Fermilab Automation of Coil Winding System

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FERMILAB-POSTER-25-0025-STUDENT

Abstract

The automated coil winder project creates a repeatable, scalable method for producing superconducting magnet coils with increased accuracy and efficiency. The design uses an ortho cyclic winding method to achieve high fill factors by combining computer numerical control (CNC), microcontroller-based controls, and sophisticated optimization techniques. The method optimizes coil turns, core geometry, and current consumption by utilizing analytical models based on magnetic moment, Ohm's law, and power constraints. For particle accelerator applications, prototype testing using a 3D-printed coil winder has shown enhanced winding repeatability, thermal management, and manufacturability.

Introduction

Fermi National Accelerator Laboratory (FNAL), builds superconducting magnets for studies in particle accelerators. Currently the winding process for these coils is done manually by trained technicians which takes multiple days to complete and makes repeatability difficult. To make the wrapping process faster and more repeatable, with less deviation between windings, FNAL tasked our team with automating the process by upgrading their manual system to a CNC coil winder that is controlled by G-code and whose motion replicates the motion of the manual winding table.

Figure 1: *FNAL manual coil winding table*

Methods and Materials

- A 3D-printer inspired feeder system using NEMA 23 stepper motors and OpenBuilds controllers, selected after evaluating several design approaches.
- PLA components were 3D-printed to create custom adapter brackets and guides, enabling precise control over mandrel rotation and wire feeding.
- MATLAB is employed to generate motion trajectories.
- CNC-based G-code is produced from detailed SolidWorks models.
- FNAL specifies coil geometries including serpentine, canted cosine-theta, and pancake coils.

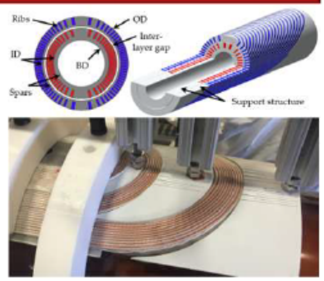

Figure 2: *Canted cosine theta and pancake coil patterns*

Results

- A prototype has been constructed in an 8020 aluminum frame and tested in a controlled environment.
- The orthocyclic winding technique increases positioning accuracy by over 30%, enhancing repeatability.
- Exact nesting reduces air gaps, leading to better thermal management and electrical performance.
- Switched rotational degree of freedom (DOF) to linear actuator DOF to reduce the system's footprint by approximately 95%.
- Changing degree of freedom with a linear actuator increased operator safety and reduced the system's resistance to change (smaller moment of inertia).

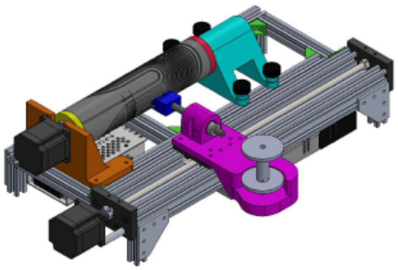

Figure 3: *3D Model of automated multi DOF coil winder*

Discussion

- MATLAB optimization procedures iteratively modify parameters (number of turns, current levels, layer configurations) to balance magnetic moment requirements under fixed-voltage constraints reducing the number of turns and improving efficiency.
- The modular, 3D-printer-inspired design enables seamless scaling from small prototype coils to full-length (5m) accelerator magnet coils, supporting future Fermilab applications.
- The system combines CNC-based precision and microcontroller-level real-time control (e.g., PWM current regulation), enabling highly accurate wire placement and consistent winding tension.
- The system uses current-limiting controls, emergency stops, and protective housing around moving parts to reduce risks of overheating, short circuits, or operator injury during operation.

Conclusion

The automated coil winder project has effectively created a reliable system that can precisely and efficiently produce superconducting magnet coils. By employing an ortho cyclic winding strategy and a thorough optimization process that takes into account mechanical and electrical constraints, the system enhances winding consistency, thermal performance, and manufacturability. For full-scale magnet production in particle accelerator applications, future work will scale the design and improve the control algorithms.

Acknowledgements

This document was prepared by Fermilab/Northern Illinois University Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics facility under CRADA FRA-2023-0054. Fermilab is managed by FermiForward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

The authors would like to acknowledge Steve Krave and Dr. Jenn-Terng Gau for their support in the design and development of this project.