

ADVANCED MANUFACTURING OF SUPERCONDUCTING MAGNETS

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SUMMARY

The development of specialized materials, processes, and robotics technology allows for the rapid prototype and manufacture of superconducting and normal magnets which can be used for magnetic suspension applications. Presented are highlights of the Direct Conductor Placement System (DCPS) which enables automatic design and assembly of 3-dimensional coils and conductor patterns using LTS and HTS conductors. The system enables engineers to place conductors in complex patterns with greater efficiency and accuracy, and without the need for hard tooling. It may also allow researchers to create new types of coils and patterns which were never practical before the development of DCPS. The DCPS includes a custom designed eight-axis robot, patented end effector, CoilCAD™ design software, RoboWire™ control software, and automatic inspection.

INTRODUCTION

The "Direct Conductor Placement System" (DCPS) was developed to provide a low-cost and high precision automated manufacturing process for 3-dimensional conventional and superconducting wire, cable and other conductor forms, and electromagnetic devices. The system allows the fully automatic design and manufacture of complex, multi-layer, and splice free coils. Through the use of sophisticated software design tools and state-of-the-art automation, the DCPS can drastically reduce R&D and product development cycles. The end result is a flexible, cost effective, and high quality process.

The ability to automatically transform coil geometry's into precise wire forms eliminates the need for expensive and complex tooling. Another major benefit to DCPS is that scientists and engineers have greater freedom to design and prototype complex coil and conductor devices. The technology even permits the implementation of design changes at almost any time during the production process.

DIRECT CONDUCTOR TECHNOLOGY

Originally developed at the Superconducting Super Collider Laboratory (SSCL), “Direct Wire” technology as it was called, has been successfully applied to the manufacturing of multipole magnets, such as dipoles, quadrupoles, sextupoles, and decapoles for accelerator applications. At the time, the process involved use of a CNC (computer numeric control) machining center, specially coated wire and substrate, and a special “wiring head” to position and bond the wires. The SSCL team utilized the technique to construct 2.5 Tesla dipole magnets that exhibited excellent performance characteristics.

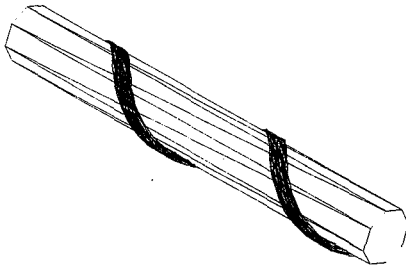


Figure 1. Helical coil directly wound.

The “Direct Wire” technique used a computer controlled coil assembly process to place wires with an accuracy of $\pm 0.025\text{mm}$. Coated wires used in the process were wound on an insulated support tube. Due to the precise placement, a high conductor packing density was achieved. The conductors in the finished wire matrix support each other, and the magnets show outstanding quench performance and random field errors are minimized. Precision manufacturing techniques and advanced material properties are required to build such magnets since wire movements of a few μm are sufficient to initiate a quench in these magnets.

The close-out of the SSCL resulted in license of the “Direct Wire” technology to the American Composites Education, Inc. (ACE) an advanced materials, manufacturing, and technology development firm. The state of the development of the technology was limited to the equipment and resources which were available during the last months of the SSCL. The ACE quickly recognized that for general industrial applications it would require collaboration with companies who had experience in robotics and automated manufacturing. As a result, the Advanced Magnet Laboratory, Inc. (AML) was created to offer a complete manufacturing system which integrates specialized materials, processes, and robotics technology.

