period would be about a year and a half. To calculate the return on investment, we also need to know the lifetime of the investment [30 pp.94–95]. A typical lifetime of an industrial robot is around 10 to 20 years, and thus using 15 years in our calculations is justified.

In general, the ROI can be calculated as shown in formula 3 [30 pp. 94–95]:

$$\text{ROI} = \frac{\text{Net project benefits}}{\text{Project costs}} * 100 = \frac{\text{Project benefits} - \text{Project costs}}{\text{Project costs}} * 100 \tag{3}$$

As shown above, for our case the ROI can be calculated as shown in formula 4:

$$\text{ROI} = \frac{15 \text{ years} * 365\frac{\text{days}}{\text{year}} * 7{,}5\frac{\text{h}}{\text{day}} * 25\frac{€}{\text{hour}} - 100\ 000\ €}{100\ 000\ €} * 100 \approx 926{,}5\% \tag{4}$$

These calculations (formulas 1–4) suggest that the investment in this case would be rational and profitable. Of course, this calculation is just an example and does not include any specific analysis of the robot's lifecycle, maintenance, reprogramming, or money-related factors like the time value of money or loan interests. This example rather shows that the rationality of a robot investment is calculatable and that with time the high capital investment could be justified. There are also other ways to calculate the ROI and the payback period depending on the case in hand, but for an example, the way through cost savings is an easy one. For example, in a case where the robot increases the production speed, the added value would be calculated differently, but in any case, the basic formulas for ROI and payback period remain the same.

In conclusion, the growth of industrialization has emphasized the focus on workplace safety and the well-being of workers. Today, especially in places like the European Union, laws and rules push for even safer work environments. This push has led to greater use of automation and robots, especially for tasks that might be dangerous for people. The advantages of robots, both in terms of operational efficiency and long-term cost savings, make a strong case for their integration into the manufacturing industry. As demonstrated above through investment-related calculations, the feasibility of adopting robots, even with the significant upfront costs, often translates to considerable returns eventually. While there are multiple factors to consider in such calculations, the primary takeaway is clear: robots, including cobots, represent a solution for a safer, more efficient, and cost-effective production environment in several cases.

2.2 Entry of Industrial Robots and Cobots

Manufacturing processes that had previously been manual and labor-intensive underwent a radical change thanks to industrial robots. Many manufacturing tasks in the past, especially the repetitive ones, were done by human hands. As mentioned above, these manual processes were prone to human error, which could result in production inconsistencies and inefficiencies [9, 17].

At the beginning of the 1960s, George Devol introduced Unimate, a ground-breaking industrial robot [31 pp. 1386–1387; 32]. Together with Joseph Engelberger, they developed the original idea into a real, programmable robot [31 pp. 1386–1387; 32]. The many industrial robots that would come after were inspired by Devol's design, which was patented in 1954 [31 pp. 1386–1387; 32]. Unimate made its grand entrance in 1961 and started in operation at a General Motors plant in Trenton, New Jersey [31 pp. 1386–1387]. In this case, it assumed the duties of spot welding and handling die castings, which were previously performed manually [31 pp. 1386–1387]. This was a pivotal moment that demonstrated how effectively and efficiently robots can improve production accuracy and efficiency. The successful implementation of Unimate created a standard in the manufacturing industry. It symbolized the beginning of a new era, Industry 3.0, in which machines could conduct tasks with a level of consistency, accuracy, and endurance previously unachievable through manual labor.

Industrial automation was evolving rapidly and a new sub-class of robots, termed “cobots" or collaborative robots, emerged towards the end of the 20th century [33, 34].

Their primary design philosophy is focusing on the idea of safe and seamless integration with human operators, in contrast to traditional industrial robots which largely operate without direct human-robot cooperation in designated zones due to safety concerns [10 pp. 85; 24].

The beginning of cobots can be traced back to 1996 when Michael Pashkin and J. Edward Colgate, researchers from Northwestern University, introduced the concept [33, 34]. Instead of being fully autonomous, these robots were designed to collaborate with humans. Their idea contrasted with contemporary robots, granting the customers all the benefits of a traditional robot, but with cost savings from programming, set-up time, and safety measures. Some of the most famous cobots include lightweight robots like the KUKA's LBR iiwa series, and the UR series from the Danish Universal Robots, as mentioned in the section ”4. Cobot Manufacturers and Models in 2023”. In 2008 Universal Robots' UR5 was the first ever commercially sold cobot by any company [35]. Cobots continue to play a crucial role in Industry 4.0, bridging the gap between humans and machines, and ensuring that manufacturing processes are effective and adaptable.

3. INDUSTRIAL ROBOTS AND COBOTS

As mentioned, cobots are a sub-class of robots. They have mostly the same features and functionalities as robots, but they also have additional safety features that make human-robot collaboration safer. This also affects the commissioning of the robots and cobots, and thus it is sensible to familiarize ourselves with the likenesses and differences. Robots have been one of the key technological advancements in the past and are still, and will be, significantly impacting various industries and operations [27, 28, 29]. They are versatile and have several functionalities making them suitable from simple repetitive tasks to complex operations [31 pp. 1385–1409]. Meanwhile, cobots are seen as a specialized subcategory of robots, designed to work together with humans in shared workspaces [10 p. 85; 24]. Cobots and traditional robots share many foundational attributes, but they also possess differences that set them apart. This chapter focuses on the similarities and differences between robots and cobots to better understand their compatibility for different tasks.

The inherent relationship between robots and cobots can be illustrated for example with object-oriented modelling. In terms of Unified Modelling Language (UML), cobots can be seen as a subclass of the broader robot class. This shows that while cobots inherit the general properties and functionalities of robots, they also have unique attributes suitable for their specific collaborative roles. This generalization or inheritance relationship between robots and cobots is visualized in a UML-like style in Figure 1.

