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# Investigating Collaborative Robotic Assembly: A Case Study of the FANUC CRX-10 iA/L in Industrial Automation at i-Labs

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**Abstract:** This study examines the practicality and limitations of using a FANUC CRX-10 iA/l collaborative robot to assemble a product component, highlighting the trade-offs between increased robotization and reduced manual intervention. Through a detailed case study in the i-Labs laboratory, critical factors affecting precision assembly such as station layout, tooling design and robot programming are discussed. The findings highlight the benefits of robots for nonstop operation, freeing up human operators for higher value tasks despite longer cycle times. In addition, the paper advocates further research into reliable gripping of small components, a current challenge for robotics. The work contributes to open science by sharing partial results and methods that could inform future problem solving in robotic assembly.

**Keywords:** robotic; assembly; FANUC; industrial collaborative robot; 3D printing; industrial automation; case study; i-Labs research; rapid prototyping

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## 1. Introduction

The contemporary industry is experiencing an acceleration in changes to productive paradigms, with an increasingly pressing demand for flexibility and product customization. To meet these needs, it is essential to have a flexible production system. Jain et al. [1] point out that there is no unique definition of a flexible production system; specifically, they distinguish between an adaptive approach, reactive to circumstances, and a proactive approach, planned in advance. Regardless of these categories, it is clear that the adaptability of a production system is crucial, especially for small and medium enterprises (SMEs). This has generated the need for more flexible production systems and complex products with a high degree of variation. Gustavsson et al. [2] add that it is often necessary to choose in advance between productivity and flexibility during the system's design, offering methodologies for this definition.

Automation has played a key role in this evolution. As Jovane [3] indicates, flexible production systems have made mass customization possible. However, traditional manufacturing solutions might not be sufficient to meet the new requirements, requiring a greater emphasis on flexibility and reconfigurability as suggested by Urbani [4]. In this context, the industry must not only adapt to changes but also anticipate them, integrating systems that are both efficient and capable of evolving in line with market trends.

Subsequently, as highlighted by Mourtzis [5], the evolution of production systems, driven by changing customer needs and technological advancements, has led to a shift from functional paradigms to customer-oriented ones (User-Centered Design, UCD). In [6], Chammas et al. explore the fundamental concepts of UCD, emphasizing the growing importance of project management through a proper balance of budget, time, and quality, necessary for more personalized production. The use of cobots (collaborative robots) in industry can benefit this triad of elements (quality, time, and budget).

Collaborative robots, or cobots, are emerging as crucial enablers in this context, not only aiding in reducing physical strain on workers but also in optimizing process efficiency through their high reconfigurability and the establishment of optimized work trajectories [7].

As emphasized by Fager et al. in [8], in the case of object sorting in a picking system, cobots can reduce costs and improve performance (time and budget) when there is significant sorting work to be done. El Makrini et al. in [9] demonstrate how the integration of cobots and humans in car assembly leads to improvements in process quality, combining human dexterity and problem-solving with the precision and strength of cobots. Another study in this direction was conducted by Safeea et al. in [10], where it is stated that a cobot can act as a 'third assistant hand' that lifts and holds parts while humans perform assembly tasks. In this way, the use of cobots can improve working conditions and productivity, and reduce safety risks.

