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HELICALLY WOUND SUPERCONDUCTING CABLE PRODUCTION SYSTEM [1]

This study presents an advanced production system for helically wound superconducting cables. The developed system addresses critical challenges in high-current applications (such as power transmission, fusion reactors, and space technologies) by combining modular design with precision engineering solutions. It is directly applicable to the production of superconducting magnets required for particle accelerators and high-energy detector systems. Key innovations of the system include an adjustable tension control mechanism (with a range of 10–20 Nm), multi-axis synchronization (seven-axis motion control), and configurable winding parameters (helix angle between 10° and 75°, diameter range of 6–25 mm). The production platform integrates up to 16 independent tensioning units and provides precision tension management via an adaptive control mechanism. The output of the device confirms the system's ability to produce industrial-quality superconducting cables while minimizing mechanical deformation. These technological advancements provide a strong foundation for integration into large-scale infrastructure projects in high-energy physics.

Keywords: helical winding, helically wound superconducting cables, high power cables, precision manufacturing, superconducting cables.

1. Introduction

1.1. Significance and applications of superconducting cables

Superconductivity is the phenomenon in which certain materials, when cooled below their critical temperature ($\mathbf{T_c}$), exhibit zero electrical resistance and perfect magnetic field exclusion (Meissner effect) [1, 2]. Superconducting (SC) cables offer significantly higher current carrying capacity compared to conventional copper or aluminum cables and can transmit electrical energy without dissipation [3]. The global superconducting cable market is projected to experience consistent growth through 2035 due to expanding investment in energy and research infrastructure [4]. Similarly, the Cable Manufacturing Equipment Market is expected to show significant development, underlining the increasing demand for advanced, precision production systems [5].

Key application areas for SC cables include:

• Power Transmission and Distribution: Minimizing grid losses and increasing power density in urban areas [6].

• High Energy Physics (HEP) and Fusion: Providing strong and stable magnetic fields for particle ac-

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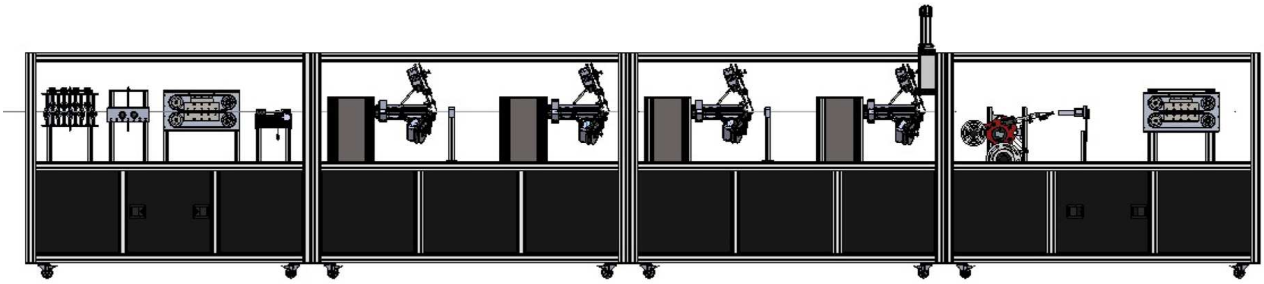

Fig. 1. Collective view of the four modules

celerators (e.g., Large Hadron Collider; LHC) and fusion reactors (e.g., International Thermonuclear Experimental Reactor; ITER) [7].

• Medical Imaging: Generating powerful and homogeneous magnetic fields for magnetic resonance imaging (MRI) and nuclear magnetic resonance spectroscopy (NMR) devices [8].

• Transportation: Powering Maglev trains and other high-speed systems [9].

1.2. Superconducting cable manufacturing process

The production of superconducting cables fundamentally relies on helically winding brittle SC tapes or wires onto a mechanically supportive substrate [10]. The Conductor on Round Core (CORC) technology, which is the focus of this work, involves layering thin SC tapes (such as ReBCO) with a specific helix angle onto a circular copper or steel core [11–13]. This design imparts flexibility to the cable while preserving the high critical current ($\mathbf{I_c}$) performance under mechanical stress and magnetic fields [14].

Critical challenges in this manufacturing process include:

• Mechanical Damage: Preventing damage to the fragile SC tapes from excessive tension or bending, which can lead to a reduction in $\mathbf{I_c}$.

• Tension Control: Maintaining winding tension within a narrow, non-damaging range (e.g., 10–20 Nm) with high precision [15, 16].

• Geometrical Accuracy: Ensuring the winding angle (e.g., 10–75°)[17].

