Machine-made Coil Winding with a Collaborative Industrial Robot

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***Abstract*— The requirements for modern electric motors, such as higher energy densities or rotational speeds, are constantly increasing and the production of the coil winding is getting more and more complex. The use of collaborative robots (cobots) in industrial applications is becoming increasingly important. This paper presents a workflow for the generation of a custom coil winding with the help of a cobot.**

I. Introduction

Driven by e-mobility, the efficiencies of electric motors have improved significantly in the last few years. This could be achieved, on the one hand, by more compact motors operating at higher rotational speeds and, on the other hand, by motors with special winding systems that lead to higher power densities. Unfortunately, these high-power motors are characterized by a small number of magnet wire turns in each individual coil and thus higher conductor cross-sections are required. Since these motors are always operated with alternating current and more frequently with frequencies in the range of several hundred Hertz, the parasitic alternating current (AC) losses increase considerably with larger conductor cross sections. Physically, these AC losses are caused by eddy currents in the conductors that occur when electrical conductors carry an alternating current (skin effect) or are exposed to an alternating magnetic field (proximity effect). To keep the parasitic AC losses as low as possible, the winding conductors are often subdivided into multiple insulated parallel strands. These strands are short-circuited at the terminals. Thus circulation currents can occur in the conductors connected in parallel, which in turn lead to additional losses. To keep these losses low, very precise arrangement of the wires in the slot is required. Figure 1 shows different conductor arrangements for single-layer winding. Conductors with the same color are connected in parallel, belong to the same strand and represent one turn of the winding.

Between the best (Fig. 1a) and the worst-case distribution of the parallel wires (Fig. 1c), the additional losses can differ by orders of magnitude. While production lines for high volume machines are available, large machines with small batch sizes are still wound manually. Examples are permanent magnet excited hydroelectric generators, as shown in Fig. 2 (left and middle) with corresponding winding as shown in 2 (right).

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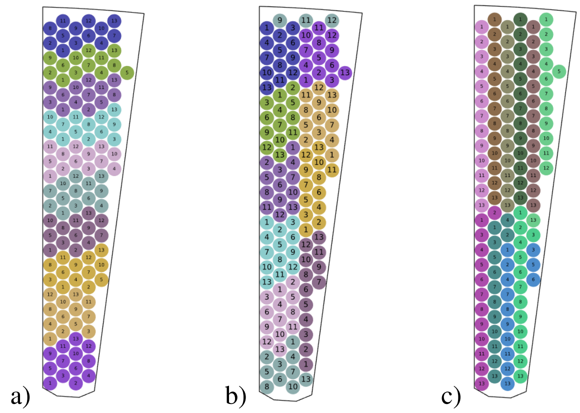

Fig. 1. Arrangements of conductors in the slot for a single-layer winding, a) bundled wire distribution (best case), b) bundled wire distribution (medium case), c) single-layer winding with radial wire distribution (worst case).

Fig. 2. Hydropower generator with corresponding coil winding

II. Mechanical Parts and Winding Concept

Typically, handmade coils do not have the accuracy of machine-made coils, which can result in higher losses and critical thermal loads. Additionally, machine-made coils can be produced more efficiently, resulting in lower cost per piece, especially for higher volumes. To minimize the losses, a winding concept was developed with the help of a cobot. There is a wide range of collaborative robots on the market. In this study a robot from Universal Robots [4], the UR10e was used. Since this one has the widest operating range (1300 mm) compared to the other cobots of Universal Robots, it is perfect for complex winding applications. The maximal payload of this cobot is 10 kg and it has a movement repeatability of ±0.05 mm under load.

In order to build up the coil winding, a device was created which serve as a guide for the winding wire. A draft of the device is shown in Fig. 3. The structure consists of two towers, which are mounted on a heavy foundation. Each tower has an individual number of segments (green and blue part). The segments are 3D-printed and stiffened with a steel shaft. The coil winding presented in this work requires two segments with ten slots total. Each slot has space for 18 parallel wires. The slots of the towers represent the grooves of the coil winding in which the wire packages are inserted. The length of the winding package is defined by the distance between the towers and can be adjusted individually. The winding starts from the bottom up. At the uppermost segment a lug is provided to reverse the direction of the winding. After the turn at the top the winding goes downwards. At the bottom another turn movement is done to reverse the direction of the winding. This process is repeated until all layers of the winding are completed.