While several studies highlight the advantages of adopting robots (both collaborative and industrial) in production processes compared to fully manual solutions, a detailed comparison of the benefits of integrating collaborative robots versus industrial robots still seems to be lacking. An article attempting to assess which solution is better between collaborative and industrial robots is that of Barravecchia et al. [11]. This study presents a methodology for evaluating the optimal layout, especially for customized production, in the use of collaborative robots in assembly. In Barravecchia's proposed model, costs related to learning and assembly time are also included. The learning process is faster in collaborative solutions than in the industrial one. The study shows that the cobot solution is ideal in situations of low production volumes, as they can reduce the frequency of defects and do not require reallocating or laying off workers. In the study by Heredia et al. [12], a comparison is made between industrial robots (IR) and collaborative ones (cobots), focusing on the energy consumption behavior of electronic components (EC) and shows that while industrial robots consume more energy, more of it is used to handle loads, in contrast to cobots which consume a large proportion of energy to power electronic components, although in absolute terms, cobots generally consume less. This observation might point out a potential downside in integrating cobots in industrial environments. Cobots allocate a significant part of their energy to powering EC (Electronic Components), unlike industrial robots, which predominantly use energy for direct task execution, like handling heavy loads. For example, a cobot might use a considerable amount of its energy just to keep its sensors and control systems running, even when not actively manipulating objects.

Comparing industrial robots with collaborative ones in terms of production flexibility, the collaborative solution brings numerous benefits over industrial robots. Collaborative robotics significantly enhances the flexibility of production as shown by several studies. In the literature review by Keshvarparast et al. [13], the authors report that in the designing phase of cobots, flexibility is considered a key feature as is the importance attached to safety. They define two types of flexibility: "Flexible cobots" (how quickly the robot can be reprogrammed) and "Flexible Collaboration" (how many tasks a robot can perform in a given time). Furthermore, there are several works that speak about the importance of cobots for flexible manufacturing, for instance, Giberti et al. in [14] define flexibility as the system's ability to quickly reconfigure itself to adapt to a new product within the same product family. The authors propose an approach to simplify the programming of collaborative robots, called Interactive Refinement Programming (IRP). This approach is based on primitives and general skills developed by expert engineers, which can then be connected in a tree structure to generate a specific task.

Lee et al. in [15] highlight that, for more high production flexibility, it is necessary to have a close collaboration between humans and robots. The authors propose a production structure specifically designed for this collaboration, demonstrating its feasibility. This is particularly important in the context of the Fourth Industrial Revolution, where customer demands are diverse and rapidly changing as also evidenced by the work of Sherwani et al. [16]. Strassmair et al. [17] further emphasize the importance of worker acceptance, which can be facilitated by granting more flexibility and considering spatial constraints in the collaboration. These findings collectively underscore the role of collaborative robotics in enhancing production flexibility. Furthermore, Othman et al. [18] highlight that Human–Robot Collaboration (HRC) has become a prominent feature of smart manufacturing environments and conduct a systematic review about new technologies that can help in the HRC system, like AI, collaborative robots, Augmented Reality, and Digital Twin, providing insights on how this topic should be addressed. A similar work is performed by Michalos et al. [19], where the authors aim to present the existing approaches to the implementation of human collaborative applications and highlight the trends towards achieving seamless integration and robots as coworkers in the factories of the future.

In the context of flexible manufacturing, robotic assembly stands out as a key solution in many contemporary industrial applications, evident in the diverse range of products on the market. The integration of advanced technologies such as collaborative robotics and 3D printing is becoming increasingly significant. Rapid prototyping, particularly bolstered by low-cost 3D printing, represents a pivotal development in this landscape. Rapid prototyping (RP) is a technology for fabricating physical objects directly from CAD parts using additive layer manufacturing techniques, eliminating the need for extensive manufacturing process planning, tooling, or fixtures [20]. Three-dimensional printing, or additive manufacturing, plays a vital role in this industrial transformation, thanks to its capability to create objects layer by layer from CAD models. This technology is increasingly utilized in various sectors, including healthcare, automotive, and aerospace. It enables mass customization and the use of diverse materials, marking a significant step towards manufacturing agility [21]. The synergy between cobots and 3D printing is crucial in enhancing the efficiency and adaptability of manufacturing processes. It facilitates a quicker turnaround from design to final product and enables greater customization in response to market demands. Notable examples of rapid prototyping include the work of Geonea et al. [22], who develop a new exoskeleton robotic system for locomotor assistance, utilizing a novel structural solution and virtual prototyping. This is followed by dynamic simulations and stress analysis. Ciceri et al. [23] analyze building designs using a genetic algorithm with parameters such as shadow length, transportation, and outdoor area. Khalid et al. [24] review developments in additive manufacturing of cellulose nanocrystals (CNCs), highlighting their applications across fields like tissue engineering, robotics, and wearable electronics. These are just a few examples from the extensive literature on rapid prototyping, indicating its widespread impact and application.