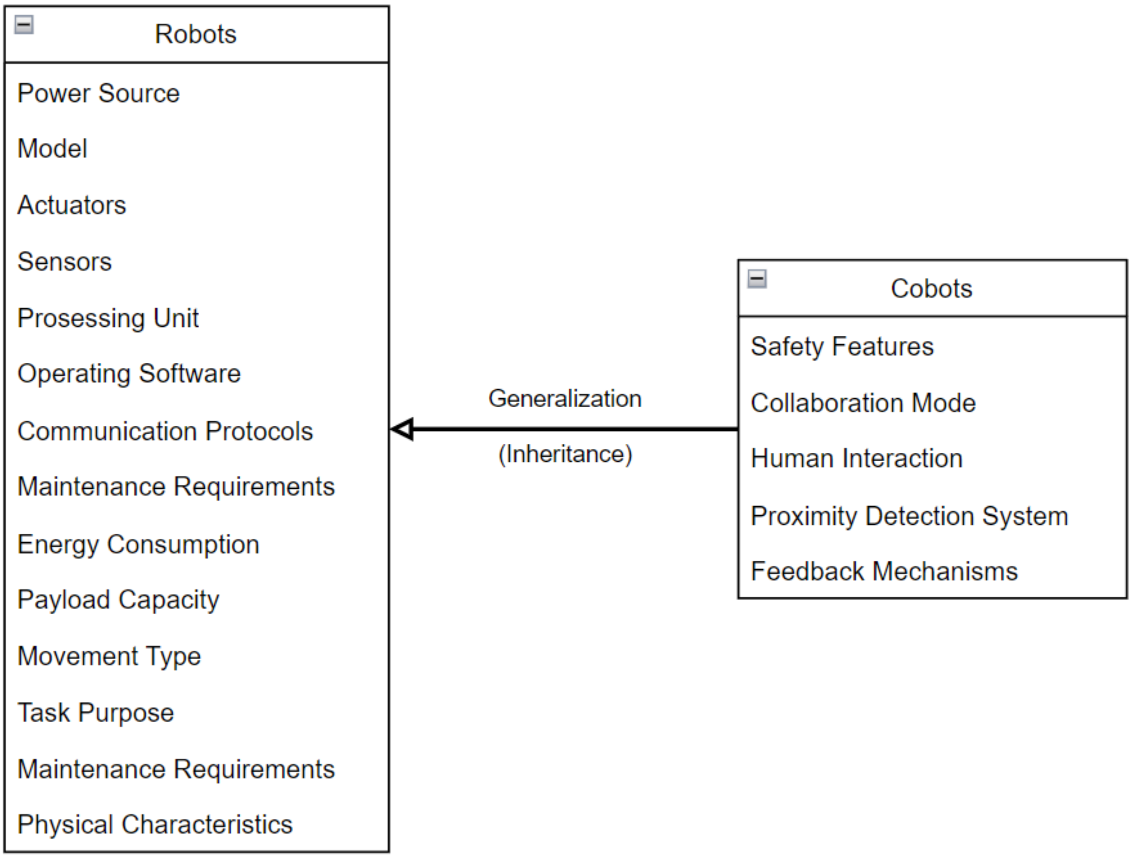

Figure 1. *Cobots as a sub-class of robots shown in a UML-like style.*

As shown in Figure 1, both robots and cobots possess the same core attributes related to their operational capacities, such as power sources and sensory abilities. In addition to these, cobots have additional properties, primarily to ensure human safety and direct human interaction. Cobots focus on bridging the gap between full automation and human intervention. Their design philosophy focuses on the relationship with humans, ensuring that they complement rather than replace human roles [10 p. 85; 24].

3.1 Industrial Robots

According to Bruno Siciliano and Oussama Khatib in their paper Springer Handbook of Robotics, “an industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” [37, cited in 36 p. 1392]. Industrial robots have been foundational elements in manufacturing industries for decades [36 p. 2]. Their consistency, speed, and precision have made them irreplaceable in multiple industrial sectors [36 p. 2; 38].

Typically, industrial robots are large and designed to carry out intensive but accurate tasks [31 pp. 1405–1409]. Their considerable dimensions and forces often require dedicated spaces within manufacturing facilities to ensure safety and optimal functionality [31 pp. 1405–1409]. The safety features of industrial robots are often implemented as physical barriers, advanced sensors, or designated operational zones, ensuring that human personnel remain safe [31 pp. 1405–1409].

The deployment and commissioning of industrial robots usually require specialized teams with automation design and programming knowledge. The teams are often sourced from robot manufacturers or external entities with expertise in robotic integration. Their role includes for example design, installation, integration, and testing to get the robot working properly. The commissioning process includes working with software platforms and, in many cases, using the robot manufacturer's programming language.

Given their large size and strong operational capabilities the industrial robots usually need special electrical configurations. Their consumption and power needs are higher than with standard industrial equipment. Traditional industrial robots typically require a 400V 3-phase current as their power supply. For instance, the Fanuc M-10iD/8L industrial robot with a load capacity of eight kilograms needs a 380-575 V 50/60Hz electrical connection [39].

While being considerably large and strong, industrial robots are often used for large-scale manufacturing, especially in the automotive and electronics sectors [31 pp. 1393–1405; 34]. The demand for high-speed and accurate automation in these industries makes industrial robots an asset [31 pp. 1393–1405; 38]. Industrial robots are suitable for material handling and welding, but also for several other applications. In many cases, the production lines must be highly automated to get the best results from the industrial robots – there is often no place for human inaccuracy [38].

The cost of an industrial robot is high, and the costly commissioning does not help the situation. However, considering their efficiency, accuracy, and the reduction in manual labor costs, the robot investment can often pay itself back as calculated in the chapter "2.1 Promoters for Robotics" [38].

3.2 Industrial Cobots

As stated before, cobots are seen as a sub-class of robots. They share several features with robots but also have some unique features that ensure safer interaction with people and thus set them apart from regular robots [7 p. 2; 10 p. 85]. Cobots are on the first hand meant to be working with people in shared spaces [7 p. 2; 9, 10 p. 85]. In this chapter, and this paper, by the word “cobot” we refer to the industrial cobots only.

The design of cobots includes numerous safety mechanisms, such as force and collision detection, which allow them to stop or adjust their operation when a person is in immediate proximity [7 p. 2; 9]. The ability to work safely near humans without additional safety cages is the most crucial difference between a traditional robot and a cobot [9]. In addition to their advanced sensors, the cobots are often made from soft materials and have rounded edges to make human interaction even safer [7 p. 2; 10 p. 85]. The cobots are also designed in a way that it would be difficult to for example get a finger stuck in between the moving parts [8].

Cobots are relatively small, and they are engineered to excel in tasks that require precision rather than brute force. They are designed to fit into workspaces that are not traditionally made for automation. This makes the commissioning of the cobot easier because usually no additional modifications for the area are needed.

Cobots have a small carry capacity compared to large industrial robots, and thus they are not able to do heavy lifting like some robots. For example, with Universal Robots’ collaborative robots’ carry capacities vary from UR3’s three kilograms to their UR20’s, twenty kilograms [40]. Thus, the cobots are usually doing repetitive lightweight tasks such as picking and placing small objects, machine tending, or quality inspection [8, 9, 41]. One advantage of cobots is that their working process is easily modified. They can for example work eight hours tending a CNC machine and after that, four hours packaging and palletizing the CNC machine’s products [8].

The programming of a cobot is made easier through their user-friendly user interfaces (UIs), and thus they can be re-programmed on short notice [41]. Of course, not all users agree about what a good UI is like, but a lot of work is done to improve the user experience [42]. The cobots can often be programmed by regular personnel with manual guidance or by using graphical programming environments [43, 56]. This shortens the learning curve and time needed for commissioning, making the cobots suitable for tasks that change sometimes.

Most cobots can operate with a standard 230V AC, 50/60Hz, single-phase power supply, which is commonly found in most industrial settings. For example, both the Universal Robots’ UR16e and UR20 cobots can operate using a 230V AC, 50/60Hz, single-phase power supply, even though they have large carry capacities for a cobot [43, 44]. This makes the cobots accessible for even small and medium-sized manufacturing companies without the need for changes in electrical infrastructure.

Cobots are often marketed to small and medium-sized manufacturing companies that require a cost-effective and adaptable automation solution. The tasks cobots are suitable for include but are not limited to assembly, packaging, quality inspection, and material handling [7, 8, 24]. These tasks are often done in cooperation with human personnel.

3.3 Differences Between Industrial Robots and Cobots

Now with the characteristics of robots and cobots in hand, it is reasonable to do a brief comparative analysis based on the previous chapters. The differences between these two classes of robots are related to various aspects from their size and structure to their deployment and use. The key technical differences between them are presented in figure 1.

Industrial robots are generally large and equipped for tasks that demand high precision and force [31 pp. 1405–1409]. They have robust structural components capable of burdensome repetitive tasks. Opposite to that, cobots are agile, compact, and designed to integrate into smaller workspaces and adjust to various tasks that require finesse rather than sheer force [7]. Cobots are also more adaptable than traditional robots, making them suitable for small batches and custom jobs where they can improve ergonomics in the workspace by eliminating the need for humans to handle dangerous or uncomfortable tasks [7]. Still, the cobots are not limited to working only in human collaboration but they can also work independently following the instructions programmed on them like any other industrial robot [9].

Safety measures in industrial robots are primarily about making a physical separation between human workers and machines [31 pp. 1405–1409]. Enclosures, light curtains, and sensor-based systems are used to prevent accidents in the hazardous areas where these robots operate [31 pp. 1405–1409]. On the contrary, cobots have advanced safety features including real-time force sensors that allow them to work with human operators [7 p. 2; 24].

Deploying industrial robots is a complex process that needs specialized technical teams and may involve alterations to existing production lines and infrastructure [31 pp. 1405–1409]. In comparison, the deployment and integration of cobots are made simple, allowing for commissioning without significant disruptions to current processes [7 p. 2]. This approach reduces the time and expertise required for implementation and makes it easier to change the cobot’s tasks.