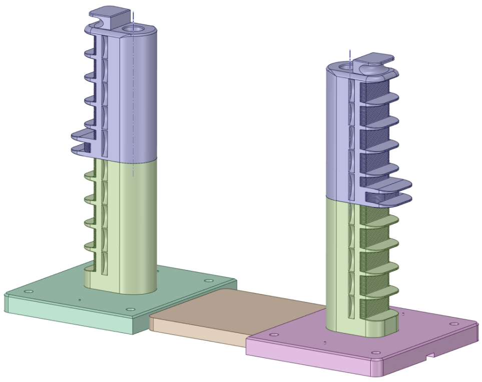

Fig. 3. Winding device

In order to handle the wire with the robot, a suitable end-effector was needed. Since there is no appropriate solution available on the market, a custom end-effector was designed and built (Fig. 4). The core and the flange of the effector are made of aluminium to achieve enough stability. The housing parts are 3D-printed. The blue line represents the copper wire passing through the end-effector and the arrow indicates the wire inlet. At the outlet of the device there is a tungsten carbide nozzle to guide the wire.

The manual wire stripping is a very time-consuming task, especially for a high number of parallel wires. Since several coils are wound on the winding device, an automatic wire stripper inside the end-effector is installed to strip the wire between each coil. It can be activated at any time of the process. The concept of the automatic wire stripper is based on rotating blades, which are driven by an electric motor. The centrifugal force cause the blades to fold up and strip the wire. Since there is not enough power to drive the wire stripper directly via the robot, an external power supply is required.

The insulation cut of, will be extracted trough a suction port. The wiring of the power supply as well as the hose of the suction system, are guided along the robot arm.

The required copper wire is wound on a spool in front of the winding device and is fed directly into the end-effector (marked with an arrow in Fig. 4). To ensure a constant wire tension during the winding process, a wire tensioner was added between the spool and end-effector.

III. Path Planning and Implementation

The next step was to plan and implement the path points of the winding process, that the robot has to pass. The idea is

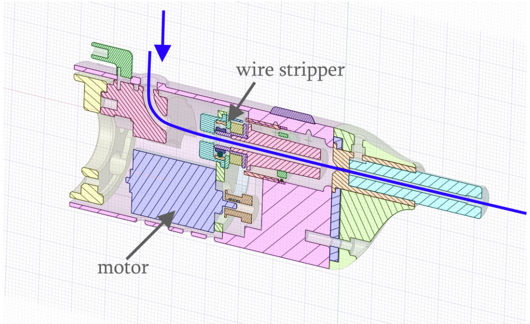

Fig. 4. End effector

to define the points of one single winding layer and then use these points with a vertical offset for all the other layers. The reference of the planned points is a fixed coordinate system on the winding device. In Figure 5 the corresponding path points of one layer are shown. The dots indicate the location in the plane and the arrows represent the direction of the longitudinal tool axis. The orientation of the end-effector is described with Tait-Bryan angles and intrinsic rotations about the $z-y-x$ axis of the tool-center-point. The blue square represents the bounding box of the winding device.

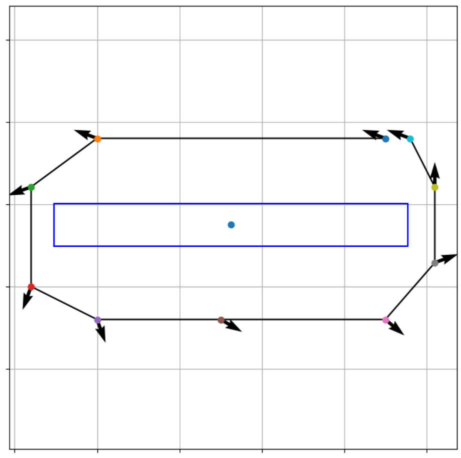

Fig. 5. Planned points for the winding process

Figure 5 shows the counterclockwise movement of the upward winding process. For the downward winding, the points and orientations are flipped along the horizontal axis. To change the winding direction, a turn movement at the top and bottom of the winding unit is necessary. The automatic wire stripping is activated during the turn movement, since the wire will be cut at this point and electrically clamped.

The Universal Robot can be controlled at two levels. One option is to control the robot directly with the teach pendant and the graphical user interface. The other way is at a script level. At the script level, the *URScript* [4] serves as a programming language to control the robot. The *URScript* includes variables, types, and the flow control statements. There are also built-in variables and functions that monitor and control I/O and robot movements. The planned path points are generated by a Python script. The result is a *URScript* which can be loaded and executed by the robot.