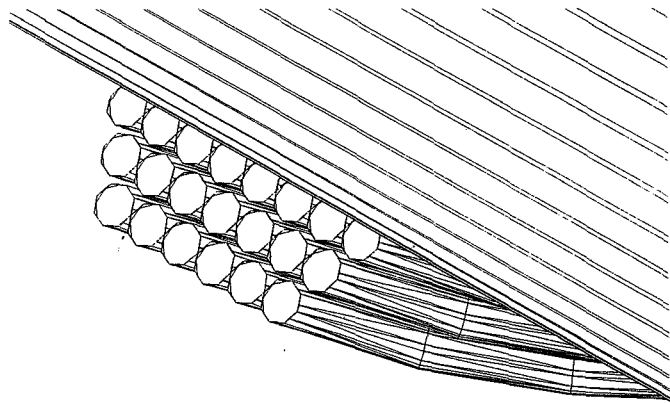


Figure 2. Three layer coil cross-section.

DIRECT CONDUCTOR PLACEMENT SYSTEM

The DCPS includes a custom designed eight-axis robot, patented end effector, CoilCAD™ design software, RoboWire™ control software, and vision inspection. The system is the result of a private collaboration between experts in superconducting magnet design, materials and manufacturing processes, and automation.

Computer Aided Coil Design

CoilCAD™

CoilCAD™ is a complete coil design package, with an easy to use Graphical User Interface (GUI) that runs under the popular Microsoft® Windows™ 3.1 environment. Running on an inexpensive PC, CoilCAD™ is capable of creating 3-dimensional spacial paths for complex and multi-layered conductor forms. Output from CoilCAD™ provides the complete set of robot path and associated control coordinates for the DCPS robot.

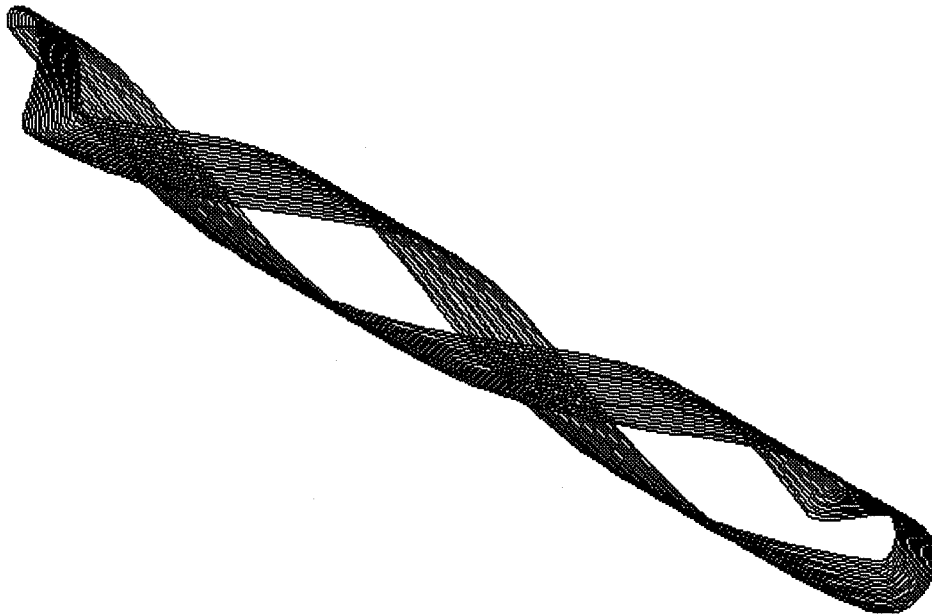


Figure 3. A 3-dimensional spacial curve created from CoilCAD™.

The “Direct Conductor” technique allows manufacturing of precise 2- and 3-dimensional conductor forms. In this assembly process a multi-axes Cartesian robot is used to accurately position and bond the conductor on to a support structure or another conductor layer. The process is ideally suited to the manufacturing of wire, cable and

other conductor-wound superconducting or normal conducting multipole magnets (dipole, quadrupole, sextupole, etc.) needed for accelerators and light sources.

In order to position the conductor in this winding process the 3-dimensional space curve of the conductor path of the coil or conductor pattern has to be defined in order to create the robot path. Even for simple dipole magnets these space curves are rather complex due to the coil ends where the conductor has to cross from one side to the other (see fig. 3). A special software program, called CoilCAD™ has been developed to generate the space curves for a large variety of magnet types and to prepare the coordinate files which are loaded into the DCPS controller and executed by RoboWire™ control software. This software was developed by internationally recognized scientists from the SSCL who are now a part of the AML.



