AUTOMATION OF 3D MEASUREMENTS FOR THE FINAL ASSEMBLY STEPS OF THE LHC DIPOLE MAGNETS

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1. INTRODUCTION

Due to the mechanical and beam optics requirements, the geometry of the LHC dipole cold masses is submitted to very tight tolerances (few tenths of millimeters) over the magnet's length (more than 15 meters). Different parts of the cold mass have to be either measured or properly positioned throughout the assembly (see reference [1]), implying the use of a portable system. The measurement system needs to be controlled by adequate software in order to allow data acquisition and data analysis so as to keep under control, in an efficient and reliable way, the real geometry of the dipole during the cold mass assembling. The only systems having all the necessary functions and responding to all precision requirements are based on optical methods as the interferometric (IFM) laser tracking and absolute distance measuring (ADM) techniques. A laser tracker combining these two techniques was chosen to perform the geometrical measurements related to the cold mass assembly: Leica LTD500 with its associated software Axyz.

The production of the 1232 cold masses has been shared by three different manufacturers. Considering the number of cold masses to be produced (series production) and the complexity of the assembly operations it was necessary to develop a script that commanded the 3D measuring system, restricting its functionalities to the ones used during the cold mass assembly. The goal was to homogenize the production, increase the speed of the manufacturing and minimize human errors.

The DGM[2] is a Visual Basic script developed at CERN. It pilots all the assembly operations and allows a complete automated treatment and analysis of data.

2. THE FINAL STEPS OF THE COLD MASS ASSEMBLY

The cold mass geometry is determined by means of a measurement routine called "mid-plane measurement" that, followed by a data analysis, allows to link the cold mass shape to a virtual theoretical shape, defined with respect to an arbitrary (fixed) theoretical reference coordinate system. Once the cold mass geometry is known with respect to the theoretical reference system, all the cold mass components can be aligned in the cold mass with respect to their theoretical position.

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2.1. The cold mass theoretical reference coordinate system

The theoretical coordinate system is an orthogonal right-handed system (see Figure 1). Its origin is located at the intersection between the connection end cover's plane, "C", with the theoretical central geometrical axis, "W". The "Y" axis is passing along the cold mass and trough the intersection of the end cover's plane on the lyre side and the "W" theoretical axis (see reference [1])

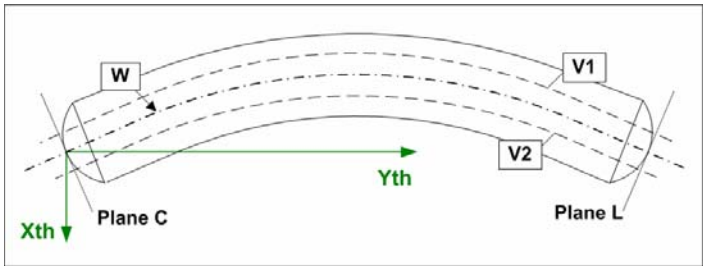

Figure 1: The cold mass theoretical reference coordinate system

V1 and V2 represent the theoretical axes of the cold mass cold bore tubes (CBT)

2.2. The mid-plane measurement

The geometry of the cold mass is defined as the geometry of the cold mass cold bore tubes (CBT). To determine it, a mechanical mole travels through the tubes carrying a reflector whose position is measured by the laser tracker. In order to get the maximum precision, both CBT are measured from both sides of the magnet resulting in four different sets of measurements, each obtained from a different position (called station) of the laser tracker (see Figure 2). Since the measurement of the CBT requires the displacement of the measuring system with respect to the cold mass, an external reference system is necessary to link the four different stations. This system is composed by eight external fixed points (called "network points") distributed around the cold mass and equipped with reflectors. The position of the network points is measured before each CBT measurement. A bundle adjustment[3] is performed on the different sets of measured points (each measured from a different position of the laser tracker). Fitting the network points measured from the second (third, fourth) position to those measured from the first position allows linking the second (third, fourth) station to the first one (see Figure 2).

[3] The bundle adjustment is a least square optimization. It takes the "bundle" of measured points and makes successive adjustments to the network parameters until there is a best fit between the mathematical model of the network and the actual measurements.

