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**Paper:**

# Automated Screwing of Fittings in Pneumatic Manifolds

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**The task of screwing is based on a set of actions with no added value, requiring precision, attention, and repeatability. These set of actions could consist of alienating and demanding activity for a human operator. Collaborative robotics can facilitate the performance of such tasks. This investigation focuses on the development of a smart station for the automated screwing of fittings in pneumatic manifolds. The collaborative robot Sawyer produced by Rethink Robotics is equipped with an appropriate end-effector and was utilized to receive the fittings from a vibrating feeder towards the end-effector. This facilitated centering of the fittings on the threaded holes, and the performance of the screwing task on a set of manifolds placed on a rotating station. The design of the end-effector and its prototype is described. In addition, the proposed automated process was experimentally tested and its effectiveness was validated.**

**Keywords:** collaborative robot, automated screwing, pneumatic manifold, pneumatic fittings

## 1. Introduction

The fourth industrial revolution, also known as Industry 4.0, has a wide range of goals including to facilitate communication among products, machines, and parts, to expand human-machine interaction, and to optimize and customize the production process [1]. The new concept of industrial environments, called smart factories, requires smart technologies and smart devices to improve flexibility, reliability, and efficiency [2]. Smart technology is represented by advanced robotics, one of the main aspects of Industry 4.0 [3]. A subfield of advanced robotics, collaborative robotics combines the advantages of automation and manual labor [4]. Industrial automation is characterized by high efficiency and repeatability in mass production, but it lacks flexibility when changes are required for customization. On the contrary, human operators can easily manage changes due to customization. However, due to limitations of physical capabilities, they may experience reduced physical strength, repeatability, and concentration [5]. Both limitations provide for a reduction in efficiency and quality [6]. Collaborative robotics overcomes these limitations by exploiting the cooperation of the robot and the humans that share, in safety, the same workspace [7–11]. This involves human-machine collaboration and allows collaborative robots to replace humans in the performance of alienating and demanding tasks.

Screwing is one of these tasks: it requires the recognition of a threaded hole, the positioning of the screw, the interfacing of the latter with a screwdriver, and finally, the screwing action. These are activities with no added values, but nevertheless require precision, attention, and repeatability. Thus, the automation of the screwing task could improve the quality of life of the human operator, and the quality of the final product.

This investigation focuses on the automation of the screwing of fittings of pneumatic manifolds by a collaborative robot. Several researchers have studied this problem by utilizing traditional and collaborative robots equipped with sensors, integrated with an advanced control system. An integration vision sensing system has been developed to find the real position of screws in a target region [12]. In addition, inbuilt cameras and landmarks have been adopted to determine the appropriate location for screwing and as points of reference [13]. Moreover, position control, force control, and active compliance modes have been utilized to identify the appropriate position of the hexagonal head of a screw using a spiral search motion for automated screw unfastening [14]. Based on functional safety requirements defined by ISO/TS 15066 [15], a balancing coupling unit to limit the force applied to an end-effector during a physical contact has been utilized in the wrist of a collaborative robot [16].

Unlike the aforementioned studies, in the proposed solution, the collaborative robot does not use sensors to identify the target region. The proper centering of the fitting on the threaded hole is performed using a specifically designed end-effector. Such an end-effector consists of a mechanical centering system with a manifold in which fittings must be screwed.

This paper is organized as follows: Section 2 outlines the background of the manifold adopted in this investigation; Section 3 describes the concept of the automated process; in Section 4, the development of the end-effector is presented; in Section 5, the details of the prototype end-effector is reported; finally, in Section 6, the experimental overview for functional validation of

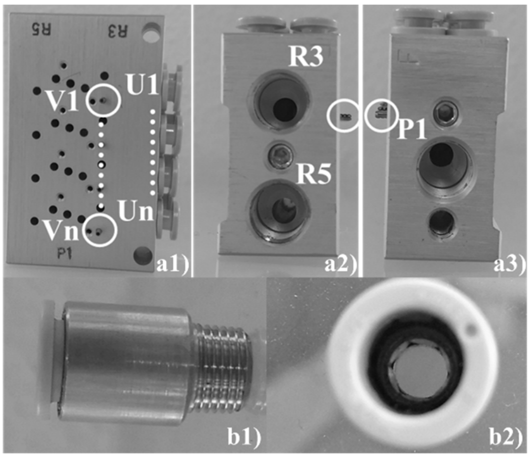



**Fig. 1.** The manifold (a1) and the threaded ports (a2, exhausts ports; a3, inlet power supply port) and fitting (b1 and b2). Vn are tubes for the inlet of the power supply air for the valves to be mounted; Un are the ports to the external devices.

the automated screwing of the fittings is described and discussed.

