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AN AUTOMATIC WINDING MACHINE MAKING SUPERCONDUCTING COILS FOR THE LHC CORRECTION MAGNETS

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Abstract

An automatic winding machine has been designed and some experimental tests have been performed in view of the production of 21600 superconducting coils for the LHC correction magnets. The main purpose of this development is to understand the problems related to the automatic winding process and find out the best solution for the required needs.

1 – Introduction

In December 1994 a project aiming to the construction of a large hadron collider (LHC) for elementary particle investigation has been started at CERN . The particle beam is collided through an intense magnetic field generated by large electromagnets.

An agreement[1] has been signed for the development, manufacture and testing of an automatic machine devoted to the production of the superconducting coils for correction magnets. The special demanding of such a machine has been required a design process in which mechanical and electrical parts[2] are studied and developed in close synergy. In particular, the motion control system has been specially designed for the rapid prototyping , and fast reconfiguration of the machine, as one of the fundamental goal of the project was to test and adjust the mechanical properties of the superconducting coils.

This paper describes the mechanical and electrical parts, and the motion control system as well. In particular next section describes the superconducting coil characteristics and parameters, when section 3 shows the structure of the motion control system.

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[1] The agreement n° 424/LHC between CERN and INFN

[2] The electrical and motion control parts of the machine have been developed in collaboration with the Engineering Department of the University of Ferrara

2 – Description of the winding machine

The winding machine has been designed on the basis of the coil geometrical specification listed in the following:

- maximum coil length : 500 mm;
- Coil types : quadrupole, sextupole, octupole, decapole;
- Coil form : double pancakes curved like cylindrical aperture;
- Coil tolerances : within +/- 0.1 mm;
- Superconducting wire section : rectangular, 0.5 to 1.5 mm^2 ;
- Fabrication rate : 6 coils/h;

Figure 1 shows a coil sample photograph, when in picture 2 the winding machine is shown

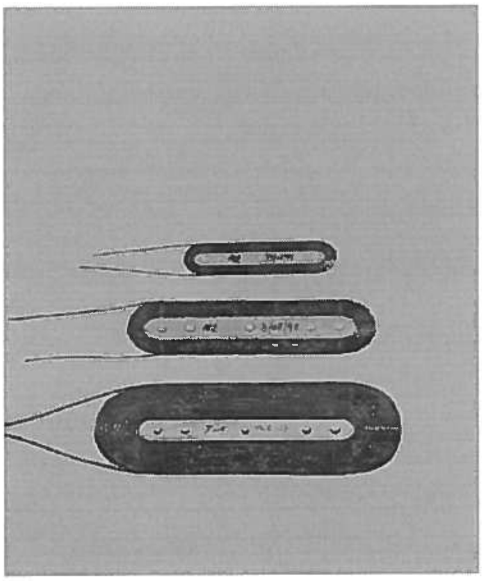

Figure 1: the superconducting coil

In order to optimize the coils production, and therefore to reach the required fabrication rate, the process has been divided in three phases:

1. **Winding.** The coil is formed by winding superconducting wire around a central post. While the winding process an automatic dispenser leaves a film of resin on the wire.
2. **Curing and pressing.** The coil is cured and pressed to make permanent its geometrical characteristics.
3. **Geometric control.** The geometrical characteristics of the coil are checked to assure quality of the final product.

These three steps are described in detail in the following subsections.

2.1 – Winding

The upper and lower layers of the coil are wound at the same time according to CERN suggestion. Two carriages move in the same direction on a guide rail system[3]. A carriage

[3] The guide rail system is produced by the HEPCO SLIDE SYSTEM LTD – TIVERTON, DEVON UK

winds the upper layer of the coil and the other carriage the lower one. The wire is wound on a mandrel around a central post. The mandrel makes two kind of motion: a pivoting and shifting motion. The wire is kept by two pneumatic clampers and a cover. The combined movements between mandrel and carriages preform the winding of the superconducting wire, as described in the following steps:

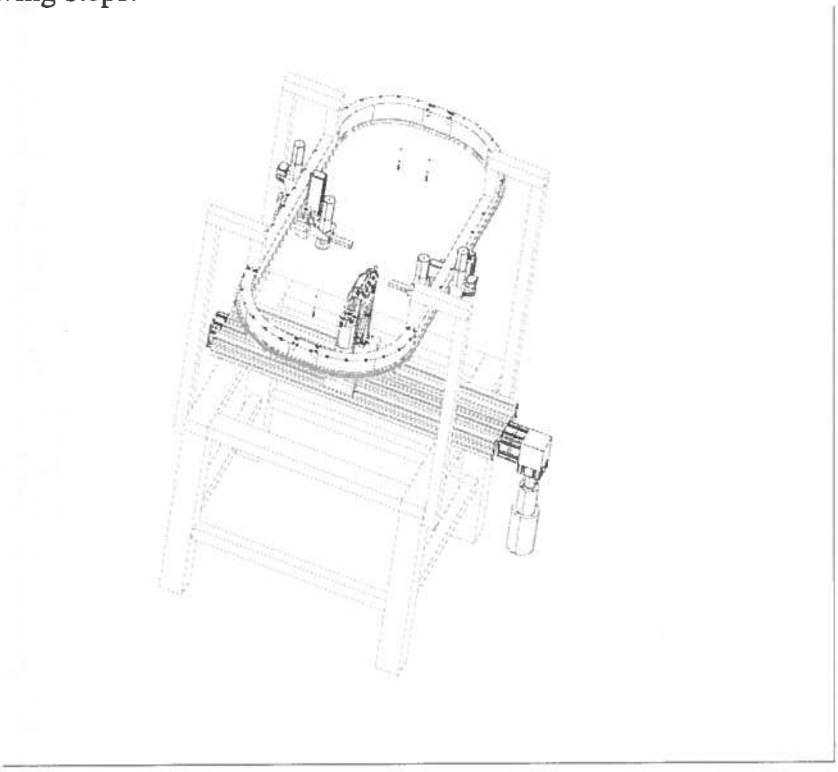

Figure 2 : the winding machine.

1. the wire is kept on the lateral surface of the central post by pneumatic clamper. The two carriages A and B are on the straight line of the wire (figure 3a);
2. the mandrel shifts on the transverse guide and the carriages A and B move on the guide rail (figure 3b);
3. the carriages make an half turn; the mandrel shift back to the opposite stop on the transverse guide (figure 3c);
4. the mandrel moves on the transverse guide and the carriages A and B move on the guide rail (figure 3d);
5. in the last step the carriages and the mandrel complete their turn to reach the machine starting position (figure 3e).

The process stops at the required number of turns. After the winding process took place, the following steps are needed:

1. Insertion of two additional clampers, which give the coil the right lateral shape;
2. Open the pneumatic clampers;
3. Cut the wires from the reels;

4. Disassemble the PTFE mandrel with coil, additional clampers and cover.

The mechanical and electrical design of the carriages has been very difficult, as the carriage

equipment should include in:
- A reel which accomodates the half coil length of each superconducting wire;
- The wire tensioning system given by an open loop constant torque DC-motor;
- Automatic resin dispenser of epoxy bi-component[4];
- The carriage motion system (a brushless motor with driver);
- Sliding contacts permitting electric connection between the carriage and the external power supply and controls.

The design of the mandrel system was less crucial, as the mandrel equipment consists of:

- A pivoting aluminum cylinder actuated by a brushless motor;
- a PTFE (teflon) mandrel assembled on the pivoting cylinder;
- pneumatic clampers (100 N at 6 bars) and cover;
- shifting motion obtained by linear guide and brushless motor.

The controlled axes are in number of six. Each axis is equipped with a DC brushless[5] apart from the tensioning system which uses standard DC motors[6] , a reduction gear, an encoder, power amplifier, switchies. The power required for the motion of each axis is less than 100 W. The maximum axis speed is 7 m/min. The rail guide length is about 3 m and the traverse linear guide length is 1 m . This parameters are a good compromise between the different types of coils and the fabrication rate. The control of the system is detailed in Section 3.