This work aims to overcome these limitations by introducing a modular, multi-axis, and precisely tension-controlled production platform.

2. System Design and Methodology

The developed system employs a modular approach, consisting of four main modules, a total of seven-axis synchronized motion system, and up to 16 independent tensioning units.

2.1. Modular structure and workflow

The system is partitioned into four functional modules, which sequentially follow the superconducting cable production workflow: Module 1 (Substrate Straightening and Feeding) prepares the core; Modules 2 and 3 (Winding Systems) apply the SC wires and insulation tapes; and Module 4 (Labeling and Pulling) finalizes the cable and manages synchronized feeding. A collective view of the system is shown in Fig. 1.

2.1.1 Module 1: Substrate straightening and feeding system

This module is essential for preparing the core material. The module processes the incoming hollow copper tube through a four-stage operation (horizontal straightening, vertical straightening, pushing band, and precise straightening) to produce the prepared core for winding. Since the incoming hollow copper tube often arrives in a deformed state, the process first requires a multi-stage straightening operation to achieve the necessary geometrical precision. The copper tube is first corrected through sequential Horizontal straightening and vertical straightening. Following this primary correction, the tube is actively pushed forward by the pushing band system, and the operation concludes with a final precision straightening stage. This four-stage sequence ensures the copper tube is prepared as a perfectly straight core for the subsequent winding process. The detailed design of this module is presented in Fig. 2.

2.1.2. Module 2 and 3: Winding systems

These modules take the straightened core and the SC wires as input. Each module is currently configured for 3 helical SC wire winding on the left side and 1 Kapton tape winding on the right side, but there can be 4 winding mechanisms on each side, supporting up to 4×2 helical wire winding in total. The design of the dual radial winding heads is shown in Fig. 3. As the copper tube is actively pushed forward, the first stage of the winding head helically wraps the three SC wires onto the core. In the second stage, the Kapton tape is subsequently wound over the superconducting wires for insulation and stabilization.

The second and third modules are identical; however, the Human-Machine Interface (HMI) and the main controller are centralized and added to Module 3 for system management.

2.1.3. Module 4: Labeling and pulling system

This final stage involves labeling the coiled cable (optional) and features a bidirectional pulling system that drives the cable through the production line. The system is configured to place an identifying mark, such as a label, at specific, programmable intervals (e.g., every 1 m), as determined by the software. The cable pulling band, located in the second part of this module, operates in synchronization with the pushing band in the first module (Module 1). The design of this module is shown in Fig. 4.

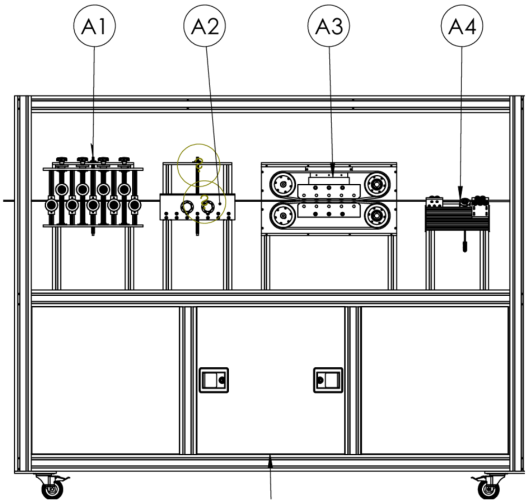

Fig. 2. Module 1: substrate straightening and feeding system; vertical (A1), horizontal (A2), precise straightening (A4), pushing band (A3)

2.1.4. Inter-Module Synchronization

The synchronized operation of the four modules is managed by the HMI and the main controller. The main controller (TrioMotion) provides communication between the seven-axis servo motor control, the tension units, and the HMI interface using Modbus or Wi-Fi protocols [18]. Fig. 5 shows the communication diagram of the units. The HMI and TrioMotion can directly communicate with tension units and with each other. TrioMotion also communicates with servo drivers.