## 2. Background

Manifolds are used to assemble packs of pneumatic electro-valves. The manifold is an efficient way to reduce the number of tubing, fittings, and fixtures. They also simplify installation and maintenance. The manifold used in this application was designed to be connected to two 5/2-way electro-valves. As shown in **Fig. 1**, the manifold used in this investigation (SS5YJ3-S41-04-C4F-Q, by SMC) has one port (P1) for the inlet of the power supply air, two ports (R3 and R5) for the exhaust, several ports (U1–Un) for the outlet of air to external devices and tubes (V1–Vn) for the inlet of the power supply air to the body of the electro-valves, for which the ports are interfaced with the ducts (holes in black) in the manifold. The ports for the connection to external devices are fixed on a side of the manifold in the form of plastic fittings. The power supply air and the exhaust ports are placed on opposite sides of the manifold and appear as $1/8''$ G threaded ducts. Each of them requires the screwing of a fitting (KQ2S08-01AS, by SMC). The latter has a $1/8''$ G gas thread and, in the inner part, a hexagonal cavity with a width across the flat faces of 5 mm. Such a cavity is necessary for coupling with a hexagonal tool such as a screwdriver for torque application. Currently, the positioning of the fittings on the P and R ports is manually performed; screwing is manually performed using a powered screwdriver. Considering only the screwing task, the overall set of actions of an operator for each manifold is as follows: positioning of the manifold on a proper support; collecting three fittings; positioning and screwing of the fitting in each R port; overturning of the manifold, and repositioning it on the proper support; and positioning and screwing of the fitting in the P port. When the fittings are screwed together, the operator mounts 2 electro-valves on the manifold and starts to process a new manifold. The screwing time required by an expert operator is approximately 11 s, which was experimentally measured during the manual screwing task process. Considering the time spent for the other assembly steps, an operator repeats the set of actions approximately 173 times in an 8-hour work shift. Thus, this task is alienating and demanding, and is often associated with a lack of concentration. For this reason, interest in automating the screwing task is high.

## 3. The Automated Process: the Concept

Three preliminary considerations have been made: 1. an automated feeding system is necessary to avoid manual positioning of the fittings on the threaded port; 2. the screwing task must be performed with a high positioning accuracy of the fittings and repeatability; 3. due to the presence of threaded ducts on opposite sides, the manifold must be overturned.

Hence, the combination of 1) a station for loading and the feeding of the fittings, 2) a station for performing the screwing task, and 3) a station for loading and overturning the manifolds has been conceived. In the case of station 1), a vibrating feeder is considered to be the most suitable solution [17]; it is commercially available and the determination of the resonant frequency to facilitate the appropriate motion of the fittings must be experimentally performed. Fittings can be moved along a tube from this station to the station for screwing by the effect of gravity.

In the case of station 2), it consists of the collaborative robot Sawyer [18], manufactured by Rethink Robotics, and an appropriately designed end-effector. Collaborative robot technology was chosen for the following reasons: 1. for robotic solutions, to exploit their positioning accuracy and repeatability, and to reduce the time for the screwing task; 2. for cobot solutions, to safely share the same workspace with a human operator; 3. compared to semi-automatic solutions, to avoid the use of sensors [19, 20] for detecting the correct position when performing the task. The end-effector of the collaborative robot was designed to support a powered screwdriver (screwdriver) and to smartly center the fittings to the threaded ports of the manifold. This station is the core of the automated process. Nevertheless, the laws of motions of the robot and the design of the end-effector depend on the third station.

The latter station is necessary for loading and overturning of the manifolds: two fittings must be screwed on one side of the manifold and one fitting on the other side. This means that one or more manifolds must be located on a plate and a 180° rotation must occur to change the side of the screwing process. Regardless of the construction solution of station 3), the automated process was based on achieving suitable positioning of the manifolds to define the motion strategy of the collaborative robot Sawyer and the technical specifications of the end-effector. The

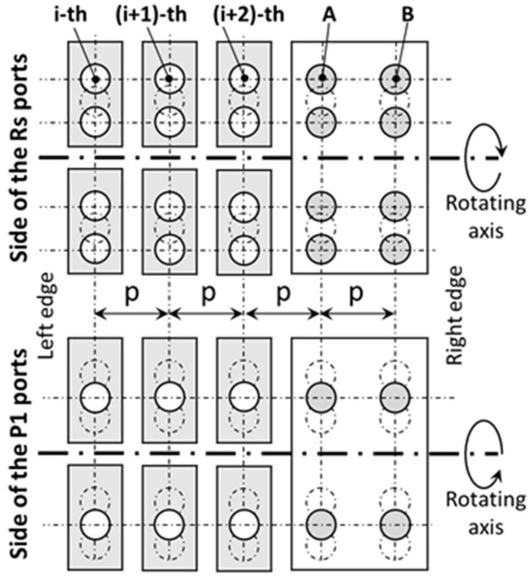



**Fig. 2.** The placement of the manifolds. A 180° rotation around the rotation axes changes the side of the screwing process.

