Ref. Ares(2024)7763071 - 31/10/2024

ACROBA

connect & produce through agile production

D6.5 Final Demonstration Tests in Electric Motor Setting

WP6. Evaluation of Performance and Sustainability of the ACROBA Framework

Lead Beneficiary Partner Name: ICPE

Delivery Date 31/10/2024

Dissemination Level: PU

Version V1.0

The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017284.

Approval Status

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History of Changes

Version	Date	Description of Changes	By
0.1	28.09.2024	First Draft	Andrea Pilloni
1.0	31.10.2024	Final Version	Andrea Pilloni

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Executive Summary

This document summarizes the results of tests conducted on the collaborative robotic system supported by the ACROBA platform for the production of electric motors. The focus is on two key processes: winding copper coils around the stator teeth and bonding permanent magnets onto rotors. The ACROBA system coordinates tasks between the operator and the collaborative robot, utilizing specific skills and hardware components to execute these tasks effectively.

1 Introduction of the Use Case

1.1 The Manual Process

ACROBA addresses two key processes in motor manufacturing procedure of ICPE. The first is the winding process, which involves winding copper wire around the stator teeth. The second is the bonding process, applied to the rotor's production by bonding specific magnets into place.

The coil winding procedure involves preparing the coils, ranging from a minimum of 3 to a maximum of 72, with the correct number of turns, allowing for some tolerance. These coils are then fitted around the stator teeth. The operator must ensure that each individual winding is executed accurately, paying close attention to achieving the precise number of turns for each coil. Once the windings are properly inserted around the stator teeth, the operator is responsible for grouping the copper wires corresponding to each phase. This is a highly repetitive process that requires a great deal of precision and care from the operator. Any mistakes in the number of turns or the arrangement of the wires can significantly impact the

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motor's performance. Therefore, meticulous attention to detail is essential throughout the entire process to ensure the final product meets the required standards.

The second process involves bonding permanent magnets onto rotors. This bonding relies on a bi-component resin consisting of an adhesive and an activator. The manual process requires both precision and speed, as the adhesive reacts rapidly (within 10 to 20 seconds), leaving the operator with limited time to make adjustments. If a mistake occurs, the magnet can only be repositioned a maximum of two times. Similar to the winding process, bonding is a repetitive yet critical task in motor manufacturing, where even minor errors can affect the motor's overall performance.

1.2 The New Process

The flowchart reported in Figure 1 illustrates the high-level sequence of human and robot tasks involved in the coils winding process. This collaborative process takes place simultaneously at two distinct spots, referred to as A and B in the figure, but the order of tasks remains consistent across both spots. The process starts with the operator placing a new stator on the rotary table and performing the preparatory operations. Subsequently, the actual robotic winding process controlled by the ACROBA platform is executed. Once the winding of all teeth of the stator is completed, the process ends with the finishing operations carried out by the operator.

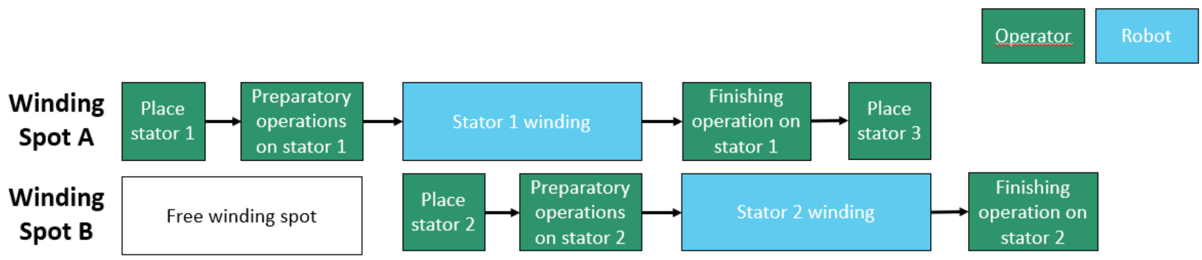

Figure 1 – Flowchart of the winding process

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Figure 2 shows the high-level sequence of human and robot tasks involved in the magnets bonding collaborative process. The process begins with the operator placing the magnet trays and loading the shaft onto the rotary table, followed by performing the angular position detection and correction procedure. Subsequently, the pick and place process for the magnets starts. The magnet with the correct polarity is picked from its fixed position on the tray, is placed under the activator spray for the activator deposition and then it is placed onto the shaft, which has been previously coated with adhesive by the operator. This process is repeated until all rows of the rotors are filled with magnets.