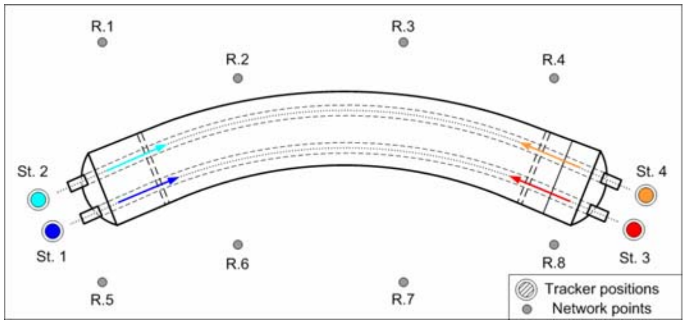

Figure 2: Top view of a cold mass with tracker positions and network points

Once this operation (called “orientation”) is done, it is possible to refer the measured data from the different stations to a common coordinate system created in station 1.

2.3. The analysis of data

Once the measurement procedure is finished there are four sets of measurements that correspond, two by two, to each aperture of the cold mass. The data analysis consists in fitting the measured geometry of both apertures to their theoretical shape. The theoretical geometry of each aperture is well known and can be linked to a previously defined (unique) coordinate reference system, so on called “theoretical coordinate reference system”. The fitting operation allows referring the measured geometry of the cold mass to the mentioned theoretical coordinate reference system, hence the deviation of each point with respect to their theoretical position

2.4. The alignment of the cold mass components

The assembly tolerances of the dipole cold mass (see reference [1]) require the use of the LTD500 measuring instrument during the positioning of the different components of the cold mass. In order to allow the positioning measurements, several pins have been very precisely machined either on the component itself, or on its physical support. These pins hold the reflector measured by the laser tracker during the positioning operations.

Once the geometry of the cold mass is linked to its theoretical shape, the different components of the cold mass can be referred and therefore positioned with respect to their theoretical nominal position.

3. HARDWARE

3.1. The LTD500

The instrument responding to all requirements is a LTD500[4] Laser Tracker measuring system. The tracking interferometer follows and measures the position of a reflector. The tracking head rotates around two orthogonal axes. Each axis has an encoder and a direct drive DC-motor to allow remote-controlled movements. The sensor unit contains a laser interferometer to measure distance differences. Via the tilting mirror, attached to the intersection between the

[4] Made by Leica Geosystems

two tracker head axes, the laser beam is sent to the reflector, placed on the point to be measured. A photo sensor beside the interferometer receives a portion of the returning laser beam, which enables the tracking. To achieve absolute distances, the operator must start by positioning the reflector at a point whose absolute distance from the measuring head is well known: the tracker's home position[5]. When the laser beam is interrupted during any measurement, the beam is no longer reflected back into the tracking head and the interferometry is lost. In this case, the high precision infrared absolute distance meter in the tracker allows continuing the operation. Equally, a measurement can be started by ADM at any point and continued by tracking, using IFM. The LTD500 allows the measurement of a moving target, called dynamic mode, but the measurement accuracy on a target at rest, called static mode, is twice as high (see reference [2]).

3.2. The PC configuration

A PC is necessary to operate the LTD500 on which an application program, named Axyz[6] is installed. Axyz operates under Windows™ environment only. The Axyz program is using the NetBios protocol to communicate with the LTD500.

3.3. The mechanical mole

Since the measurements have to be performed inside and along the CBT of the dipole cold mass, a mechanical mole is used to hold the reflector, target for the measurement. The reflector is centered in the mole, which is mechanically centered inside the CBT.

3.4. The motor

A DC motor combined with electromagnetic clutches, linked to the mole by a cable, is used to pull the mechanical mole in the CBT. The electromagnetic clutches allow the operator to choose and to control the mole displacement direction.

3.5. Data Acquisition (DAQ) Card

The measuring system uses a PCI-MIO[7] card to control the movement of the motor. A rack with electronic devices has been designed at CERN to give the power to the motor according to the input voltage given by the DAQ card.[8]

4. SOFTWARE

4.1. Axyz

The measuring system includes a software package, called Axyz, which can be used for large-scale 3D metrology. Axyz is a modular program, containing a Laser Tracker Module (LTM), a Core Data Module (CDM) and a graphical module called CAD module. Axyz is very

[5] The laser tracker's home position is a point (called "Birdbath") attached to the instrument head and which is calibrated together with the system.
6 Made by Leica Geosystems
7 Made by National Instruments
8Card and driver from National Instrument™

flexible for implementation and users can configure different measuring sequences, related analyses and calculations. Axyz can also be programmed directly via OLE[9] commands.

