Dual-Arm Manipulation of a T-Shirt from a Hanger for Feeding a Hem Sewing Machine

Filipe Almeida[1][a], Gonçalo Leão[1,2][b], Carlos M. Costa[1,2][c], Cláudia D. Rocha[1][d], Armando Sousa[1,2][e], Lara Gomes da Silva[3][f], Luís F. Rocha[1][g] and Germano Veiga[1][h]

[1]*Centre for Robotics in Industry and Intelligent Systems of INESC TEC, Porto, Portugal*

[2]*Faculty of Engineering of the University of Porto, Porto, Portugal*

[3]*ESI Robotics, Esmeriz, Portugal*

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Abstract: The textile industry is experiencing rapid advancement, reflected in the adoption of innovative and efficient manufacturing techniques. The automation of clothing sewing systems has the potential to reduce the allocation of repetitive tasks to operators, freeing them for more value-added operations. There are several machines on the market that automatically sew the bottom hem of T-shirts, a key component of the garment that fulfills both functional and aesthetic purposes. However, most of them require the fabric to be positioned manually by an operator. To address this issue, this work presents a solution to automate the process of feeding a T-shirt into a SiRUBA sewing machine using a YuMi dual-arm robot. In this scenario, the T-shirt arrives at the workstation with the main front and back pieces of cloth sewn together, seams facing out, and with no sleeves yet. This setup starts by turning the garment inside out with the aid of an automated hanger, ensuring that the seams are facing inward (as the machine requires), and then using the dual-arm robot to feed the garment into the sewing machine. With our approach, the feeding and hemming process took less than 35 seconds, with a feeding success rate of 98%. Therefore, this work can serve as a steppingstone towards more efficient automated sewing systems within the garment production industry.

1 INTRODUCTION

Since the Industrial Revolution in the 18th century, the textile industry has been one of the most predominant global industries. In subsequent decades, the industry continued to grow rapidly in revenue and employment, but created very low-quality labor standards. Over time, this inevitably led to most manufacturing being outsourced to factories in developing countries, allowing lower labor and manufacturing costs. The repetitive and tiring working conditions of this industry remain a concern to this day, and automation could provide a viable answer by alleviating some of the workload of factory workers. The issue is that manipulating flexible objects, such as textiles, remains a challenge for automation as their shape changes as they are handled (Sanchez et al., 2018; Zhu et al., 2022).

The process of manufacturing garments consists of taking large rolls of fabric, cutting them into smaller pieces, and sewing them together to obtain the desired shape (Grishanov, 2011). There are already several machines in the market that automate parts of the process. The issue with these types of systems is that the garment needs to be placed in a specific position for the machine to function properly. This creates a production line where several small processes are automated, but require the operators to transfer the garments between several machines, creating a very repetitive and labor-intensive workload.

In the manufacturing of T-shirts, one important step during assembly is the sewing of the bottom hem. The bottom hemming step consists of folding

[a] https://orcid.org/0009-0000-1129-2916
[b] https://orcid.org/0000-0002-9081-9268
[c] https://orcid.org/0000-0001-8453-4031
[d] https://orcid.org/0000-0001-7254-0346
[e] https://orcid.org/0000-0002-0317-4714
[f] https://orcid.org/0009-0006-8412-137X
[g] https://orcid.org/0000-0002-8680-4290
[h] https://orcid.org/0000-0003-3044-6938

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up a small margin of the bottom tip of the T-shirt and stitching it down. This hem is important for both aesthetic and functional purposes, namely, for maintaining its shape more easily, preventing the bottom edge from fraying and tearing, thus increasing durability and adding a small weight for a smoother drape.

This paper presents a solution to automate the process of feeding a T-shirt to a SiRUBA ASC-TBH200 (an automated bottom hem sewing machine). In this scenario, the T-shirt arrives at the bottom hemming process with the main front and back pieces of cloth sewn together, seams facing out, and with no sleeves yet, which corresponds to the typical state of the garment in this stage of production. Our approach starts by turning the T-shirt inside out, so the seams are facing inward, as the machine requires, and then uses a dual-arm ABB IRB 14000 YuMi robot to place the T-shirt in the correct position. This setup was developed for the EU-funded TexP@ct[1] project, which aims to study the automation of several garment manufacturing processes.

The paper is structured as follows. Section 2 reviews related work on the use of robots to automate sewing systems. Section 3 presents the cloth manipulation system, including the robotic setup and the grasp planning algorithm. Section 4 presents and discusses the experimental results of the robotic system. Section 5 summarizes the findings and presents ideas for future research.

2 RELATED WORK ON ROBOTIC AUTOMATED CLOTH SEWING

There is already a body of research, spanning over 35 years (Gershon and Porat, 1988; Tokuda et al., 2024), on the use of robot arms for automated cloth sewing and assembly systems. Several approaches involving feeding a cloth item into a sewing machine have been developed, using either one or more robotic arms.

2.1 Approaches with One Robot Arm

Most of the related work resorts to a single-arm robot to perform the sewing task.

