



ScarfiingTool: An Advanced tool to repair Carbon Fiber Reinforced plastic

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ABSTRACT

Carbon Fiber Reinforced Plastic (CFRP) is going to assume more and more importance in mechanical and aerospace engineering in the near future. This is due to its intrinsic high lightness and resistance, if compared to traditional metallic materials. CFRP is characterized by a proper production and repair technology. The tool showed in this paper is conceived to repair and verify the restoration of such kind of material. Its application is limited to the first part of the repair process: in jargon the scarfiing operation, otherwise called “defect removal”. This operation is similar to a high-speed grinding.

For this reason, the designed tool can be easily applied to other contexts, such as sanding, polishing or deburring.

Basically, the ScarfiingTool is composed by a high-speed electro-spindle and a 3D smart snapshot sensor. This tool is conceived to be as light as possible to be installed on a light collaborative robot. Moreover, its specific design assures great compliance that, as needed, can be regulated. A high efficiency suction inlet completes the tool and guarantees a clean environment during operation. The scarfiing process has already been dealt with in [1] to which the interested reader is addressed.

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Specifications table

Hardware name	ScarfiingTool: Advanced Tool to Repair and Test CFRP
Subject area	Engineering and materials science
Hardware type	Mechanical engineering and materials science
Closest commercial analog	ATT's AOV-10 Axially-Compliant Orbital Sander [2] FerRobotics Easy Finishing Kit [3]
Open source license	Creative Commons Attribution-ShareAlike 4.0 International. To view a copy of this license, visit https://creativecommons.org/licenses/by-sa/4.0
Cost of hardware	18,180.20 €
Source file repository	https://doi.org/10.17632/h2zrpf3pf.1

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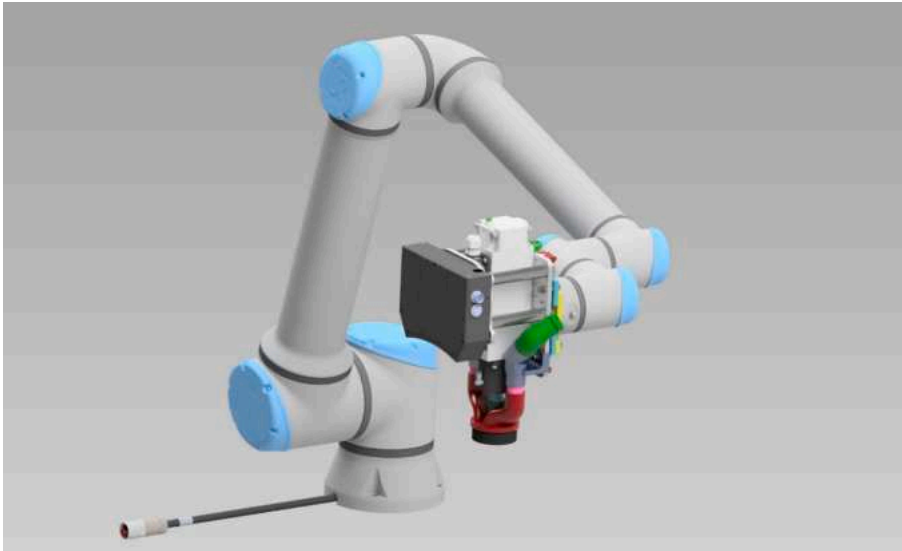


Fig. 1. A Collaborative Robot (UR10e) equipped with the ScarfingTool.

1. Hardware in context

The tool illustrated in this work deals with the repair process of CFRP. In particular the ScarfingTool focuses on the defect removal and the quality testing of aeronautical components. The interested reader can find useful information about the CFRP repair process in [4] and [5]. For our purpose the defect removal (i.e., the scarfing) can be compared to a light milling or, better, to a grinding operation.

This process has been addressed in different ways around the world. The Japan Aerospace Exploration Agency (JAXA) has been working with Shinmei Industry Co. to develop an Automated Scarf Sanding Device [6]. The device is attached to the composite airframe with ten “legs” and conducts the scarf sanding automatically by a grinding wheel. Nonetheless, the operation mode is quite similar to that of a mobile machine tool instead of a robot. The high precision of the operation is guaranteed by the increased stiffness of the machine and its intrinsic accuracy, so no quality testing system is required.

Lufthansa Technik created a mobile scarf joining robot during the “CAIRE” research project [7,8].

In this case a big industrial robot is equipped with an electro-spindle and it acts as a milling machine. The robotic system is able to scan the surface to machine, to represent it in a 3D environment and to execute on it the scarfing by an end mill.

None of these are open hardware tools. Moreover, the issue is faced using huge and stiff hardware in both cases.

This work, starting from the same issue, deals with it differently. The proposed tool is collaborative, light, and damped to simulate a human arm. It is designed to operate in a laboratory or a workshop and can be adapted to be used in other situations. In addition to scarfing operation, it can perform polishing, cleaning, brushing, deburring, and finishing.

Due to its intrinsic compliance the tool trajectory (and thus the machined surface) does not have the same accuracy of that of the automatic machines described in [6,7]. For this reason, the tool is equipped with a 3D snapshot sensor, to measure and evaluate the quality of the worked surface.

From this point of view, the ScarfingTool introduced here is more similar to the tools described in [2] (by ATI –Industrial Automation) or [3] (by Ferrobotics). However, they do not address the CFRP repair. Moreover, they are not open hardware tools, and they do not execute any measure or control quality test on the machined surface.

For all these reasons, the ScarfingTool is an innovative tool to execute light machining and testing on various materials in a laboratory environment.

A research article about this tool was published at the International Conference “SPIE Optical Metrology 2023”. See [9] for more details.

2. Hardware description

Fig. 1 illustrates a collaborative robot equipped with the ScarfingTool. The idea at the core of the ScarfingTool design is to implement a tool that would have been intrinsically “human friendly”; so the choice of a robot that is “collaborative” has been a direct result of this requirement. Under this assumption it is possible to share the robot workspace with a human operator. The ScarfingTool is designed to be as light as possible so that it can be installed on a light robotic arm as the UR10e [10]. The UR10e has been chosen because it has all the features required for the project, but any other collaborative robot can be used. The most stringent requirement is the payload, that must be at least 10 kg.

In Fig. 2 there is a close-up view of the ScarfingTool.

To better understand its operation, the ScarfingTool is disassembled in functional unities in Fig. 3. Table 1 lists them along with their functionalities.

The ScarfingTool is characterized mainly by two items: the 3D Snapshot Sensor (1) and the Main Tool (3). These are the fundamental tools to machine and test.

The Main Tool drives the Backing Pad (2) to remove the material and the 3D Snapshot Sensor checks the surface quality at the end of the operation. Due to the large amount of dust during working, the Vacuum Inlet (4) vacuums it as near as possible to the abrasive disk: this guarantees a high efficiency in dust removal.

The plates 5 and 6 are connected each other by an air cylinder that ensures the correct damping force.

Plate 5 gets the rails, while plate 6 carries the carriages. So, plate 5 can slide towards plate 6, realizing an auxiliary axis with a stroke of 12 mm. This feature assures to work with a constant force acting along the tool axis (conventionally said as “Z” axis) even if the working surface has small variations in its height. These variations must be less than the auxiliary axis stroke. The constant force is guaranteed by a low friction mechanical design of the auxiliary axis, exploiting the force supplied by compressed air action inside the pneumatic cylinder.

A significant added value in designing the tool is the capability of working with a constant force while compensating for height variations. This functionality simulates the behavior of the human arm in terms of flexibility and adaptability. In general, a scarfing solution cannot be developed without this feature and this issue would have been dealt with a solution like those in [6] or [8]. The damping system is a key factor to success in similar applications.

In fact, till now, the scarfing operation on CFRP has been performed manually by skilled workers. The ScarfingTool is an attempt to join humans and collaborative robots to execute a critical job simultaneously exploiting the precision and the resistance to fatigue typical of robots with the manual ability of human workers. The goal of the tool is to machine and reconstruct the machined surface. To this last aim, the ScarfingTool is equipped with a 3D snapshot sensor. The 3D sensor is not intended to increase the tool’s stiffness and accuracy, but to reconstruct the machined surface by a 3D digital model.

Fig. 4 illustrates the general structure of the ScarfingTool and its connections to the external supplies. To work with it some connections are needed:

- An electrical supply, 230 V – 50 Hz;
- An air pressure source, 6 bar, according the standard ISO 8573–1 Class 5 quality;
- A vacuum cleaner or a connection to a centralized suction system;

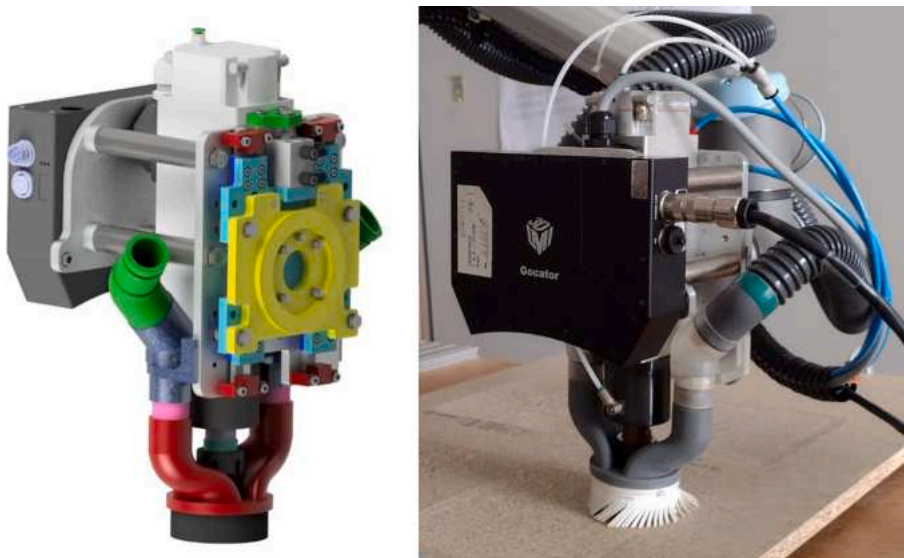


Fig. 2. The ScarfingTool: CAD model (on the left) and real prototype (on the right).

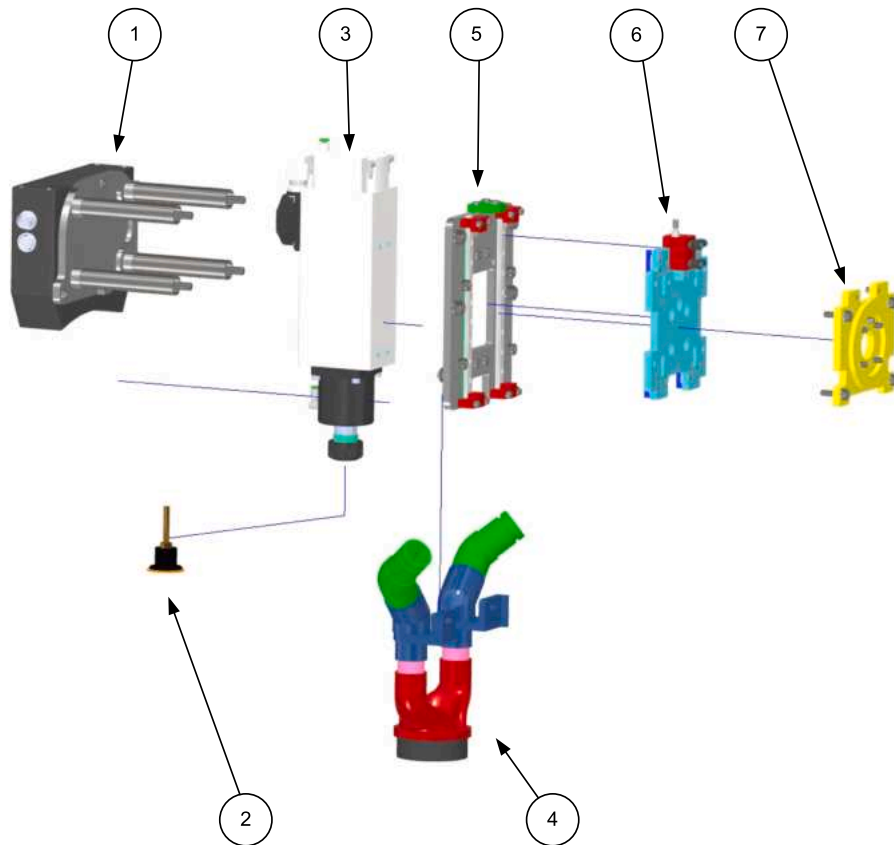


Fig. 3. ScarfingTool's Functional Unities.