Programming of industrial robots often requires expert knowledge of certain coding languages the manufacturer uses. The matter is completely different with cobots, where programming is user-friendly and intuitive. Cobots are often equipped with graphical user interfaces or hand-guiding capabilities, allowing operators with limited programming skills to reconfigure the tasks. Now with the cobots in play, the cooperation between machines and human operators has tended to fasten, leading to improvements in the production line's performance, but also changing the production line's personnel's job to include more interaction with the automation. Thus, most of the cobots have remarkably simple user interfaces (UIs) compared to traditional robots to ensure the easiness of the robot-human interaction [45]. The importance of the fluent cooperation between the human operator and the cobot is proved for example in Paliga's article "Human–cobot interaction fluency and cobot operators' job performance. The mediating role of work engagement: A survey" [46].

One often overlooked aspect that distinguishes cobots from traditional industrial robots is their electrical connection requirements. Traditional industrial robots typically require a 400V 3-phase current as their power supply, whereas most cobots can operate with a standard 230V AC, 50/60Hz, single-phase power supply, which is commonly found in industrial sites. For instance, the Fanuc M-10iD/8L industrial robot with a load capacity of eight kilograms necessitates a 380-575 V 50/60Hz electricity connection [39], whereas the Universal Robots' UR16e and UR20 cobots, both with higher carrying capacities than the Fanuc robot, can operate using a 230V AC, 50/60Hz, single-phase power supply [43, 44]. The ease and availability of power supply with cobots is a key factor that contributes to their versatility when compared to traditional industrial robots. This is probably a markable benefit, especially for small and medium-sized companies.

The investment in industrial robots is costly because of their expensive parts, complex installation, and programming requirements. Yet, they are designed for long-term operation, which may result in significant ROI. In contrast, cobots have a lower cost, and their adaptability serves better the needs of small and medium-sized companies that may have to change production demands. Although the ROI for cobots is probably lower than for industrial robots, they offer cost-effectiveness and adaptability that can be beneficial for SMEs with smaller budgets.

4. COBOT MANUFACTURERS AND MODELS IN 2023

The commissioning plays a vital role in the successful integration of a cobot. This chapter will compare several cobot manufacturers and models with a focus on their capabilities that affect the commissioning. The complexity of commissioning varies between manufacturers because the designs of the cobots vary to serve different needs. As mentioned in the “1. Introduction”, this paper will focus on the commissioning of Universal Robots’ (UR) cobots, and thus the focus is on their products. Other manufacturers are mentioned too to see the key differences in their offerings.

In 2023, UR possesses the frontrunner position in the cobot market with its e-Series [1, 2, 3]. Other noteworthy brands include KUKA, FANUC, and ABB, for example [47]. Each of these manufacturers has cobot models with their strengths and weaknesses. For example, ABB’s YuMi series is specifically designed for small parts assembly and has dual-arm configurations enabling complex tasks that need “two hands” [48]. Likewise, KUKA's LBR iiwa is known for its sensitive touch and compliance control which are better suitable for more gentle operations [49]. These features naturally affect the commissioning process. For example, KUKA's LBR iiwa’s sensitive touch response system requires a more accurate commissioning process, especially when calibrating force sensitivity for specific tasks. In the same way, ABB's YuMi needs a precise mechanical setup for its dual-arm coordination, which also may extend the commissioning time. The accurate commissioning of KUKA's and ABB's robots is not always necessarily more complex by default compared to UR, but it is reflective of their capabilities and the precision required for the tasks they are built to execute.

Universal Robots has taken a user-friendly aspect on commissioning [3, 8]. The process is streamlined by the simplicity of its software and hardware, equipped with tutorials from UR Academy, which is an interactive tutorial platform for setting up the UR cobots [8, 50]. UR’s commissioning process differs from other brands in setup complexity, integration flexibility, and user training requirements. UR’s approachable user interface and design make the commissioning time shorter and costs lower [3]. UR is actively developing their cobots’ deployment process to make it even easier. They have, for example, added certified cobot applications to their UR+, which is an ecosystem of certified accessories and software, to make the deployment easier and more hassle-free with several common cobot applications [3, 51]. The deployment has significant financial impacts, especially for small and medium-sized companies. Reducing direct costs like labor and downtime as well as indirect costs like long-term maintenance and training gives UR a competitive advantage in the cobot market.

The UR e-Series family of cobots offers several options to suit the various needs of customers [40]. Specific UR models, like the UR3e, UR5e, UR10e, UR16e, and UR20, all offer different capabilities in terms of payload and reach, but they also share many features, like six joints in their robot arms, as seen in figure 2 [40, 43]. The model decision must fit the task, and it should be noted that these features affect the commissioning process in terms of installation space and work envelope [52]. With UR, and other manufacturers too, the price is often higher with models that have larger carry capacities and wider work envelopes. Thus, choosing the largest one is not always the right decision.

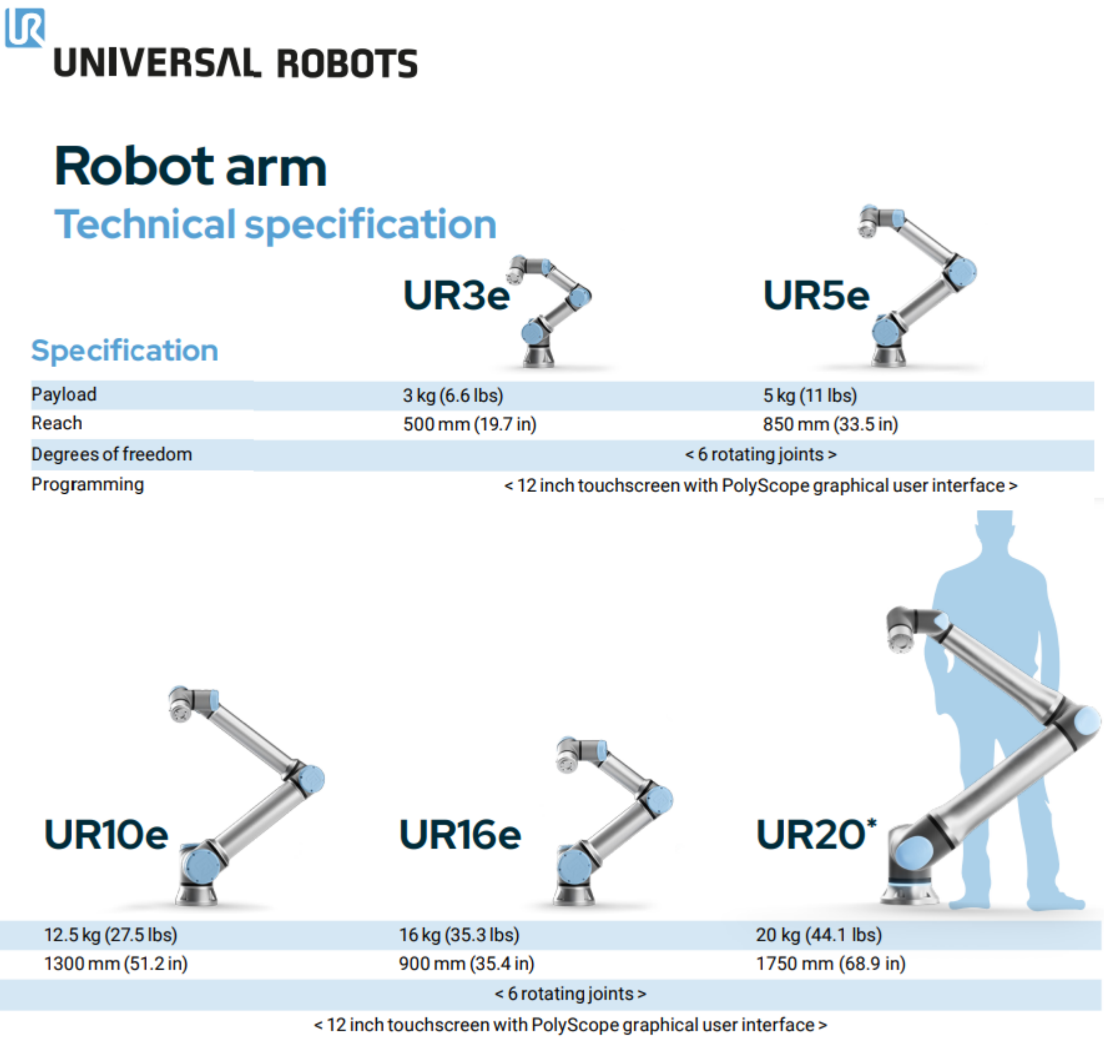

Figure 2. *Universal Robots' e-Series [40].*

Commissioning of UR cobots involves several steps: mechanical setup, software setup, programming, physical integration, and safety checks [8]. Each step benefits from UR's focus on simplicity and efficiency, which is particularly advantageous for small and medium-sized enterprises [3, 8]. While mechanical and software setups are relatively straightforward for UR cobots, the physical integration phase can vary substantially depending on the application. Custom end-of-arm tooling or specific environmental adaptations may introduce additional complexity to the commissioning process but in most cases, there are certified applications in UR+ environment that suit the needs of the customers [3, 51]. One of UR’s strengths is also their UR Academy, which has virtual tutorials for all these steps [50].