The principle underlying this article is that of open science, with a commitment to sharing detailed insights related to a specific industrial application. Our aim is to contribute to the broader dissemination of knowledge by presenting methods, solutions, and critical observations gleaned from our research. To this end, we detail a comprehensive case study conducted at the i-Labs Industry Laboratory in Jesi, Italy. This study centers on a robotic assembly operation and rapid prototyping [25], offering a practical demonstration of these advanced technologies in an industrial setting and exploration of their operational the impacts on the manufacturing process. Through this approach, we aspire to provide valuable information that can be leveraged by other practitioners and researchers in the field. Furthermore, this article follows the same philosophy as the one proposed in [26], where it not only provides practical results but also defines a procedure for solving problems.

*The structure of the paper is outlined as follows*: Section 2 delves deeper into the topic of robotic assembly, highlighting its importance and relevance in the current industrial landscape. This section sets the context for the subsequent discussions and underscores the significance of robotic automation in manufacturing. Section 3 explains the specific task that the study aims to accomplish, providing insights into how the task is traditionally performed manually. Section 4 details the tools and methods utilized in this project. It encompasses a comprehensive exposition of the technologies, strategies, and programming techniques employed. Section 5 presents the results of the study. This section is dedicated to discussing the findings, observations, and data analysis, providing a critical evaluation of the project outcomes. Finally, Section 6 offers the conclusions of the paper. It synthesizes the key takeaways, assesses the impact of the study, and discusses the broader implications of the findings within the field of robotic assembly. This section also contemplates future directions and potential areas for further research.

## 2. Robotic Assembly Task

The field of robotic assembly has long been a critical area of research and development. Initially explored in the early 1980s [27], it continues to be a pivotal topic in modern industries, with applications ranging from precision operations [28] to complex tasks like in-space assembly [29]. The inherent complexity of robotic assembly as outlined by Sanderson et al. in 1983 [30] lies in the need for precise positioning, handling complex geometries, and managing physical interactions. Within this complexity, an essential element is the development of methods for instructing robots to perform task independently, an area explored by Eicker in 1989 [31]. These advancements in robotic assembly are crucial for improving adaptability, reliability, and performance across various industries.

The literature is fit with works that address the multifaceted challenges of robotic assembly. For instance, Popa et al. [32] tackle the issue through a multilayer approach, dividing the workspace into mesoscale and microscale operations. Part of the robotic system is developed for coarse operations like positioning, while manipulation tasks are executed at the microscale using grippers and fixtures.

Similarly, Chen et al. [33] focus on high-precision assembly in semi-structured environments, such as inserting a piston into the hole of a valve body. To do this, they utilize a vision system to identify the position and orientation of parts, coupled with a force/torque control algorithm for tight-tolerance assembly.

Saric et al. [34] propose a method to estimate and correct part positioning uncertainties in assembly tasks, using contact trajectory data collected during active part interaction. This approach effectively addresses uncertainties through sensing.

Lastly, Peña-Cabrera et al. [35] discuss the challenge of threaded fastening operations in small batch production industries, which demand flexibility due to varied product types. They introduce and test a novel identification algorithm in a semi-structured environment.

Through these diverse approaches, the literature demonstrates the ongoing evolution and problem-solving in robotic assembly, highlighting the field's dynamic nature and its critical role in modern manufacturing.