Table 1
Functional Unities of the ScarfingTool.

Number	Unity Name	Function
1	3D Snapshot Sensor	Tool to test the final working
2	Backing pad with abrasive disk	Tool to remove material
3	Electro-Spindle	Main tool
4	Vacuum Inlet	Vacuuming of the process dust
5	PlateSpindle	Support for the electro-spindle
6	PlateUR10-Floating	Damping System
7	PlateUR10	Connection to the robot flange

These Functional Unities are graphically represented in Fig. 3. See it for more details.

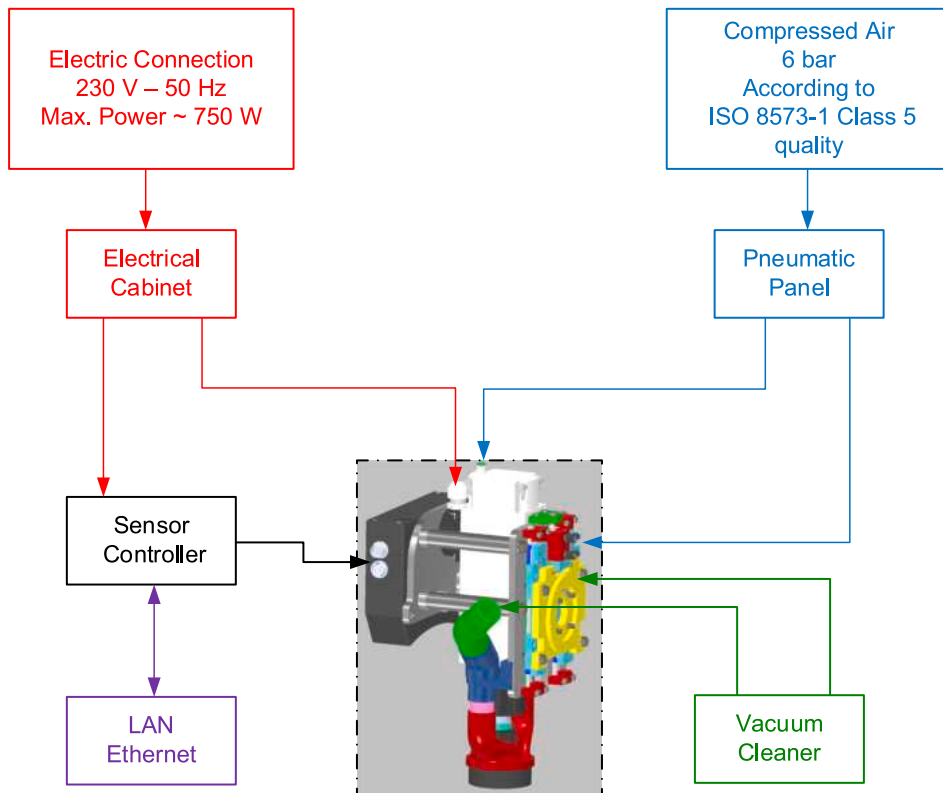


Fig. 4. Block Diagram of the ScarfingTool and its connections to external supplies.

Table 2
Requirements for the ScarfingTool.

N°	Requirements	Value
1	Rotating Speed	3,000 ÷ 24,000 rpm
2	Base Speed	12,000 rpm
3	Tool	Backing pad with abrasive disk
4	Tool diameter	38 mm
5	Electrical supply	230 V – 50 Hz
6	Pneumatic supply	6 bar – ISO 8573-1 Class 5
7	Field of view	71.0 x 98.0 – 100.0 x 154.0 mm
8	Scan Rate	4 Hz
9	Resolution (XY)	0.060 mm
10	Repeatability (Z)	55 µm
11	Total weight	< 10 kg

Lines from 1 to 4 are mechanical specifications;

Lines 5 and 6 are specifications for connections to the mains;

Lines from 7 to 10 are specifications for the 3D Snapshot Sensor.

Line 11 specifies the weight, that is very important to install the ScarfingTool on a light collaborative robot.

- A router to connect it to a LAN Ethernet.

The general requirements of the scarfing tool are summarized in [Table 2](#):

As an open source hardware, the ScarfingTool design can be easily modified by simple edits on the 3D models supplied in this paper. Other changes are possible on its specifications.

For example, it is possible to exchange the electro-spindle power, or to choose another 3D sensor: for some application a Laser Line Profile Sensor could be better than a Snapshot Sensor.

To recap, the open source ScarfingTool provides the following advantages:

- To face various light mechanical machining (scarfing, deburring, polishing, grinding...) on several different materials (CFRP, glass fiber, wood, particle board, metals...);
- To be as light as possible to be installed on a light collaborative robot;
- To be as compliant as possible to mechanically compensate the irregularities of the surface where it is working;
- To perform machining, measuring and quality test at the same time and by only one tool.

In conclusion, because of the complexity involved, the scarfing operation on CFRP is still done manually in most cases: the ScarfingTool is an attempt to automate it by exploiting human–robot cooperation.

3. Design files summary

The table below summarizes all the design files. For what concern the mechanical design the classification follows this rule:

- Prefix 0: The main assembly, i.e., the ScarfingTool;
- Prefix with one digit (1-...): The sub-assemblies as illustrated in [Fig. 3](#) (the numbers in the balloon are the same as the prefix);
- Prefix with two digits separated by (1_1-...): The parts. The prefix in the filename is the same as the ID in the Bill of Material Summary.

The mechanical design is done by Autodesk® Inventor® Professional 2022.

All the design files are supplied by Inventor files (.ipt,.iam).

The machined parts are supplied as STEP files (.stp) and the 3D printed components are supplied as STL files.

All the other files (Build and Operational Instructions, Hardware Descriptions, Electrical and Pneumactical diagrams...) are provided as Visio files (.vsdx).

N°	Design file nameID	File type	Open source license	Location of the file
1	0-ScarfTool7-Disk38	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
2	1-PlateGocator2	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
3	2-NortonDisk38	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
4	3-TeknomotorSpindle-Disk38	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
5	4-VacuumDust7-Disk38	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
6	5-PlateSpindle3	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
7	6-PlateUR10-Floating1	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
8	7-PlateUR10-4	CAD file(.iam,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
9	1_1-PlateGocator3	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
10	1_2-BarUp1	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
11	1_3-TubeBar2	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
12	4_1-Curve45	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
13	4_2-BracketTube4	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
14	4_2b-BracketTube4_MIR	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
15	4_3-Tube28-2	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
16	4_4-Vacuum Skirt38-Rev3	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
17	5_1-PlateSpindle4-NSK	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
18	5_5-Stop1	CAD file(.ipt,.STL)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
19	5_7-CylJig1	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
20	6_2-PlateUR10-Floating1	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
21	7_1-PlateUR10-4	CAD file(.ipt,.STEP)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
22	Build Instructions – Rev1	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
23	Cabinet Drawings	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
24	Electrical Diagram – Rev7 – EN	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
25	Hardware Description	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
26	Operational Instructions – Rev2	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1
27	Pneumatic Diagram – Rev3 – EN	Visio file(.vsdx)	CC BY-SA 4.0	https://doi.org/10.17632/h2zrpf33pf.1

Legend:

Line 1 is the main assembly of the ScarfingTool (Prefix 0);

Lines from 2 to 8 represents the sub-assemblies (Prefix with one digit);

Lines from 9 to 21 are the single parts of each sub-assembly (Prefix with two digit separated by _);

Lines from 22 to 27 are diagrams illustrating the electrical and pneumatic systems, the build and operational instructions.

The paragraph below describes each design file. The first section is related to the mechanical design, while the second one describes the other issues.

0-ScarfTool7-Disk38:	Mechanical Design of the whole ScarfingTool;
1-PlateGocator2:	Sub-assembly to install the 3D sensor, see Fig. 3;
2-NortonDisk38:	Abrasive Disk with Backing Pad, see Fig. 3;
3-TeknomotorSpindle-Disk38:	Electro-Spindle, see Fig. 3;
4-VacuumDust7-Disk38:	Sub-assembly of the cuff to vacuum the process dust, see Fig. 3;
5-PlateSpindle3:	Sub-assembly of the plate to install the Electro-Spindle; see Fig. 3;
6-PlateUR10-Floating1:	Sub-assembly of the plate with the carriages, see Fig. 3;
7-PlateUR10-4:	Sub-assembly of the plate for the flange of the robot, see Fig. 3.
1_1-PlateGocator3	Plate for the 3D sensor (machined part);
1_2-BarUp1	Threaded Bar;
1_3-TubeBar2	Spacer;
4_1-Curve45	Vacuum hose, 45° deg, 3D printed;
4_2-BracketTube4	Holder for the vacuum hose, 45° deg, 3D printed;
4_2b-BracketTube4_MIR	Holder for the vacuum hose, 45° deg, mirrored, 3D printed;
4_3-Tube28-2	Coupling for the vacuum hose, 3D printed;
4_4-Vacuum Skirt38-Rev3	Cuff to vacuum the process dust, 3D printed;
5_1-PlateSpindle4-NSK	Plate to install the ElectroSpindle, machined;
5_5-Stop1	End stroke stop that acts as a bumper, 3D printed;
5_7-CylJig1	Coupling for the cylinder rod, machined;
6_2-PlateUR10-Floating1	Plate with the carriages, machined;
7_1-PlateUR10-4	Plate for the flange of the robot, machined.

Build Instructions: File Visio illustrating the mechanical constructions of the ScarfingTool. The same figures are reported in the paper, in the section “Build Instructions”. It is composed of 12 sheets.

Cabinet Drawings: File Visio with the mechanical design of the electrical cabinet. It represents the disposition of all the electrical components: external (switches, push-buttons) and internal (contactor, terminal blocks, drive...) It is composed of 4 sheets.

Electrical Diagram – Rev7 – EN: It is the electrical diagram to follow to wiring the whole system: either the electrical cabinet, either the connections between the devices. It is composed of 10 sheets.

Hardware Description: Schematic representation of the whole system and its internal and external connections. It is composed of 3 sheets with figures reported in the section: “Hardware Description”.

Operational Instructions – Rev2: File Visio that resumes the safety issues and other points about the operation of the ScarfingTool. The same figures are reported in the section: “Operation Instructions”.

Pneumatic Diagram – Rev3 – EN: It is the pneumatic diagram of the machine. It is composed of 3 sheets. It is useful to install the pneumatic system and it is related, in some points, with the electrical diagram.