In case of a serial production it is important to reduce the measuring time as much as possible and to simplify the procedure. This way, the measurements can be done by standard qualified operators, but guaranteeing the same measurements accuracy and reliability. Programming into Axyz allows to reduce the possible errors made by operators, to assure the reproducibility of the measuring technique and measuring sequence in the three industrial sites of the series production and helps the operator to follow correctly the different 3D measurements-assisted steps of the final assembly.

The development of the program can be made in standard programming languages, such as Visual Basic™ (VB) or C++. Axyz knows high and low level OLE commands. The low-level commands are capable to run a function alone, while a high-level command needs the intervention of an operator. For the adaptation of Axyz to our specific application we have chosen VB as programming language. When an OLE command is sent, the control returns immediately to VB. As soon as the tracker operation has finished, the LTM sends out a message.

As the dedicated program requires a full control of the automation, all automated sequences included in Axyz software must be disabled.

4.2. Message Blaster

The MessageBlaster32 is an OCX[10], designed to handle Windows Messages easily in VB program. It is possible to use it in 32bit VisualBasic6. To use Message Blaster with VB, a “MsgBlst32 OLE Control module” should be added. Once the MessageBlaster32 OCX is inserted, it is possible to watch for designated Windows messages. When a specified message arrives, the MB32 fires “Message” event, which can be easily handled in the VB program

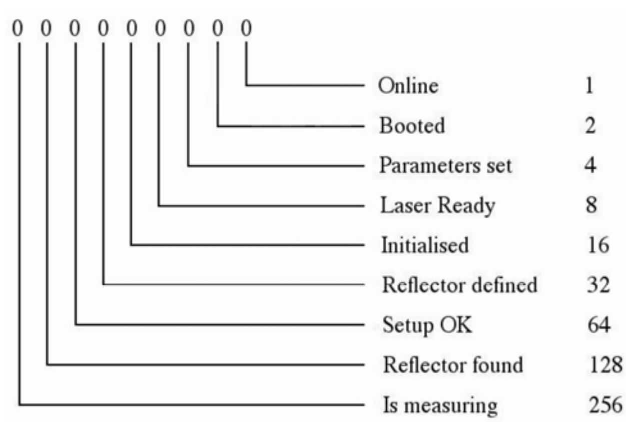

Figure 3: The LTM status message

[9] Object Linking & Embedding
[10] OLE Custom Control

Note that each message contains two fields of information. One field returns the name of the function. A second field gives the status of the instruction. Figure 3 shows the structure of the status field of the message that LTM is giving.

4.3. National Instrument Data Acquisition (NI-DAQ) Driver

The NI-DAQ driver that is installed on the PC allows controlling the DAQ card. The card has to be configured to use both analogue and digital input and output channels. VB commands exist to manage all configured devices.

5. THE DIPOLE GEOMETRIC MEASUREMENT SCRIPT

The DGM is the VB script that pilots the geometry measurements performed along the cold mass assembly process and executes the necessary treatment and analysis of data. The aim for the conception of the script was to simplify the assembly process and reduce the measuring time as much as possible. By integrating the script into the assembly procedure, the measurements can be done by standard qualified operators but the measurements accuracy and reliability is guaranteed. Since the treatment and storage of data is as well completely automated, the origin and the quality of the data are also guaranteed.

Figure 4 shows the assembly operations guided in an automated way by the script. The mid-plane measurement and the data analysis are automated and provide the theoretical reference coordinate system that will be used for the alignment of the cold mass components. The relevant geometric data generated by each assembly operation will automatically be stored by the script for its later transfer to CERN.