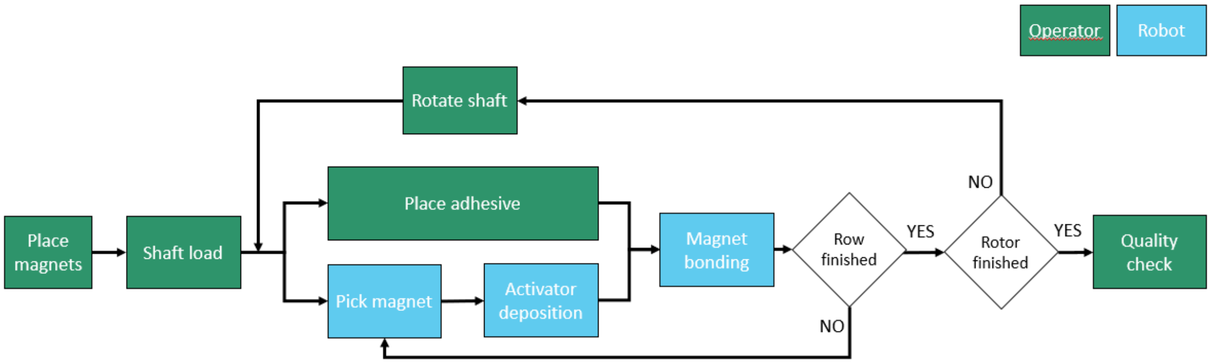

Figure 2 – Flowchart of the bonding process

2 Integration

2.1 The Hardware Integration

A list of the hardware component integrated is reported:

- Fervi m049/320 self-centering chuck.
- Homberger orthogonal gearboxes DE-DG55.

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- Stepper-online Nema 23 ST-M2.
- FIPA GR04 122-20S air gripper.
- FIPA BC GT NF05 + FIPA BC NY05BJ pneumatic cutter.
- Bianchini 5x E521-16-10-K13 electrovalves.
- Bianchini 1x Manifold E52C.
- KEYENCE Light curtains gl-r18l +brackets GL RB01.
- KEYENCE LR-XH50-XH100-XH250 laser sensor.
- Rittal AX 1034.000 electrical cabinet.
- PC Processor: Intel Core i9 11900 11th gen with integrated video Intel UHD Graphics 750
- Motherboard: ASUS Z590
- RAM: 16GB DDR4, 3200 MHz
- Storage: Solid-State Drive (SSD) SAMSUNG 870 QVO, 1TB, SATA3, 2.5"
- GPU: NVIDIA RTX 3060 12 GB
- ARDUINO MEGA 2560 X CONTROLLO 3 ASSI.
- Ringfeder DKN-100-47-20-19 metal bellow coupling.
- Ringfeder DKN-045-41-08-15 metal bellow coupling.
- DAV Tech spray valve DAS 100 EV, activator dispenser.
- DAV Tech volumetric pump manual glue dispenser.
- DAV Tech pressurized tanks PT, pressurized tank for glue and activator.
- DAV Tech controller for PCP pumps, microprocessor-control

In Figure 3 the winding cell is shown, while in Figure 4 the bonding one is reported. Both robotic cells have been installed at STAM facilities.