3.1. Bill of materials

The General Bill of Material summary (BOM) is supplied as an Annex in the form of an Excel spreadsheet:

- General_BoM-Rev2-EN.xlsx

The BOM is divided in 6 sheet: Mechanical, Electrical, Main_Cable, 3D Sensor, Pneumatics, Vacuum Cleaner. The General_BoM-Rev2-EN is uploaded on the Mendeley Data Repository.

(<https://doi.org/10.17632/h2zrpf3pf.1>).

4. Bill of materials summary

The Table below includes all the components necessary to build the mechanical part of the ScarfingTool, as described in Section 5.1. It is filled following the build instructions. So there are some rows that can include the same component more than once.

N°	ID	Component	Quantity	Cost per unit – (€)	Total cost – (€)	Source of materials	Material type
1	1.1	PlateGocator3	1	170.00	170.00		Metal (Machined)
2	1.2	BarUp1	4	3.00	12.00		Metal
3	1.3	TubeBar2	4	10.00	40.00		Metal (Machined)
4	1.4	ISO 4032 M8	4			smallware	Metal
5	1.5	ISO 4762 – M6x16	3			smallware	Metal
6	1.6	Gocator 3210	1	16,000.00	16,000.00	LMI Technologies	3D Sensor
7	3.1	ElectroSpindleTeknomotorCOM31400305Model: 3140-C-DBL-P-ER20-PR-AC-RH	1	739.00	739.00	https://www.teknomotor.com	Other
8	5.1	PlateSpindle4-NSK	1	220.00	220.00		Metal (Machined)
9	5.2	ISO 4762 – M6x12	4			smallware	Metal
10	5.3	NSK rail – PU series195 x 9 mm	2	64.17	128.34	https://it.rs-online.com RS Code:619–2414	Other
11	5.4	ISO 4762 – M3x10	20			smallware	Metal
12	5.5	Stop1	4	5.00	20.00	Flexible 80A Resin by Formlabs	3D Printed
13	5.6	ISO 4762 – M4x25	8			https://formlabs.com	Elastomer
14	5.7	CylJig1	1	25.00	25.00	smallware	Metal
15	5.8	ISO 4762 – M5x20	2			smallware	Metal
16	6.1	NSK carriage 30x20x9	4	60.34	241.36	https://it.rs-online.com RS Code:619–2442	Other
17	6.2	PlateUR10-Floating	1	190.00	190.00		Metal (Machined)
18	6.3	Air Cylinder	1	47.50	47.50	https://www.festo.com/it ADVC-16–15-A-P	Other
19	6.4	Pneumatic Connector	2	5.90	12.00	https://www.festo.com/it QSMLV-M5-4-I	Other
20	6.5	ISO 4762 – M4x40	2			smallware	Metal
21	6.6	ISO 4762 – M3x8	16			smallware	Metal
22	6.7	ISO 7089 6	1			smallware	Metal
23	6.8	ISO 4035 M6	1			smallware	Metal
24	0.1	ISO 7089 8	4			smallware	Metal
25	0.2	ISO 4032 M8	4			smallware	Metal
26	4.1	Curve45	2	20.00	40.00	Grey Resin V4by Formlabs	3D Printed
27	4.2	BracketTube4	1	20.00	20.00	https://formlabs.com	Polymer
28	4.2b	BracketTube4_MIR	1	20.00	20.00	Grey Resin V4by Formlabs	3D Printed
29	4.3	Tube28-2	2	15.00	30.00	https://formlabs.com	Polymer
30	4.4	VacuumSkirt38-rev3	1	40.00	40.00	Grey Resin V4by Formlabs	3D Printed
31	4.5	Skirt38	1	15.00	15.00	https://formlabs.com	Polymer
32	4.6	O-Ring ø28x3	4			smallware	Silicone Rubber
33	4.7	O-Ring ø22x3	4			smallware	Elastomer
34	0.3	ISO 7093 A ST 5	2			smallware	Elastomer
35	0.4	ISO 4017 M5x16	2			smallware	Metal
36	7.1	PlateUR10-4	1	130.00	130.00		Metal (Machined)
37	7.2	ISO 4762 – M6x12	4			smallware	Metal
38	7.3	ISO 4017 – M6x25	4			smallware	Metal
39	7.4	ISO2338 – 6 h8x14	3			smallware	Metal
40		Total Smallware			40.00	smallware	Metal
		Total Cost			18,180.20		

Legend:

Lines from 1 to 6 describe the components for the 3D Snapshot Sensor;

Line 7 is the Electro-Spindle (Main Tool).

Lines from 8 to 15 describe the support for the electro-spindle;

Lines from 16 to 23 refer to the damping system;

Lines 24 and 25 are smallware to connect the 3D Snapshot Sensor to the whole system;

Lines from 26 to 33 refer to the vacuum inlet;

Lines 34 and 35 are smallware to connect the vacuum inlet to the whole system;

Lines from 36 to 39 describe the connection to the robot flange.

The cost of smallware (blank fields in the table) is neglected. It is estimated in about $20.00 \div 40.00$ €.

The “Stop1” bumper (5.5) is made by additive manufacturing using the Flexible 80 A Resin.

All the costs of additive manufactured parts are an estimate.

All the parts indicated as “Metal (Machined)” are machined in a mechanical workshop.

5. Build instructions

Build instructions are separated in two main sections: 5.1) mechanical instructions and 5.2) electrical instructions.

5.1. Mechanical Build instructions

The sequence for the mechanical assembly follows the main sub-assemblies’ diagram in Fig. 3. The numbers in balloons are used to identify the sub-assemblies in the whole procedure: they are referred to by round brackets. For example (1) refers to the 3D sensor. Number (0) refers to a component in the main assembly.

The sequence is organized as follow:

1. The 3D sensor (1) is assembled;
2. The Electro-Spindle (3) is attached to the PlateSpindle (5);
3. The PlateSpindle (5) is assembled with the rails and the other accessories;
4. The four carriages are inserted on the rail by sliding;
5. The air cylinder is screwed on the PlateUR10-Floating (6);
6. PlateUR10-Floating (6) is assembled on the carriages;
7. The 3D sensor (1) is screwed on the PlateSpindle (5);
8. The Vacuum Inlet (4) is installed on the PlateSpindle (5);
9. PlateUR10 (7) is screwed on the robot’s flange;
10. At this time, the whole assembled tool can be fixed, by screws, on the PlateUR10 (7).

As appear from the previous instructions, the PlateSpindle (5) plays an important role in the ScarfingTool working: it is the core where all the elements are attached.

5.1.1. Assembly of the 3D sensor

This step is split in two sub-steps. First, the support for the 3D sensor is assembled as in Fig. 5 and then the 3D sensor is installed on its support as in Fig. 6

Screw the four M8 bars (1.2) in the corresponding threaded holes in plate (1.1). Fix them by the locknut (1.4). The tubes (1.3) are used as spacers in the final assembly of the sensor to the ScarfingTool (see section 5.1.7 and Fig. 14).

Install the 3D sensor (1.6) on plate (1.1) by the three socket cap screws (1.5), see Fig. 6.

Design variant:

The procedure illustrated in the second sub-step is also useful to install another 3D sensor. In fact, with a small modification on the holes in plate (1.1) the 3D Snapshot Sensor can be substituted with another sensor: i.e., a 3D Line Profiler to scan a surface.

5.1.2. – assembly of the Electro-Spindle

The Electro-Spindle (3.1) is installed on its plate (5.1) by socket cap screws (5.2), see Fig. 7.

Pay attention to read the Electro-Spindle User’s Manual. In particular, at this time, avoid to install the tool on the spindle. The tool is the last component to be installed.

5.1.3. Assembly of the PlateSpindle with the rails

This step installs the rails, the bumpers and the cylinder attachment.

Please follow the instructions in sequence.

First install one rail (5.3) by socket cap screws (5.4) on plate (5.1). The mechanical guide (green in Fig. 8) is useful to guarantee a correct alignment. Then install the other one, in the same way.

Caution:

Pay attention that at the end of rails installations, could be necessary to regulate one of them in terms of parallelism. It depends on

the construction tolerances of plate (5.1). If tolerances of plate (5.1) (flatness and parallelism) are not so good, some adjustment are necessary.

Once installed the rails, the bumpers (5.5) can be installed by socket cap screws (5.6). At this time install only two bumpers, because the other side must be free to enter carriages.

At last, the attachment (5.7) is screwed by socket cap screws (5.8).

5.1.4. installation of the carriages

The rails and the carriages are a critical component for this application: a correct choice and installation are important to guarantee the lowest friction in the movement. The choice falls on NSK:

- Cod. P1U090195SKN-PCT is the rail;
- Cod. PAU09TRS is the carriage.

The four carriages (6.1) are inserted on their rails: two on the left and two on the right.

The carriage is supplied inserted on its fake (plastic) rail: see Fig. 9.

The insertion of the carriages on the real rail requires attention, because it is mandatory to align them with the rails using the plastic rail. Once the alignment occurs, slide them from the plastic rail to the real rail. The result is represented in Fig. 10.

Fig. 11 illustrates the ScarfingTool and its main components at this level of integration.

5.1.5. installation of the pneumatic cylinder

Now the cylinder (6.3) is installed on plate (6.2) by socket cap screws (6.5). Then two air connectors (6.4) are applied. Later these connectors will be connected to \varnothing 6 mm air hoses. See Fig. 12.

5.1.6. PlateUR10-Floating – Installations on carriages

At this time, we get two main sub-assemblies (for reference see Fig. 3):

- the PlateSpindle (5) with the electro-spindle and the rails installed;
- the PlateUR10 (6) with the carriages and the air cylinder.

The next step it to install (6) on (5) as illustrated in Fig. 13.

To do this connect first the piston rod to the cylinder attachment by washer (6.7) and nut (6.8). For now don't tighten the nut, to allow some clearance to the rod. This clearance is good to align the carriages.

Then insert the socket cap screws (6.6) in their holes, to fix the carriages.

Tighten four screws a time (one carriage) and then verify the sliding of plate 6 with respect plate 5.

If the friction is too high (you feel it as the balls inside the carriages that scrape) try to unscrew a little bit the screws (6.6). This is due to a misalignment of the carriages with respect the rails.

If necessary don't tighten enough the screws (6.6) and lock them by the threadlocker (i.e., Loctite Blue 243).

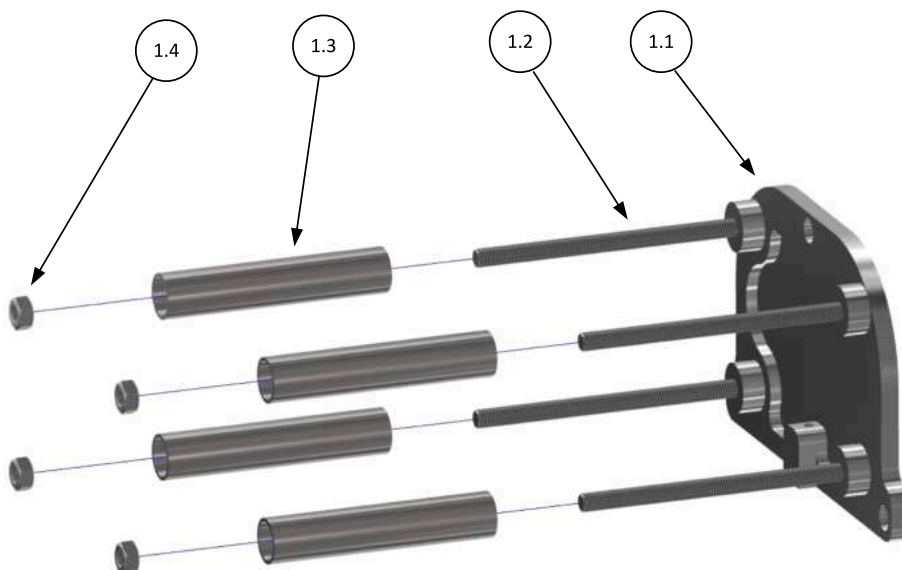


Fig. 5. Assembly the support for the 3D sensor.