Figure 4. CoilCAD™ Graphical User Interface (GUI).

CoilCAD™ is a menu driven computer program with a powerful GUI. The user specifies the standard parameters of the conductor form to be created, like coil type (magnet, motor or other winding), coil length and diameter, conductor dimensions, and conductor spacing. The user can choose various shapes of coil ends to meet the special requirements of the application. The program generates the 3-dimensional space curve describing the coil geometry. For multi-layer coils the conductors are perfectly nested which is of particular importance for the performance of superconducting magnets.

The complete knowledge of the space curve describing the conductor path in the coil enables a precise calculation of the magnetic field of the coil. Even small effects like layer-to-layer crossings of the conductor and coil lead wires, which are normally neglected in field calculations, are automatically taken into account in this method of field calculation. CoilCAD™ is therefore not only a powerful tool to design magnets for the Direct Conductor process and to generate the coordinate files for the DCPS robot, but also to optimize the magnetic field of magnets with various goals like overall field homogeneity or field strength enhancements in the coil ends.

Direct Conductor Placement System Robot

System Flexibility

The system can be configured to produce round, square, rectangular, hexagonal, or other geometric coils. Flat conductor patterns utilize a vacuum frame for fixturing the coil substrate. Cylindrical patterns are achieved by the use of an additional robot axis for coordinated rotation of the coil support structure. CoilCAD™ allows the user to create or change coil types easily. RoboWire™ control software provides a means for changing or offsetting conductor patterns real-time during the manufacturing process.

Robot Manipulator

The DCPS is designed to manufacture a broad range of 3-dimensional or spacial patterns. The system features include (a) eight axis coordinated Robot Manipulator, (b) patented end effector, (c) RoboWire™ software, (d) vacuum frame table top for flat patterns, (e) rotational tube for 3-dimensional patterns, and (f) real-time vision/video feedback option.

The DCPS robot incorporates eight axes of coordinated control and is capable of placing conductors over a large envelope. The current AML system work area allows placement of conductor over an area of 1.5m X .3m. AML is planning to increase the envelope to 3m to accommodate large helical dipole magnets under development for the Brookhaven National Laboratory (BNL). The eight axes are X, Y, Z, rotation (Theta), support tube rotation (C), conductor feed (A), bonding feedback (T), and drum rotation (D).