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Figure 3 – The winding cell

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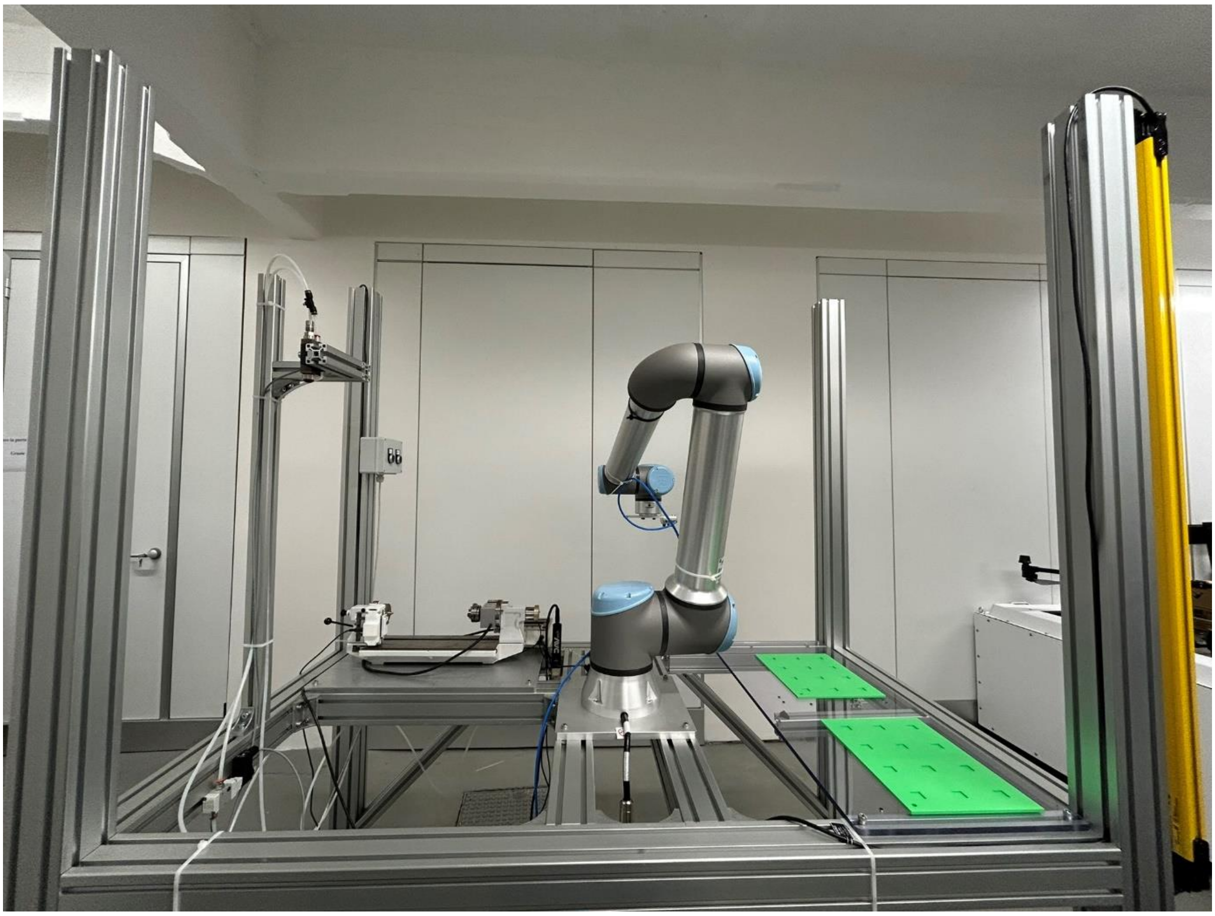

Figure 4 – The bonding cell

2.2 The Software (ACROBA) Integration

For the two robotic cells, the software integration parts foresaw the creation of the "cell config" GitHub repository, which includes all the information required to properly integrate a robotic cell into the ACROBA platform.

Figure 5 and Figure 6 show the scenes of the two cells displayed in Rviz, after the successful creation of the cells' configurations.