## 3. The Task to Be Accomplished

The assembly of the subcomponent, which is the focus of this study and depicted in Figure 1, was initially performed manually by an operators. Although the operations were straightforward for the human operator, they consisted of repetitive tasks that lacked perceived added value for the end user, yet were essential for the completion of the product.

The sequence of operation that should be performed to assemble the product is as follows:

- Pick and place the *Cap*.
- Pick and place the *Magazine*.
- Pick and place the *Cone* (the cone is a reusable tool for inserting the ring into the housing. The principle of the cone could be seen in reference [36], shown in Figure 2).
- Pick and place the *Ring*.
- Insert the *Ring* into its seat.
- Remove the *Cone* from the piece and reposition it in its base.

The cone, a reusable tool depicted in Figure 2, is instrumental in the component to be assembled process of the system shown in Figure 1. It is used to guide the insertion of the ring into its housing, a method well established and commonly employed as referenced in [36]. The cone is designed to facilitate the elastic deformation of the ring as it is pressed towards the wider part of the cone, which is its base. This process causes the ring to expand and conform to the dimensions of its housing. Upon insertion, the ring attempts to return to its original size, thereby securing the CAP to the MAG through a clamping action. The subsequent step of palletizing the assembled product, although integral to the process, is not within the purview of this paper's discussion.

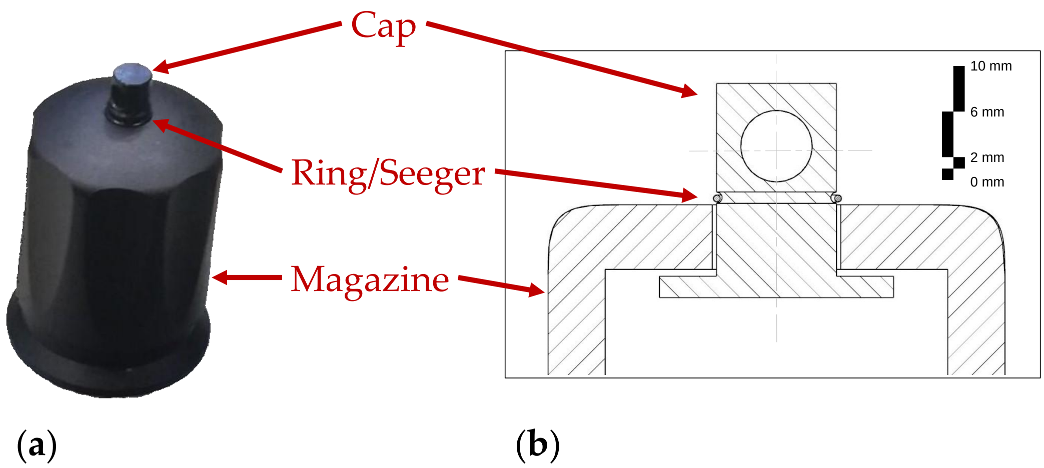


**Figure 1.** The sub-component subject of the assembly study. On the left (**a**), a real image of the component is shown; on the right (**b**), a simplified cross-section is presented to demonstrate the assembly of the sub-components.


**Figure 2.** Set-up of the assembly system used for this operation. At the bottom left, you can see the cone used for the assembly of the part. The graduated scale in black and white is to be considered for a better understanding of the distances involved.

The list of operations we provided outlines the essential steps required for the assembly process. However, it does not dictate the actual sequence that must be followed. Figure 3 illustrates a potential assembly process solution, where operations can be parallelized rather than being sequential, enabling simultaneous task execution. This is achievable using dual anthropomorphic arms like YUMI [37]. The solution adopted with YUMI, although not elaborated upon here because it was explored in a separate research project, essentially revolves around the use of the robot's double anthropomorphic arms to parallelize certain steps, shown in the UML (Unified Modeling Language) diagram (Figure 3).

