Data Acquisition and Management in the Calibration Processes of the CMS Barrel Muon Alignment System

Z. Szillási[1], Gy.L. Bencze[3,4], N. Béni[1], J. Imrek[2], J. Molnár[2], D. Novák[2], P. Raics[1], Zs. Szabó[1], G. Székely[2]

[1] Institute of Experimental Physics, University of Debrecen, Debrecen, Hungary
[2] MTA Atomki, H-4001 Debrecen, Pf. 51, Hungary
[3] Institute of Particle and Nuclear Physics, Budapest-114, Pf 49, Hungary
[4] CERN, CH-1211 Geneva 23, Switzerland

Abstract

In order to be able to match correctly the track elements produced by a muon in the Tracker and the Muon System of the CMS experiment [1] the mutual alignment precision between the Tracker and the Barrel Muon System must be no worse than 100-400 micrometers depending on the radial distance of the muon chambers from the Tracker. To fulfill this requirement an alignment system had to be designed. This system contains subsystems for determining the positions of the barrel and endcap chambers while a third one connects these two to the Tracker. Since the Barrel muon chambers are embedded into the magnet yoke of the experiment a non-conventional alignment method had to be developed. In this paper we restrict ourselves to the Barrel Alignment System and the calibration methods of its components.

I. THE BARREL MUON ALIGNMENT SYSTEM

The CMS Barrel Muon Alignment System (Fig. 1) is based on an optical network of LED light sources and video-cameras. The full system contains very large number of cameras (approx. 600 pcs) and LEDs (approx. 10000 pcs). Overwhelming part of these LEDs are mounted on the 250 barrel muon chambers while the cameras observing these LEDs are mounted on rigid structures called MABs (Module for Alignment of the Barrel). The MABs (36 pieces altogether) are fixed on the iron yoke of the magnet. Furthermore, there are about 300 LEDs and 100 cameras making direct connections between the MABs (called diagonal connections). Finally there are 6 long carbon-fiber bars located inside the barrel muon system containing in total 144 LED light sources allowing direct measurement of the Z coordinates of 24 MABs (where Z direction in the experiment corresponds to the direction of the proton beam path).

The results of individual measurements are the positions of the centroids of the images of the LEDs measured by the cameras. In order to be able to reconstruct the positions of the muon chambers additional data -in addition to the measured centroids- is required. These are the parameters of the cameras (magnification, and tilt angles of the sensor with respect to the optical axis of the camera, sensitivity and homogeneity of the video-sensors of the cameras) and the positions of the LEDs on their holders. Also, the positions of the cameras and the LED holders in their embedding objects (muon chambers, MABs, Z-bars) are also needed. These additional data are obtained by the calibration of the elements.

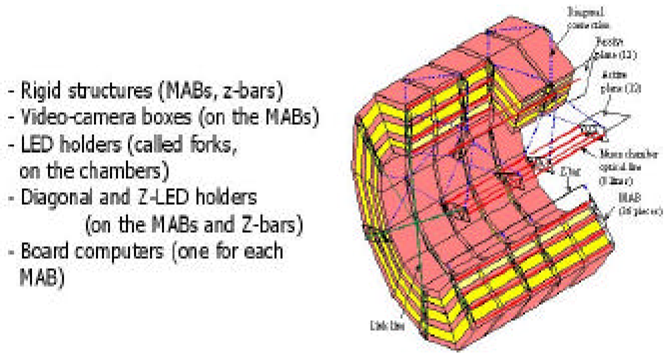

Figure 1. CMS Barrel Muon Alignment scheme

II. CALIBRATION OF THE COMPONENTS

The main requirement on the muon chamber alignment precision is in the range of 100-400 microns. Since this value depends also on the calibration precision of the components, the calibration methods had to be established such that the resulted precision of the full system could meet the above mentioned requirements. The individual calibration steps of the light source-related objects are the LED holder calibration and the barrel muon chamber alignment calibration, while calibration steps of the camera related objects are the camera quality control, the camera calibration and the MAB calibration.

A. *Light source related objects*

As it is mentioned above the basic components of the Barrel Muon Alignment System are the LEDs and the cameras. Individual LEDs are grouped into mechanical structures called LED holders containing 10 (for DT chambers), 3 (diagonal LED holders) or 6 (Z-LED holders) LEDs according to the measurement type.

During the calibration process positions of the LED centroids in the frame of the LED holder are determined. The optical network requires most of the LED holders to be observed from both sides. This can be solved by introducing an auxiliary frame of reference which can be seen from both sides. Technically, this is a calibration tool containing multimode optical fibers illuminated by noncoherent light sources and shining into both directions. Positions of these light sources are measured in a high precision metrology lab and produce light distributions similar to those of the LEDs to be measured. Since the light spots are observed by cameras there was a requirement to exclude geometrical distortions and the error on centroid calculation caused by the un-even gain on the sensor surface. This has been solved by mounting the calibration tool (and therefore the LED holders) on a precise two-dimensional moving table and by constructing a successive method for moving all the centroids to a predefined position on the sensor surfaces. Therefore LED positions correspond to the position readouts of the moving table.