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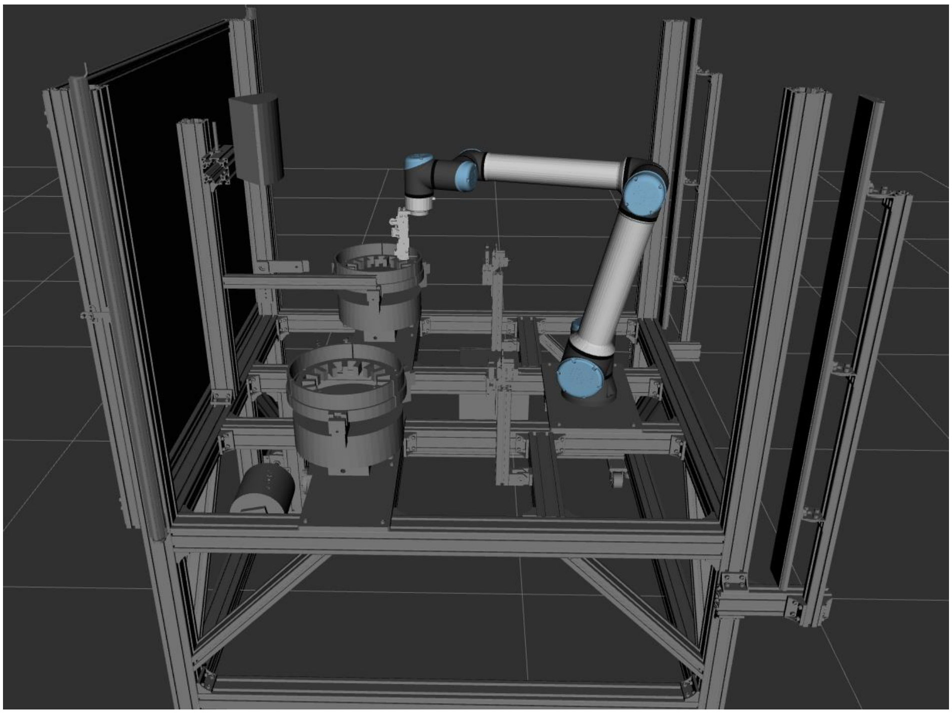

Figure 5 – Rviz scene of the winding cell

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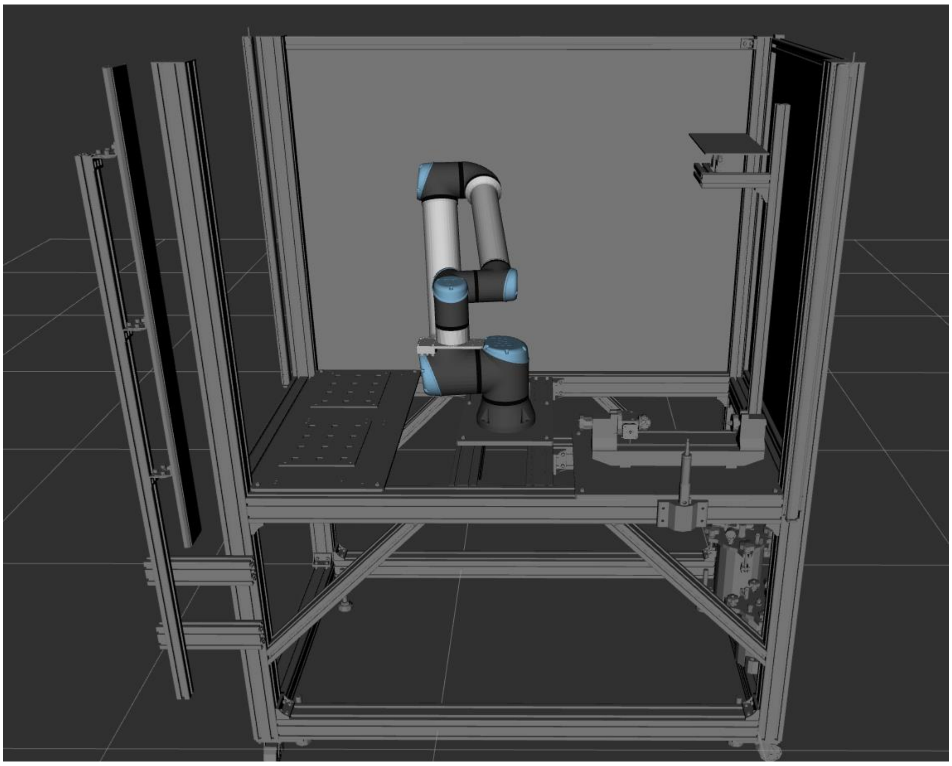

Figure 6 – Rviz scene of the bonding cell

Table 1 reports the complete list of primitives identified for the two ICPE processes, highlighting whether these are general primitives available on the ACROBA platform or specific ones of the ICPE use-case, specifying who has been the partner responsible for its development, and indicating in which of the two processes are used.