concept of the automated process has been utilized to find a solution that facilitates the advantageous adoption of the collaborative robot in terms of working time and production capacity compared to a human operator. The achieved solution involves manifolds placed according to a matrix, as shown in **Fig. 2**. For clarity, only six manifolds are represented. Regardless of the side of the ports, the gray rectangles represent the top views of the schematized manifolds, and the white circles are the threaded ports. The white rectangle is a frame fixed on the third station, and the gray circles are holes of the same diameter as the threaded ports. Despite the good position repeatability of the robot Sawyer ($\pm 0.1$ mm), the centering of the fittings that are screwed in a threaded port cannot be based only on the programmed path of the robot. Fixed external references are necessary. For this reason, manifolds must be placed in suitable compartments that fix them to station 3) to ensure that the threaded ports are equally spaced with a pitch $p$ along a row. The robot starts to move rightward from the first manifold of the first row on the left edge to the last one on the right edge. When the fitting must be screwed in the $i$-th port, the next two ports $(i+1)$-th and $(i+2)$-th must act as centering references of the robot: a positioning error of $\pm 0.1$ mm is nulled. When the fitting must be screwed in the port of the last manifold of a row (in **Fig. 2**, the $(i+2)$-th port, on the right edge), holes A and B are the next two centering references. The robot then moves backward to the first manifold of the next row on the left edge, and repeats the same previous motion task until the last manifold is reached, always maintaining the same orientation. Alternatively, it is possible to replicate the frame with holes A and B on the left edge. Thus, when the robot completes the first row, it can rotate the end-effector by 180° about the vertical axis, move to the next row, remain on the right edge, and start to move towards the left edge to complete the second row. Hence, it repeats the same motion, according to the same strategy proposed in [21]. The distance between the lines passing through the ports of the same manifold is 18 mm. This distance is different from that between two consecutive rows of consecutive manifolds. When the fittings are screwed in all the ports of a given side, a 180° rotation about the horizontal axis provides for the new set of empty threaded ports on the opposite side. They are positioned using the same pitch, and the screwing of the fittings requires the same previous motion strategy of the robot. Based on this concept, the third station was designed to allocate 40 manifolds and to rigidly fix them to a plate. Simulations of the behavior of station 3) were conducted. Encouraging results have been obtained regarding the effectiveness of the proposed station.

## 4. The End-Effector

Since the core of the automated process is the screwing task and a standard solution does not exist, research activity has been focused on the development of an end-effector. In the following sections, the design and the prototyping of this component will be described.

### 4.1. Technical Specifications

The end-effector should:

- have a mass less than 4 kg (payload of robot Sawyer);
- be equipped with a channeler for handling the fittings from the vibrating feeder to the threaded ducts of the manifold;
- be equipped with a centering system to ensure proper placement of the fittings on the threaded ducts;
- support the screwdriver;
- allow, from the rest position, the vertical motion of the screwdriver to perform the screwing task;
- allow autonomous recovery of the rest position of the screwdriver when the screwing task has been executed.

### 4.2. The Design of the End-Effector

To satisfy the technical specifications, the end-effector is made of: 1) a channeler of the fittings, 2) a support to fix the screwdriver, and 3) a guidance system for the vertical motion of the screwdriver.

#### 4.2.1. The Channeler

This component receives the fittings from the vibrating feeder and centers each descending fitting on the appropriate threaded duct. As such, the thread of the fitting must be placed in correspondence with the threaded duct

