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Abstract

European electrical machines manufacturers need to increase the flexibility of production process, due to the high cost of equipment setup at the beginning of each new production batch. Overall, most of these European manufacturers are striving to reduce costs while preserving the quality of products, in order to face the competition by Far East companies. There is a strong need for increasing productivity, flexibility and quality. In particular, in wound coils manufacturing process, current technologies allow only to big international manufacturer to automate their production lines, due to high machinery cost and set-up time, while small and medium manufacturers are forced to direct themselves towards manual production. This work aims to reduce costs and increase flexibility with the following contributions: (1) important reduction of setup time and costs of the winding machine, thanks to the simplicity and flexibility of the proposed approach; (2) increase in the quality of the final motors, thanks to the increased amount of copper that the robot will be able to insert in each coil with respect to manual winding; (3) possibility to parallelize the winding operations, dramatically increasing production rate; (4) decreased number of defected cores, thanks to an advanced quality inspection system; (5) reduction of environmental impact of the production process, thanks to a reduction of wasted copper wire.

1 Introduction

An automatic system for coil winding has to be affordable to a wide range of users: from small-medium enterprises (SMEs), producing small batches of motors and frequently changing products design, to big companies, having a market request of several thousand standard units. The low flexibility of automated winding machines [1], i.e. the time and costs required to switch from one design to another, coupled to their high cost (up to 100k Euros), force small manufacturers (especially SMEs) to employ human operators in this task. The handcrafted job is obviously much more flexible, but more expensive (because of labor cost and equipment), and for the worker it is distressing, frustrating and repetitive. Few attempts of robotic cell for coil winding have been made [1]. In this work, we aim at achieving the product flexibility required for this business sector by developing an interactive robotic cell for this task. Such a reconfigurable cell has been provided with learning capabilities. The cell is suitable for winding the coils of several kind of electric machines, starting from the information of a simple teaching interface that can be easily used by operators without specific skills in robotics. The concept of a flexible production will use a needle winding technique. The production process is divided into coils manufacturing and insertion of these on the stator. The coils are wound on frames, after which they are mounted onto the stator. For this particular application the winding process is restricted to concentrated windings. However, distributed windings or even complex winding schemes are achievable by winding individual coils. The proposed production process will have the potential to allow three dimensional shapes of the coils and complex winding schemes. During the project, we faced the following challenges: (1) teach the robot how to properly wind the coils of stator/rotors; (2) robotize the manufacturing process of electric machines, in particular the winding of coils on stator or rotor cores; (3) detect and report non-compliances in the process of the coil winding. In the proposed work, the selected electric motors have the following features: (1) frameless torque motors designed to be compact, high performance and cost effective; (2) allow direct coupling with the payload, eliminating parts of mechanical transmission; (3) maintenance free; (4) high energy NdFeB magnets maximize torque density. Main applications for the proposed motors are electric vehicles, machine tools, laser scanning and printing, motion simulators, rotary stage, robots, tracking systems.

The remains of the paper is structured as follows: Sec. 2 illustrates the data information available from motor manufacturer for motors and coils. Sec. 3 describes the functioning of the overall robotic system , while in Sec. 4 the outcomes of the tests are presented with considerations and analysis. Finally, Sec. 5 summarizes the achieved results while proposing some future extensions of this work.

2 Data

The manufacturer worked on redesign the electric motors in order to allow the winding process by mean of a robotized device: stator core electromagnetic design, stator core mechanical design, winding design, and coil frame mechanical design in order to allow an interlocking function with the stator core. For an accurate performance prediction of the motors redesign structures, Finite Element (FE) analysis has been used. Five different types of electric mo-

Table 1 Specifications of the motors produced by the manufacturer during the project.

Params	Unit	M1	M2	M3	M4	M5
Ext. diam.	mm	128	178	178	252	252
Inner diam.	mm	80	120	120	160	160
Act. length	mm	30	20	30	30	50
Rated power	W	1600	2400	3100	3000	4500
Conn. torque	N m	13	24	30	36	54
Peak torque	N m	30	53	69	82	124
Rated speed	rpm	1200	1000	1000	800	800
Noload speed	rpm	1500	1350	1200	900	850
Inertia	Kg m^2	0.09	0.03	0.032	0.055	0.06
Weight	Kg	3.7	5.65	6.65	8.5	10
Phase conn.		Y	Y	Y	Y	Y
N. of poles		14	20	20	20	20

tors were designed and optimized in order to allow a flexible production of the windings. The stator consists of a laminated steel core in whose slots is located a three phase star connected winding. The rotor consists of a magnetic steel ring on which there are placed high energy permanent magnets. Applications for the proposed motors are electric vehicles, machine tools, laser scanning and printing, motion simulators, rotary stage, robots, tracking systems.
The specifications of the proposed outer rotor frameless motors are reported in **Table 1**, while **Figure 1** shows some of the real components derived from the manufacturer designs.