Table 1 - Primitives list for the ICPE use-case

Primitive name	General / Specific	Resp. partner	Winding process	Bonding process
GenerateTrajectory	G	SIGMA	✓	✓

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ExecuteTrajectory	G	SIGMA	✓	✓
GenerateWindingWaypoints	S	SIGMA	✓	
ComputeRotorPositions	S	SIGMA		✓
ComputeMagnetPositions	S	STAM		✓
ControlGripperWinding	S	STAM	✓	
ControlGripperBonding	S	STAM		✓
ControlPincher	S	STAM	✓	
ControlCutter	S	STAM	✓	
ControlSpray	S	STAM		✓
ControlTensioner	S	STAM	✓	
LoadRotor	S	STAM		✓
LoadStator	S	STAM	✓	
LoadWindingInfo	S	STAM	✓	
RotateTableWinding	S	STAM	✓	
TableWindingInplace	S	STAM	✓	
TableWindingReferencing	S	STAM	✓	
ButtonWinding	S	STAM	✓	

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ButtonPickBonding	S	STAM		✓
ButtonPlaceBonding	S	STAM		✓

Table 2 reports the complete list of skills identified for the two processes, indicating for each skill which actions it includes, specifying who has been the partner responsible for its development, and indicating in which of the two processes are used.

Table 2 - Skills list for the ICPE use-case

Skill name	Included actions	Resp. partner	Winding process	Bonding process
MoveTo	GenerateTrajectory	SIGMA	✓	✓
	ExecuteTrajectory			
WindSingleTooth	GenerateWindingWaypoints	SIGMA	✓	
	MoveTo			
FirstToothProcedure	LoadStator	STAM	✓	
	MoveTo			
	TableWindingReferencing			
	RotateTableWinding			
	TableWindingInplace			
FixWireProcedure	MoveTo	STAM	✓	

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	ControlPincher			
CutWireProcedure	MoveTo	STAM	✓	
	ControlGripperWinding			
	ControlCutter			
	ControlTensioner			
PickMagnet	MoveTo	STAM		✓
	ControlGripperBonding			
SprayMagnet	MoveTo	STAM		✓
	ControlSpray			
PlaceMagnet	MoveTo	STAM		✓
	ControlGripperBonding			

The flowcharts of primitives and skills for the two ICPE processes have been outlined. These are reported in Figure 7 and Figure 8, which highlight in blue the blocks corresponding to robotic/system task, and in red the human ones.

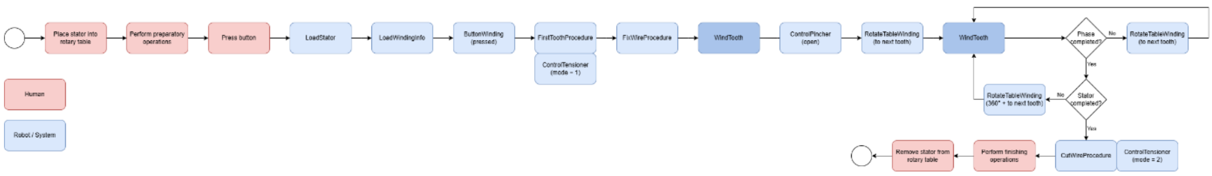

Figure 7 – Skills/primitives flow of winding process

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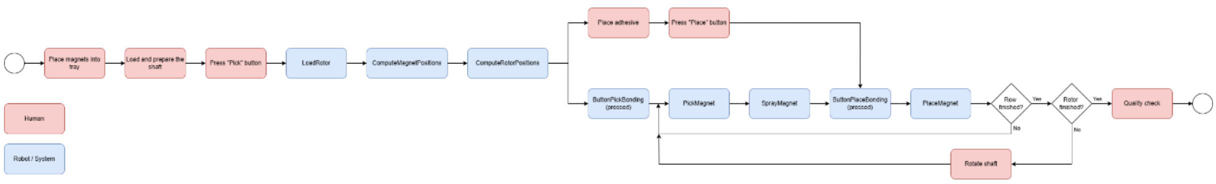

Figure 8 – Skills/primitives flow of the bonding process

3 The Description of the Video Demonstrating for Testing

The following sections describe the video created to demonstrate the functionality of the two collaborative processes implemented for the ICPE use case. Key scenes from each process are highlighted, with specific timeframes noted in brackets for easy reference. Both robotic processes shown in the video have been appropriately sped up during post-production to create a more compact viewing experience

3.1 Winding process

Preparatory operations (00:26)

The winding process begins with the operator positioning the stator inside the chuck and checking that the wire correctly passes into the end-effector's needle. Once the preparatory operations are over, the operator presses the button of the corresponding table where the robotic winding process can start (00:44).