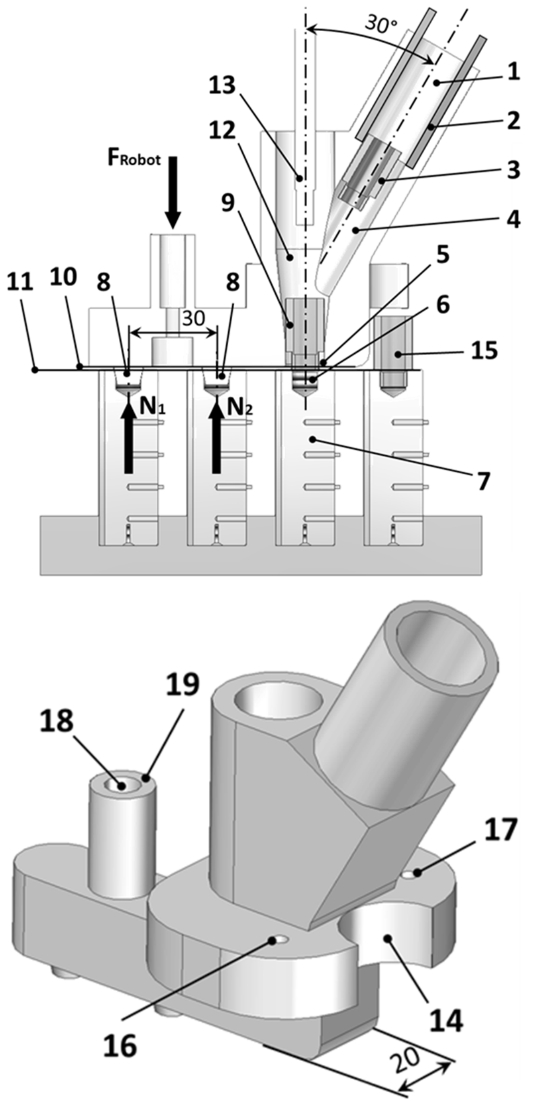



**Fig. 3.** The channeler.

of the manifold. Moreover, the channeler must allow the passage of the hexagonal rotating tool of the screwdriver through its cavity, to approach the fitting and to screw it in the manifold. During this phase, the rotating tool should not collide with the body of the fitting, but instead, move inside the fitting and couple with its inner hexagonal cavity. The channeler was designed as shown in **Fig. 3**. In this figure, the axisymmetric duct inclined at 30° with respect to the vertical direction has two hollow cylindrical segments: a higher segment (1) 22 mm diameter, connected to the vibrating station by a PVC tube, and (2) (diameter 22 mm, int. diameter 16 mm) for the handling of the fitting. The fitting that arrives from the vibrating station is denoted by (3). The lower segment (4), 16 mm in diameter, guides the fitting to the releasing hole (5), centered with the threaded port (6) of the manifold (7). Centering is assured due to two truncated conical pins (8), with axes that are 30 mm apart (equal to the pitch between two consecutive manifolds placed in the station for their loading and overturning). When the $i$-th fitting (9) arrives in front

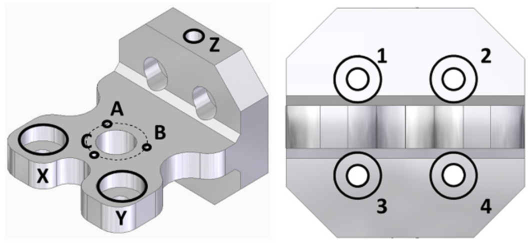



**Fig. 4.** The support of the screwdriver.

of the threaded duct, centering requires the next two manifolds. The channel is moved by the robot to vertically approach/leave the manifold. During the vertical motion, the lower surface (10) of the channeler remains parallel to the upper surfaces (11) of the manifolds. The axisymmetric duct (12), which has a vertically oriented axis, has a first cylindrical segment with a diameter of 20 mm, and a second conical segment for the proper fitting of the threaded port (6). Both segments intersect the 30° inclined duct. Tool (13) rotates and moves vertically along the duct (12). On the back side, an empty space (14) inhibits interference with the previously screwed $(i-1)$-th fitting (15). Finally, a set of 3 holes (16), (17), and (18) is required to attach the channeler to the guidance system of the screwdriver. The force $F_{\text{Robot}}$ applied by the robot Sawyer acts on surface (19). It is applied in the middle between the two truncated conical pins; thus, the normal reactions $N_1$ and $N_2$ are equal and no unbalancing occurs. The width of the lower surface is 20 mm to avoid contact with the fittings mounted in the previous steps of the automated process.

### 4.2.2. The Support of the Screwdriver

In this case, the objective is to fix the screwdriver and connect the end-effector to the wrist of the Sawyer. Moreover, the support moves vertically with respect to the channeler: when the latter ends its vertical motion, that is, the 2 truncated conical pins perform centering, the robot continues to move vertically to perform the screwing task. This means that the support of the screwdriver vertically approaches the channeler. The vertical motion is facilitated by the guidance system. In **Fig. 4**, the support of the screwdriver shows the $X$, $Y$, and $Z$ holes, corresponding to the previously mentioned (16), (17), and (18) holes of the channeler, respectively, for the attachment of the rods of the guidance system. Moreover, it shows the holes A, B, and C for attaching the screwdriver. The screwdriver is a FIAM® e-Tensil E8C3A-1200 (mass 0.78 kg; rated power 80 W; two speed rates: 980 and 1180 rpm; maximum torque 3 Nm; power supply 230 Vac) [22].