3 System

The system takes into account the coils dimensions (height, width, and depth), the number of turns in the coil, the wire thickness and allowed tension. The considered features are used to plan the path for winding a coil. The planning is based on a learning framework previously developed in [3] [4]. These characteristics improve the previous system capabilities [5] [6] to compute the trajectory to be covered by the robot tool. The learning system has been trained with several examples generated by using an initial set of human demonstrations, with the idea to improve the internal model in an iterative manner and increase the performances of the whole winding procedure. Of course, it is still possible to refine the computed trajectory by teaching the robot a better route through human demonstration. The objective is to enable the system to wind up a coil to be mounted on a stator never seen before. The parameters of pole dimensions, number of turns in the coil, wire thickness and desired tension are provided as input to the robot by the operator, without the need of specific sensors to identify them. Based on the given information, the system chooses the proper coil from a coil hub and the robot tool gripper picks and places it on the adjustable winding stage. Later, the tool clamps its wire to the winding stage and starts winding the coil. A set of basic quality inspection protocols, based on turns count, wire tension and wire round distribution unity have been introduced, in order to guarantee a high standard of the winding process. A tension sensor has been integrated into the robot end effector in order to control the wire tension. The output of the sensor has been used to close the loop in the controller, adjusting the joint trajectories to match the desired output. This feature allows the robot to keep the wire tension as much as possible within the prescribed range, in order to avoid picks in the tension and reach optimal performances of the winded coil. Finally, the robot gripper picks the wound coil and places it on the empty stator slot. The process is summarized in **Figure 2**.
The robot working process has to be able to adapt to different sizes of poles and input parameters to control the winding process. The system does not need human intervention in wire handling, online quality control, pick and place. In fact, the robotic platform has been provided with automating wire clamping and cutting, sensors for determining wire tension and wire rounds position, and a custom gripper for coil pick and place from the hub to the winding stage and from winding stage to the stator.
The whole system is completely integrated in the ROS framework [8], with the idea to easily modify and update the framework with different robots or sensors.

4 Results

We tested the complete system in a new robotic cell set up at Fraunhofer IPA in Stuttgart for the EuRoC project[**?**]. This field-test was meant to prove the robot capability to work with different sizes and characteristics of the coils, and the correctness of both pick and place tasks. Tests concentrated on the winding and pick and place tasks (**Figure 3**).
A monitor showed wire tension during winding operations, in order to identify in real time picks that could break the wire. The framework has been tested with several different coils, the robot performed the required tasks after an operator manually inserted the parameters for the considered motor. The performance have been tested in terms of productivity, repeatability, reduced manufacturing costs, flexibility, and setup time. At the end of each winding process, the coil has been compared with standards coming from actual industrial manufacturer by checking copper fill factor, inductances, resistances, and conductance at high voltage. In particular, the copper fill factor is the ratio of the copper conductors area over the total slot area. For a section of coil (**Figure 4**), the copper fill factor is computed as explained in **Equation 1**.

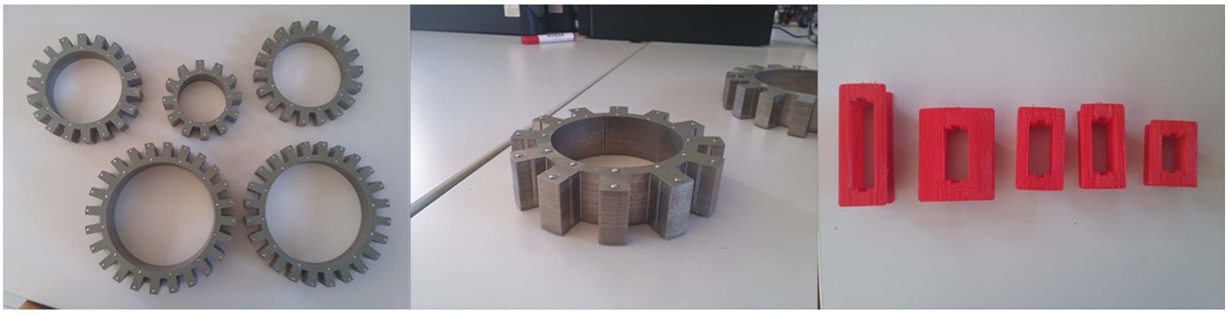

Figure 1 Stators and coils composing the motors used in the project.