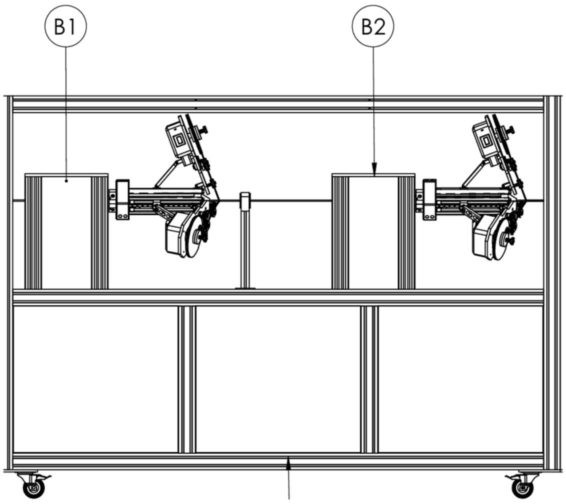

Fig. 3. Module 2 and 3: winding systems. Two radial winding heads; SC winding servo motor (B1), Kapton tape winding servo motor (B2)

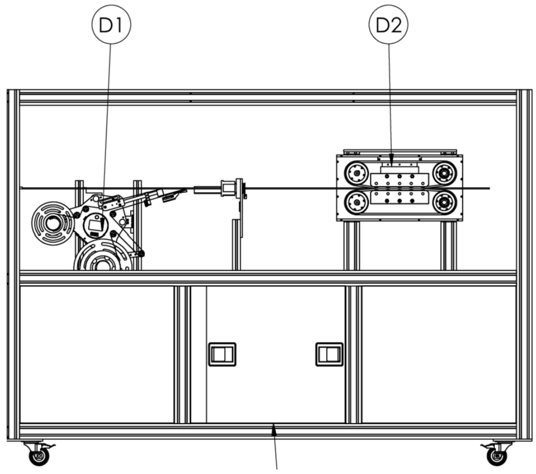

Fig. 4. Module 4: Labeling and pulling system; labeling (D1), bidirectional pulling band (D2)

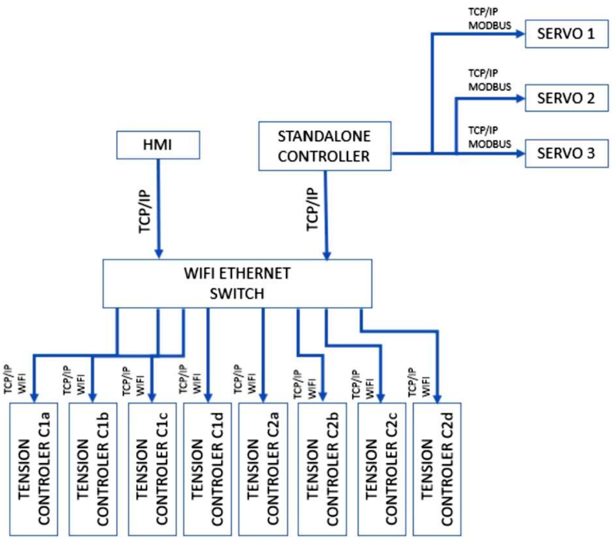

Fig. 5. General communication block diagram of the system

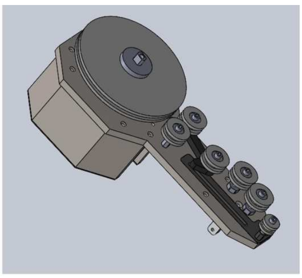

Fig. 6. Mechanical design of the tension control system

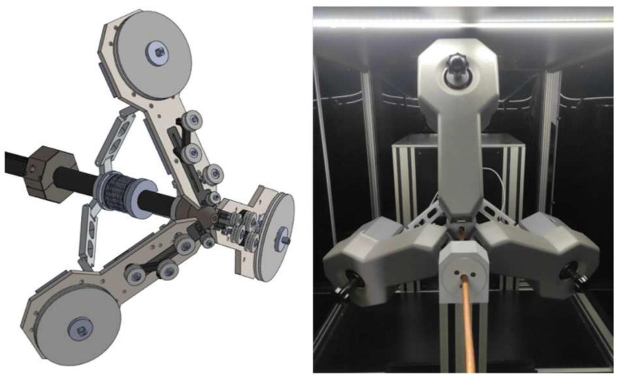

Fig. 7. Design and realization of the 120° radial placement of standard tension systems

Module 1 (Feeding) and Module 4 (Pulling): Speed control mode synchronization is applied to maintain the substrate material at a constant winding angle [16]. Module 2 and Module 3: A master-slave angular synchronization architecture ensures simultaneous winding [17]. Rotation speed is adjusted based on the pulling and pushing speed of the cable. Tension Units: Adaptive PID control algorithms optimize filament tension with real-time speed adjustment [15,19,20]. It is independent of pulling – pushing speed and rotation speed of the winding mechanism. Tension units measure tension by obtaining the angle of the SC wire via the potentiometer [21].

2.2. Tension control mechanism

The tension control mechanism is the most critical sub-component, ensuring the integrity of the SC tape.