The flange coupling shows three M3 holes spaced 120° angularly, and placed on a circle with a 25.4 mm diameter. In the mandrel, a hexagonal tool (length 125 mm and 5 mm across the flat face, made of Ergal) is mounted. Four holes (1)–(4) are required for connecting to the wrist of the robot Sawyer using screws. For dimensioning, the support of the screwdriver is modeled as a cantilever that

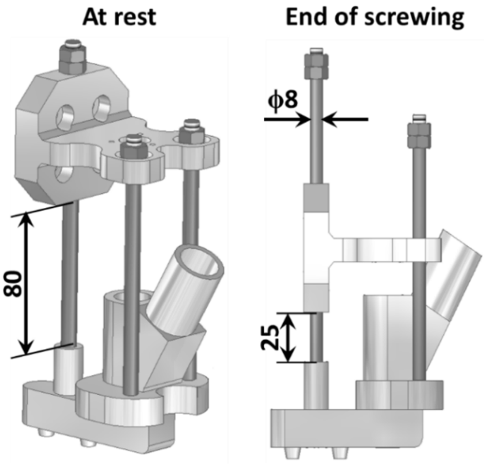



**Fig. 5.** A 3D model of the end-effector (for clarity, the elastic springs and the screwdriver are not shown) formed by the channeler, the support of the screwdriver, and the guidance system.

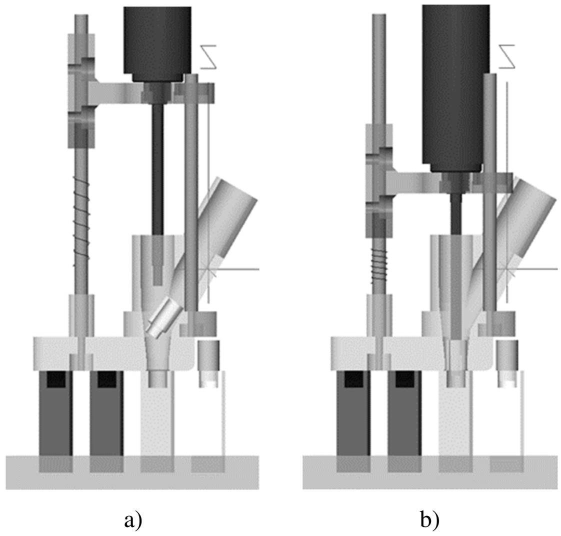



**Fig. 6.** The kineto-dynamic model: a) an instant of the free-fall of the fitting; b) end of the screwing process.

is fixed in correspondence to the holes (1)–(4), with an over-estimated distributed vertical load of 40 N (the payload of Sawyer) applied to the dashed circle including the mounting M3 holes (A, B, and C) of the screwdriver.

Considering the construction material (resin for high-resolution rapid prototyping Formlabs CLEAR FLGPCL04), the thickness of the supporting plate of the screwdriver is 12 mm.

Moreover, the thickness of the plate that interfaces with the wrist of the Sawyer is 15 mm. The shape shown in **Fig. 4** was achieved via topology optimization performed using a finite element solver.

#### 4.2.3. The Guidance System

This system consists of 3 parallel rods. For each rod, the lower end is fixed to the body of the channeler; the other end has 2 nuts to keep the support of the screwdriver firmly in place. The length of the rods was fixed based on the stroke of the screwdriver, and the length of the hexagonal tool. In **Fig. 5**, the guidance system facilitates 2 end stroke positions: the position at rest, when the screwdriver is in the upper position, and the lower position that corresponds to the end of the screwing process. The motion from one position to the other is performed by the robot. Nevertheless, the presence of an elastic force must guarantee that the rest position is maintained when the robot does not move the end-effector; it is necessary to avoid interference between the descending fitting and the hexagonal tool, and to avoid vertical oscillation of suspended masses. Under quasi-static conditions (for a stroke of 55 mm, maximum elastic force is 20 N, diameter of the rod is 8 mm, and the length is 80 mm), 2 commercial elastic springs ($k = 0.4$ N/mm, length at rest 54 mm, external diameter 11.5 mm, internal diameter 8.5 mm; 10 coils) are mounted in series around the rod with dimensions in mm as shown in **Fig. 5**.