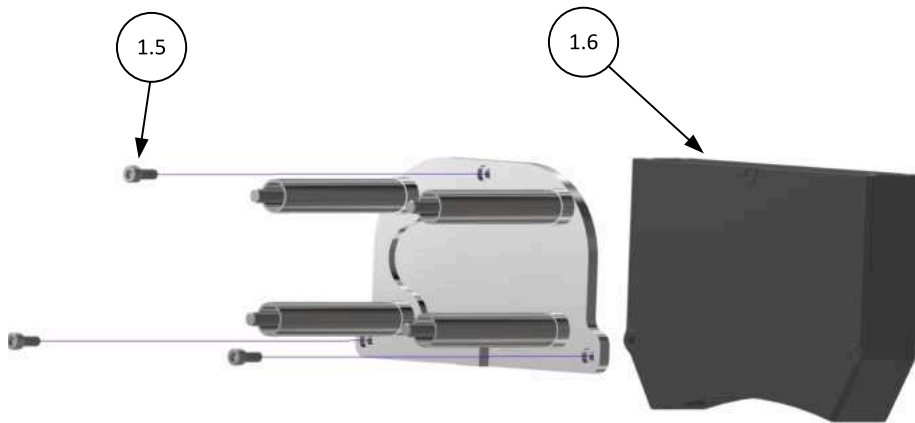


Fig. 6. The sensor is installed on its support.

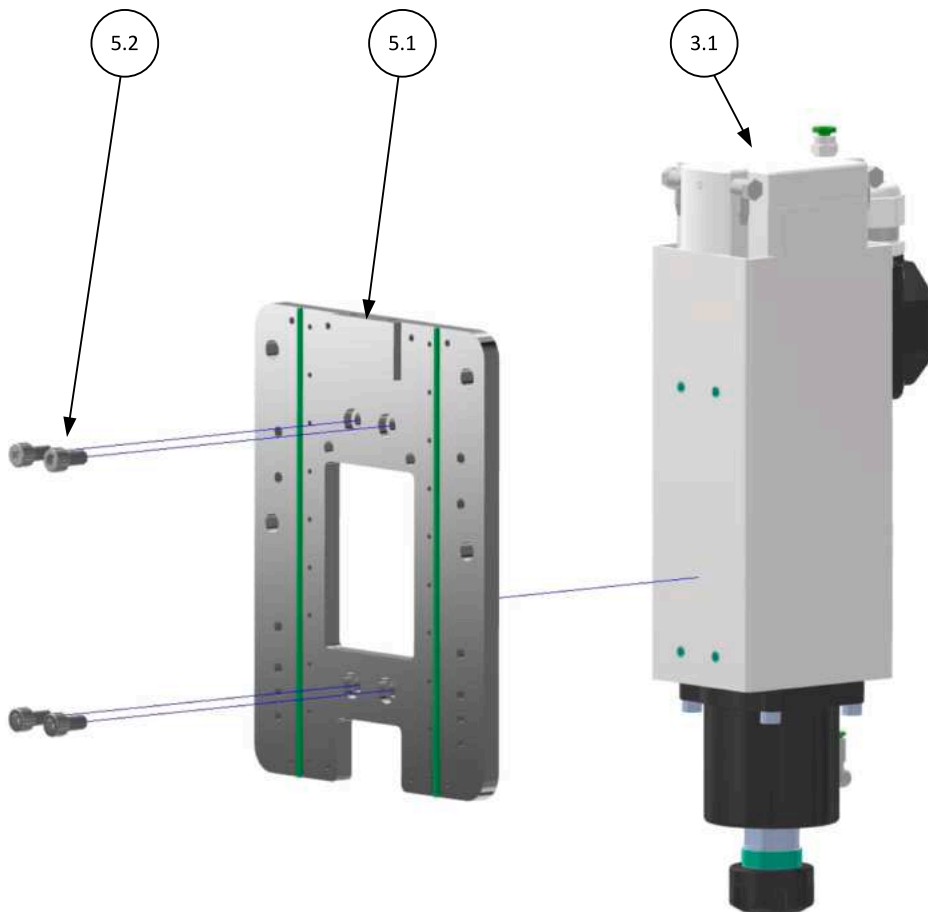


Fig. 7. The Electro-Spindle is assembled on its plate.

The sensibility of the operator is important in this regulation process.

5.1.7. installation of the 3D sensor Sub-Assembly on the Electro-Spindle plate

Now it is the time to install the 3D sensor sub-assembly (1) on PlateSpindle (5). See [Fig. 14](#). To do this use washer (0.1) and nut (0.2). The four TubeBar2 (1.3) act as spacers.

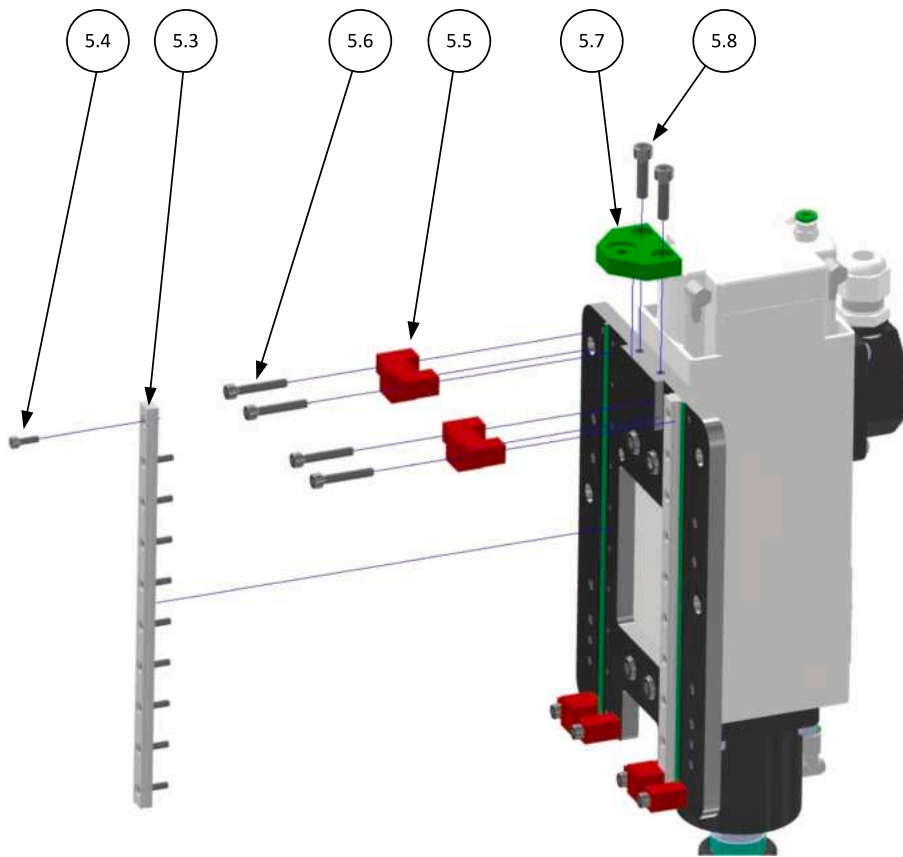


Fig. 8. Installations of rails and bumpers on PlateSpindle.



Fig. 9. Rail and Carriage to be installed on PlateSpindle.

5.1.8. Assembly of the vacuum Inlet

The exploded view of the vacuum system is represented in Fig. 15. A very efficient vacuum system is important in this kind of applications, because it guarantees a clean working environment.

To achieve this goal the most important feature is to vacuum the dust as close as possible to the abrasive disk. With this concept in mind a skirt is included, in the form of its support, called VacuumSkirt38 (4.4) and two counter wrapped curtains (called Skirt38), represented by block (4.5) in Fig. 15. They are made by a strip of silicone rubber with a lot of 45°degrees fringe. To assure the maximum efficiency the fringes of one curtain are oriented on the left, the others on the right. This part is handmade, cutting the strips from a sheet of silicone rubber (thickness 1,5 mm), and then realizing all the fringes by scissors.

All the components in Fig. 15 are plug-in. The sealing is assured by the O-Rings (4.6) and (4.7).

The skirt is placed in its seat by a staple.

In Fig. 16 (on the right) the two curtains are clearly identifiable.

In Fig. 17 the vacuum system is installed on PlateSpindle (5) by washer (0.3) and screw (0.4).

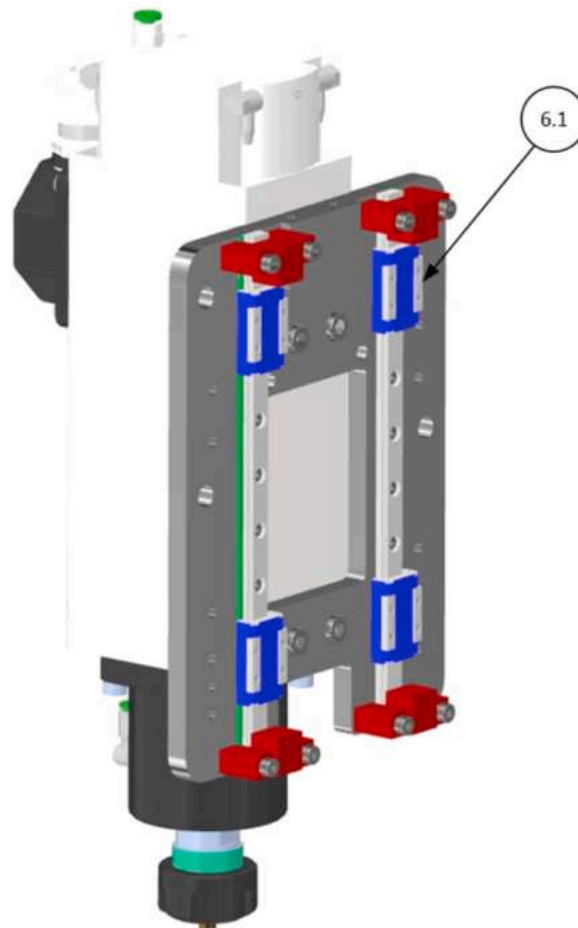


Fig. 10. Installation of the four carriages.

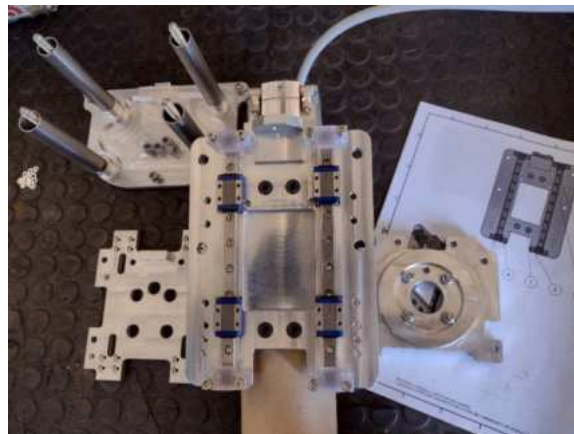


Fig. 11. The ScarfingTool and its main components. The central piece is the PlateSpindle with the four carriages.