5. APPLICATIONS OF COBOTS

Collaborative robots have been increasing in manufacturing where they are primarily used for assembling, material handling, welding, quality inspection, and picking, packing, and palletizing of goods [9, 24, 41, 47]. The tasks the cobots are assigned to are usually monotonous and might include risks for injuries, and many of these tasks are also impacted by a worker shortage [9, 53]. The integration of cobots into these areas not only addresses these risks but also helps with the shortage. The characteristics of different cobot applications will be evaluated by reviewing them in this chapter.

To understand the versatility of cobots, it is important to understand the role of end-effectors. The cobot arm itself is not suitable for complete work tasks. The cobot's arm must be fitted with a tool (end-effector) that suits the application [8]. For example, in machine tending the tool could be a gripper and when screwing, the tool could be an electric screwdriver, and so on [8, 51]. There are many options, and this modularity is central to the cobot's ability to adapt to a wide range of tasks. These tools are mostly easy to install and initialize, making the cobot a flexible investment [8, 51]. The ease of changing these tools enhances the robot's operational agility. Physically the tools usually consist of an actuator, mechanical coupling, and sensors [51]. In addition to those, there is usually a need to connect the tool via a cable to the cobot for I/O signals to control the tool. Some known application kit manufacturers for UR cobots are for example OnRobot and Robotiq [3, 51].

In manufacturing companies, tasks like picking, packing, palletizing, welding, assembling, and handling materials are time-consuming and prone to errors [9]. Cobots sharing the workload with humans can be beneficial for such tasks [9]. Cobots are designed to work alongside humans, providing them with extra support and taking care of repetitive and risky tasks [7, 8, 9, 10 p. 85; 24]. This collaborative approach is reshaping traditional production lines, leading to enhanced human-machine interactions. This chapter focuses on various UR cobot applications and their advantages in manufacturing.

Precision and pace are important in today's market, and cobots are successful in both. Cobots can be programmed to carry out picking, packing, and palletizing tasks accurately and quickly [8, 9, 41]. Unlike humans, who can become fatigued and make mistakes, cobots can work all day [9, 26 p. 2147; 27, 28, 29]. Manufacturing companies are therefore able to meet their production targets more quickly and with fewer errors [9]. Cobots can select components needed to assemble a product, package them in cartons, and palletize them. For packaging and palletizing, cobots can be equipped with advanced conveyor tracking and vision systems to handle a diverse array of products, supporting rapid changeovers in production lines that range from high to low-volume mixes [41]. Cobots are perfect for these tasks because they can handle large payloads at a quick pace. In addition to this, cobot palletizers, like any other cobot applications, are user-friendly and do not need a robotics expert to oversee them, which leads to cost savings [9].

In a manufacturing plant, welding, gluing, and soldering are laborious operations requiring a high level of accuracy. High-precision tasks, such as welding, require the kind of consistent performance that cobots are designed to deliver. Cobots can complete these tasks with exceptional accuracy, guaranteeing outstanding results [9, 41]. Cobots can also decrease waste and increase output while improving work quality due to their accuracy [9]. In addition to this, training cobots may be quicker than training new employees for such tasks [41].

In addition to the prior, automation of assembly line operations is growing, and cobots can collaborate with humans to complete jobs that do not require isolating the cobot [24]. Like with other applications, cobots can improve speed, quality, and reliability [9]. Some key selling points of cobots are that they are quick to redeploy to new assembly configurations, they are lightweight, and they are simple to program [9]. Cobots bring manufacturing flexibility and quick payback without the need for specialized and time-consuming programming, commissioning, or work cells that come with traditional robotics [9]. These features lower the barrier for businesses of all sizes looking to adopt automation solutions.

Moving materials across a factory floor and inside a manufacturing unit is a laborious task. Cobots can transport materials to the intended location more quickly and without getting tired [9]. Cobots are also able to work with harmful materials so that the personnel do not have to, making the working environment safer [9]. With the benefits of cobots in material handling, manufacturing companies can experience improved worker health and safety, lower costs, quicker production, and less downtime [9]. A more specific example of material handling is machine tending. In the context of machine tending, cobots can significantly increase productivity by simultaneously attending to multiple machines [41]. They have specialized I/O interfacing hardware that coordinates their operational cycles so that the cobot knows when the CNC machine is ready [41].

In conclusion, cobots can be used for a variety of tasks in manufacturing, such as material handling, welding, packing, palletizing, and picking [8, 9, 24, 41]. As mentioned in the earlier chapters, cobots offer advantages like higher output rates, better quality output, less waste, safer operations, and lower expenses [9].

6. SYSTEM DESIGN FOR COBOT IMPLEMENTATION

In this chapter, the focus is on the preliminary steps necessary for the successful deployment of UR cobots in a manufacturing setting. This phase, designing the cobot system, is important as it shapes the following commissioning process and ensures that the cobot serves its intended purpose safely, effectively, and efficiently. Attempting the commissioning process without proper design would lead to several problems, especially if the intended cobot application would be complex by for example including other machinery.

Before deploying a cobot within a manufacturing environment, analyses must be done to ensure the suitability of the automation solution for the intended tasks [24]. It is important to examine the details of the tasks the cobot will do, whether it is assembly, machine tending, packaging, or something else. This involves looking at how the cobot system will affect productivity, errors, and worker safety. A well-made system design will justify the need for the cobot application by showing its benefits, but it also ensures that the desired application will be made safely and answer its demand.

According to the methodology provided by Gualtieri et al. in their paper “Methodology for the Definition of the Optimal Assembly Cycle and Calculation of the Optimized Assembly Cycle Time in Human-Robot Collaborative Assembly”, an important step when designing a cobot system for manufacturing is to identify the potential assembly scenarios [54]. For example, if an assembly of a product can be divided into several smaller steps, the steps can be done by a human or by the cobot, and often in different orders [54]. Now it is possible to measure which steps are suitable for the cobot and which for the human, and in which order these steps should be done to get the most effective outcome for the collaboration [54]. These different combinations for the assembly can be called assembly scenarios. An important part of the system design is conducting an economic analysis that focuses on finding which of these scenarios offers the best cost-effectiveness. It is mentioned in the Gualtieri’s paper that it is possible the most efficient scenario in terms of time may not always be the most financially effective because of varying costs associated with each setup, like different end-effectors [54]. The payback period, which was introduced in the chapter “2.1 Promoters for Robotics” can be used as a key indicator to find which scenario is the most cost-efficient [54]. This approach of combining task analysis and economic analysis to cobot system design makes sure that the deployment is not only technically but also economically viable. The paper by Gualtieri et al. focuses on cobots for assembling but the theory can be used for other scenarios too. The scenarios can be found in other cobot applications too and evaluating them to find the best possible one can be beneficial. For example, with a machine tending application, some scenarios could include additional tasks for the cobot like preparing the next set of materials, whereas in some other scenarios, a human would do that.