### 4.3. Modeling of the End-Effector

Before prototyping of the end-effector, a numerical model was investigated with the following aims: to examine the effectiveness of the proposed solution (the motion of the fitting along the tube and the channeler, the centering of the descending fitting with the manifold, and the interaction between the hexagonal tool and the fitting); to investigate geometrical interference among the components, to determine the achieved length of the hexagonal tool, and to investigate the behavior of the set of springs. A kineto-dynamic 3D model was developed using the commercial numerical code SimWise 4D 9.8 (Design Simulation Technologies, Inc., USA) for the analysis of rigid multi-body systems. As shown in **Fig. 6**, the model includes the entire set of components of the end-effector, including the screwdriver. Moreover, the end-effector interfaces with a set of four manifolds that are equally spaced at 30 mm.

The manifolds and the lower flat plane are fixed; the gray-colored fitting is fixed on the right manifold; the screwdriver is fixed to its support; the tube is fixed to the channeler; vertical prismatic couplings are used for all the moving components, except for the descending white-colored fitting, and the ends of the spring are fixed to the support of the screwdriver and the channeler, respectively.

The channeler can collide with all the manifolds, the gray fitting, and the descending white fitting; the latter can also collide with the tube, the hexagonal tool, and the gray-colored manifold.

The white-colored fitting is in free-fall; from the rest position, the support of the screwdriver moves vertically downward by 20 mm to the centering position (**Fig. 6(a)**), followed by a stroke of 55 mm. During the last 5 mm of the stroke, the hexagonal tool is rotated at 980 rpm to perform the screwing task (**Fig. 6(b)**); finally, it moves vertically upward to the rest position.

The effectiveness of the solution has been investigated;

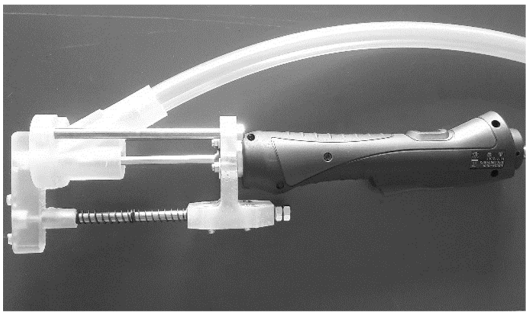


**Fig. 7.** The prototype of the end-effector.

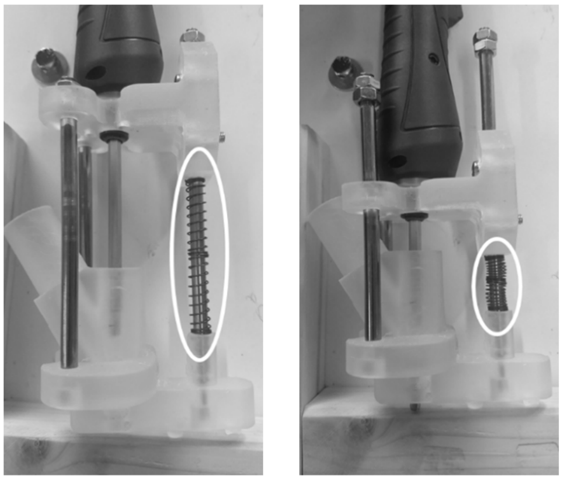
no interference occurred between the channeler and the previously mounted fitting, the descending fitting and the hexagonal tool, the support of the screwdriver, and the channeler; a stroke of 55 mm satisfies the screwing requirements; the springs allow the support of the screwdriver to reach the rest position and do not inhibit its downward stroke. Moreover, the springs act as shock absorbers in the case of accidental impacts between the truncated conical pins and the manifold.

## 5. The Prototype

The channeler and the support for the screwdriver were fabricated using a stereolithography 3D printer. Three stainless steel rods were adopted for the guidance system. In the lower end of the rods, a geometrical shoulder and several M4 nuts were used to eliminate the axial motion of the rods relative to the channeler. The other end had an M8 thread: several nuts were used as the end stroke. The length of the road interfaced with the spring was 210 mm, and the length of the remaining rods was 155 mm. The diameter of all the rods was 8 mm. Commercial screws were used to attach the screwdriver to its support, and the support to the wrist of the robot Sawyer: three M3 $\times$ 15 and four M6 $\times$ 15, respectively. The overall dimensions of the end-effector without the screwdriver was 95 mm $\times$ 70 mm $\times$ 216 mm (W $\times$ L $\times$ H); neglecting the electric power supply cable of the screwdriver and the tube used to handle the descending fitting, the overall dimensions of the end-effector were 95 mm $\times$ 70 mm $\times$ 435 mm. The mass of the channeler was 0.175 kg, the mass of the support of the screwdriver was 0.162 kg, and the total mass of the springs, rods, and commercial screws was 0.195 kg. The overall mass of the end-effector was 1.312 kg, which is much less than the 4 kg payload of the robot Sawyer. The prototype is shown in **Fig. 7**.