IV. Virtual Commissioning and real Setup

Virtual Commissioning is used to test the setup and the generated robot program in the virtual environment. It is used to find the correct position of the winding device and to avoid collisions between the robot and the winding device. With this procedure, it is possible to quickly test different travel paths of the robot without having to change the real setup. Unfortunately, it is not possible to simulate the copper wire itself.

The used tool for Virtual Commissioning is IndustrialPhysics from Machineering. IndustrialPhysics is a physics-based 3D simulation software that offers real-time capability for Virtual Commissioning of mechatronic system in a holistic digital engineering approach [1]. This simulation technology makes it possible to simulate complex systems and robots quickly and easily in addition to check test runs of the PLC programming created precisely. Many functions are integrated in IndustrialPhysics for a wide range of applications in development, commissioning, production, service, and sales. Figure 6 shows the Virtual Commissioning model of the winding setup.

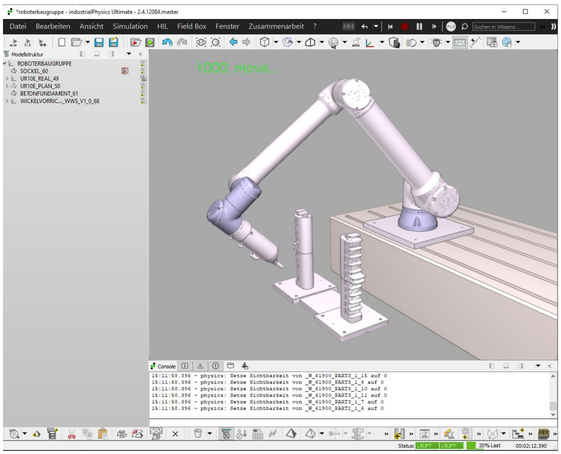

Fig. 6. Virtual Commissioning

The virtual setup was created with the CAD software PTC Creo [2] and is then transferred to IndustrialPhysics. In order to test a new setup, the winding device or the robot has to be moved. Afterwards the reference coordinate system of the device has to be teached and then the robot program can be executed. The winding program runs on the Universal Robots offline simulator, which transfers the movement of the UR10e via the real-time-data-exchange (RTDE) interface to IndustrialPhysics.

After a successful virtual test, the setup is build up in the laboratory, which is shown in Fig. 7.

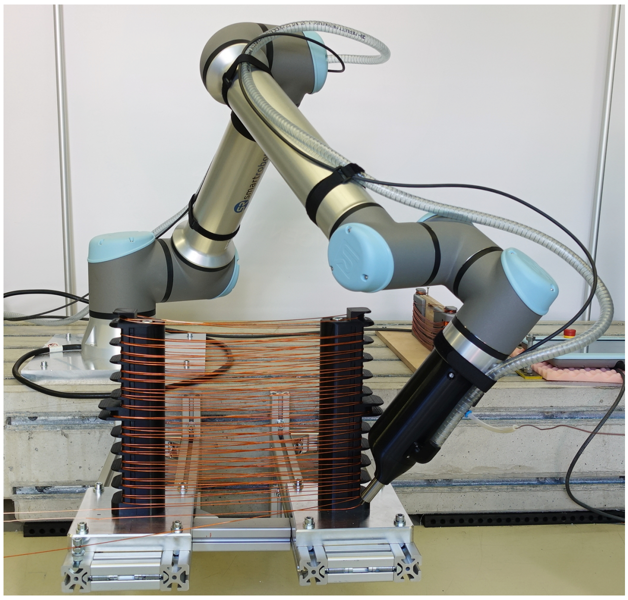

Fig. 7. Universal Robots UR10e with winding device and end-effector

V. Process Automation with SyMSpace®

The next step is to automate the whole winding process, from the creation of the CAD model of the winding device, to the G-code for the 3D printer and the robot program. The used tool to orchestrate various software platforms is SyMSpace®. SyMSpace® [3] which stands for 'System Model Space', is a software environment for system simulation and optimization. Based on subsystem models, or so-called 'Components', with certain inputs and outputs, the complete simulation model tree can be created intuitively. The Components which can be included in SyMSpace® may hold the actual computation or simulation in the form of functions or methods. Equally, Components may include the interface to third party software used for simulation or calculation.

The goal is, to have a SyMSpace® component for every process step. For example one component, which generates the G-code files to 3D print the winding device or another component which produces the robot program from the CAD model.

VI. Summary and Outlook

In this work a concept to produce a machine-made coil winding with the help of a collaborative robot was presented. First test windings have been successfully completed. The next steps are to implement the SyMSpace® components, to automate the workflow and to compare a hand-made with a machine-made coil winding in operation, in terms of thermal properties.

Acknowledgment

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