First tooth procedure (00:50)

The next step involves resetting the rotary table. Since the table is driven by a stepper motor without an absolute position encoder, an initialization procedure is required to determine its

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position. This process uses a laser sensor mounted on the end effector, which is positioned by the robot in a fixed position above the stator to detect one of its teeth. The table is then rotated until the tooth is no longer detected by the laser (00:55). Once the edge of the stator tooth is identified, and with the stator geometric parameters known, the table rotates in the opposite direction by the necessary angular distance to align the tooth with the nozzle of the end effector, from which the wire will flow (00:57 – it's possible to notice that the green light of the laser sensor is positioned exactly at the center of the tooth).

Fix wire procedure (01:04)

At this point, the robot approaches the pincher that will grip the wire (01:09) and hold it in place for the initial part of the process.

Teeth winding (01:13)

Following the winding instructions, the robot begins winding the first tooth of the stator with a predetermined number of turns and winding direction. The wire advances along the tooth by an increment equal to its diameter (0.4 mm).

In the meanwhile, the operator can start the preparatory operations on the other free rotary table of the cell (01:45).

Once the winding sequence for a tooth is completed, the end effector moves to a position diametrically outside the rotor (02:03). The rotary table then rotates to position the next tooth for winding, based on the winding information, and the sequence is repeated until the first, second, and third phases are completed.

Cut wire procedure (03:31)

After the winding process is finished, the robot moves to the cutting position, where the cutter severs the copper wire (03:46).

Finishing operations (03:58)

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The operator can then remove the stator from the chuck and manually cut the wire according to the three phases of the motor, thus performing a sequence of finishing operations.

3.2 Bonding Process

Preparatory operations (04:43)

The bonding process of the magnets on the rotor begins with the operator fixing the rotor onto the spindle (00:46).

For some rotors, including the one shown in the video, there are flat surfaces where magnets will be positioned, requiring that these surfaces are precisely parallel to the robotic cell plane. This alignment is achieved with a custom-built tool equipped with an inclinometer. Using the spindle plane as a reference (05:11), the tool measures the angle of the rotor's flat surface (05:16) and rotates the motor until the angle between the two surfaces is zeroed (05:24). Then, the operator communicates the number of rotor poles (05:44) so that the system can rotate the rotor by the exact degrees needed to present each surface for magnet placement (06:02).

Finally, the operator places the north and south polarity magnets onto two separate trays (06:07). All north-polarity magnets are placed on the left tray, and all south-polarity magnets on the right.

When the preparatory operations are over, the operator presses the “Pick” button of the cell so that the robotic picking process can start (06:45).

Magnet bonding process (06:48)

The robot picks up a magnet from the designated tray (06:54), and then moves it under the spray that applies a small amount of activator (07:09). The operator applies the glue to the rotor surface (07:17) and then he presses the “Place” button, communicating the robot to

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position the magnet on the rotor. This procedure is repeated until the first row of magnets is completed (08:25).

Once a row is complete, the operator rotates the rotor, and the cycle is repeated until the entire rotor is completed.

Placement approach (09:21)

A different placement approach is used after the first magnet of each row, which is simpler to place. Due to the radial attraction between magnets, each subsequent magnet is positioned through a tilted motion (09:25). Then, to withstand the axial repulsive force, the robot presses the magnet against the previous one (09:39) until the polymerization of the glue.

Finishing operations (09:55)

Once the bonding process is completed, the operator removes the rotor from the spindle and performs a visual quality check.

4 Conclusion

The document and the accompanying video demonstrate the validation tests performed on the two robotic cells, designed to carry out the winding and bonding processes. The tests confirm the correct communication between the software and hardware, showing how the geometric parameters of stators and rotors are accurately transmitted and processed by the skills underlying the ACROBA process.

The validation tests focused on ensuring the correct execution of each step in the process, verifying both precision and repeatability—crucial characteristics for producing high-quality motors.

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