Now when focusing on UR, the cobot model choice will depend on several factors such as payload capacity, reach, and precision, such as mentioned in the chapter “4. Cobot Manufacturers and Models in 2023”. The cobot's capabilities must meet the demands of the task to ensure smooth operation [24, 52]. It is often so that the smaller cobots are the cheaper ones. Thus, choosing just the right fit instead of the bigger one can also allow cost savings and better ROI. In addition to choosing the cobot itself, the selection of end-effectors is also important. These must be compatible with the items the cobot will handle and the actions it will perform. Also, the prices between the end-effectors vary. For example, with grippers there are various designs where the decision should be made by the size of the object to be gripped, but by also its shape, weight, and material. There would be no point in trying to pick “heavy”, porous, and uneven slabs with a suction gripper for example.

As mentioned in chapter “3.2 Industrial Cobots”, cobots are designed to fit into workspaces that are not traditionally made for automation, which makes the commissioning of the cobot easier than with traditional industrial robots because no additional modifications for the area are needed. The layout should consider the cobot's range of motion and the placement of machinery and workstations with which it will interact. In addition to these, there should be enough space for personnel if human-cobot collaboration is intended.

The safety features of UR cobots allow them to work alongside humans [7, 8, 9; 10 p. 85]. However, with every cobot application, an additional safety evaluation must be done to ensure that the setup complies with all applicable standards and regulations. For example, the standards ISO 10218 and ISO/TS 15066 have several detailed analyses of hazards related to robotics and guidelines for human-robot collaboration [24, 25 pp. 1845–1847]. The safety assessment of a cobot application must not be limited to just the robot arm. Instead, a comprehensive look is needed, where every component of the system, like the end effector, tools, workpieces, additional equipment, and software, are all thoroughly evaluated to ensure it meets safety standards for the entire application. Even with cobots, complying with the standards and regulations may involve the installation of barriers, sensors, or other safety mechanisms to protect human workers. For instance, if the cobot's end-effector poses a potential hazard, additional safeguards such as barriers or sensors might be necessary to ensure worker protection. In the safety assessment, it is crucial to understand that even if the cobot's force would be limited to a hundred newtons (10kg pressure), for example, a needle-like end-effector with that kind of force could cause a lot of damage. Thus, carefully planning the cobot's motions to "hide" the end-effector's possible sharp objects may be advisable. There is also a possibility to create a virtual cage for the cobot. With a solution like this, the cobot's movement area could be limited so that there would be completely safe areas somewhere around it.

Designing the cobot system also includes optimizing [24]. Optimization can also be seen as a task for the commissioning phase, but also optimized design is important. This ensures that the system is used at its best capacity and may mean optimizing the cycle time, motion paths, task allocation, energy consumption, or something else. Many of the optimizations are related to the optimization of the cycle time of the system. In practice, cycle time optimization means calculating the time it takes for the system to complete one cycle of its tasks and trying to reduce it [24]. For example, when tending a CNC machine, the piece must be first inserted into the CNC machine, then the cobot must wait for the CNC machine to finish, then the completed piece must be removed. This would be repeated, and the second cycle would begin. It is crucial for the cobot's programming to be finely tuned so that it aligns perfectly with the CNC machine's timing. This can also be achieved with I/O signals that communicate with the CNC machine for more reliable operation. With one of the prior options, the cobot can prepare to insert the next piece just as the CNC machine is ready for it, which reduces idle time. Further optimization might include streamlining the cobot's movements to reduce transition times between tasks or programming the cobot to handle additional processes during the CNC machine's operation, such as quality checks or preparing the next set of materials, to fully utilize the cobot's capabilities without causing delays. The cycle time can also be used to accurately calculate the ROI as mentioned in the chapter "2.1 Promoters for Robotics".

Now with the basic design tasks done, the cobot system's behavior may be simulated. With the help of simulation software, the proposed cobot system can be virtually commissioned to validate the system design, identify potential issues, and fine-tune the cobot's paths and cycles. Simulations are not completely necessary, but they can significantly reduce the time and resources required for actual commissioning, as many adjustments can be made in the virtual environment before the actual commissioning begins.

7. COMMISSIONING OF THE COBOTS

The commissioning of the cobot includes a series of steps that ensure the cobot is properly configured, calibrated, and tested before it is put into operation [55]. It involves setting up the cobot physically, connecting it to necessary utilities, and ensuring it operates as intended. Each step benefits from UR's focus on simplicity and efficiency, which is particularly advantageous for small and medium-sized enterprises. Proper commissioning is vital for smooth operation and achieving optimal performance from the cobot. This chapter discusses the commissioning process of UR cobots in detail and covers all the necessary aspects related to cobot commission ranging from mechanical setup to troubleshooting and support. In addition to the general aspects, we also address the commissioning specifically through the UR10e and UR16e cobots, based on their user manuals. The user manuals are also used as a source when discussing the UR cobots in general when the information applies to other UR cobots too.

7.1 Mechanical Setup

The mechanical setup is the first step in the commissioning process of the cobot [56]. Physical components are assembled, installed, and prepared for operation [43, 56]. The steps related to mechanical setup are unpacking and inspection, mounting and installation, and connecting it to the needed utilities [43, 56]. The UR10e cobot, like other UR cobots, consists of a control box, a teach pendant, and a robot arm, which are shown in figure 3 [43, 56].

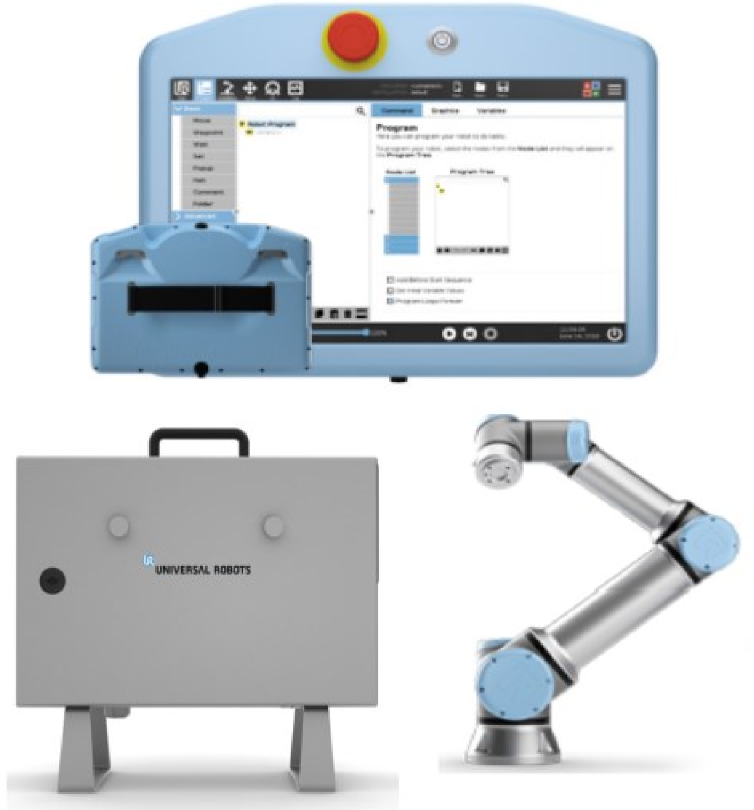

Figure 3. *Teach pendant, control box, and robot arm of a UR cobot [40].*

The first step of commissioning is to unpack the goods and inspect that all required parts are available and in good condition [56]. This inspection should verify that no physical damage has occurred during shipping and that all components are present because any damage might lead to issues with the cobot. Then, the cobot must be securely mounted to ensure stability during the operation [43, 56]. This involves choosing a suitable location that has enough space for the cobot's motion and accessibility for the operators, as mentioned in the previous chapter “6. System Design for Cobot Implementation”. The mounting surface should be rigid and able to prevent any vibrations or movements that could disrupt the cobot's precision [43, 56]. The robot arm can be bolted to a fixed surface but there are also various moveable cobot desk solutions available [8, 43, 56].