(Gershon and Porat, 1988; Gershon, 1990) developed one of the first automated sewing systems within the FIGARO project, where a PUMA 560 arm with two spring-loaded, rubber-tipped grippers holds and moves a cloth panel while it is being sewn in the other end by a sewing machine. This setup is common to most other approaches, in which the robot arm holds the cloth by one end while the sewing machine's needle sews the cloth on the other end. The main differences between approaches lie in the hardware used for the sewing arm, gripper and sensors, alongside the approach used for motion planning. (Zacharia et al., 2008; Zacharia, 2010) used fuzzy control to adjust the circular motions of a gripper around a needle. The gripper holds a cloth panel with curved edges to a worktable during sewing. (Triantafyllou et al., 2011) use a Selective Compliance Assembly Robot Arm (SCARA) robot equipped with a pneumatic gripper to hold one edge of two plies of fabric while the other edge is being sewn at an unknown velocity. They use a Proportional–Derivative (PD) fuzzy controller to move the gripper based on the difference between the desired and measured force, according to a force-torque sensor. (Koustoumpardis and Aspragathos, 2014) improve this later work by adopting a hierarchical control loop where the force fuzzy control is performed using an online trained neural network, which is fed with an estimation of the fabric's extensibility given by an off-line trained neural network. (Misios et al., 2019) later further improved on this work with a similar setup by obtaining the desired tensional force of the robot on the fabric via a Kelvin-Voigt non-linear model that emulates the fabric's physics based on estimations of the fabric's type and length. Finally, (Tang et al., 2024) control a Denso VS-068 arm using a time-scaling model fed with data from a high-speed camera, and force-torque impedance control.

One single arm approach that differs from the others was developed by (Arai et al., 1989), who instead mounted a lightweight sewing machine on the robot arm while the fabric to be sewn was hung in a fixture. A proportional controller based on force feedback was used to move each of the robot arm's joints.

2.2 Approaches with Multiple Robot Arms

There is also research on the use of two robot arms for sewing automation. This allows for a finer control of the cloth but also requires coordinating both arms.

(Kudo et al., 2000) use two different robot arms, a 4-axis SCARA robot and a 5-axis robot, both with spring-loaded, rubber-tipped fingers, to hold the fabric and move it while it was sewn by the sewing machine. (Schrimpf et al., 2012; Schrimpf and Wetterwald, 2012) use two UR5 arms to join the four leather parts of a footstool cover. The use of two robot arms allows for the parts to be held independently, which is useful given that they have distinct geometries. They later incorporated one extra arm in the layout for finer

[1]https://texpact.pt

material handling and to control the seam when releasing it in front of the sewing machine, given that the other two robot arms release the part beforehand to avoid collision with the sewing machine (Schrimpf and Mathisen, 2016). (Shungo and Hisashi, 2021) use a horizontal dual-arm manipulator with rollers as end effectors, which allow for wrinkles in the grasped cloth to be eliminated more easily. Finally, (Tokuda et al., 2024) use a DENSO VS-068 dual-arm to sew two stacked fabric parts together along a desired seam line printed on the top fabric part. Unlike all the previous work, rather than feeding the fabric part to the sewing machine, they hold the fabric on both sides, and the sewing head is solely used for stitching. This allows the position and tension of the fabric parts to be controlled exclusively by the dual-arm manipulator.

Unlike the previous approaches, which use multiple single-arm robots, (Sun et al., 2019) use the same YuMi dual-arm robot model of this work to place a cloth piece with holes on a fixture composed of vertical locating pins. The cloth is then sent to a sewing machine to be sewn, but it is not detailed in their work.

2.3 Comparison with this Work

In comparison with most of the literature, this work proposes a novel solution as the robot arm does not have to hold the fabric item during the sewing process, which is instead inserted around two cylinders of the sewing machine (similarly to (Sun et al., 2019), who also rely on fixtures). A dual-arm hardware setup, along with dual finger grippers, is used to have better control over the garment, which is similar to most of the related research. In addition, the T-shirt being sewn has larger dimensions than those used in most related work. As this manuscript corresponds to early work with a novel robotic setup, no motion control was performed.

3 CLOTH MANIPULATION SYSTEM

The cloth manipulation system consists of several components that work in unison to ensure the successful hemming of the T-shirt. The entire system is displayed in Figure 1. The following subsections provide details on each component and the final subsection details the robotic cell's entire process in detail.

It should be highlighted that the robotic workstation developed in this work will be integrated into a larger production cell, which will include another robot that will pick up the 2 sides of the T-shirt from a stack for sewing them together, after which the T-shirt is inserted into a modified version of our T-shirt holder (to allow it to alternate between a horizontal configuration alongside the Yumi robot for inserting the T-shirt and a vertical configuration in front of the YuMi robot for turning it inside out), after which the system and processes described in the following subsections will be used to manipulate the T-shirt and perform the hemming process. Therefore, in the complete system, a human operator will not be required to place the T-shirt in our workstation, since the entire production process will be automated.

We developed this prototype to test our T-shirt feeding approaches, but it will be improved and upgraded for the integration in the final production cell. Although it will have several modifications to make it ready for industrial deployment, the current version is enough for validating our T-shirt feeding approaches.

3.1 Sewing Machine

As previously stated, the SiRUBA ASC-TBH200 (Figure 2) is an automatic sewing machine that hems the bottoms of T-shirts or other pieces of clothing with similar shapes, such as polo shirts and long-sleeve shirts. The basis for this system is a regular model of an interlock sewing machine fitted with guiding wheels and cylinders that move the bottom of the T-shirt through the machine. There are also several sensors and air pressure actuators that shape the hem throughout the sewing process. Once the T-shirt is correctly placed, a button can be pressed to start sewing, and the machine automatically detects when the hem is finished, completing the cycle by releasing the T-shirt.

The process of feeding the T-shirt to the sewing machine, which is the focus of this paper, has three main conditions to ensure the hem is properly sewn.