5.1.9. Installation of the PlateUR10 (7) on the robot's flange

Now the ScarfingTool is assembled. The remaining steps aims to install it on the robot. To get this, first the connecting plate (7.1) is installed on the robot's flange and then the ScarfingTool is screwed to it.

Fig. 18 illustrates how to install PlateUR10 (7.1) to the robot's flange. It is centered by pins (7.4) and fastened by screws (7.2). Screws (7.3) connect the ScarfingTool.

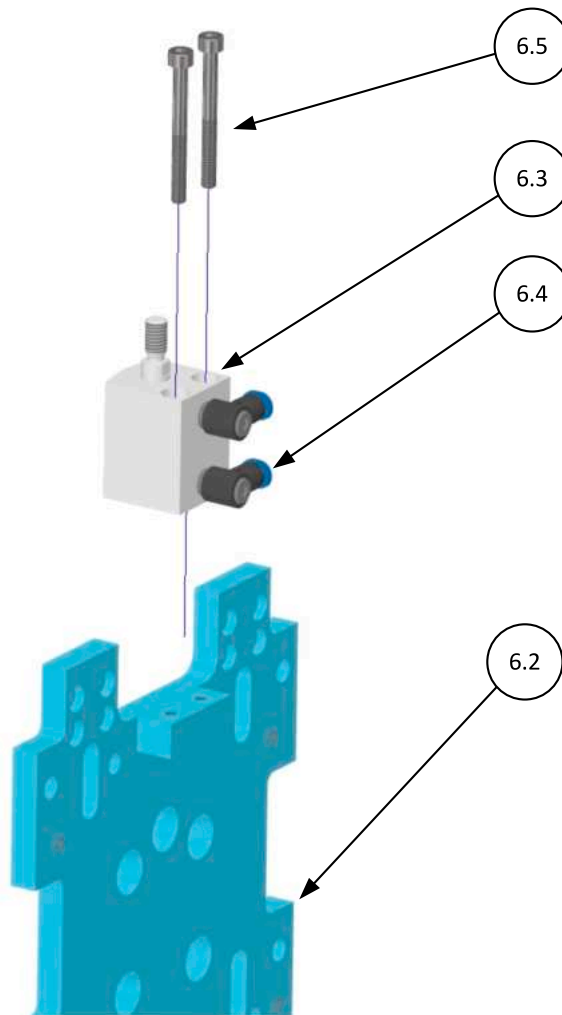


Fig. 12. Cylinder installation on PlateUR10-Floating.

Design variant: Here PlateUR10 (7.1), as the name suggests, is customized on the UR10e robot by Universal Robot [10]. Editing the design of this plate it is possible to install the ScarfingTool on another robot, without modifying any other component.

5.1.10. The ScarfingTool is installed on the robot

The ScarfingTool is finally installed on the robot in Fig. 19. The four bolts (7.3) fix it to the robot's flange. The aim of the figure is to show that this is the main interface to assemble the ScarfingTool on the robot.

5.2. Electrical Build instructions

For what concern the assembly of the electrical parts refer to the Electrical Diagrams:

- Electrical Diagram-Rev7.vsdX (Visio File)
- Electrical Diagram-Rev7.pdf (the same file, in pdf format)
- Cabinet Drawings.vsdX (Visio File)
- Cabinet Drawings.pdf (the same file, in pdf format)

Fig. 20 represents the general diagram of the Scarfing Tool, with the Electrical Cabinet, the Robot and its Control System, the vacuum Cleaner and all the connectors and connections between them.

For a more detailed representation the annexed file Electrical Diagram-Rev7.pdf illustrates the electrical diagram.

In particular:

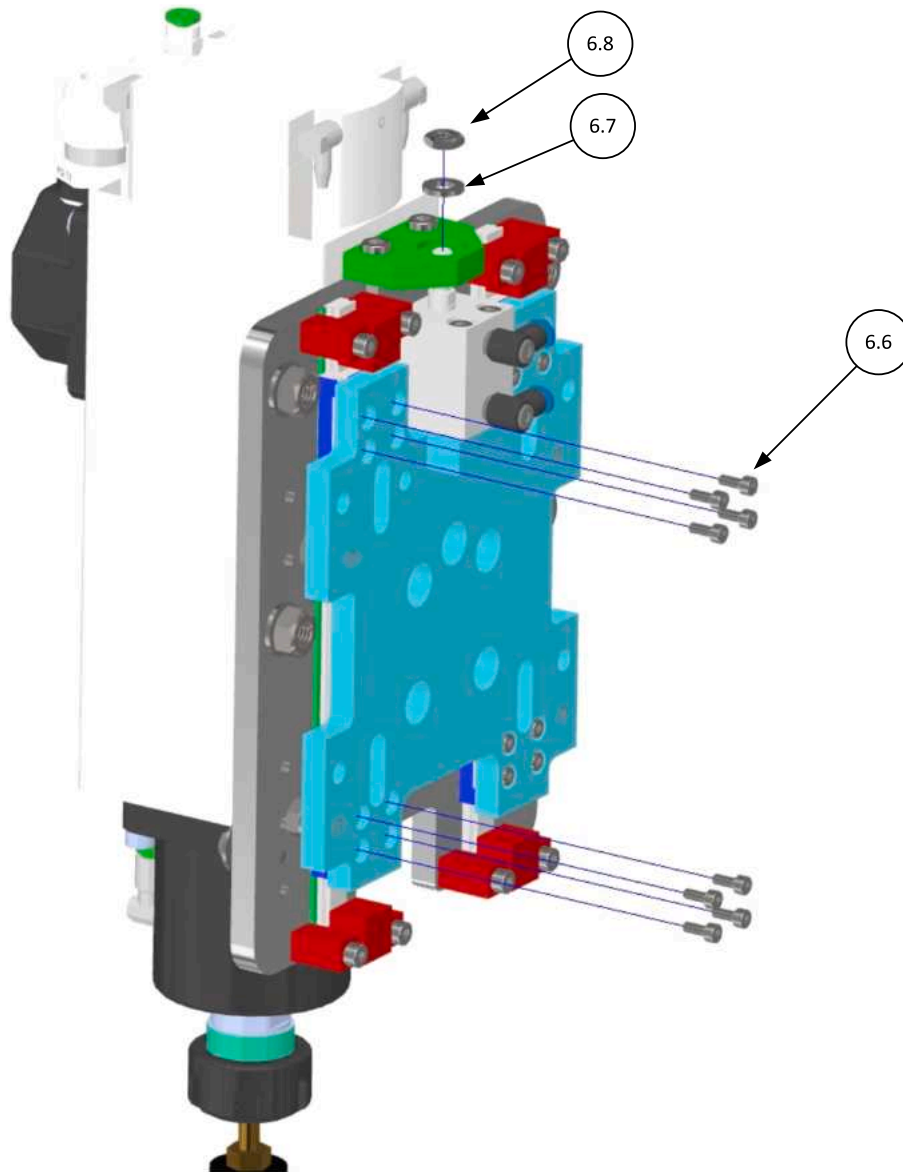


Fig. 13. The PlateUR10-Floating is installed on the four carriages.

- Page 1 is the diagram of the power circuits, with contactors, plugs for external tools, EMI filter and the Inverter for the Electro-Spindle;
- Page 2 and Page 3 are the diagram of the auxiliary circuits, with the low voltage power supply and the safety relay by Pilz;
- Page 4 represents the connections of the Inverter;
- Page 5 is a Table for the speed selection of the ElectroSpindle by manual push-buttons, using the multistep functionality;
- Page 6 represents the cable connecting the Electrical Cabinet to the Robot Controller;
- Page 7 illustrates the connection of the electro-valve and the air pressure switch.

Fig. 22 and Fig. 21 represent the external views of the Electrical Cabinet. They illustrate the placement of the electrical components: switches, plugs and connectors. The reported label is the same as that reported in the electrical drawings.

Fig. 23a illustrates the internal view of the electrical cabinet after wiring. In the door, it is possible to see the analog signal cables covered by a braiding sleeve of copper to protect the analog signals from electro-magnetic interference (EMI). Another precaution used in the wiring process to guarantee a right electro-magnetic compatibility is to separate signal cables from power cables. Moreover, the cross between them is realized at 90° deg.

Fig. 23b is the embodiment of the drawing in Fig. 22.

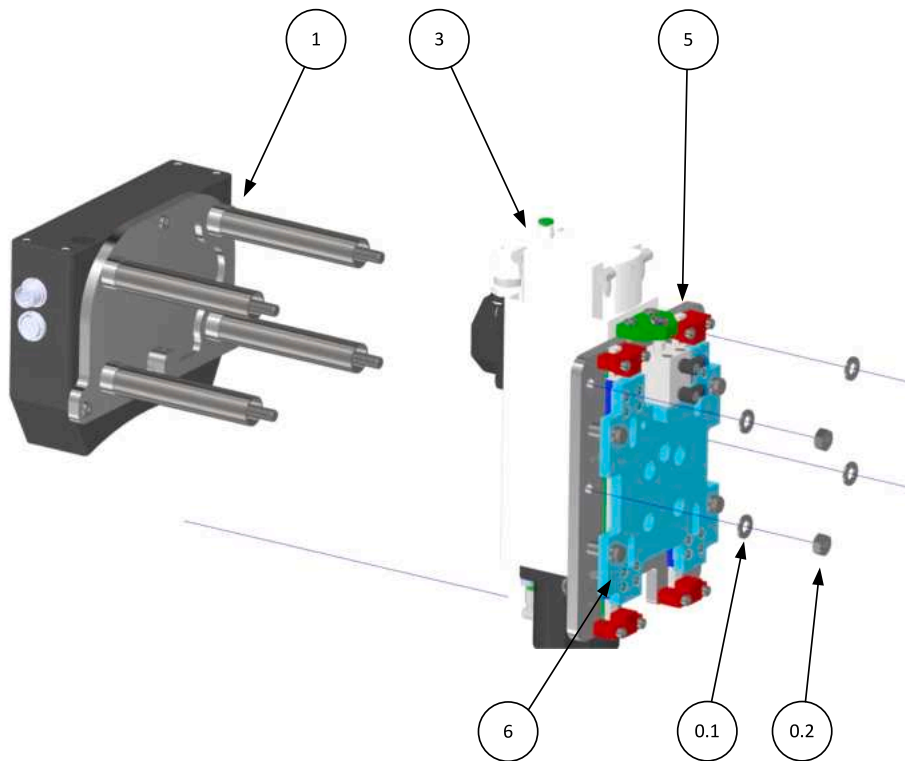


Fig. 14. The 3D sensor sub-assembly is installed on PlateSpindle.

Fig. 23c represents the Pneumatic Panel, as drawn in the pneumatic diagram.

6. Operation instructions

The ScarfingTool has been designed with the idea to be used in a robotized application. The manual operation is not allowed. So, it must be installed on a robot, as indicated in Section 5. Then all the connections illustrated in Fig. 4 are necessary: Electric Power, LAN, Air pressure and vacuum must be supplied.

Start-Up.

After having done all the indicated connections, the steps to operate the ScarfingTool are (see Fig. 24):

1. Open the shut-off valve of the air pressure;
2. Turn ON the Main Isolator Switch QS1; after this the light HL0 is ON;
3. Turn ON the Robot: so doing it is possible to give power to the drive (by relay KA1);
4. Push SB1 to give power to the spindle drive. Now the ScarfingTool is ready to rotate; this condition is indicated by light HL1b and HL2b (green);
5. By SB4 you can rotate the spindle without vacuuming, while by SB5 the spindle rotates and the vacuuming is ON; in both cases the light HL3 is ON (blue);
6. Now it is possible to regulate the speed of the spindle. Two possibilities are given: by the potentiometer POT or by push-buttons MI3-MI4-MI5-MI6 (multistep method). The speed is reported in the Table 3 and Table 4.