The assembly steps performed in this research begin with "Pick CAP", grasping a cap, and is succeeded by "Place CAP", for positioning. This pattern continues with other components like "Pick MAG" and "Place MAG", leading up to the picking and placing of a "CONE" and a "RING". The "Push RING" operation secures the ring within its seat. Post assembly, the "CONE" is detached ("Remove CONE") and is reverted to the starting point ("Home CONE"). The concluding stages involve lifting the assembled component

("Pick Assembled Component") and its palletization ("Palletize"), marking the process completion. A summary of the main steps performed is illustrated in Figure 4.

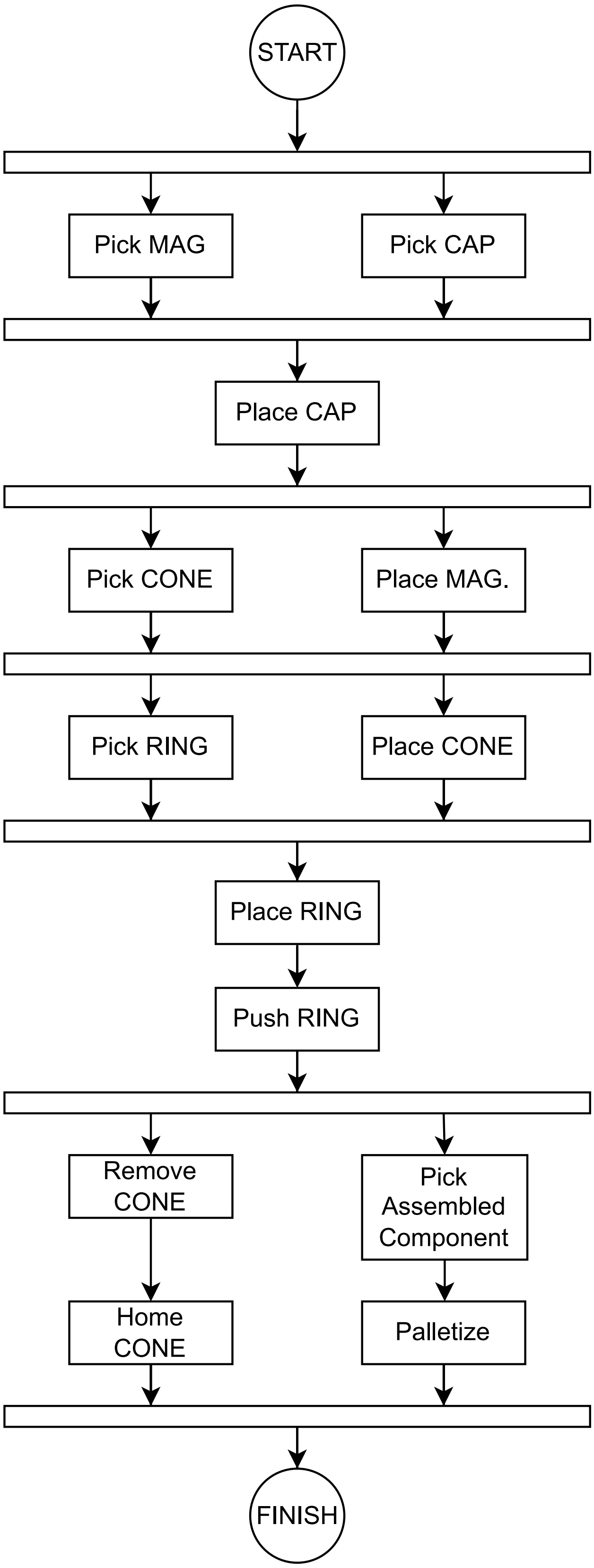


**Figure 3.** The UML diagram visually represents the parallelized step-by-step automated assembly process, from component selection to final assembly completion.