- Since the machine will sew the hem by pulling the edge under the rest of the cloth, the T-shirt needs to be inserted with the lateral seams facing inwards. As the T-shirt arrives at this production stage in the opposite orientation, it needs to be flipped inside-out.
- When feeding the machine, the two main cylinders (in black in Figure 2) and all the parts between them need to stay inside the T-shirt. The cloth should fit well around this structure, and although it does not need to be perfectly aligned, large wrinkles or folds should be avoided.
- The T-shirt detection sensor seen in Figure 3 needs to be activated by the bottom edge of the T-shirt for the sewing to start. Once this sensor is

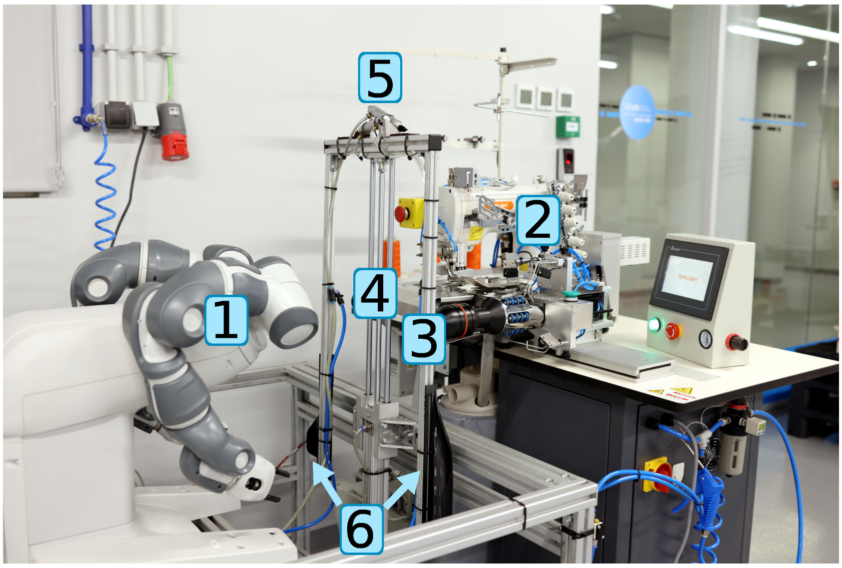


Figure 1: Cloth manipulation system and all the individual components numbered in blue. Dual-arm ABB YuMi robot (1), automatic sewing machine (2), hanger structure for initial placement of the T-shirt (3), vertical cylinder to move the hanger (4), smaller cylinders to hold the T-shirt's collar in place (5), side supports to open the bottom of the t-shirt.

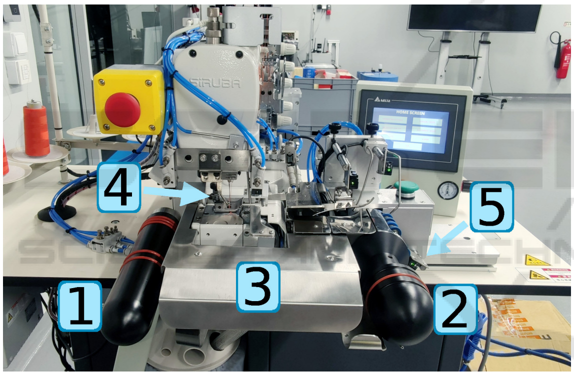


Figure 2: Automatic sewing machine (SiRUBA ASC-TBH200). Numbered in blue, the components are: left cylinder that extends to the left side when a T-shirt is detected (1), right cylinder with guiding wheels to rotate the T-shirt (2), guiding platform that keeps the T-shirt straight between the cylinders (3), presser foot and needles of the sewing machine (4), T-shirt detection sensor (5).

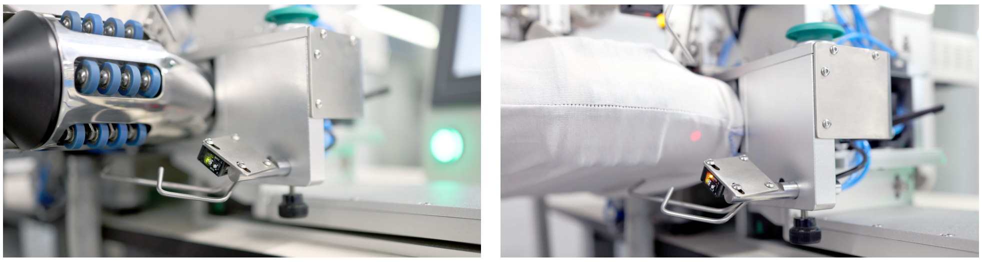
activated, the left cylinder extends to stretch the T-shirt and begin the hemming process. Ideally, at this point, the cloth over the left cylinder is mostly aligned with the one on the right.

If all these conditions are met, the placement of the T-shirt does not need to be very precise, since the machine, before starting to sew the fabric, rotates the T-shirt around the cylinders and uses its sensors and actuators in an attempt to align as well as possible the bottom edge, to guarantee the hemming is done correctly.

3.2 Hanger Structure

The structure that initially holds the T-shirt can be seen in Figure 1. The basis for this structure functions essentially as a regular hanger with side profiles for additional support, ensuring a more predictable starting position. To this structure, two components were added for improving grasping repeatability.