Alternatively, it is possible to turn ON and OFF the spindle by the robot's teach pendant. This condition is revealed by the light HL1a (red).

To do this, and referring to the UR10e robot controller, the connection to the output C01 must be executed.

See the Electrical Diagram – page 4 for more information.

The electro-spindle speed can be set by an analogue value between 0 and 10 V. The analog value is the output of the potentiometer "POT1" in Fig. 21. All the speed between 2,400 and 24,000 rpm are possible.

Shut-Down.

To shut-down the spindle simply turn the rotating switch SB4-SB5 in its central position. Now the light HL3 is OFF.

If a safety condition is needed the drive must be de-energized: to do that push the button SB2. As a consequence, the lights HL1b and HL2b are OFF. **In this condition and only in this condition the spindle is safety stopped** and service operations can be

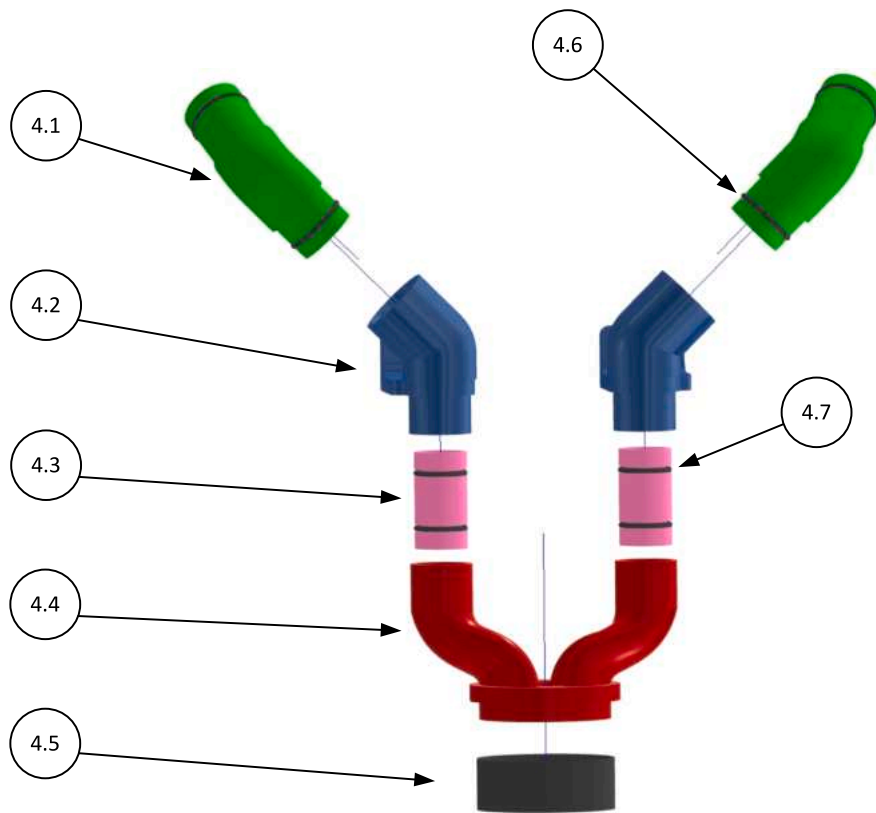


Fig. 15. Vacuum Inlet Assembly.

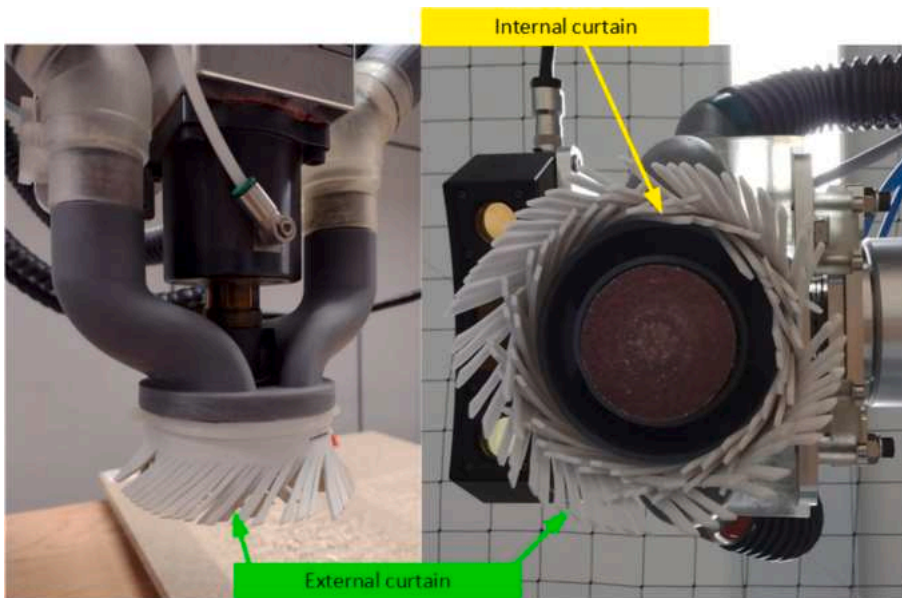


Fig. 16. A close-up view of the vacuum skirt.

performed on it.

When the job has finished remember to turn OFF the robot and then the main switch QS1. DO NOT reverse this sequence because it would cause a wrong robot stop (also the robot is supplied by QS1).

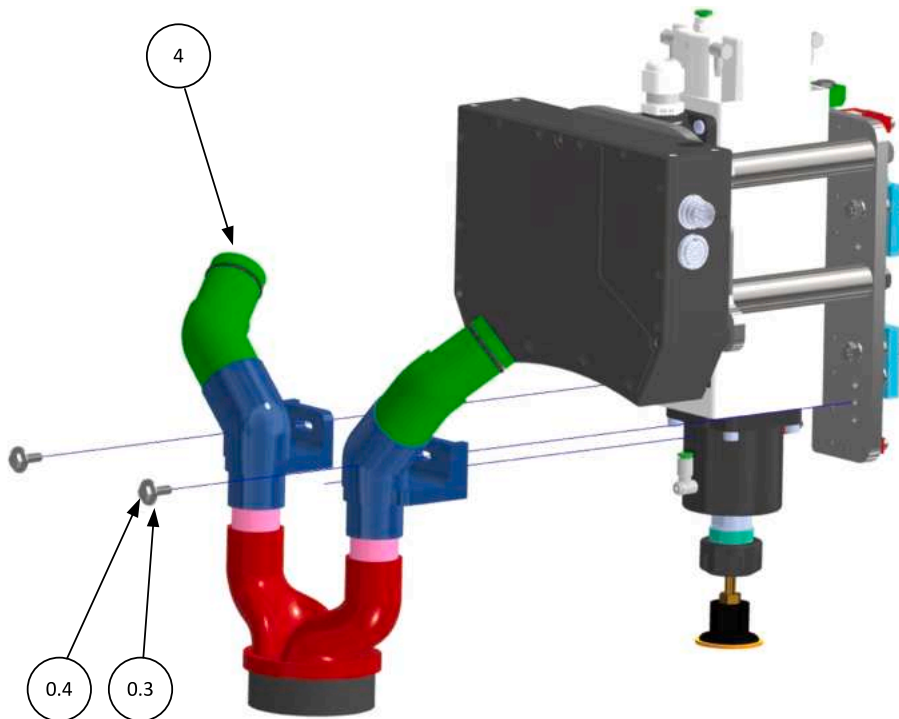


Fig. 17. The vacuum system is installed on PlateSpindle.

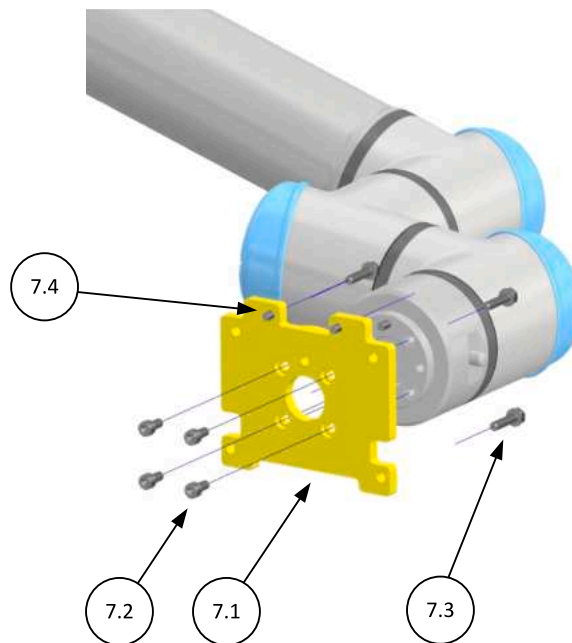


Fig. 18. The PlateUR10 is installed on the robot wrist.

At last close the shut off valve of the compressed air.

Emergency Stop.

If something goes wrong push the emergency stop SB3. Now the spindle's drive is stopped according the International standard EN/ISO 13,850 **Stop Category 0**. This condition is confirmed by the switching off of lights HL3, HL1b and HL2b.

According the electrical diagram supplied also the robot executes a safety stop.

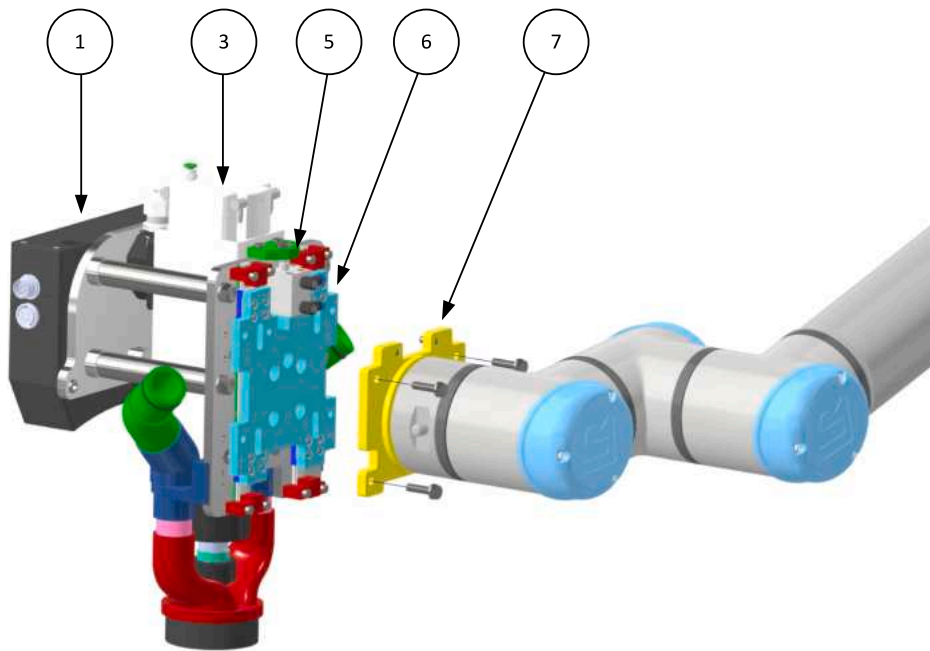


Fig. 19. Final assembly of the ScarfingTool: Plate 7 is the interface to customize the tool on a specific robot.