2.2 – Curing

The PTFE mandrel with coil, additional clampers and cover, moves to the curing station and is assembled on a reference support (see figure 4). A controlled pressure system which operates on the mould, allows to reach the final geometry of the coil before sending the current into the superconducting wire. The upper current limit is done by the coil's temperature, which does not exceed 110 degrees centigrade to avoid the melting of the wire's polyesterimide insulation. The PTFE mandrel and the inner PTFE surface of the cover, reduce the thermal conductivity, speed up the process, help in detaching the coil and cleaning the tooling.

The curing station consists of:
- support with two reference pins; they give the precision in positioning the coil and the mould;
- pneumatic cylinder moved by a controlled pressure system (max force 1000 N at 6 bars); it gives the right shape to the coil;
- two pneumatic cylinders (max force 50 N at 6 bars) with pliers; the piers hold and assemble the end caps on the round ends of the coil;
- power supply DC system (0-30 V, 0-40 A) for the wires heating;
- air pressure cooling system which reduces the temperature at 30 degrees centigrade;
- fume hood which eliminates the hurtful vapor of the resin;

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[4] ARALDIT AW 106 and HARDENER HV 953 U (produced by CIBA GEIGY – BASEL CH)
[5] by MINIMOTOR SA – CH Croglio, Switzerland
[6] by MINIMOTOR SA – CH Croglio, Switzerland

The curing process ends after 10 minutes at 100 degrees centigrade. The control of the system is given by a PC with I/O board.

2.3 – Geometric control

After curing, the dimensions of the coil are controlled by a set of micrometers[7] which send the data to a PC through an interface module[8] . The PC is used for data acquisition, comparison, filing and statistic control.

3 The control system

The design and validation of the control system of manufacturing machinery is a difficult job, often requiring time-consuming re-design and set-up adjustment either in the mechanical and electrical parts. In particular, for the development of machinery prototypes, the availability of general platform for the design and validation of the control system leads to costs and time-to-market substantial cuts.

This section details the methodology used in the control architecture of the coil winding machine. The architecture of the control system of the coil winding machine is based on personal computer equipped with some specialized hardware foe motion control and analog-digital signal acquisition. In order to reduce the development time only standard components have been used in the design of the control architecture.

The block scheme of the control system architecture is depicted in figure 5. The system is based on a powerful Personal Computer (PC) with Pentium II processor and Windows NT operating system hosting the development, run time, debugging and the monitoring systems. The use of a standard PC platform gave several advantages with respect more traditional approaches, like using Programmable Logic Controller (PLC) with proprietary architecture. PC systems have greater computational power than PLCs, they can be programmed in well-known high level languages, like “C” and they conform to a de facto standard. Therefore the PC-based control system is not linked to a single proprietary architecture, but is totally open to all the hardware and software products which agree with the PC standard.

The control system is formed by:

- **The development system**. The development system comprises several software tools, which are used to control the operative sequence of the machinery. In the following the development system is detailed.
    - The basic task performed by the designer is to draw the state flow describing the sequential steps which will be performed by the machinery. The stateflow toolbox[9] is a useful package which permits to design graphically the state-transition flow of the machinery.

    The state flow diagram comprises states and transitions.

    The states are correlated with basic operations performed by the machine (move one axis, open a servo valve, heat the coil, etc.). These actions are forced on the machine through a motion control board[10] (axes movements), and a general purpose input-output board[11] (on-off actuators). The hardware boards come with proper software drivers which allow complete hardware control using a “C” interface.

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[7] DIGIMATIC 10C absolute - MITUTOYO
[8] DIGIMATIC 264 - MITUTOYO
[9] by the Mathworks Inc.
[10] by Baldor Inc.
[11] by National Instruments Corp.

The conditions are tests performed on actual values of input sensor signals, both analog and logical, which enable or disable transitions between subsequent states. The signals are collected by the input-output board.