- Two lateral supports were designed, 3D printed and installed at the bottom of the vertical profiles, for ensuring that the robot had reliable and fixed grasp zones in the T-shirt, as seen in Figure 4. Initially, the tests were conducted without using these 2 supports, and the system was not capable of having repeatable grasping points, reinforcing the importance of the addition of these 2 lateral supports for achieving higher grasping robustness. The bottom of the supports is larger in width and depth, where it is in contact with the bottom edge of the T-shirt, for separating both sides of the edge of the T-shirt and for straightening the T-shirt side facing the robot, creating a good grasp point and enough free space for the gripper to move through. From the bottom to the top, the piece narrows using smooth surfaces, ensuring that the T-shirt does not become entangled or stuck in the structure.
- Two pneumatic cylinders were placed on top of the hanger, for holding the T-shirt's collar in place, while it is being manipulated by the robotic arm. The cylinders are placed along the same plane as the hanger but are diagonally relative to the top



(a) Detection sensor not activated. (b) Detection sensor activated.

Figure 3: Sensor to detect the T-shirt's presence in the sewing machine.

bar, ensuring that the tip of the pneumatic cylinders are in contact with the profile, locking the T-shirt in place, as seen in Figure 5. Holding the T-shirt was critical for ensuring that it was turned inside out correctly and reliably.

3.3 Dual-Arm Robot

The most practical way human beings manipulate pieces of clothing is by using both hands, with two grasping points near the extremities of the fabric's shape. As the sewing machine was designed for human usage, the most precise and time-efficient manner to feed it with T-shirts is by using both arms to guide the T-shirt. This allows the insertion in the left and right cylinders to happen simultaneously, providing better coordination between the actions.

Creating a robotic system that can mimic human behavior in this action requires a dual-arm setup. For this task, the robot chosen was the ABB IRB 14000 YuMi (Figure 6), along with its parallel electric grippers. This setup presents the following advantages:

- It already possesses a dual-arm setup fully integrated and programmable, with tools to ease communication between both arms. This means there is no need for a dual robot setup.
- It is a collaborative robot, meaning it was designed to work safely alongside humans. This is important for textile factories, since they currently still rely on a lot of people working alongside robots in their facilities.
- It has a 7-axis configuration on each arm, unlike the typical 6-axis robots used in this field (Gershon and Porat, 1988; Schrimpf et al., 2012; Tang et al., 2024; Tokuda et al., 2024). The additional joint is fairly similar to the elbow rotation in human arms and helps create movements similar to humans.
- It is capable of fast and accurate movements with a high repeatability. Making the process of feeding the machine as fast as possible is crucial since it is used for mass production. The YuMi robot allows movements up to 1500 mm/s while maintaining accuracy and safety guarantees.

Despite these advantages, some drawbacks need to be considered for the application studied in this paper, mainly related to its physical capabilities. On the one hand, there is a limited payload capacity of 0.5 kg per arm. Although that is sufficient to hold a regular T-shirt, it does not allow a lot of stretching of the fabric, which may be necessary for smaller T-shirt sizes to fit into the sewing machine. On the other hand, the robot's reach is only 559 mm, which often forces it to be used near its range limits, making reaching certain poses more difficult.

3.4 Vertical Pneumatic Cylinder

The entire hanger structure presented in Section 3.2 is supported by a vertical pneumatic cylinder with a 700 mm of course. This allows the T-shirt to be removed from the hanger in a much more compact working area, reducing the vertical size of the entire setup. It also ensures that the hanger does not block the path for the robot to feed the sewing machine once the T-shirt is removed from it.

3.5 Sewing Machine Feeding Pipeline

Figure 7 portrays a full cycle performed by the robotic cell and shows how all the components work together to feed a T-shirt into the sewing machine.

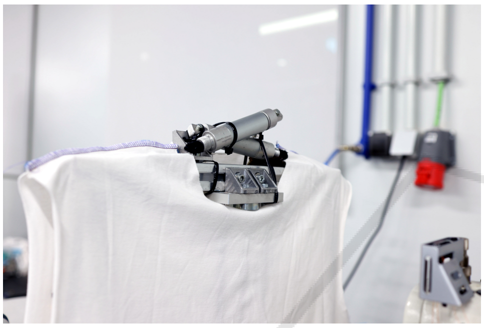
The T-shirt starts by being manually placed in the hanger, with the seams facing out and the vertical cylinder in the highest position (Figure 7(a)). The bottom edge of the T-shirt falls over the wider part of the 2 lateral structures, and the top pneumatic cylinders are in the retracted position. The workcell then performs the following sequence of steps:

1. The top pneumatic cylinders extend for locking the top of the T-shirt in place (Figure 5(b)).

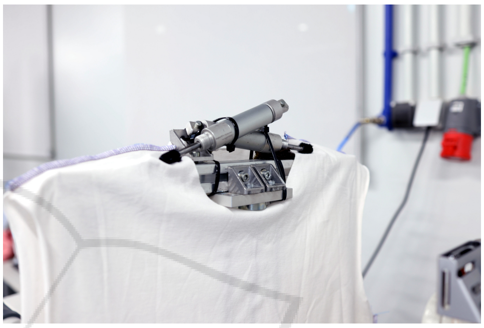
(a) Lateral support.

(b) Lateral support with T-shirt placed in the structure.

Figure 4: Lateral support structures added on each side to help find grasping points.



(a) Pneumatic cylinders in the retracted position.



(b) Pneumatic cylinders extended for holding the T-shirt.

Figure 5: Pneumatic cylinders on the hanger to hold the T-shirt in place.