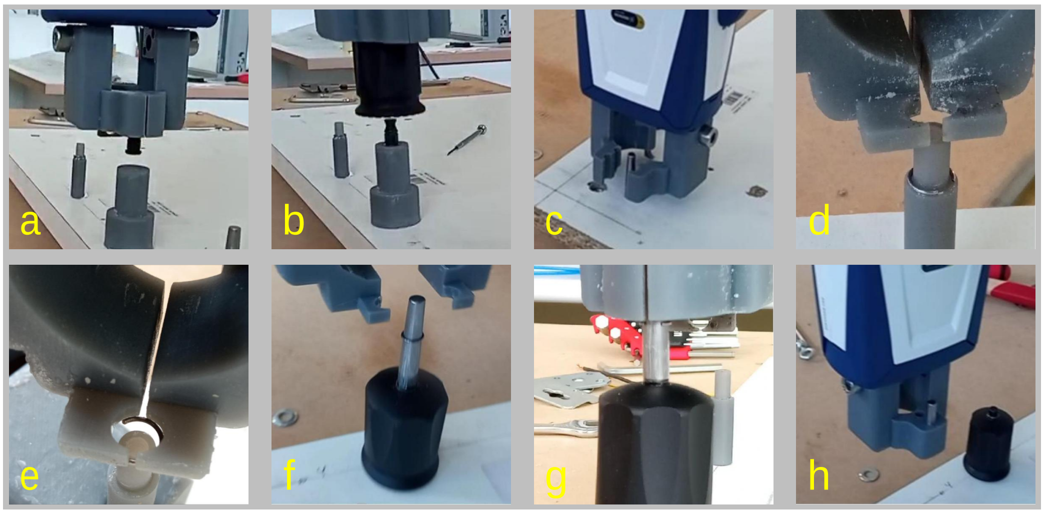


**Figure 4.** Automated assembly sequence: (**a**) positioning of the CAP, (**b**) positioning of the MAG, (**c**) gripping of the guiding cone (CONE) by the robot, (**d**) detail of the approach position for gripping the RING, (**e**) close-up view of the RING correctly gripped by the robot, (**f**) positioning stage of the RING in preparation for insertion, (**g**) insertion of the ring into its housing assisted by the CONE, and (**h**) removal of the CONE after assembly, signaling the preparation of the component for subsequent palletization.

## 4. Tools and Methods

The project primarily utilizes the FANUC CRX 10iA/L robot [38] and the Formlabs 3 SLA 3D printer [39]. The Formlabs 3, employing laser technology for resin curing, ensures high precision and detail, though it comes with limitations such as slower print speeds and additional post-processing. Complementing these tools, the SCHUNK Co-act EGP-C gripper [40] is optimized for collaborative operations, enhancing safety and versatility in handling diverse tasks. Further, Siemens NX [41] is used for creating CAD models, which are subsequently exported in STL format for the Formlabs printer through the proprietary software PreForm [42], showcasing Siemens NX's extensive capabilities in computer-aided design and manufacturing.

This integration of advanced technologies illustrates the project's alignment with Industry 4.0's emphasis on flexible automation and customized production.

The process followed a trial-and-error approach, testing various CAD solutions and setups. Results from these attempts were shared online, adhering to open science principles. However, certain proprietary data, like the final product version, remain exclusive to the company.

The procedure followed to obtain the company's compliance with the order is as follows:

- Understanding customer requirements.
- Determining what tasks can be executed solely by the robot and which need automation.
- Identifying various tasks and figuring out their execution.
- Testing and evaluating functionality.
- Using the results to make modifications, greatly aided by 3D printing.
- Repeating this process until a satisfactory solution is achieved.

This sequence of steps led to two distinct outcomes: a corporate solution and a research-focused one. The solution detailed in this research diverges from the one implemented by the company. It is important to note that the company did not fund this specific project. What has been undertaken is the extraction of an innovative resolution from the corporate solution, aiming to explore new methodologies in the application of cobots.