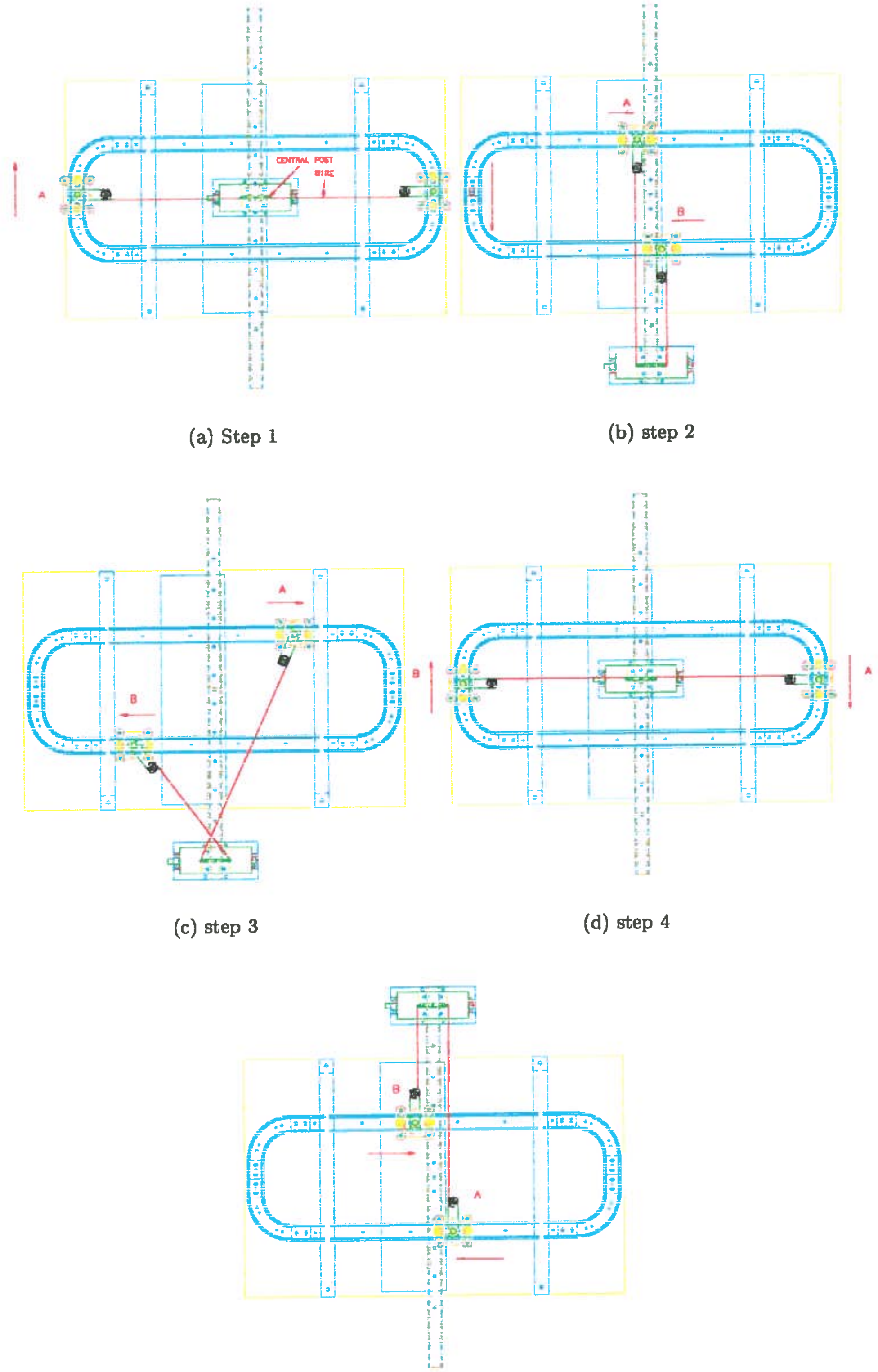
The graphical description of the machinery state-transition flow is translated automatically into "C" code by the *State Flow Coder* and *Real Time Workshop*. This source code is then linked with the hardware device drivers to obtain the executable code.

In this way the design and the subsequent adjustments of the control code are easy and quick. The described development system tools required as operating system Windows NT[12] .

- **The run time system.** The run time system task consists of running the control code generated by the development system. The real time constraints of the machinery control system are not satisfied by windows NT, therefore the Hyperkernel real time kernel for windows NT has been chosen as run time system. Hyperkernel works as a layer between hardware and windows NT, allowing an easy integration between non-real time applications (development and debugging systems), real time applications (run-time systems) and specialized hardware (motion control and I/O).