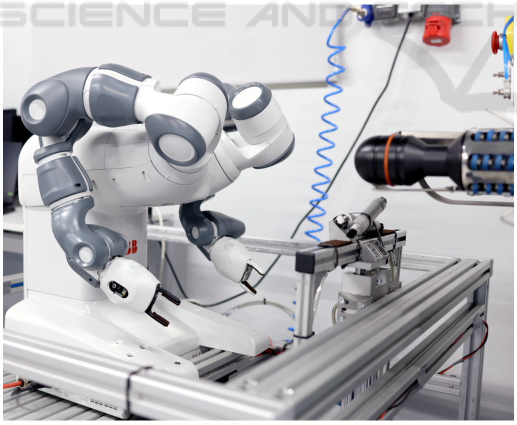


Figure 6: ABB IRB 14000 YuMi dual-arm robot.

2. The robot starts moving its arms towards the pre-grasp positions, underneath the T-shirt (preprogrammed for the T-shirt size).
3. The grippers then move slightly upwards to the grasp points inside the 2 lateral supports. When both are in the right position, the gripper closes their fingers, grabbing the T-shirt (Figure 7(b)).
4. The vertical cylinder starts lowering while the robot slowly moves the T-shirt upwards (Figures 7(c) and 7(d)). These opposing motions remove the T-shirt from the hanger and by relying on the pneumatic cylinders to hold the T-shirt, the robot is able to turn the T-shirt inside-out reliably.
5. Once the T-shirt is out of the hanger, the robot pushes it through the guiding cylinders of the sewing machine with the grippers slightly above the structure (Figure 7(e)). At this stage, since the grasp points used in the T-shirt were slightly shifted towards the robot from each lateral seam, there should be enough fabric hanging underneath so that it can pass around the cylinders without getting stuck.
6. The left arm inserts the left side of the T-shirt all the way through, releases it and moves out of the way (Figure 7(f)).
7. The right arm carefully places the right side of the T-shirt as forward as possible for ensuring that the sewing machine sensor is activated (Figures 7(g) and 7(h)). This will cause the left cylinder of the sewing machine to extend and stretch the T-shirt (which is why the left arm needs to finish and move out of the way first, otherwise the sewing

machine left cylinder would collide with the left robotic arm). The right arm then releases the T-short and moves out of the way.

8. The top pneumatic cylinders then retract, releasing the T-shirt from the hanger.
9. The sewing machine can now start the hemming process.

4 EXPERIMENTAL RESULTS

This section begins by describing the T-shirts used for the experiments, followed by the three types of tests performed.

- Machine feeding tests, where the T-shirts are fed to the machine (but not sewn), focused on measuring the robotic operation's time.
- Stress tests, where the T-shirts are displaced with respect to their expected initial state in the hanger, in order to evaluate the system's robustness.
- Full sewing tests, where the full cycle time of the robotic cell is evaluated, alongside the success rate of correctly sewing the T-shirt. These metrics are compared with two human operators.

A video of the robotic cell in operation was made publicly available at the URL below [2].

4.1 T-Shirts Testing Samples

All the T-shirts used in the experiments were identical (depicted in Figure 8) and made of cotton fabric. For the fabrication addressed studied in this paper, it is assumed that the T-shirts arrive at this production stage with no sleeves yet, so all the T-shirts used in our tests were sleeveless. A total of 32 different T-shirts were used in the tests. The mean and standard deviation for their height and hip width (Figure 8), and curved edge score are presented in Table 1. These measures correspond to an XL-sized T-shirt, but results may vary based on the comparison chart used.

After being handled for some time, the T-shirt fabric starts to curl near the edges, which can introduce some variance in the T-shirts. To quantify this curl, a "curved edge score" was subjectively evaluated for each T-shirt, indicating how rounded the bottom edge was on a scale from 1 (least rounded) to 5 (most rounded). As all the 32 T-shirts were never used in prior experiments, this score tended to be low, as seen in the last two columns of Table 1.

[2] https://github.com/GoncaloLeao/Scientific-Research

Table 1: Mean and standard deviation (SD) for metrics related to the size and shape of 32 T-shirts.

Height (mm)		Hip (mm)		Curved edge score	
Mean	SD	Mean	SD	Mean	SD
795	5	577	8	1.56	1.01

4.2 Machine Feeding Tests

The sewing machine is designed for mass production of garments in an industrial setting, and as such, we tested our prototype under similar conditions. To simulate this scenario, the cycle described in Section 3.5 was repeated a total of 86 times. On every iteration the time necessary to complete each stage were recorded (grasping the T-shirt, pulling it out of the hanger while flipping, inserting the left side, inserting the right side, and total time), alongside the success rates. These results are presented in Table 2.

Table 2: Performance metrics for some steps of the T-shirt feeding process (detailed in subsection 3.5), over 86 runs.

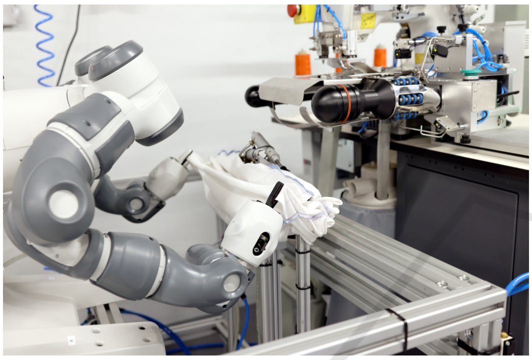
Steps	Time (s)		Success rate
	Mean	SD	
Grasp (1-3)	2.242	0.013	1
Lower hanger (4)	2.234	0.013	1
Insert left (5-6)	2.798	0.022	0.98
Insert right (7)	2.186	0.015	1
Total (1-8)	9.461	0.031	0.98

From the results, some conclusions can be drawn.