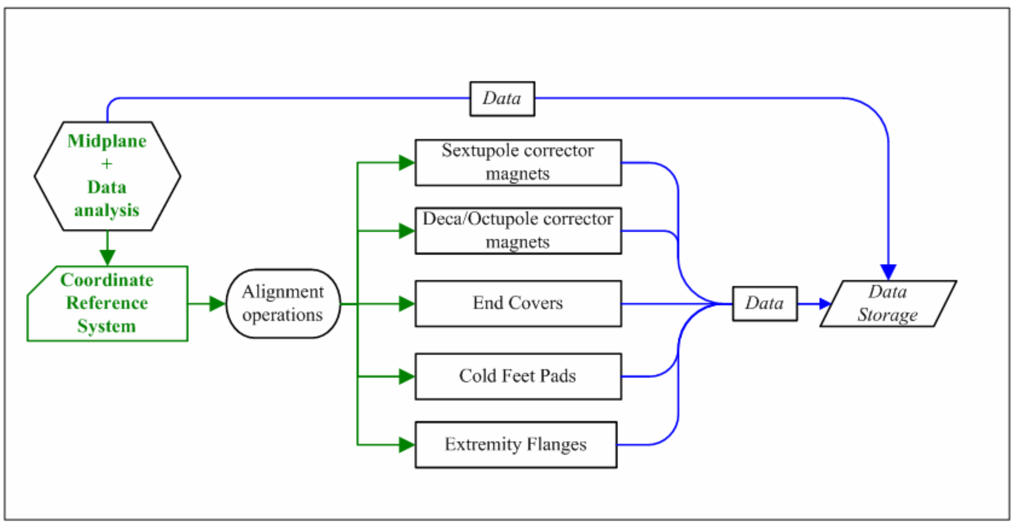

Figure 4: Ensemble of operations guided by the DGM script

5.1. File creation with the DGM script

For the creation of a new measurement file, the script asks the operator to give the identification of the cold mass and the stage of assembly. The script classifies and name the file depending on the information provided. All the relevant Axyz modules are automatically opened and the tracker is initialized.

5.2. The database for the DGM script

As it has been exposed in Chapter 2.2, an external fixed network is needed in order to link the measurements taken from different positions of the measuring system. After a bundle operation, the measurements are expressed in the same coordinate reference system. This operation is needed as well for each of the alignment measurements. In addition, in all the cold mass components (or in their physical supports) several reference points have been defined to identify their position. These points are measured repeatedly until the correct positioning is reached.

A database has been created mainly to save time when measuring fixed or known points. The software knows where to find these points (and consequently, the reflector) from each of the predefined tracker positions. The DB, made in Access™, contains all the fixed or known points used during the cold mass assembly. It is created by making a first manual measurement of each point. Once the DB is created, the script allows locating and measuring each of these points in a complete automated way, without the intervention of any operator.

5.3. The mid-plane measurement in the DGM script

When starting the module of the mid-plane measurement, a configuration window allows the operator to enter the approximate length of the magnet. By using this parameter the script stops the mole before it reaches the end of the CBT. The same window allows the user to define the minimum required measurement accuracy (e.g. 6ppm). The program repeats the measurement until this minimum accuracy is achieved or the maximum number of repeated measurements (input from user) has been reached.

Before starting the measurements, the operator must set the motor parameters, voltage and running time. These determine the distance between two adjacent measurements inside the CBT.

When the user clicks on the "Start" button, the program automatically goes to the first point to be measured in the tube, previously measured and saved in a DataBase (DB). The "Go Location" function is used to take this first point. The VB program, through the DAQ card, makes the motor run to pull the mole to its next position. In order to get the best achievable accuracy, the measurements are made with the IFM in stationary mode. The ADM mode is used when tracking the reflector is not possible. The script detects when the measuring beam is cut and sends the beam back to the last point measured, in order to find the reflector. Since the CBT is only slightly curved and the distance between two measured points does not exceed 500mm, the reflector is found even if the motor already pulled the mole to its next position. At this moment the tracker is asked to use the ADM and to set its initial distance.