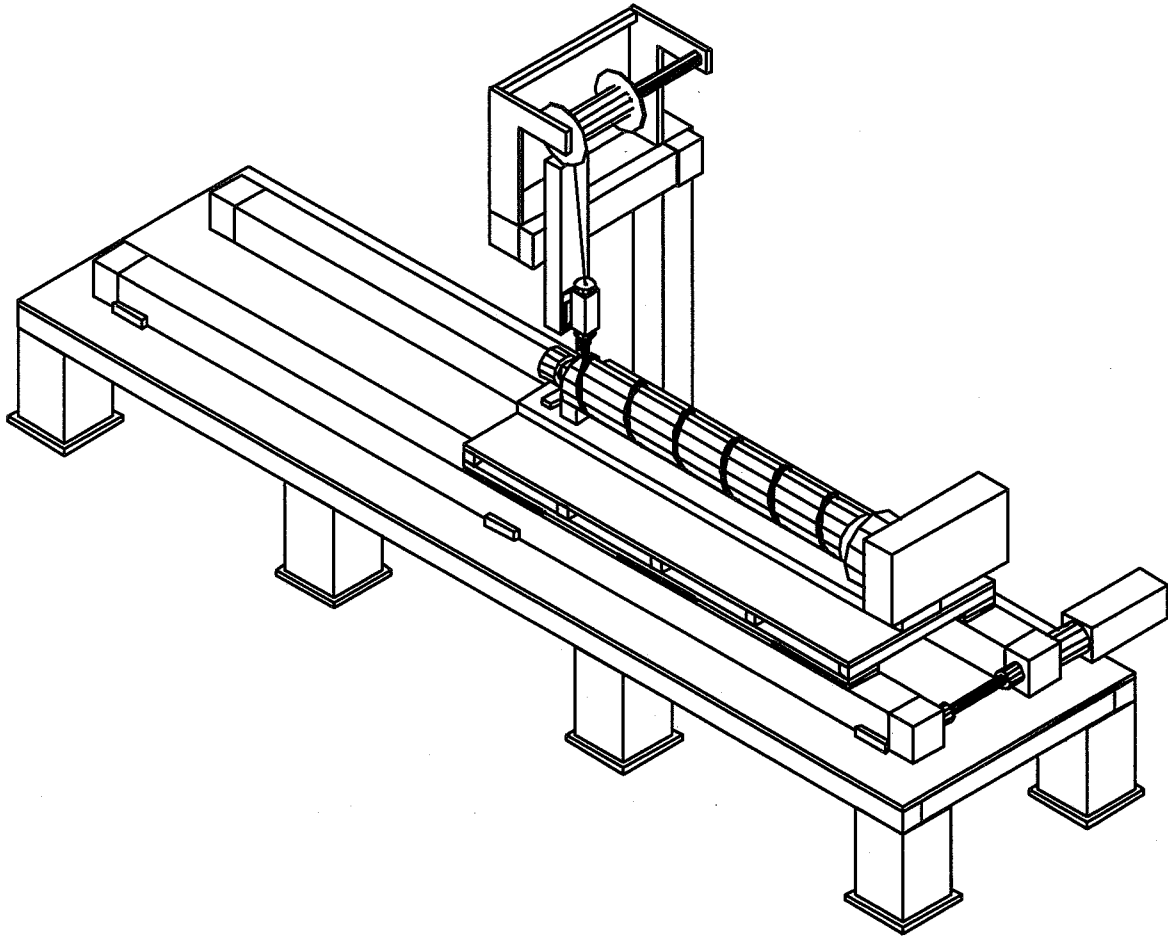


Figure 5. Direct Conductor Placement System.

Table 1. Current DCPS Robot Specifications

| | |
|----------------------------------|------------------|
| X-axis stroke | = 1.5m |
| Y-axis stroke | = .3m |
| Z-axis stroke | = .3m |
| Theta axis stroke | = Unlimited |
| C axis (Tube rotation) | = 540° |
| A axis (Feed) | = Unlimited |
| T axis (Temp control) | = Unlimited |
| D axis (Wire drum control) | = Unlimited |
| Accuracy (X, Y, Z, θ , C) | = ± 0.025 mm |
| Speed Max. | = 254 mm/sec. |

End Effector. This is where the tire hits the road. The development of the end effector is the most critical part of the robot and manufacturing process. The DCPS end effector provides for continuous rotation and real-time feedback of the placement process. The theta axis provides unlimited rotation for the conductor feed allowing the system to follow a circular path. The feed axis controls the amount of conductor to pay out during the conductor placement process. The bonding control allows the system to vary the adhesive process used to bond the conductor. During conductor placement, the specially designed end effector monitors the conductor tension. This is of particular importance in the coil end radii to assure precise conductor placement.

Special end effectors which allow the automatic winding process with controlled conductor tension are presently under development. The end effectors are important, for example, for winding solenoid magnets.

Video/Vision. Live magnified video can be used to monitor the process real-time. This can be especially helpful during the initial set-up and debug of coil patterns. Vision feedback can be used to inspect newly completed runs. The camera rides behind the placement head and looks at the placement of conductor real-time. Good images can be stored to disk and used to compare to those in process.

The vision system (see fig. 6) also allows quality analysis of coil patterns. For example, image analysis could be performed after placement of each conductor layer/pattern. This would prevent the operator from covering a "poor" or defective pattern.