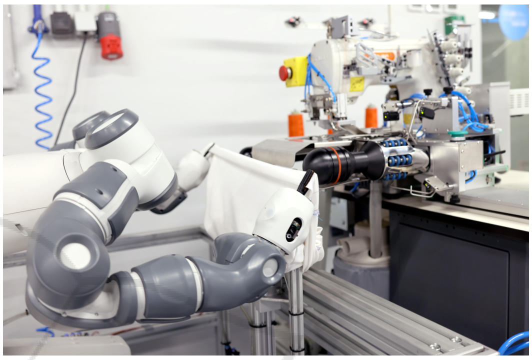
- A total of 84 of the 86 tests were successful, which shows that the setup can consistently perform the T-shirt feeding task.
- The only 2 tests that failed had the same issue, that was excessive force in one of the robotic arm joints while pushing the T-shirt towards the machine. The most likely cause for these failures could be a slight desynchronization between the start of the motions of the left and right robotic arms. This stretches the T-shirt, provoking the excessive force on the joints of the robot.
- All the robotic arm movements were done at the maximum possible speed, limited either by the motors' maximum speed or the payload, except the ones close to the sewing machine, to guarantee precision. Moreover, both arms' tasks were coordinated to be performed simultaneously whenever it was possible to do so. This allowed the total cycle time to be lowered to under 10 seconds.
- The robot takes approximately the same time running the cycle without grabbing the T-shirt, meaning the weight does not affect the motor's performance significantly. This is the most likely expla-

(a) Initial position.

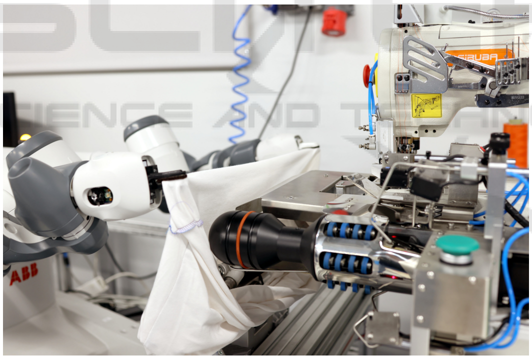
(b) Grasping.



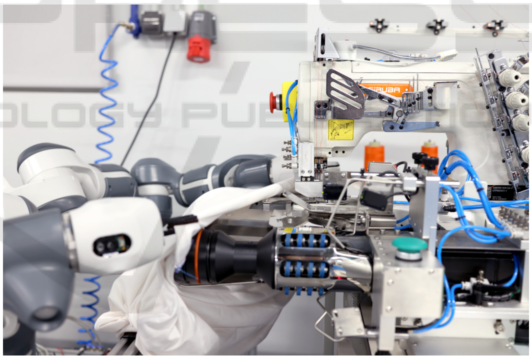
(c) Flipping the T-shirt inside out.



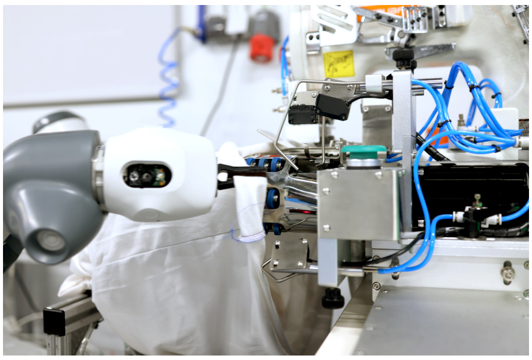
(d) T-shirt flipped inside out.



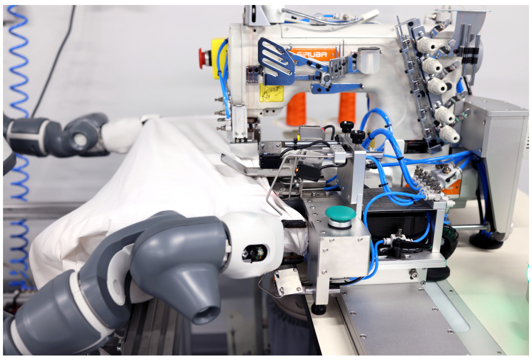
(e) Starting insertion into sewing machine.



(f) Inserting left arm.



(g) Inserting right arm.



(h) Activation of sewing machine sensor.

Figure 7: Sewing machine feeding pipeline.

Figure 8: Example of a T-shirt's height and hip width.

nation for the low standard deviation values for the execution time.

- All the 32 T-shirts were used 2 or 3 times, half of them with the front facing the robot and the other half facing the sewing machine. Neither the variations in the T-shirts nor the rotation appeared to have any effect on the time or success rate.

4.3 Stress Tests

Since the setup is dependent on the starting position of the T-shirt when it is placed in the hanger, it is important to know how much margin of error there is when placing the T-shirt in the initial pose. To retrieve some data on this metric, some stress tests were performed that increasingly introduced more variation in the starting state, to try to find possible points of failure. This section will present those variations and the results obtained.

The first test consisted of adding a horizontal shift to the T-shirt. This was achieved by moving the T-shirt collar on top of the hanger so that the point that meets the lateral seam of the T-shirt with the bottom edge is at a certain distance from the lateral supports, as seen in Figure 9(a). The results of this experiment are presented in Table 3.