- **The debugging and supervision system.** The operative conditions of the machinery are steadly monitored by the debug and supervision system which is built around the Matlab packages.

[12] By Microsoft Corp.



(a) Step 1

(b) step 2

(c) step 3

(d) step 4

(e) step 5

Figure 3 – Winding steps.

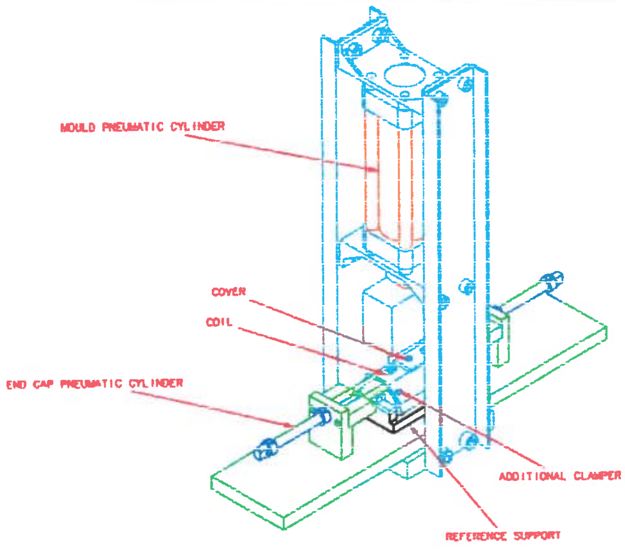


Figure 4: The curing equipment.

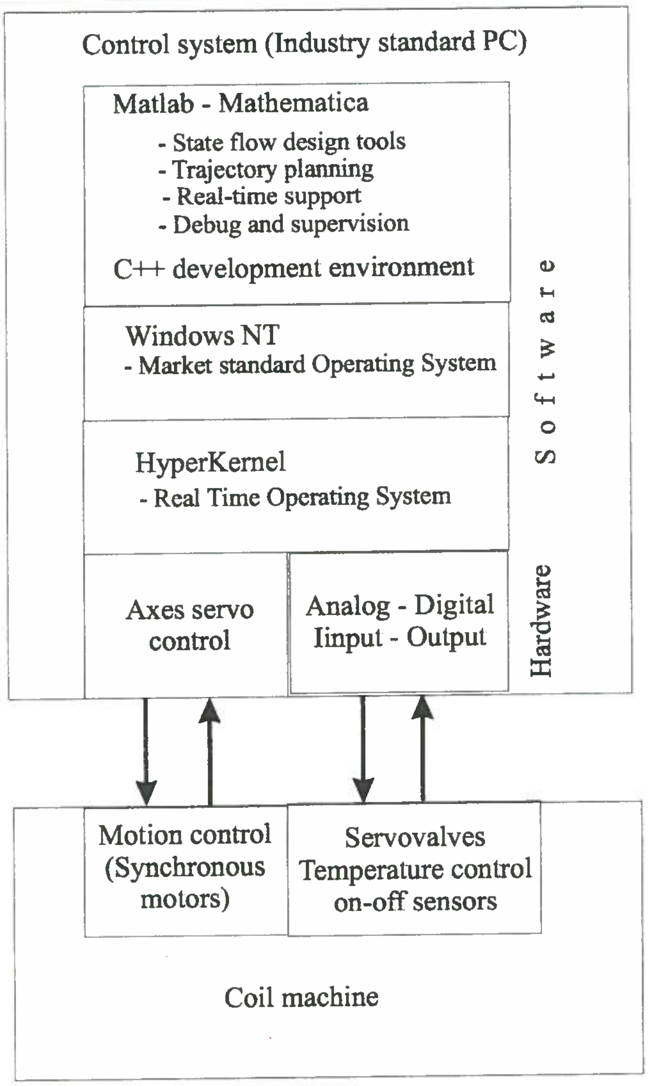


Figure 5: The block scheme of the control system of the coil winding machine.