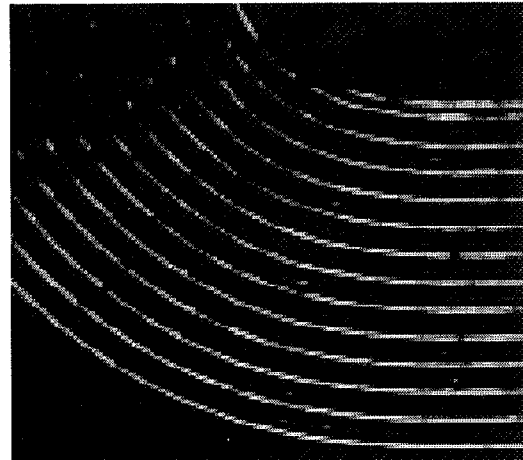


Figure 6. Vision Inspection of Coil.

RoboWire™ Controller

The DCPS controller is built around a standard 486-66 PC, advanced motion controller board, and Micro-PLC machine-I/O control. This provides three levels of dedicated control working asynchronously and simultaneously. Essentially, we have divided up robot control into three dedicated controllers - each with their own processor and firmware. The result is a powerful multi-tasking controller. While RoboWire™ is managing the "system" control, the motion controller can concentrate on motion control and the PLC handles I/O operation.

RoboWire™ SOFTWARE

RoboWire™ provides the overall management of the robot control and includes numerous features for setup, programming, security, peripheral control, factory networking and program execution. RoboWire™ is used as the front-end interface and provides transparent control of the conductor placement process and machine control.

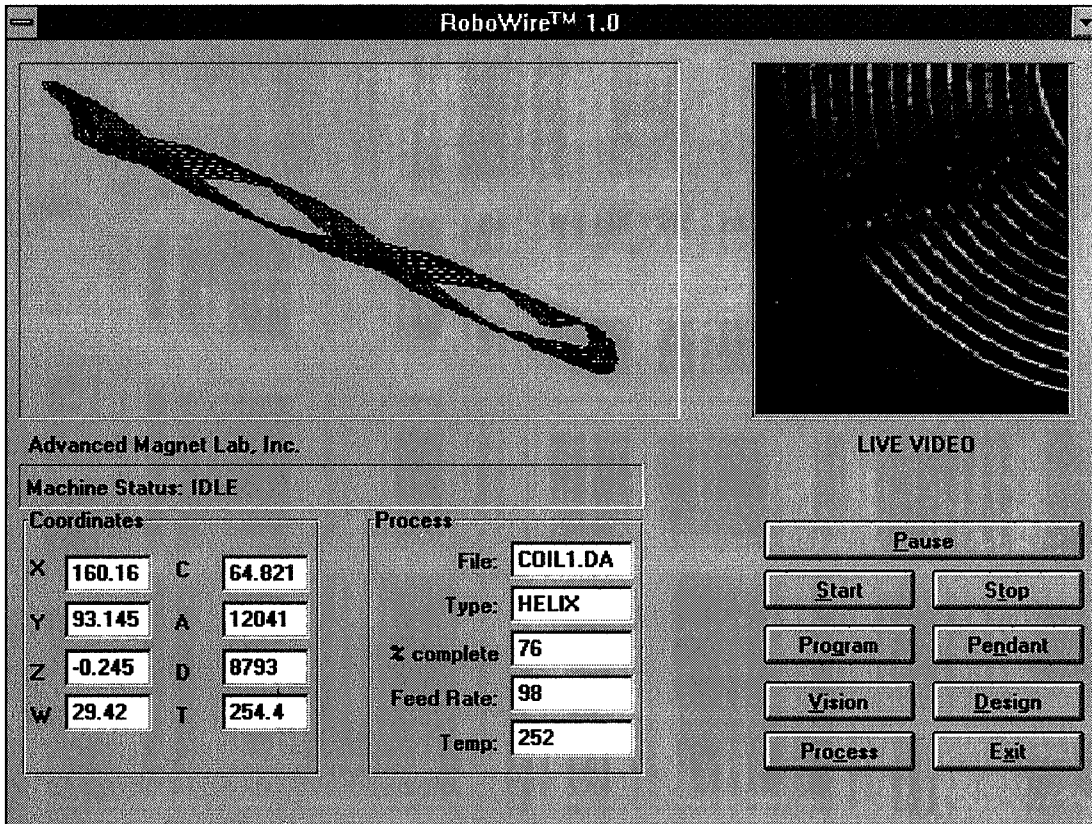


Figure 7. RoboWire™ Control Software Interface.