2.2.1. Mechanical and Electronic Design

The integrity of the fragile SC tapes is maintained by the tension unit, which is primarily composed of a series of precision pulleys designed to guide the wire. This unit incorporates a mechanical arm whose angular position is monitored by a rotary potentiometer. The core principle of tension management is based on controlling the SC wire's feed angle through this arm. The tension is derived from the potentiometer's output value, which changes as the wire angle is adjusted.

Angular Control: The system operates within defined mechanical limits, where the minimum and maximum angle values of the wire correspond to minimum and maximum output values of the potentiometer. The control loop continuously reads this potentiometer value to ensure the SC wire feed angle is maintained within the non-damaging range. The mechanical components of the tension control system are illustrated in Fig. 6. The 120° radial placement of the standard tension systems within the helical winding module is presented in Fig. 7.

2.2.2. Custom-designed control board

The tension system is managed by a custom-designed electronic control board. The control board is based on a microcontroller, leveraging its dual-core Xtensa LX6 processor, 520 KB SRAM, and integrated Wi-Fi/Bluetooth for industrial IoT applications [22, 24, 25]. The custom PCB design integrates all necessary components, including the 24V/12V/5V power stages, motor driver, load cell module, angle encoder/ADC input, and communication interfaces

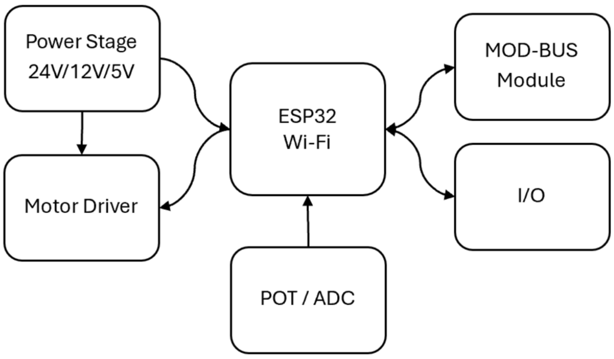

Fig. 8. Block diagram of the tension control card

(ModBus and Wi-Fi) [23, 26]. This independent tension system control card block diagram is provided in Fig. 8.

2.2.3. Electronic control and feedback

The pulling and pushing speed is set by the user. In addition, a load cell connected to the pulling band gives information about the pulling force. On the tension board, feedback control for the motor speed is implemented via a potentiometer. Based on the potentiometer the angle of the SC wire is measured [18].

2.2.4. Communication protocols and network architecture

The communication architecture provides industrial automation flexibility. The tension systems communicate with the 10.1 inch main HMI panel via wireless Wi-Fi or wired Modbus. The Modbus RTU protocol provides reliable data transfer (9600–115200 baud rate) [27].

The main HMI panel (Fig. 9) serves as the central control interface with several dedicated pages for system management. Key functionalities realized on the HMI include: the adjustment of servo and tension motor parameters, configuration of semi-auto and auto operation modes, manual control of individual axes, and the fine-tuning of PID control parameters.

2.3. Control Algorithm

The control algorithm at the core of the system uses adaptive PID methods to continuously optimize filament tension. This control strategy minimizes tension