Figure 2 showcases the setup used to test the assembly operation described in this paper. The setup is straightforward and allows for the required evaluation to be conducted effectively. The components (MAG, CAP, RING, and CONE) are arranged in a line to the left, although their positioning is not mandatory for the operation's success. Additionally, in the same figure, the RING holder and the assembly support near the gripper are depicted. The entire assembly process is carried out directly on this support. In the git repository of the project, there is a video that shows the complete procedure to assembly the component [43].

In this project, the programming of the robot was carried out using Fanuc's TP (Teach Pendant) language as requested by the company. The TP language is known for its relative simplicity, which facilitated the programming process. Specifically, it allowed for precise fine-tuning, a critical feature for this project. This meant that we could approximate the robot's positioning and orientation and then make exact adjustments as needed, enhancing the accuracy and effectiveness of the robot's operations in the assembly process. This capability proved essential in achieving the desired precision in the assembly tasks.

## 5. Results

The key findings in this paper are categorized into two main areas: practical industry applications and conceptual research insights. For the industrial application, significant outcomes include the comprehensive operational cycle time of the setup and the development of CAD models, specifically detailing the final dimensions of the robotic fingers. These results offer valuable insights for both industrial implementation and academic study. The upcoming sections will focus on conceptual results, aimed more at research-oriented discussions and generalizations, furthering the theoretical understanding in this field.

### *5.1. Design of the Fingers*

The design of the fingers in this project is tailored to perform multiple tasks within a single setup. This section will showcase the various functionalities of these fingers, aiming to share problem-solving methodologies that could be useful for addressing new challenges, applying the principle of problem abstraction.

Figure 5 presents two global views of the fingers designed for this project. Developed using Siemens NX, the designs were exported in STL format for printing with the Formlabs 3 SLA printer. The fingers were printed using gray resin, and their specifications can be found in [44].

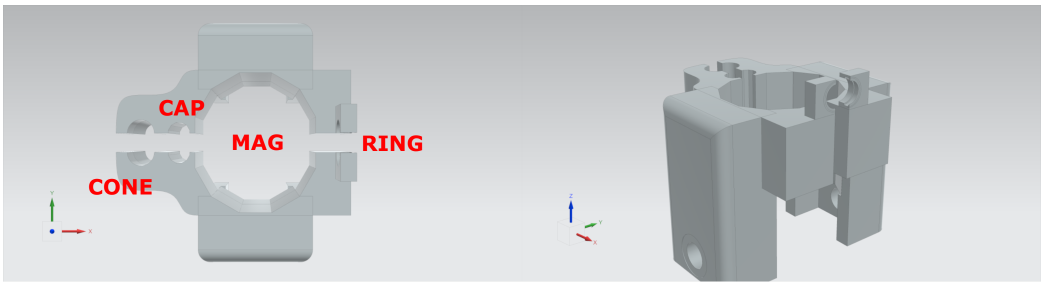


**Figure 5.** The left view is a top–down perspective highlighting the central decagonal (10-sided) hole for gripping the MAG. Moving to the right, there is a hole for the CAP and a conical hole for gripping the CONE.

#### Description of the Functional Parts of the Fingers

The fingers of the gripping mechanism are multi-purpose. There are several parts specifically designed to perform specific tasks. In the remainder of this section, the individual parts will be explained. Table 1 gives a summary description of the parts that make up the fingers and their functionality.

**Table 1.** Summary description of the functional parts of the robot fingers.

| Component | Shape and Function | Special Features |
|---|---|---|
| MAG Grip | Irregular cylindrical, decagonal shape | Adaptable to various positions |
| CAP Grip | Cylindrical with linear geometry | Ensures secure and universal grip |
| CONE Grip | Negative form, narrow at base | Prevents CONE from being pushed out |
| RING Grip | Triangular and elliptical internal space | Selects and grips small rings (Ø 9 mm, thickness 0.7 mm) |

Note: The RING Grip is critical due to the small size of the rings it needs to handle.