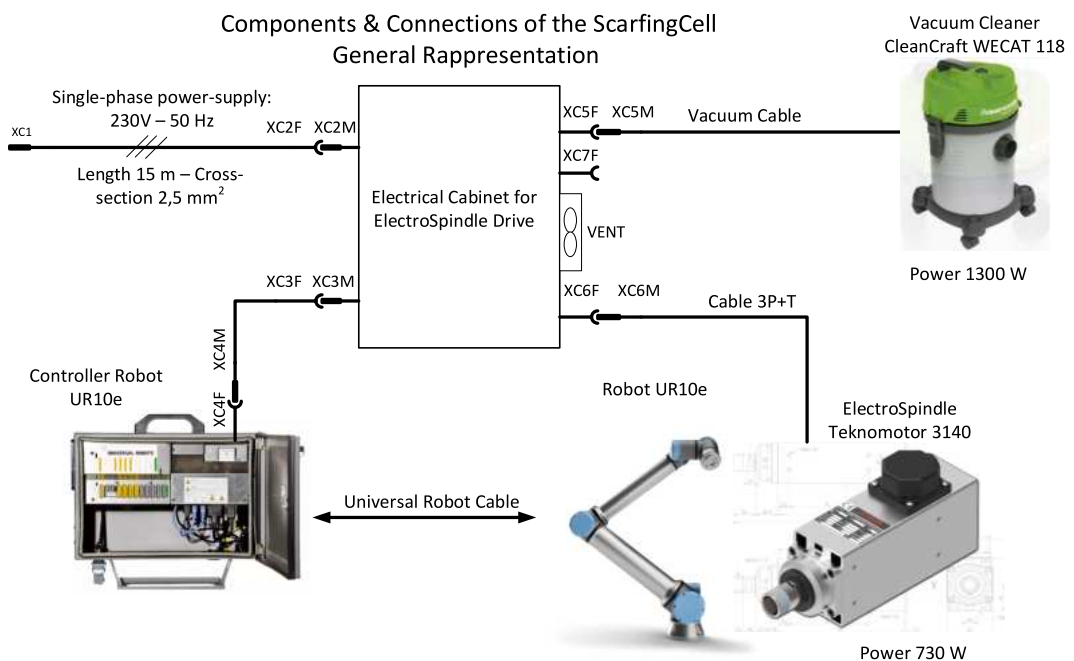


Fig. 20. General Diagram of the ScarfingTool.

Safety Issues.

Safety concerns are illustrated in Fig. 25.

The main hazards are:

a) Dangerous Voltage.

The robot and the ScarfingTool are supplied by a dangerous voltage of 230 V – 50 Hz. All the common safety rules about electrical equipment must be implemented when working with the ScarfingTool.

b) Automatic Starting.

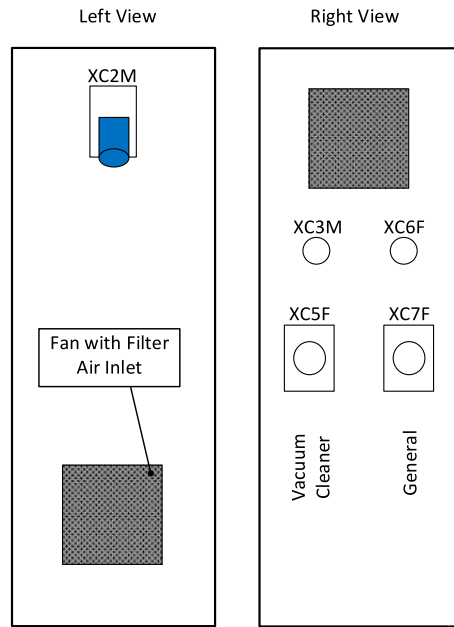


Fig. 21. External view of the Electrical Cabinet – Left and Right View.

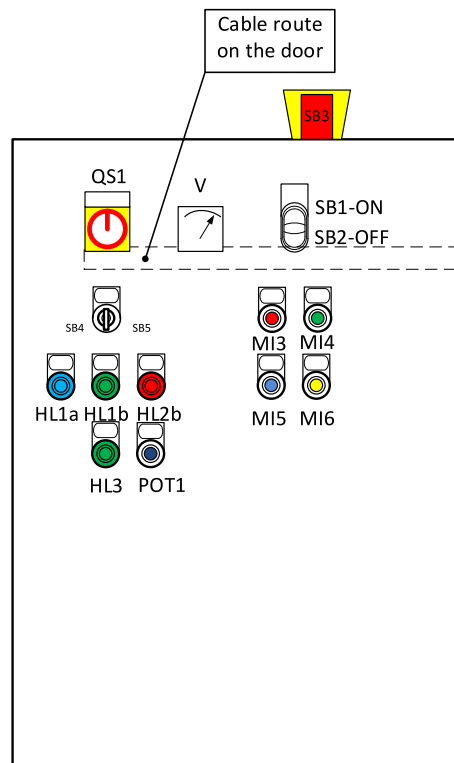


Fig. 22. External view of the Electrical Cabinet – Front View.

Due to its intrinsic nature the robot starts working automatically. Consider this circumstance when working with it.
 c) Risk of cutting injury.

The abrasive disk spins at high speed. It can reach about 24,000 rpm with the selected electro-spindle. Pay attention to don't approach it when active. There is the possibility of serious injuries.



Fig. 23. Picture of the Internal View of the Electrical Cabinet (a), External Front View (b) and the Pneumatic Panel (c).

d) Dangerous Noise.

Noise is generated, due to the outflow of compressed air. Wear protection for your ears.

The main prohibitions are:

e) Do not execute wet machining.

The tool is not conceived to work in wet conditions, especially for the presence of the 3D sensor. If it is the case of wet machining supplementary precautions must be adopted.

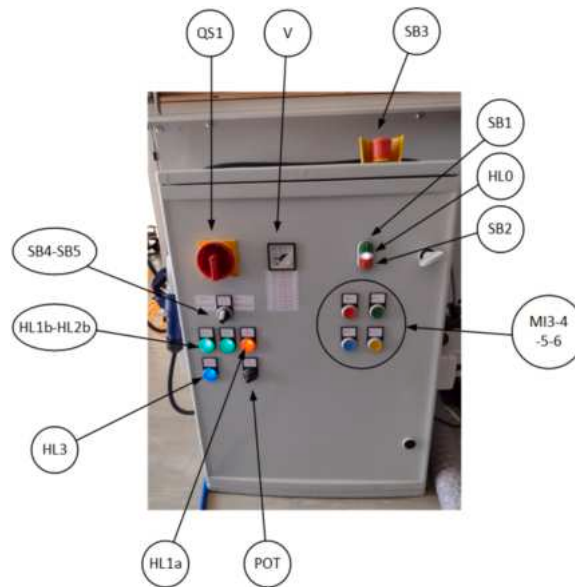


Fig. 24. Switches and Push-Buttons to operate the ScarfingTool.

Table 3

Speed selection: multistep method.

N°	rpm	Hz	Master Frequency	MI6 = 4 OFF	MI5 = 3 OFF	MI4 = 2 OFF	MI3 = 1 OFF
1	3,000	Par 05.00 = 50	1st speed	OFF	OFF	OFF	ON
2	6,000	Par 05.01 = 100	2nd speed	OFF	OFF	ON	OFF
3	9,000	Par 05.02 = 150	3rd speed	OFF	OFF	ON	ON
4	12,000	Par 05.03 = 200	4th speed	OFF	ON	OFF	OFF
5	15,000	Par 05.04 = 250	5th speed	OFF	ON	OFF	ON
6	18,000	Par 05.05 = 300	6th speed	OFF	ON	ON	OFF
7	21,000	Par 05.06 = 350	7th speed	OFF	ON	ON	ON
8	24,000	Par 05.07 = 400	8th speed	ON	OFF	OFF	OFF
9			9th speed	ON	OFF	OFF	ON
10			10th speed	ON	OFF	ON	OFF
11			11th speed	ON	OFF	ON	ON
12			12th speed	ON	ON	OFF	OFF
13			13th speed	ON	ON	OFF	ON
14			14th speed	ON	ON	ON	OFF
15	1,500	Par 05.14 = 25	15th speed	ON	ON	ON	ON

Lines from 1 to 8 set the electro-spindle speed with a step of 3,000 rpm. The speed selection is done by push-buttons MI3, MI4, MI5, MI6; Lines from 9 to 14 are not assigned and are reserved to future developments; Line 15 is a low speed running mode (only for test purpose).

Table 4

Speed selection: potentiometer method.

1	1 V=2,400 rpm
2	2 V=4,800 rpm
3	3 V=7,200 rpm
4	4 V=9,600 rpm
5	5 V=12,000 rpm
6	6 V=14,400 rpm
7	7 V=16,800 rpm
8	8 V=19,200 rpm
9	9 V=21,600 rpm
10	10 V=24,000 rpm

Conversion between Volt and rpm scale.

f) Do not use the electro-spindle by hand.

The ScarfingTool is designed to work installed on a robot. Due to its mass and to the process reaction forces it is not suitable to be operated by hand.

The Personal Protective Equipment (PPE) required are:

g) Protective gloves to handle CFRP panels and to operate on abrasive disks;

h) Safety glasses must always be worn when the ScarfingTool is working; there could be splinters emission during material removal. There is also the risk that the abrasive disk detaches from the backing pad.

i) Earmuffs are needed due to the noise generated by compressed air and vacuuming.

For service operations:

j) Always read the operating instruction of each component of the ScarfingTool;

k) Disconnect the machine from the mains.

Always:

Due to the presence of a dangerous voltage, verify the connection of the electrical cabinet and the robot to ground.

Fig. 25 illustrates all the safety concerns.

Trajectory Planning.

At this point, it is needed to program the robot to execute a job with the ScarfingTool.

This activity goes beyond the aim of this paper, because it is strictly related to the specific machining task. The suggestion is to use a dedicated software environment as RoboDK [11]. RoboDK (see Fig. 26) is a powerful and cost-effective simulator for industrial robots and robot programming. RoboDK has an extensive library with a lot of industrial robot arms; it is not limited to the UR10e.



Fig. 25. Safety issues about the ScarfingTool.

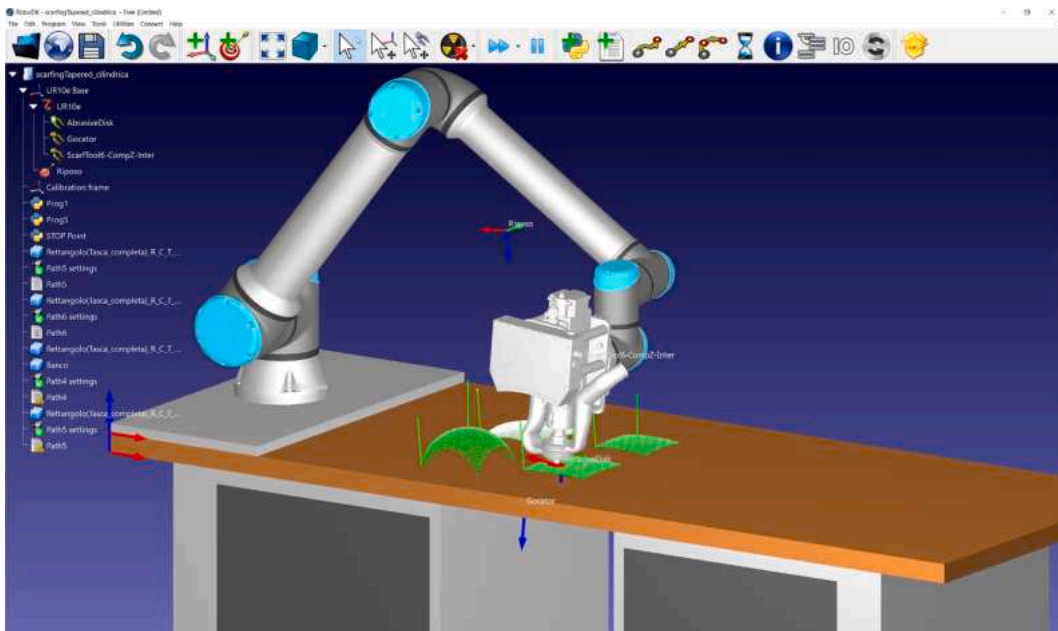


Fig. 26. Trajectory Planning into RoboDK environment.