## 6. The Experimental Activity

The first set of functional tests was performed to evaluate the performance of the stroke, from the rest position to the lower end stroke. This was done to investigate the structural stability of the components and the occurrence



a) b)

**Fig. 8.** The end-effector a) at rest position and b) at the lower end stroke.

of jamming between the support of the screwdriver and the rods. As shown in **Fig. 8**, the two truncated conical pins of the channeler were pushed against a flat wooden surface. The vertical motion of the screwdriver was then manually initiated for 150 cycles (downwards and upwards). The motion speed was adjusted during the tests in the range from very slow (approximately 1 mm/s) to very fast (approximately 55 mm/s). The end-effector had an expected stroke (55 mm) without jamming and structural bending of the support of the screwdriver. Moreover, several tests were performed to investigate the behavior of the springs. As the manual external forces were individually removed from the screwdriver, the elastic force of the springs moved the screwdriver upward until the rest position was reached.

A second set of tests was performed to examine the effectiveness of the proposed solution for automated screwing. In particular, the tests investigated the centering of the channeler, the free-fall of the fitting, its positioning in the releasing hole, the downward motion of the screwdriver, automated screwing, and the upward motion of the screwdriver. For the second set of tests, the end-effector was mounted on the robot Sawyer. Three manifolds were fixed to a flat rigid surface mounted on the base of the robot Sawyer using a plate made of commercial aluminum profiles. Manifolds were placed at a separation distance of 30 mm to match the distance between the axes of the two truncated conical pins: 2 manifolds were used to center the channeler. The other manifold was used to screw the fitting.

**Figure 9** shows the testbed: it consists of the collaborative robot Sawyer, the rigid plate, 3 manifolds, the previously described end-effector, a push button, and a power supply unit. The controller of the robot Sawyer guided its path and communicated with the external environment using a 24 V DC digital input and a 24 V DC digital output: the push button was used for initiation of the automated task and the activation command of the screwdriver.

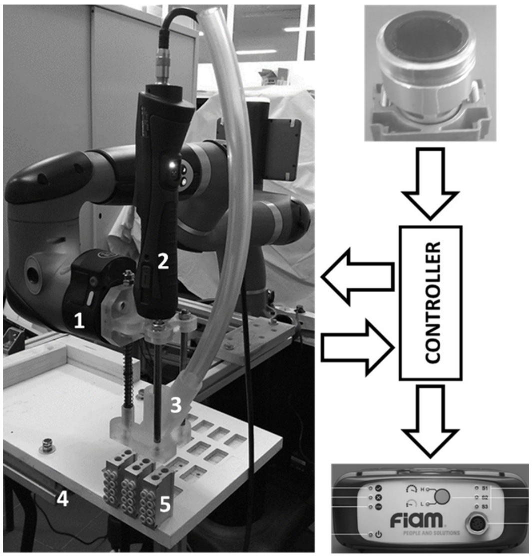



**Fig. 9.** The testbed: 1: robot Sawyer, 2: screwdriver, 3: channeler of the end-effector, 4: rigid plate, and 5: manifolds.

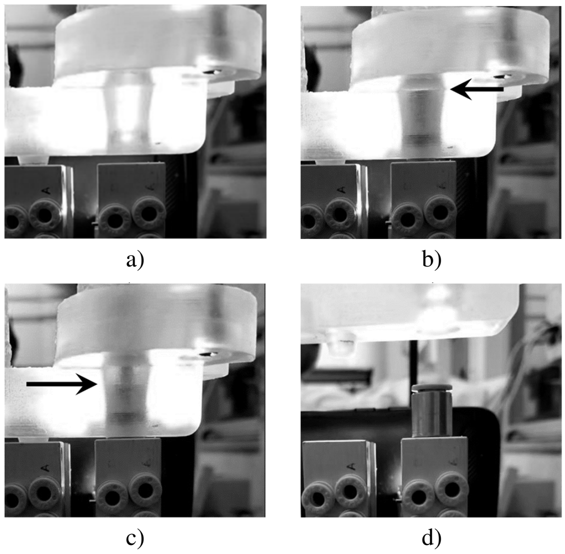



**Fig. 10.** Frames of the screwing task: a) final stage of the centering phase; b) the fitting reaches the releasing hole; c) final stage of the screwing task; d) the fitting is screwed in the manifold.