*MAG Grip*: The MAG has an irregular cylindrical shape. The adoption of a decagonal shape for the grip interface has shown practical effectiveness, as its geometry increases the contact points. This design advantage was observed through empirical testing, where the decagonal grip consistently accommodated various placements of the MAG, resulting in stable and secure handling without the need for precise positioning. *CAP Grip*: The CAP grip utilizes a similar principle to the MAG grip. With the cylindrical shape of CAP, a linear geometry aids in ensuring a more secure and universal grip. Figure 5 illustrates the concept behind this choice for both MAG and the CAP. *CONE Grip*: The CONE grip is designed for interference with a negative form fit. To ensure a firm grip on the CONE and prevent it from being pushed outward, the negative form is designed narrower at the base and wider towards the top. Forces at play tend to push the CONE upwards, which is then blocked by form interference. This part of the fingers also serves to push the ring into its final seat. Being narrower at the base ensures that the ring does not get trapped inside the CONE. *RING Grip*: This component is the most critical because of the small size of the ring it has to take (outer diameter of 9 mm and thickness of about 0.7 mm), which makes it difficult to grip. To better understand how this part of the fingers must work, the procedure by which the rings are gripped is explained: the rings are inserted into a special holder, lined up one above the other. The gripper is brought into position and then closed with the component shown in the Figure 6. The lower triangular geometry selects only one ring, and the inner space of the housing allows only one ring to enter. Furthermore, the internal space is elliptical, not circular, to accommodate the ring and allow for slight deformation. The ring is then transported and inserted into the upper part of the CONE already positioned over the previously assembled component. The ring is released and, with the seat of the CONE, is pushed into its final position.

**Figure 6.** The image illustrates in isometric view the particular RING (Figure 5) of the pliers' fingers. Its particular geometry makes it possible to take a single ring with an external diameter of 9 mm and a thickness of 0.7 from a pile of rings arranged one above the other.

Normally, the pushing force does not require more than 3 kg, but the presence of various frictions can increase the necessary force to unacceptable levels. Additionally, during this phase, the CONE and the gripper must be vertically aligned, as misalignments can lead to a force development that could exceed the robot's 10 kg payload or even break the gripper. This could be avoided by a force control, here not developed.

### 5.2. Cycle Time

The manual assembly process, normally taking about 15 s, contrasts sharply with the robotic operation's 50 s cycle time, which is longer due to the serialized nature of the tasks. However, the robotic solution offers significant advantages, such as enabling continuous assembly outside of regular working hours or with fewer staff. This allows operators to focus on more critical and value-adding tasks within the product development process.

## 6. Conclusions

In conclusion, this study underscores that, while the task could technically be executed entirely by a collaborative robot, it is not recommended due to the complexity of tasks such as gripping and inserting small-sized rings. The sensitivity and malleability of human hands facilitate a simpler grip, which is challenging to replicate with current robotic technology. This limitation has spurred the idea for further research aimed at reliable ring gripping.

The key conclusions of the study are as follows:

- Shifting from manual to robotic assembly in this application is feasible but not advisable. It is important to consider redesigning products with robotic assembly in mind, incorporating specific design features to simplify robot training and facilitate easier assembly by robots.
- Slower operational speeds are crucial for maintaining precision in assembly tasks, particularly due to vibrations caused by motors in various configurations.
- The use of wait commands is essential to minimize vibrations and enhance the repeatability of the cycle.
- The introduction of vibrations during assembly, especially for handling rings, is suggested as a method to reduce interference and improve operational efficiency.

All results obtained in this study are freely available online in the project's GitHub repository [43]. The outputs of this research have also been instrumental in better understanding the potential challenges in executing certain robotic assembly operations. This has allowed us to provide solutions that can be utilized by other companies or researchers, while also highlighting the weaknesses of this process. The aim is to use these findings to enhance the flexible framework proposed in [45], thereby improving its efficacy and applicability.

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