RoboWire™ is a complete Graphical User Interface (GUI) designed as an easy to use, graphical, motion control package that runs under the popular Microsoft® Windows™ 3.1 environment. Running on a low-cost PC, RoboWire™ is capable of controlling robots with multiple axes using a powerful set of motion control tools. The user interface is fully menu and icon driven and includes full on-line help and documentation. In addition to motion control, RoboWire™ also provides full support for CoilCAD™, binary I/O and serial communications. RoboWire™ also includes capabilities for performing other robotics related functions, such as axis calibration, vision-based inspection and laser calibration.

Bonding Technologies

There are three primary methods currently used for bonding conductors: (a)heat transfer, (b)ultrasonic heating, and (c)direct adhesive.

The **heat transfer** method was used at the SSCL successfully on 3-dimensional coils. It can handle a large variety of conductor types and diameters. Disadvantage of this process is the increased material costs because it requires the conductor to be coated with special adhesive. The **ultrasonic heating** has been successfully implemented for use in manufacturing single layer and 2-dimensional coils. This process has limitations when handling miniature superconducting cables which are made of several strands or large diameter or cross-section conductors.

Direct adhesive provides significant cost benefits to the DCPS technology and this patent pending technology is based upon advanced polymeric materials and process techniques. It also reduces process variables and tooling (end effector) requirements.

APPLICATIONS FOR DCPS

The use of DCPS is already being internationally well received in academia, government, research laboratories, and industry. This includes a broad range of applications such as a variety of superconducting magnets, solenoid magnets, linear induction and other motors, transformers, medical MRI and several proprietary developments.

DCPS Application Examples

Spin Rotators. The Advanced Magnet Lab and Brookhaven National Laboratory are working together to design and build helical “spin rotator” dipole magnets in industry for the RHIC (Relativistic Heavy Ion Collider). Benefits of the DCPS design approach for dipole magnets include: (a)compact coil design to optimize mechanical stability of the conductor matrix, (b)optimized coil-end design keeps peak field in magnet to a minimum, (c)experiences from prototype testing can be easily incorporated.

Particle Storage Ring Corrector and Trim Magnets. The Large Hadron Collider (LHC) presently under construction at CERN; Geneva, Switzerland has very similar technical requirements as the SSCL, where the Direct Wire technique was successfully used. The AML is also collaborating with the BNL to utilize Direct Conductor technology to build corrector coils for the “g-2” project.

MRI Correctors. The DCPS is very adaptable to MRI applications. This could allow MRI manufacturers to directly place coil patterns on MRI tubes. Benefits include greater accuracy in coil placement, higher field qualities, reduced labor costs, reduced tooling and greater flexibility between product variations.

MAGLEV. American Maglev Star, Inc. is working with AML to develop and produce proprietary electromagnetic devices including superconducting magnetic suspension and propulsion conductor forms.

AML has been organized to handle applications that could develop through future programs such as the NASA MagLifter, Holloman Air Force Base Propulsion Sled and others. The DCPS could be used to automatically fabricate the advanced electromagnetic systems required for the smart guideways and magnet systems.

Motors. DCPS is well suited for the development and manufacturing of these applications. Due to the precise conductor placement the weight of such devices can be reduced.

Cornell University. Cornell is currently upgrading the magnet systems for the interaction region of the CESR e^+e^- -storage ring. The required correction magnets are proposed to be manufactured with the DCPS.

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