The last step in the mechanical setup is connecting the cobot to the necessary utilities. The primary utility of cobots is the electrical power they consume [56]. As mentioned in the chapter “3.2 Industrial Cobots”, the UR cobots work with the regular wall outlet, making the commissioning easier than with traditional robots [43, 44, 56]. It is important to ensure that wiring does not interrupt the cobot's movement or create trip hazards. If the cobot application involves pneumatic components, the air supply must be connected, and its pressure checked according to the manufacturer’s instructions.

The mechanical set-up is easy and cheap especially when compared to traditional industrial robots. The cobots are light and do not usually need additional protective structures or fences, as mentioned in the chapter “6. System Design for Cobot Implementation”.

7.2 Connectivity Setup

This part of the commissioning involves connecting the cobot to communicate with other systems. This includes input/output (I/O) wiring, network connection, and safety system integration. After the mechanical setup, it is possible to proceed by connecting I/Os, by establishing the ethernet connection, or by configuring the software. Establishing the I/O connections or ethernet connection is not mandatory and the cobot can be operated without them, but they are needed for some more complex systems including other equipment in the automation system [43, 56]. Also, for example, the end-effector often needs to be connected through I/O.

For the cobot to communicate effectively with other systems, I/O connections are needed [43, 56]. The cobot receives inputs and sends outputs to other devices through I/O connections. Input devices like sensors, switches, and buttons need to be wired to the appropriate input ports on the control box, while output devices such as actuators or signal lamps must be connected to the output ports [43, 56].

The cobot’s network settings must be configured if it is wanted to be connected to other systems through the internet for coordinated operation [43, 56]. Additionally, networked I/O devices can be used [43, 56]. They need a different approach than traditional direct I/O wiring. These devices must be connected through industrial protocols like EtherCAT or PROFINET which allow for real-time control and monitoring through the network [43, 56]. The choice between traditional I/O and networked I/O can be affected by several factors. Traditional I/O is generally simpler, more reliable, and more secure, but they are not as scalable and flexible as networked I/O. Thus, the choice of communication method should be considered to meet the requirements of the system.

Then all that is left for communication setup is the integration of safety systems. This involves connecting any necessary safety devices such as emergency stop buttons or safety gates. The safety features must be configured in the cobot’s software, as instructed in the next chapter “7.3 Software Setup”, to correspond with the setup to make the right safety actions when activated. The control box of UR cobots has dedicated ports for safety I/O wiring [43, 56].

7.3 Software Setup

After the physical set-up, it is time to focus on the software side. With UR, the teach pendant's Graphical User Interface (GUI) is called PolyScope [43, 56]. On the first start, the user-friendly PolyScope guides the user through the initialization process of the system [43, 56]. After the initialization is finished, the user should configure the basic settings like language, measurement units, and network, as mentioned in the chapter "7.2 Connectivity Setup", if it is needed [43, 56]. The completion of the software setup ensures that the cobot is functional, ready to be programmed, and prepared for integration into the production environment.

Depending on the desired cobot application there may be a need to install other modules or plugins from the UR+ ecosystem. [51] The ecosystem has plugins that allow enhanced functionality like advanced gripping or specialized application tasks that may be needed for the cobot's equipment. [51] These modules must be selected based on the application requirements and compatibility with the cobot's tasks.

At this time, it is good to check that the safety configuration is done as intended. The safety configuration can be accessed with the teach pendant and by navigating to the "Installation" tab on the header and "Safety" on the left side panel [43, 56]. The safety settings include various options to go through. There is a possibility to establish limits for the cobot's movement and tool positioning, for example. [43, 56] There is also the possibility to define the actions for the I/O connected safety equipment like emergency buttons or safety gates [43, 56]. Configuring the safety actions from I/O signals ensures that when a safety device is activated, the cobot responds as it is supposed to. The triggered actions include several modes for the cobot which are for example reduced mode and emergency stop [43, 56].

Software setup also includes the configuration of the I/Os in the PolyScope [43, 56]. The wired I/Os mentioned in the chapter "7.2 Connectivity Setup" must be configured so that the communication with external devices and systems works as intended. In the PolyScope, the "I/O Setup" can be found through the "Installation" tab and by choosing "General" from the panel on the left side. [43, 56] For inputs, the configuration manages what each signal received by the cobot will represent, such as a start command or a stop signal [43, 56]. Also, sending outputs is possible and needed to activate or deactivate other machinery and equipment.

In addition to configuring safety features and I/Os, the end-effector (tool) should be configured in the software setup phase. [43, 56] This end-effector might be a gripper, a welding torch, or any other tool, but the key is that it directly interacts with the workpiece [51].

Like the “I/O Setup”, the tool-related configurations can be found from the PolyScope through the “Installation” tab and by choosing “General” from the panel on the left side. [43, 50, 56] Here, it is possible to determine various tool parameters like the tool centre point (TCP), payload, centre of gravity, and tool I/O [43, 50, 56]. These parameters are easily configured and important for the cobot's control system to accurately calculate the dynamics and kinematics for precise and safe operation. For example, the tool I/O is configured in a remarkably similar way to other I/Os, including the assignment of control commands to specific I/O ports [43, 56]. PolyScope also includes several tools related to software setup that make the commissioning easier. There are for example functions that help in calculating the TCP and built-in modules like “Conveyor Tracking” and “Screwdriving” to help with applications that use them [43, 56]. The tool’s software setup process is well-instructed in the UR Academy [50]. It is also important to test that all these configurations, safety, I/O, and tool, are working as expected (see chapter “7.6 Testing and Validation”).

7.4 Programming the Cobot

Programming the cobot is a central phase in the commissioning process. This establishes the tasks the cobot will execute and how it will interact with other machines. The programs on the cobot are being created and executed mostly through the PolyScope [43, 56]. The UR series is targeted to all sizes of companies from various fields including labor-intensive tasks, where the personnel does not necessarily have any robot programming skills. The cobots are designed for possible human cooperation where the cobot’s user would be the worker at the workstation, who is not necessarily the possible robotics expert in the company [7, 8, 9; 10, p. 85]. Thus, most of the tasks the UR cobots do (see chapter “5. Applications of Cobots”) are programmed by using only the PolyScope. The PolyScope operating skills for the staff can be learned for example from the UR Academy’s online courses [50, 56].

It is good to understand the basics of the cobot's scripting language before the actual programming. Universal Robots uses its own scripting language named URScript, which controls the cobot’s movements and operations [43, 50, 56]. A view of the syntax and structure of URScript is advisable for creating reliable programs, even if the programming would be done through manual manipulation, which is commonly referred to as “teach mode” or “manual programming”. The manual manipulation refers to teaching the cobot its movement by manually moving the cobot arm and saving specific locations to its memory, which the cobot can later reach through the program [50]. The view on the syntax helps understand how to declare variables, write functions, and use control structures such as loops and conditionals [50].

URScript's syntax is a lot like in traditional programming languages. URScript has a user-friendly format with clear rules for declaring variables and defining functions [43, 50, 56]. Functions in URScript are defined using the 'def' keyword, followed by the function name and parentheses including optional parameters like in Python [43, 50, 56]. Control structures like “if-else” conditionals or loops are presented in a C-like syntax that provides robust tools for decision-making and repetitive tasks within the program. [43, 50, 56] For example, a loop might be used to instruct the robot to perform a task repeatedly until a certain condition is met.

With an understanding of the basics of URScript, it is possible to start programming the first programs. The programming interface in UR cobots has built-in options for both text-based programming and a graphical interface, which can be used to “teach” the robot paths by manually guiding the arm by hand and saving waypoints [43, 56]. The cobot has several built-in functions that help to program parts like handling I/O signals or controlling the gripper [43, 56].

At its core, the programming of a cobot means teaching it and the attached tool their movements and actions [43, 56]. The cobot follows these instructions one by one. The tasks cobots are optimal for are usually repetitive (see chapter “5. Applications of Cobots”), and thus using loops and if-structures, combined with I/O signals is often necessary for the optimal outcome. There are various ways to program a UR cobot, of which the main way is Teach Pendant/PolyScope programming. The cobot can also be programmed with text-based programming software, with URSDK, URSim, Robot Operating System (ROS), or with other suitable software or platforms. At first, programming a UR cobot may seem difficult, but with the correct tools, information, and education (see chapter “8. Training, Troubleshooting, and Maintenance”) it should be doable even for personnel with no previous programming experience [8, 50]. The PolyScope is designed in a way that the end-user does not necessarily need any automation or robotics knowledge, and thus one opinion about PolyScope programming is that the programming is already done, and the user must only browse through the graphics user interface to achieve their goals [8].