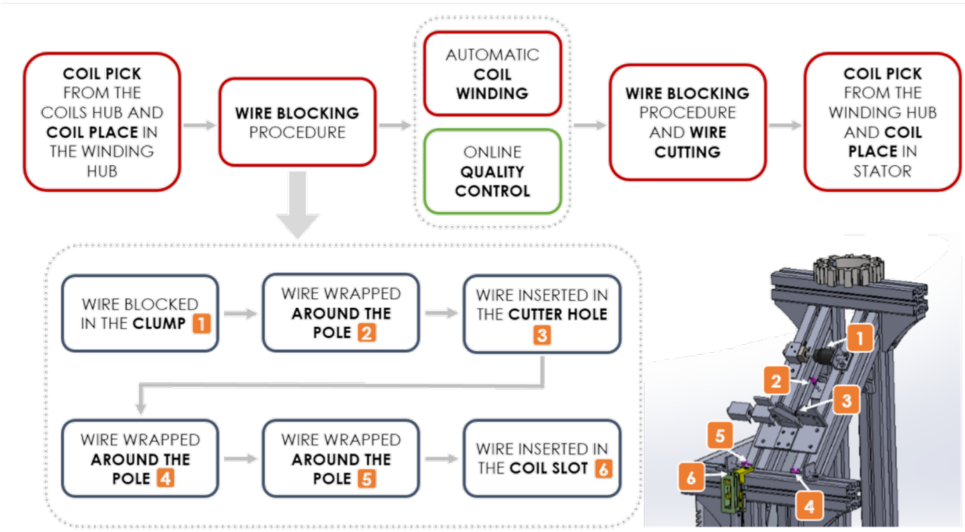

Figure 2 Sequence of automated winding procedure.

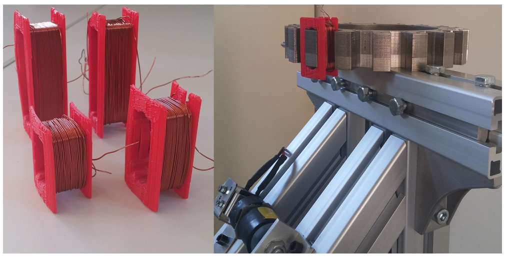

Figure 3 A set of wound coils ready for testing and a coil mounted on the stator.

$$copperFieldFactor = \frac{nS}{bh} \quad (1)$$

where:

- n is the number of copper turns (conductors);
- S is the part of cross section composed by copper conductor;
- b is the base of the cross section of a coil slot;
- h is the height of the cross section of a coil slot.

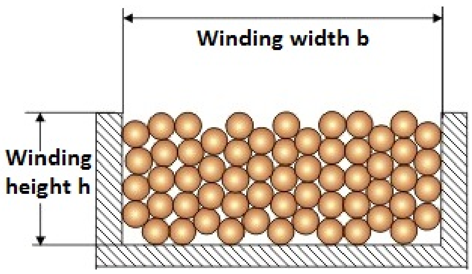

Figure 4 Cross section of a coil slot.

During the tests in Stuttgart, we were able to reach a Copper Fill Factor of 0.5. For electric motors used in standard applications, the copper fill factor is usually around 0.2. Moreover we achieved a valuable advantage in terms of productivity and repeatability. At the current state the production system in the manufacturer facility is able to wind 7 stators in 8 hours. In ours case the robotic arm provides 15 completed stators every 8 hours. Finally, the repeatability has also increased in a very significant manner due to the robotized approach. On the other hand, we faced a major problem with an increased number of faulty products. The results can be certainly improved with a more accurate tuning of the overall system, but some parts of the frame-

Table 2 Results obtained during the testing phase at Fraunhofer IPA.

Metric	Manufacturer	Our system
Number of stator wound every 8 hours	7	15
Correct wound coils	90%	50%
Mean Copper fill factor	0.2	0.5
High voltage	Pass	Pass
Resistance	Pass	Pass
Repeatability	20%	100%

work should be revised in order to avoid failures. A simple example regards the material used for the coils. It was too fragile and sometimes it broke while winding the copper wire. The breaking problem could be avoided by 3D printing the coils perpendicularly with respect to the winding direction. The geometry of the piece would have helped in making it more robust. Another possibility could have been to completely change the plastic material, for example by using nylon instead of polylactic acid. Anyway, it is worth to notice that the copper material (the most expensive one) used for the spare parts can be recycled in the very same process, and it had not been wasted. Another very important aspect of our system is the high flexibility provided with respect to industrial winding machines available in the market. The capability to switch between different types of motors with minimum cost for additional tooling is essential. Commercial winding machines usually do provide very limited flexibility with expensive additional tools requested to wind different stators types. Moreover, the time needed for switching from one tool to another is quite long taking from some hours to a day. With our system, a complete change of the entire production from a motor type to a different one require more or less 15 minutes, reducing drastically the minimum number of pieces for a sustainable production, and opening the market to small-medium enterprises with a low margin of investment.

5 Conclusions

In this work, we introduced an innovative automatic technology able to increase considerably the competitiveness of European enterprises operating in the electric motors manufacturing field. The system is meant to introduce a flexible approach for winding motor coils of different types, sizes, and power with a reduced and limited human intervention in the process. Nevertheless, if necessary, the human operator can still be part of the loop in order to improve the performance of the system. The proposed technology has the potential to reduce costs, time, risks for electrical machine manufacturers in the near future and put the basis for a different way of producing high performance electrical components with an improved copper fill factor.

Acknowledgements

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