The principle of the mid-plane measurement has been described in Chapter 2.2. Using the DGM script, the measurement process is performed as shown in Figure 5

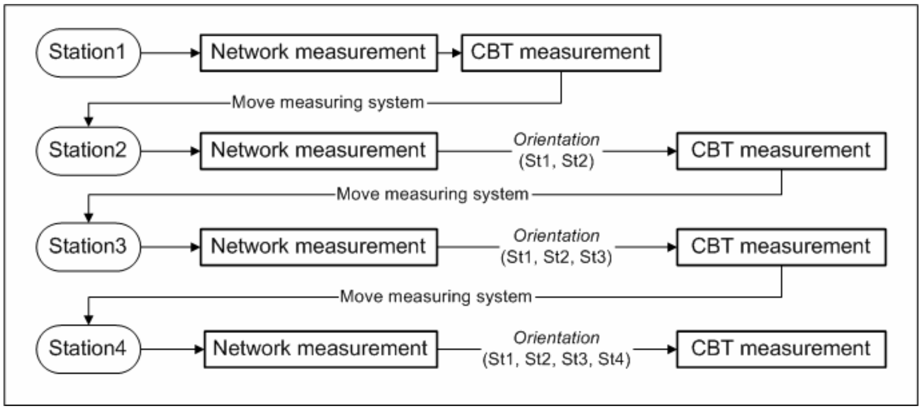

Figure 5: Flowchart of an automated mid-plane measurement

All the measuring operations described in Figure 5 have been automated and the saving in time during this measurement process is of 60% with respect to the manual measurement. The mid-plane measurement is performed at least three times during the assembly.

5.4. The analysis in the DGM script

Once the mid-plane measurement is finished, the script launches automatically the data analysis module. The analysis procedure described in Chapter 2.3 is performed without any manual intervention using an interface written in Labview^{TM}. Since there is no manual data manipulation, the correctness of the analysis is guaranteed. The saving in time for the analysis of data is of 80% with respect to the manual analysis.

5.5. Positioning modules of the DGM script

Each positioning module of the script has been conceived to simplify the alignment operations of all the cold mass components. The alignment consists in the positioning of each element with the best possible accuracy into its theoretical nominal position.

The position of each element is represented by the position of a relevant point of the component that, in most cases does not exist physically. The alignment is done therefore with the help of some secondary points (very precisely machined) used as references. Once the position of the reference points is referred to the theoretical reference coordinate system, the position of the relevant point (and therefore that of the element itself) can be easily deduced by geometric calculations.

The location and measurement of all points (included the network points, when they are needed) is automatic since they can be included in the data base. Once all points have been measured, the script performs automatically the necessary calculations so that the alignment can be done using directly the relevant point of each component. The DGM guides the alignment operations with the help of graphical views in which all the measured and calculated points are represented, providing simultaneously the acceptance criteria based on the tolerances.

All the cold mass components (sextupole and deca/octupole spool pieces, end covers, cold feet pads and extremity flanges) can be aligned by using the DGM script.

The intervention of the operators is therefore limited to the physical positioning of the component searching the ideal position suggested by the script with the consequent saving of time. Since the theoretical position of each element is also provided by the script there is no possible error due to calculations.

5.6. The storage of data in the script

During the full assembly of the magnet, the relevant information about the cold mass shape and components are kept in an encrypted file that is automatically filled in by the script. As soon as the assembly is finished and the encrypted file is completed with all the assembly data, the script extracts the information contained in the encrypted file and copies them to an Excel write-protected file called "traveler". The traveler file contains all the information concerning the geometry of the cold mass and is evaluated at CERN for acceptation or rejection of the cold mass.

6. CONCLUSIONS

The cold mass assembly process has been implemented with an automated script that pilots all the assembly operations in order improve the efficacy of the process. There is a significant time reduction in all the assembly measurements (more than 60% for the mid-plane measurement, which is the longest and complex of all assembly measurements)

The repeatability of the measurements is improved and there is no more need of a high-qualified operator. Human errors during the assembly have been minimized as well, since all the calculations are automatically done by the script.

Given that the dipole cold mass production is going to be completed in 3 different industries in Europe, this automated process assures homogeneity in the measuring and assembly techniques.

The script controls the storage of the relevant geometric data obtained during the assembly measurements. At the end of the cold mass assembly it automatically creates the file containing all the geometric data that will be transferred to CERN for acceptance or rejection of the cold mass. The origin and the quality of the data transferred to CERN are therefore automatically guaranteed.

7. ACKNOWLEDGEMENT

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References

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[2] "Axyz System concepts and procedures", Leica Geosystems A.G.