Selecting a programming interface is a good start in programming a UR cobot. UR cobots can be programmed using a variety of programming interfaces, including the built-in PolyScope [43, 56]. It is important to select the interface that best suits the demands of the application and the skills and knowledge of the programmer because all interfaces have their advantages and disadvantages.

Writing a program is the next step after selecting the programming interface. The majority of UR cobot programs are made up of a set of instructions that specify what the robot should accomplish [43, 56]. These instructions might be as straightforward as moving the robot's arm to a particular location or as complex as reading sensors or controlling other tools in the workspace. The programming method depends on the chosen programming interface. For example, PolyScope programs often use a graphical interface to generate programs, but ROS programs can be created by writing in a text editor using a programming-language-specific syntax.

PolyScope programming is the quickest and easiest way for many beginners [50]. With the PolyScope in hand, all the programming is done in the “Program” tab, while some of the parameters and I/O connections must be established on other tabs as mentioned in the chapter “7.3 Software Setup” [43, 56]. The “Program” tab can be found on the PolyScope by choosing the “File Path” -window, and then tapping “New…”, and selecting “Program” [43, 56]. Now if the cobot is wanted to be programmed by text-based programming, it can be written with PolyScope or added from an external script file. [43, 56] One of the key selling points with UR cobots is still the ability for manual manipulation, and UR provides a nice example of how to utilize it in programming.

A simple example of programming a UR cobot with PolyScope is presented in the UR 10e user manual [56]. The program moves the cobot arm from one point to another, highlighting the easiness of the programming with the PolyScope and the Teach Pendant [56]. To add a waypoint for the cobot, the user must choose “Basic”, and Waypoint from the “Program” page [56]. A new Waypoint variable and a MoveJ command are added to the program tree [56]. Now to set the correct location value for the Waypoint variable, the user must choose the Waypoint in the “Command” tab [56]. The cobot arm can now be moved to the desired position through the PolyScope’s arrows or by holding down the “Freedrive”-button and physically moving the cobot arm [56]. Once the desired position is reached, it can be saved as Waypoint_1 by pressing “OK” on the “Command” tab under the Waypoint [56]. Additional Waypoints can be created by repeating the previous steps starting from the addition of the Waypoint on the “Program” page [56]. The order of the waypoints can be easily changed by moving them up or down in the PolyScope [56]. Now the program can be executed by pressing the “Play” button [56].

As seen with the example program, programming the UR cobots with the PolyScope is considered easy. There is also a possibility to connect digital and analog signals to the cobot's control box to connect sensors and other equipment in the production line, as mentioned in the chapter "7.2 Connectivity Setup". [43, 56] These signals can be read and sent within the program. For example, PolyScope offers an easy way to define the signals and to add them to be a part of the programs. Connecting and defining the I/O signals is a part of the UR Academy's basic course (see chapter "8. Training, Troubleshooting, and Maintenance") [50].

The final step of the programming is to test, debug, and deploy the program. In practice, this step heavily varies between the chosen programming interfaces and the purposes of the programs, but few basic principles are the same. In all cases, the testing starts with a basic functionality testing which verifies that the cobot is moving normally and that the possible sensors and actuators are behaving as supposed. If no issues arise, it is time to test that the cobot works as intended with the specific program and accomplishes the desired task. These steps can also be done as a simulation before running them in the physical world, which is often recommendable. For example, PolyScope, Robot Operating System, and URSim all offer the possibility of simulating the program [43, 56]. With PolyScope, there is a simulation mode for this purpose, that when enabled does not move the actual robot at all [43, 56]. If any issues were found it is time to debug the program. Most of the programming interfaces have built-in tools for identifying the problems. When the program is working as intended, it is time to deploy the program to the cobot. Testing of the cobot application is more comprehensively discussed later in the chapter "7.6 Testing and Validation".

In conclusion, programming a UR cobot is a process that combines choosing the right tools, understanding the basics of the cobot's scripting language, and thorough testing. While PolyScope provides a more accessible entry point for those without prior programming knowledge, text-based programming offers greater flexibility for complex tasks and may be easier in some integration cases for example.

7.5 Integration with Additional Equipment

Integrating the cobot with additional equipment may be needed to achieve better efficiency and reliability of the cobot application. The additional equipment needed varies between the applications. In some cases, the cobot application may include external cameras and sensors, and in some other cases, it can include other machinery and conveyors for example [9, 41, 51]. The one piece of equipment that is needed for all cobot applications is the end-effector. This step of the commissioning involves connecting and configuring all additional equipment that the cobot will need to interact with during its operation.

The end-effector, such as a gripper or tool, is needed to make the cobot functional, as mentioned in the chapter “5. Applications of Cobots”. With UR cobots the installation process of the end-effector involves mechanical attaching and configuring it in the software [43, 56]. The configuration may involve calibrating the end-effector's force, speed, and positional parameters depending on the end-effector in use [43, 50, 56].

The cobot applications may include external sensors and cameras that can increase the cobot's capabilities like making part recognition or quality inspection possible [9, 41, 51]. Integrating these components requires setting up the equipment, connecting it to the cobot’s control system, and programming the cobot to process and respond to the input [43, 56]. This may include defining the logic for decision-making based on sensor data or camera images. The cobot may also be integrated with other machinery, like CNC machines, conveyors, or packaging equipment, as mentioned in the chapter “5. Applications of Cobots” [41]. This involves establishing communication protocols and connections, which may include I/O, ethernet, or other industrial communication standards [41, 43, 56]. The cobot needs to be programmed to work in coordination with these machines and to react to signals that indicate the status of the other equipment [43, 56]. For example, if a conveyor belt feeds the cobot with parts, there could be sensors that sense that the part is ready to be picked up. Now the sensor would send an input signal to the cobot’s control box and the cobot would react accordingly to its programming [56]. Most likely it would pick up the part and complete a desired task with it, like feeding the part to a CNC machine. Now, the cobot would send a signal to the CNC machine that the part is ready to be machined. These kinds of complex systems are possible with additional equipment and proper communication like I/Os.

The successful integration of the cobot with additional equipment ensures that the cobot application operates as a unit, where the cobot is just a single part of a larger automation system. This step of commissioning requires careful planning, precise execution, and thorough testing to verify that all elements of the automation system communicate and function together correctly.

7.6 Testing and Validation

Once the cobot and the additional equipment have been integrated the phase of testing and validation can begin. This phase of the commissioning is done to ensure that the cobot operates as expected and performs its tasks safely and effectively. Safety is important in any automation system and even more important when robot-human collaboration is intended. A thorough safety check involves verifying that all safety features are functioning correctly, installed emergency stops are operational, and t the cobot’s movements restricted to its designated area. A risk assessment should be done to identify potential hazards associated with the cobot's operation. The safety assessment should not be limited to just the cobot itself but should consider the end-effector and everything else related to the cobot application as mentioned in the chapter “6. System Design for Cobot Implementation”.

In addition to safety testing functional testing is advisable. The purpose is to confirm that the cobot performs the tasks it was programmed to do accurately and consistently. The means for this testing are that the programs on the controller are executed but in a safe environment and it is checked that everything goes as expected. This involves monitoring the cobot's movements, verifying the correct operation of end-effectors, and ensuring that interactions with additional equipment occur without errors or delays. It is also advisable to test the cobot’s response to any unexpected situations or errors to confirm that it reacts appropriately. These could be for example situations where the cobot’s movement is blocked. The testing should not be limited just to the cobot if the cobot is part of a larger automation system that may include other robots, machines, and human workers. Verifying interoperability means checking that the cobot communicates and cooperates effectively with these other elements. For example, if a conveyor belt speed changes or a CNC machine’s cycle time varies, the cobot must adjust its behavior accordingly. The testing and validation steps are iterative, often requiring multiple rounds of testing to identify and fix the issues. Once testing and validation are completed, the cobot application can be considered ready for optimization and production deployment.