Another good alternative to simplify the robot programming along 3D surfaces is SprutCAM X Robot [12].

Calibration

To reconstruct and to visualize the machined surface the 3D Snapshot Sensor need to be calibrated.

Fig. 27 shows the reference frames and the transformation matrices to calibrate the system. In detail:

- O_U is the UR10e base frame;
- O_{GU} is the Gocator-UR10e end-effector frame;
- O_G is the Gocator frame;
- O_T is the target frame.

The transformation matrices involved are:

- A_{GU} fixed transformation matrix from the Gocator uncalibrated frame O_G to the end effector of the UR10e robotic arm O_{GU} . This transformation is the unknown and it is computed along the whole kinematic chain, from the UR10e base to the calibration plate;
- A_G that expresses the fixed transformation between O_T and O_G ;
- A_U which maps the frame O_{GU} in the frame O_U ;

The last two transformation matrices are known during the calibration process and are exploited to compute A_{GU} by solving an optimization problem.

The calibration processes is extensively described in [13] to which the interested reader is addressed.

7. Validation and characterization

The ScarfingTool has been designed to deal with the repair of CFRP.

The validation has been tested on a particle board for safety reasons. It is worth noting that CFRP processing implies realizing containment measures for the processed dust that are not present in our laboratory yet. CFRP dust is toxic and electrically conductive: measures for safeguarding human beings and all the electrical and electronic equipments are mandatory. To validate the ScarfingTool properly on CFRP a glovebox (safety cabin with gloves for the operator) must be built around the robot and the workpiece.

Since ScarfingTool is a general purpose tool, as explained in the Abstract and in the “Hardware in Context” section, validation has been conducted on materials with less stringent safety requirements.

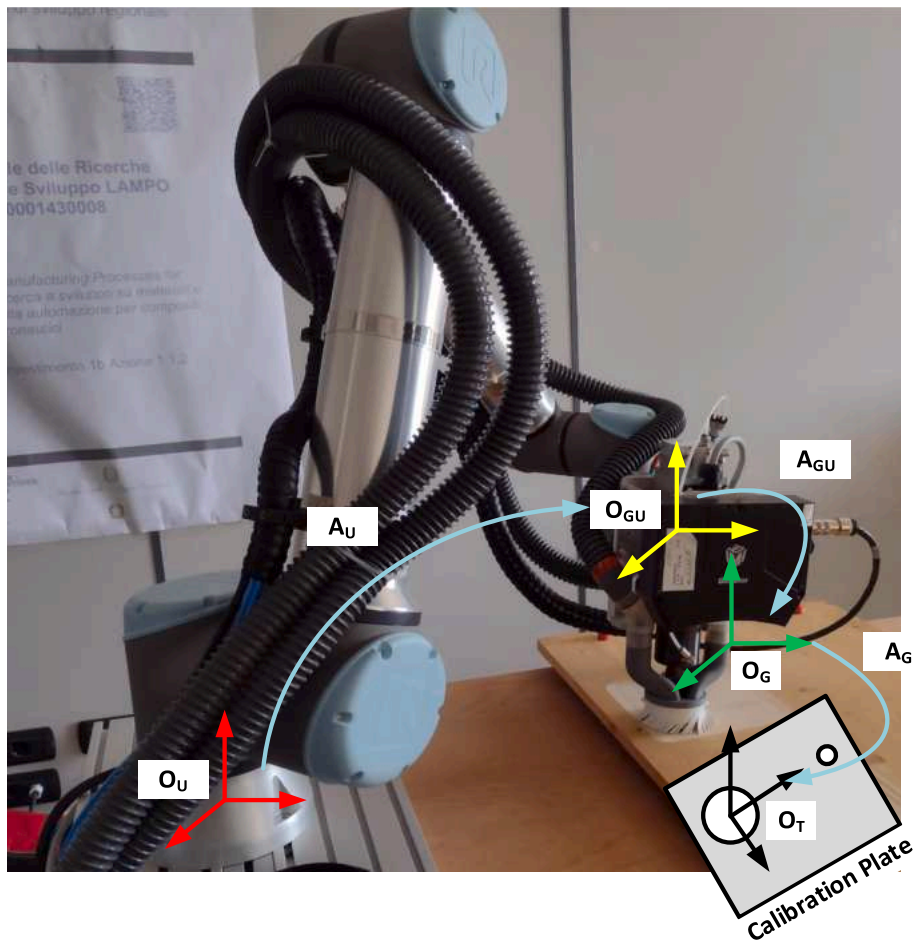


Fig. 27. Reference frames and transformation for 3D sensor calibration.

Fig. 28(a) shows a circular pocket machined by the ScarfingTool. The steps are clearly visible. In our intention each step reflects the single ply of CFRP.

The process is detailed in Fig. 28(b) that represents a rectangular pocket after the machining of the first step. It is completed in Fig. 28(c) where six steps are realized.

Fig. 28(d) is the image acquired by the 3D sensor (Gocator 3210) while Fig. 28(e) is an elaboration executed in a corner on the pocket in Fig. 28(c). With the standard software supplied by the sensor it is possible to do measures on the part: the depth of the pocket is represented by colors in Fig. 28(e). For what concern the repeatability of the measure two contributes must be taken into account: the repeatability of the sensor and the repeatability of the robot. The overall repeatability of the system (in the worst case) is given by the sum of these contributes. The repeatability of the sensor is $5\ \mu\text{m}$, while the repeatability of the robot is $50\ \mu\text{m}$ so the total repeatability is $55\ \mu\text{m}$.

At last, in Fig. 28(f) there is the comparison of two different pockets: on the left a tapered scarfing procedure is simulated and it is compared with the stepped scarfing on the right.

In conclusion, the requirements listed in Table 2 are met, and the tool shown here has been approved by people skilled in CFRP repair for these main features:

- It executes the scarfing process by an abrasive disk and not by an end mill, avoiding damaging the CFRP by the cutting forces typical of a milling process.

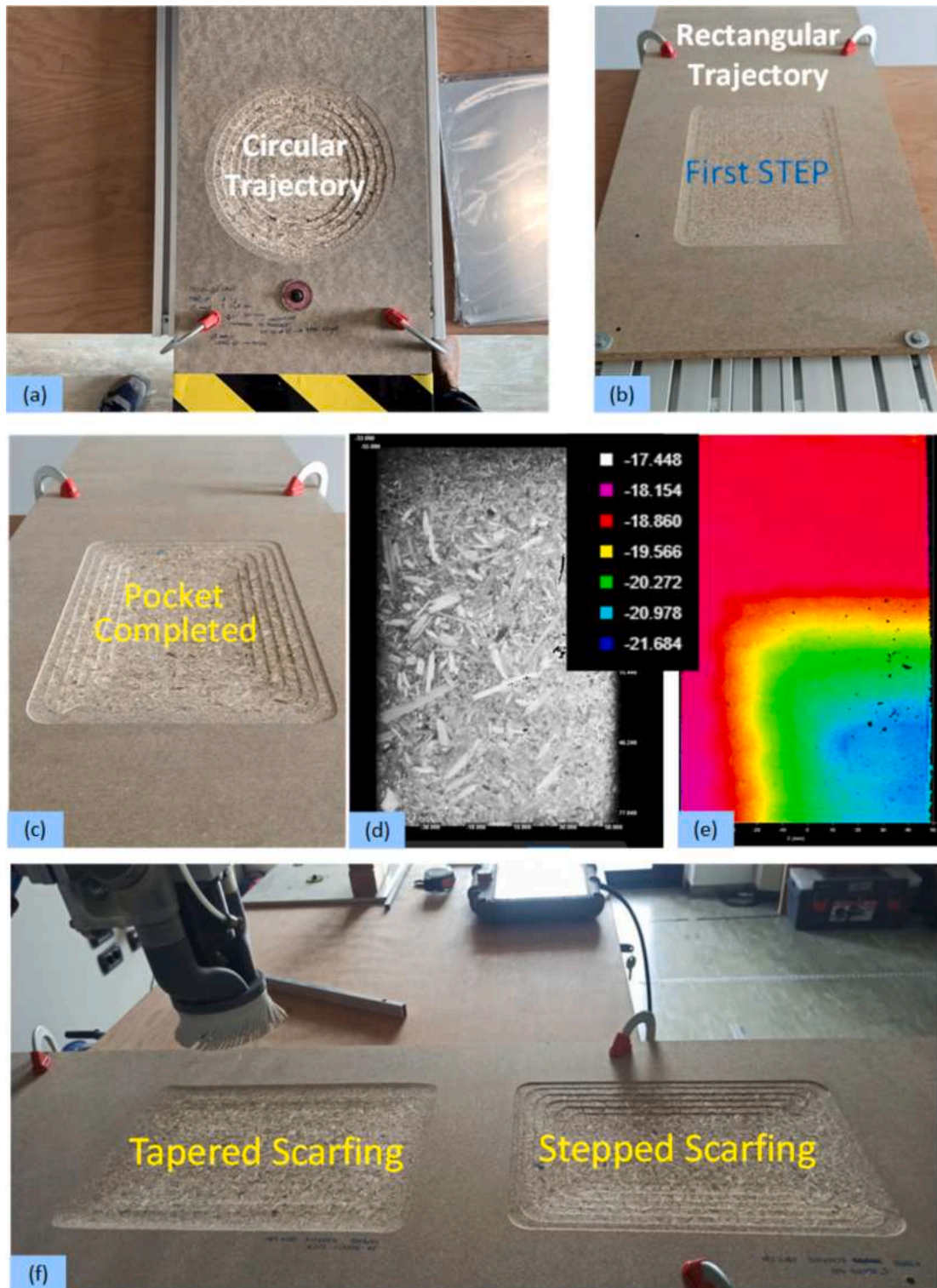


Fig. 28. Machining and measurements executed by the ScarfingTool: Circular pocket machined by the ScarfingTool, the steps are clearly visible (a); Rectangular pocket after the machining of the first step (b); The pocket in (b) is completed with six steps in (c); Example of an image acquired by the 3D sensor (Gocator 3210) (d); Image visualized by the Gocator's Software (e). It illustrates a corner of Fig. 28c; Comparison of two different scarfing method: tapered and stepped scarfing (f).

- It is a semi-automatic collaborative robotic cell. This implies that the operator can program a trajectory, test it, measure the work done and decide if to continue the job or modify one or more parameters.
- The human-robot cooperation at the core of the ScarfingTool design enables the human operator to manually adjust for possible inaccuracies (by a pneumatic angle die grinder, as in the traditional CFRP repair).
- The presence of a 3D sensor gives the possibility to build a 3D model of the pocket to make a perfect patch.

CRedit authorship contribution statement

Simone Pio Negri: Writing – original draft, Methodology, Investigation, Conceptualization. **Massimiliano Nitti:** Writing – review & editing, Validation, Investigation. **Nicola Mosca:** Writing – review & editing, Validation, Methodology. **Vito Renò:** Writing – review & editing, Validation, Methodology. **Ettore Stella:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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