Despite the large shifts, the tests remained successful, and the cycle times were unaffected. It is important to note that the larger the shift, the more likely it becomes that the top cylinders of the hanger are no longer capable of holding the T-shirt in place due to the shape of the collar. This will cause the setup to lose some control of the T-shirt and can prevent it from flipping properly, creating a possible point of failure. Even considering this, the shifts tested were very significant, so it is possible to say that the system

Table 3: Stress testing the setup by rotating the T-shirt horizontally.

Direction	Shift (mm)	Result	Time (s)
Right	60	Success	9.492
Right	110	Success	9.518
Right	160	Success	9.480
Right	210	Success	9.483
Left	60	Success	9.484
Left	110	Success	9.495
Left	160	Success	9.462
Left	210	Success	9.505

is very resilient to horizontal shifting.

The following experiment was to attempt a vertical shift of the position where the bottom edge of the T-shirt sits on the lateral supports. This was achieved by pulling up or pushing down the edge of the T-shirt, as seen in Figure 9(b), and letting it hold itself in position with the friction with the hanger, as can happen accidentally when placing the T-shirt at the start. Table 4 shows the results of these tests.

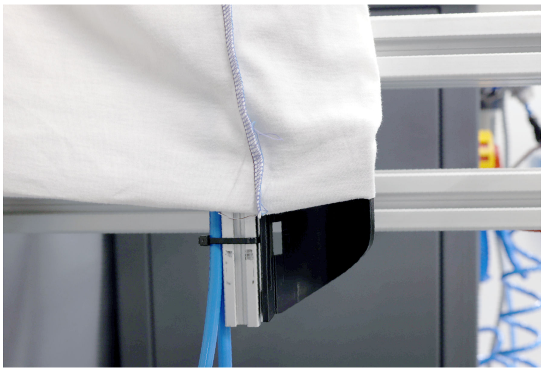
Table 4: Stress testing the setup by shifting the bottom edge of the T-shirt vertically.

Direction	Shift (mm)	Result	Time (s)
Up	10	Success	9.456
Up	20	Success	9.438
Up	30	Failed	-
Down	10	Success	9.426
Down	20	Success	9.438
Down	30	Success	9.426
Down	40	Success	9.436

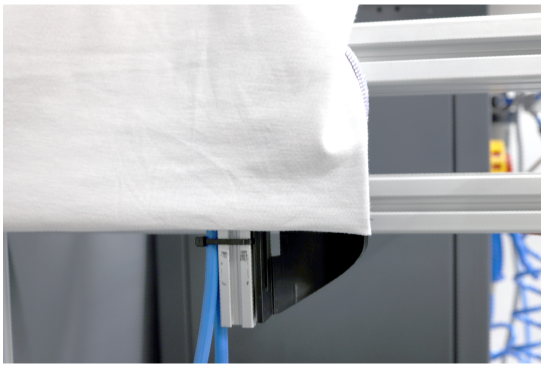
When pulling the T-shirt up, the problem that first occurred at 30 mm was that the grip achieved was too weak, and the robot dropped the T-shirt when pulling it out of the hanger. Pushing the T-shirt down does not result in a failure to feed the machine, but it causes the robot to grab too much fabric. It ends up placing the T-shirt too close to the sensor, which can lead to problems with the hemming process. The system is much more sensitive to vertical shifts. Future iterations of the prototype should include a way to adjust the height of the grasping points.

4.4 Sewing Tests with Human Comparison

Although this paper focuses more on the automated feeding process, it is also necessary to ensure that the T-shirt's placement in the hanger is good enough for a successful hemming. To evaluate this stage, after being inserted by the robot, a total of 21 T-shirts were sewn, and the results were observed. To get a base-



(a) Placement with horizontal shift (pulled to the left).



(b) Placement with vertical shift (pulled down).

Figure 9: Examples of placements from the stress tests.

Table 5: Performance metrics for a set of sewing tests performed by the prototype and the experienced/unexperienced operators (using solely the sewing machine).

Operator	Num. experiments	Success rate	Perfect hem rate	Time (s)	
				Mean	SD
Inexperienced	10	0.7	0.6	18.865	3.461
Experienced	10	0.9	0.8	9.573	2.079
Prototype	21	0.76	0.67	9.445	0.024

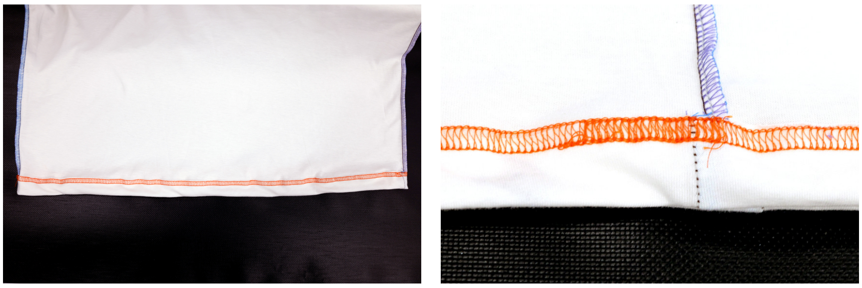
line of comparison, another 20 tests were done with a person performing the same procedure of picking up the T-shirt, flipping it, and inserting it into the machine. Half of these tests were done by an operator with more experience with the sewing machine, and the other half by one with less experience. Table 5 shows the results for this experiment.