7.7 Optimization and Tuning

After the cobot has been tested and validated, the next step is to focus on optimizing and fine-tuning its performance. Optimization may start with an analysis to identify any bottlenecks in the cobot’s operation or in the whole production. Adjustments can include adjusting the cobot's movements to be more effective or tuning the timing to match with the other elements more effectively. The goal is to have the cobot performing efficiently while still maintaining safety and quality.

As mentioned in the chapter ”6. System Design for Cobot Implementation”, optimizing the cycle time is a part of the design phase but also a part of the commissioning. Even optimizations of some parts of a second can end up in markable savings in the long run. The optimization may involve reprogramming the cobot to take shorter paths, reducing wait times between operations, enabling the cobot to perform parallel tasks, or adjusting the timing of the operations according to the rest of the automation system.

7.8 Re-commissioning for a New Task

It is likely that at some point in the cobot's lifetime, its tasks will be changed. At that time, a modified commissioning process is needed. This might not mean starting totally from scratch, but it would certainly involve reconfiguring the software, changing the end-effector if necessary, and reprogramming the cobot for its new task. It may also involve adjusting safety settings and testing and validating the new setup to ensure it operates safely and effectively. The easier and quicker the re-commissioning is, the lower the threshold to change its tasks is.

UR has made their cobots' commissioning quite quick and easy. Especially, when compared to traditional industrial robots that often form large entities [31 pp. 1405–1409]. The PolyScope is designed in a way that it is easy to find all the necessary parts and nothing software-related (in simple applications) is left outside of the PolyScope. The easiness of re-commissioning benefits especially the companies where the tasks change rapidly. The streamlined commissioning process could for example allow a company to first collaborate with the cobot in some tasks when the personnel are working at the premises, but then the cobot could be re-commissioned for evenings or weekends to complete a different task that does not require human-robot collaboration. For example, during the days the cobot could do collaborated assembly, but at the weekends it would pack and palletize the assembled products by itself. This could be especially beneficial for smaller companies that do not produce large quantities and possibly do not want to invest in two robots.

8. TRAINING, TROUBLESHOOTING, AND MAINTENANCE

The commissioning of a cobot system culminates in ensuring that the human operators are trained to operate and reprogram the cobot. Personnel training is important for successful long-term integration. It is also viable that the selected personnel can do the basic troubleshooting and maintenance.

UR has their own training environment, named UR Academy, which offers free e-learning and paid training courses about UR cobots [50]. They offer free low-threshold interactive e-learning for example for the e-Series cobots [50]. These e-learnings are divided into three categories by their complexity: e-Series Core Track, e-Series Pro Track, and e-Series Application Track [50].

The e-Series Core Track offers a basic view of the cobots and their use. There are eight modules in this course ranging from the first look on the cobot to the optimization [50]. In total, there is almost an hour and a half of content to teach the learner the basics [50]. With these lessons, the learner should be able to program basic cobot applications that may also include some other machines and simple I/Os. The content is simple and should be understandable for almost anyone.

The e-Series Pro Track dives a bit deeper [50]. The topics are more complex including “program flow”, “feature coordinates”, and “force control” [50]. With these three modules, offering content for about 40 minutes, the learner should be able to use more complex features of the UR cobot. Still, these topics seem to be presented easily enough for most people to learn them. Prior programming or automation knowledge should not be needed but would help in understanding the content.

The final track, the e-Series Application Track focuses on different cobot applications [50]. The three modules included are ”palletizing”, “screwdriving”, and “machine tending” [50]. The total length of the content in this track is a bit over fifty minutes and offers a comprehensive look at each of the mentioned applications [50]. The content is instructional, and most people should be able to complete the applications according to these modules if the hardware corresponds to the ones in the modules.

Beyond basic operation, for example, maintenance personnel should be able to perform regular maintenance and troubleshoot common issues. This involves understanding the mechanical and software aspects of the cobot, being able to diagnose errors, and knowing how to execute repairs or replace components. In addition to e-learning, UR Academy also offers paid in-class and virtual training to ensure that their customers have all the knowledge they need to succeed with their cobots [50]. UR Academy offers for example “service & troubleshooting training” to learn about diagnosing, troubleshooting, service tasks, and calibration, to mention a few [50].

Commissioning a UR cobot extends beyond basic operation to include troubleshooting and maintenance. At least some of the personnel should be able not only to use the cobot but also to diagnose and solve common technical challenges. This involves checking physical connections, ensuring the operational status of the cobot and additional equipment, and applying software updates. For more detailed support, UR has resources including online forums, technical support lines, and an online library with troubleshooting guides and instructional videos.

In conclusion, the training provided by UR Academy is helpful for the effective commissioning of UR cobots. The structure of the training program ensures that personnel of varying skill levels can find appropriate resources to learn about the cobots. UR academy is an essential part of the integration of the cobot system because it allows the regular personnel to learn how to use and benefit from the cobot.

9. CONCLUSION

Robots, including cobots, have become an essential part of the manufacturing sector. Robots have been able to release humans from several repetitive, dull, and hazardous tasks. Still, robots themselves have been perceived as dangerous because they are often large and move with great force. This led to isolating the robots behind safety fences and other safety protocols, which made the human-robot collaboration expensive and difficult to establish safely. The cobots were introduced to fix this issue. They are designed to safely work with humans in shared workspaces, which allows for seamless cooperation and easier commissioning due to the redundancy of strict safety protocols.

Nowadays, cobots are used in several applications like welding, picking, machine tending, quality control, and packaging. Cobots can do these tasks in collaboration with humans or other machinery, but also on their own if required components and tools are provided. The versatility of the cobots can fully be utilized only if the commissioning process is easy and quick enough to be effective. It could be said that the quicker and easier the re-commissioning of the cobot is, the more likely it will serve the changing needs of companies. This may particularly benefit small and medium-sized manufacturing companies where the adaptability of manufacturing processes may often be needed due to changing market conditions.

Commissioning of UR cobots includes several steps each with varying demands. The commissioning process of UR cobots begins with a mechanical setup that includes unpacking, inspecting, and installing the cobot. That is followed by the connectivity and software setups which involve installing and configuring the I/O wiring, the network connection, the end-effector, and the safety systems. These steps are followed by programming the cobot, or in other words, instructing the cobot on its tasks and its interactions with other machinery and equipment. Integrating the cobot with additional equipment like sensors, cameras, or other machinery is not necessary, but it allows for efficient and reliable cooperation for the whole system. The programming requires some knowledge of the UR's URScript language. This knowledge, like any needed knowledge for simple cobot application's commissioning, can be easily learned from UR Academy allowing the cobot to be commissioned by the regular personnel without prior knowledge of robotics.

Testing and validation are seen as a part of the commissioning of UR cobots. Ensuring that everything works and is safe is important and needs attention. After testing, the focus shifts to optimization, which may include reprogramming and timing adjustments to improve efficiency while maintaining safety and quality. The commissioning process culminates with training, troubleshooting, and maintenance, for which UR provides training through its UR Academy. The UR Academy offers free interactive modules from basic operation to advanced features and applications, ensuring a successful long-term integration.

In summary, the commissioning of UR cobots involves a comprehensive process that spans from mechanical setup to programming and integration. It demands a blend of some technical skills, some software knowledge, and some understanding of safety and operational integration with other automation elements. The skills and knowledge can be obtained from UR Academy, making the need for prior robotics knowledge absent. The focus on an approachable user interface (PolyScope) and comprehensive training resources (UR Academy), combined with the cost-effective implementation, makes UR cobots a viable option for various industrial applications, especially where industrial robots would be too large and challenging entities in terms of costs and demands. UR emphasizes simplicity, efficiency, and user-friendliness, potentially making their cobots more accessible compared to traditional industrial robots, especially for small and medium-sized companies.

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