The output signal is received by the FIAM® TPU [22] power supply that facilitates the activation of the screwdriver, provided that the output signal is enabled.

The test execution is based on the following steps:

*Step 1*: At the home position, far from the set of manifolds, the Sawyer waits for the start command from the push button.

*Step 2*: When the start command is initiated, the Sawyer quickly (at the max velocity = 0.5 m/s) reaches the position shown in **Fig. 9**: this corresponds to the expected centering position, vertically translated by 40 mm.

*Step 3*: The Sawyer moves vertically by 40 mm to center the channeler.

*Step 4*: The Sawyer waits for 2 s; in the meantime, the fitting is manually inserted in the top surface of the PVC tube and reaches the releasing hole.

*Step 5*: The Sawyer continues to move vertically. The channeler is fixed, and the support of the screwdriver starts to move vertically. The screwdriver is activated and starts to rotate at 980 rpm. The Sawyer stops when the vertical force, detected by the force sensors of its joints, reaches 20 N.

*Step 6*: The screwdriver is disabled, and the Sawyer moves vertically upward by 95 mm (it reaches the position at the end of *Step 2*).

*Step 7*: The Sawyer moves horizontally by 18 mm (the distance between the axes of the threaded ports). The robot then repeats the tasks from *Step 3* to *Step 6*.

*Step 8*: The robot quickly (at a maximum velocity of 0.5 m/s) reaches the home position.

In **Fig. 10**, several frames of the task sequence are shown. A backlight is necessary to highlight the cavities inside the channeler. **Fig. 10(a)** shows the channeler during the final stages of the centering phase: the truncated conical pins (only one is visible to magnify the area of the fitting) are coupled with the adjacent manifold, and the empty releasing hole is positioned in correspondence to the center of the manifold involved in the screwing task. **Fig. 10(b)** shows the end of the centering phase, wherein the fitting has reached the releasing hole. The black arrow indicates the height of the top surface of the fitting. The end of the screwing task is shown in **Fig. 10(c)**. The black arrow indicates the height of the top surface of the fitting, placed approximately 5 mm lower than the height of the previous frame. Above the top surface of the fitting, it is possible to identify the shadow of the hexagonal tool. **Fig. 10(d)** shows the fitting, screwed in the manifold.

A final test was performed to investigate the correctness and effectiveness of the screwing action. An attempt to manually unscrew the fitting was undertaken: no rotation was recorded.

Except for the movements from and to the home position, the average speed of the robot Sawyer was fixed at 30 mm/s. Intera Studio software [23], the Sawyer's operative system, was utilized to program the robot. It was used to record the position along the path, to define the speed values, to communicate with the external environment, and for the implementation of the automated task. The program used for the robot was generated using the teaching-playback method: a sequence of points was recorded, and the fit of these points was determined using Intera for each test. Rotation of the wrist was fixed to maintain the lower surface of the end-effector parallel to the upper surfaces of the manifolds. Several attempts were made before establishing a reliable law of motion and initiation of the final tests. During the execution of the task, Intera Studio displayed data related to the $X$, $Y$, and $Z$ positions of its wrist, the current speed, and data about the forces along the $X$, $Y$, and $Z$ directions. The tests were repeated 30 times: the automated process was successfully conducted. Jamming between the mounted fitting and the channeler was not observed during the removal of the channeler. Due to the safe values that regulate the speed of the robot Sawyer, the screwing of a single fitting requires 14 s. We estimate that this can be improved to less than 9 s.

## 7. Conclusions

An application of collaborative robotics has been reported in this report. The manual task of screwing the fittings onto the manifolds of 2 pneumatic electro-valves was replaced by an automated screwing process performed by a collaborative robot Sawyer. A system was developed to fully automate the screwing task. It consisted of a vibrating station to load the fittings, a loading and overturning station for the manifolds, and a screwing station. The latter utilized the robot Sawyer and its end-effector. This research focused on the development of the end-effector.

It was made of a channeler, a support to fix the powered screwdriver, and a guidance system. The design and the details of the prototype end-effector were reported. The experimental results demonstrated the effectiveness of the system. Several improvements can be implemented. The channeler could be improved by utilizing springs with the truncated conical pins to serve as shock-absorbers to mitigate accidental collisions with the manifolds. In the tube, the fitting could be driven by compressed air instead of gravity, to reach the channeler along a horizontal path. The length and the stroke of the hexagonal tool can then be reduced. Optimal control of the robot could be achieved to reduce the overall time for the screwing task. Hence, prototyping of the loading and overturning stations of the manifolds, and interfacing with the vibrating feeder will be investigated in the future.

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