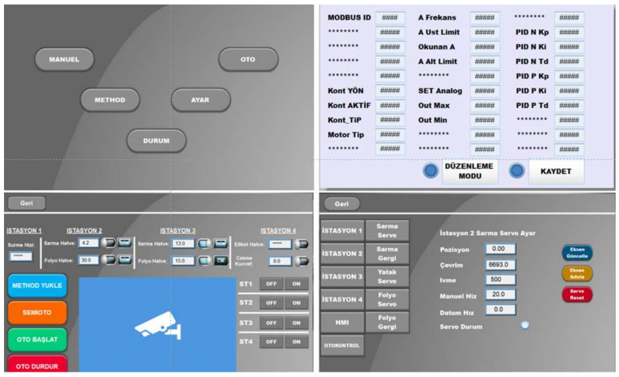

Fig. 9. Operator panel interface (HMI) of the main system

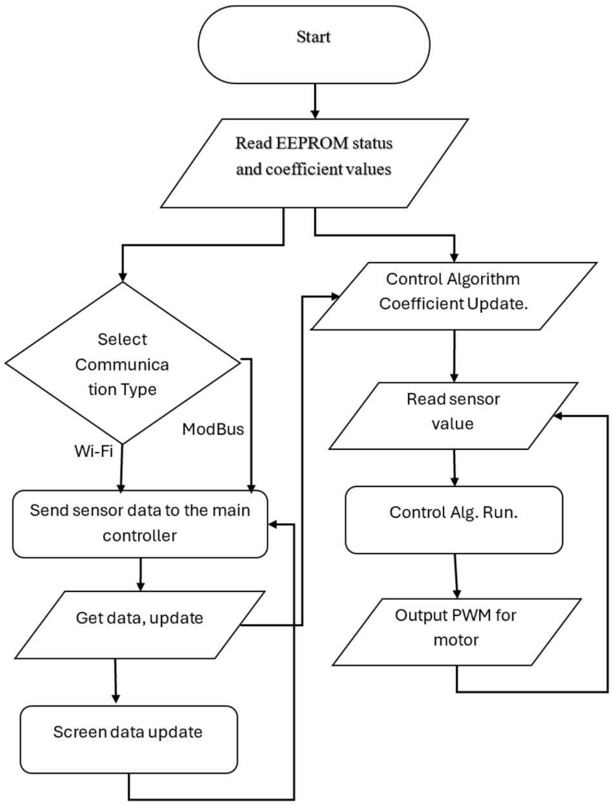

Fig. 10. Flow diagram for tension systems (microcontroller)

fluctuation, even during highly dynamic periods. The flow diagram for the tension systems is detailed in Fig. 10. The dual processors of the microcontroller are used at the same time. One of them is used for communication with HMI and other is used for controlling the tension of SC wire.

3. Results and Discussion

The developed system successfully addresses the key manufacturing challenges in SC cable production, presenting significant innovations:

The microcontroller-based tension boards provided reliable local closed-loop control and telemetry over Wi-Fi/Modbus. Communication latency and packet loss were within industrially acceptable thresholds for system coordination.

The four-module architecture and up to 16 independent tensioning units integration provide flexibility for various cable geometries and production capacities.

The custom-designed control board and the implementation of adaptive control algorithms enable robust, real-time control necessary for handling delicate SC materials.

Certain thin, brittle superconducting tapes showed sensitivity to high helix angles (>60°) at small diameters (<8 mm). This limitation suggests an operational envelope that must be respected for each tape type.

Finally, some samples of the cables produced by the machine are shown in Fig. 3. Three helical SC wires were wound onto 6 mm, 8 mm, and 10 mm copper pipes.

The measured performance shows the system meets or exceeds several primary design goals (tension and angular precision, modular changeover time). The tension sensing approach based on a potentiometer mounted on a pulley performed adequately for closed-loop control; however, periodic calibration against a direct load cell is recommended to mitigate long-term drift. Furthermore, the implementation of laser-based spacing and alignment measurements would reduce setup time and improve reproducibility when changing cable diameters.

Fig. 11. Device output: 6 mm, 8 mm, 10 mm SC cables

4. Conclusion and Future Work

The developed helically wound superconducting cable production system enables the fabrication of next-generation SC cables for HEP and power transmission applications. Its precise tension control, modular design, and adjustable winding geometry contribute to overcoming global manufacturing difficulties.

Future work will focus on further enhancing the system's performance and efficiency, including implementing laser-controlled winding systems, exploring reduced-pulley designs and testing and comparing alternative control methods.

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СИСТЕМА ВИРОБНИЦТВА СПІРАЛЬНО НАМОТАНИХ НАДПРОВІДНИХ КАБЕЛІВ

Це дослідження представляє передову систему виробництва спірально намотаних надпровідних кабелів. Розроблена система вирішує критичні проблеми у високострумових застосуваннях (таких як передача енергії, термоядерні реактори та космічні технології), поєднуючи модульну конструкцію з досягненнями точного машинобудування. Вона безпосередньо застосовна для виробництва надпровідних магнітів, необхідних для прискорювачів частинок та систем детектування високоенергетичних частинок. Ключові інновації системи включають регульований механізм керування натягом (з діапазоном 10–20 Н · м), багатоосьову синхронізацію (семиосьове керування рухом) та налаштовувані параметри намотування (кут спіралі від 10° до 75°, діапазон діаметрів 6–25 мм). Виробнича платформа інтеґрує до 16 незалежних натяжних блоків та забезпечує точне керування натягом за допомогою адаптивного механізму керування. Результати тестування пристрою підтверджують здатність системи виробляти надпровідні кабелі промислової якості, мінімізуючи механічну деформацію. Ці технологічні досягнення забезпечують міцну основу для інтеграції системи у великомасштабні інфраструктурні проекти в фізиці високих енергій.

Ключові слова: спіральна обмотка, спірально намотані надпровідні кабелі, кабелі високої потужності, точне виробництво, надпровідні кабелі.