From the analysis of these results we can conclude the following:

- Regarding the time of insertion, there is a significant difference between an experienced (9.573 seconds) and an inexperienced person (18.865 seconds). As the mean and standard deviation results show, with more practice, operators can get faster and achieve better success rate.
- The prototype has a very similar mean time (9.445 seconds) when compared to an experienced operator (9.573 seconds). The operator can perform the task faster (fastest time was 8.0 seconds), but it is very hard to do it consistently, as demonstrated by the standard deviations. Over time, the average times seem to even out.
- The sewing machine operation times were also registered, with the sewing of the hem taking on average 20.7 seconds. This makes the complete hem sewing process take around 30 seconds.
- As for the success rate, the prototype performed better than an inexperienced operator but not as well as an experienced one.
- Some tests were considered successful even if the hem had some flaws. Perfect hem rate only considered the ones where no defects were found, such as the one in Figure 10.
- Compared to the overall success rate, it decreases consistently for all operators by around 0.1 seconds, which is probably due to the fine-tuning of the sewing machine.
- Most of the prototype failures seem to be due to excess fabric being pushed beyond the sensor on the sewing machine (5 on 21 tests). This caused the machine to not properly align the hem fold of the T-shirt and to sew either with no fold or too many folds (Figure 11(a)).
- Other defects were incomplete hem in which the sewing did not catch the inside of the hem (1 on 21 tests) in some sections (Figure 11(b)) and also misalignment at the end of the hem (1 on 21 tests) (Figure 11(c)).

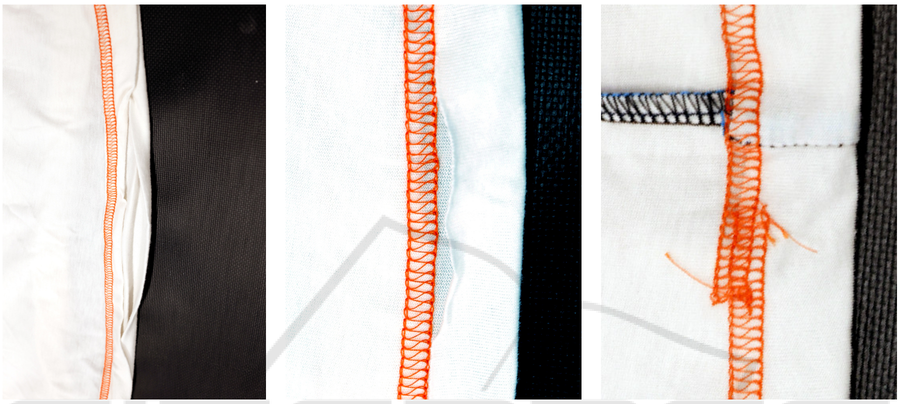
5 CONCLUSIONS

The main contribution of this work was a robotic system that is able to sew the bottom hem of a T-shirt using an industrial sewing machine and a dual-arm robotic arm. Although fabric manipulation is a very difficult problem which requires precise manipulation and grasping, our prototype performed this task efficiently and consistently, achieving a T-shirt feeding success rate of 98%.



(a) Hem. (b) Hem ends overlapping correctly.

Figure 10: Example of a correct hemming done by the sewing machine.



(a) Hem sewing failure due to excessive folding of the fabric. (b) Hemming did not fully catch the fabric. (c) Hemming did not have correct overlap at the end.

Figure 11: Examples of hemming failures.

The experimental results provided some generalized insights into fabric manipulation. For industrial applications, focused on speed and repeatability, robotic manipulation alone can pose some problems due to the unpredictability of the material. In this prototype, the most successful solution relied on mechanical holding and guiding components. One of them is the top pneumatic cylinders that hold the T-shirt collar on the hanger, which, in combination with the two grippers, create a total of four grasping points, well distributed along the T-shirt. The conclusion is that the more the T-shirt is constrained, the less loose fabric will exist, leading to more repeatable manipulation of the T-shirt. Another phenomenon that can be used is the fact that, when a fabric is stretched, it transitions from being deformable to having more elastic properties, creating a much more consistent shape. The 2 lateral supports of our prototype that take advantage of this effect, which stretch the fabric in the bottom edge to ensure good grasping points.

This work opens several lines of future work, where this robotic workcell can be improved. First of all, our prototype that feeds the sewing machine will also need to be fed, which is not a trivial problem. Namely, another workcell will be performing the sewing of the side of the T-shirt, after which will feed it to our hanger.

Secondly, grasp and motion planning can be performed, rather than using fixed grasp points and post-grasp robot motions for both arms. Providing the system with perception capabilities is the best solution as it would both allow the system to work with different T-shirt sizes, and make it more robust against potential defective initial T-shirt placements, fixing the problem shown in Section 4.3. This way, the robot could also have better and more reliable grasping points, avoiding the problem described in Section 4.4, of too much fabric going over the sensor.

Thirdly, a different robot arm could be used for manipulation. Although ABB YuMi presented a lot of advantages, its low payload and limited reach were the two main issues. There are plenty of alternatives that could be considered and that could result in improvements in reliability and speed. Alternatives include other dual-arm robot models, but also a pair of single-arm robots, similar to most of the related work presented in Section 2.2.

Finally, it could also be interesting to have one robot operating several sewing machines at the same time. Namely, while one machine is sewing, the dual-arm can rotate 180º and feed another sewing machine or the dual-arm can be mounted on a track and feed several sewing machines.

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