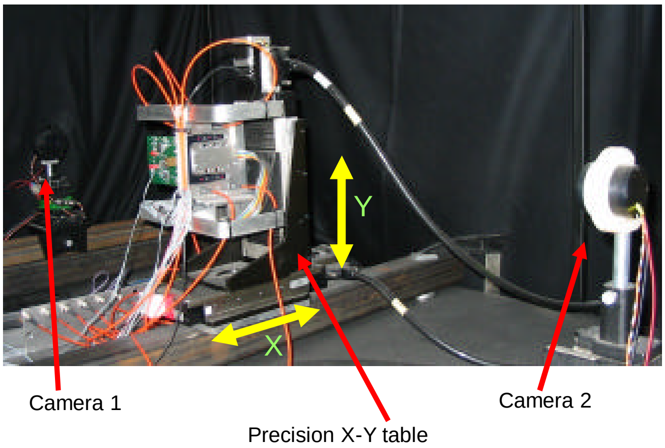

Figure 2. Calibration bench for the LED holders.

As the amount of LED holders is very large (>1200 pieces) a highly automated measurement method had to be developed. Both the successive centroid measurements and the control of the moving table and the LED holders are computerized. The operator only has to change the LED holders, identify it and start the measurement. The successive status then can be monitored on the computer console.

Also due to the large number of LED holders an effective way of data handling and storage had to be developed. For such a large number of data (five complete measurements of all the LED holders ~ 100 k lines of raw data + 20 k lines of analyzed data) the use of a commercially available database solution is inevitable. Our team decided to use MySQL because it supports all the programming languages used in this calibration process under all operating systems. This database server also had an advantage because its installation requires only a moderate disk space and it is also freely available for research purposes. For data security reasons measurements are recorded as ASCII files which are automatically uploaded as the measurement finishes. Therefore one can assure to have two identical copies of the raw data and in case of critical failure of the database server data can be recuperated by using the same method used for synchronizing the database to the ASCII files. However, storage of data in a relational database provides a very easy way to compare the individual measurements therefore pinpointing any measurement errors based on statistical methods. This statistical analysis and the data recuperation are done by web-based Perl scripts allowing the access to the data from virtually everywhere without the need for special data handling software.

Calibration methods of the diagonal and Z-LED holders are very similar to that of those ones described above.

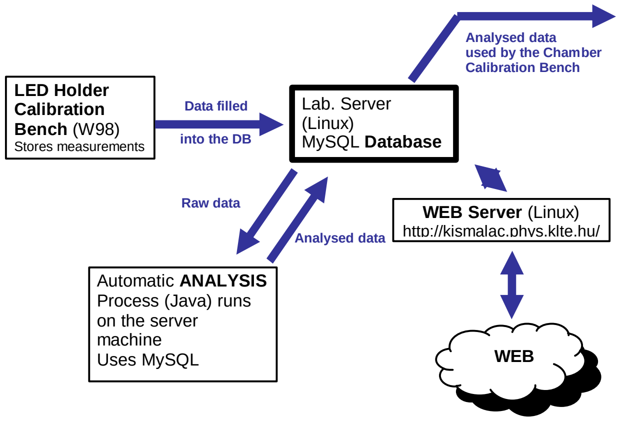

Figure 3. Data flow during the LED holder calibration [5]

The main goal of the alignment system is to locate the anode wires of the muon chambers with respect to the Tracker.

Muon chambers have a construction which doesn't allow the observation of their anode wires after construction. This construction doesn't allow either to determine the LED holder's position with respect to the wires during chamber building. To overcome this problem the following technology has been developed:

1. During construction position of every anode wire (approx. 400 per chamber) is measured during the construction with respect to mechanical reference objects known as corner blocks mounted on each corner of a muon chamber's Super Layer [2] (4 pieces per Super Layer). Since a muon chamber consists of two or three Super Layers depending on its type, a muon chamber can have eight or twelve corner blocks in total. These corner blocks serve as position references.

2. Since the position measurement of the LED holders is based on a centroid measurement while positions of the corner blocks can be determined by standard survey techniques (photogrammetry) an additional calibration bench had to be built. Here the corner blocks can be located by photogrammetry and the LED holders mounted on the chambers can be measured by cameras with pre-calibrated (known) positions with respect to the calibration bench. For this pre-calibration a specially designed calibration plate containing both optical fiber light sources and target holes for the photogrammetry is used. Internal parameters of these plates could be determined by a metrology laboratory. During the pre-calibration of the chamber bench these plates are localized by photogrammetry while a simultaneous measurement of the optical fibers has been performed by the cameras. A geometrical reconstruction is able to recuperate both the camera positions and their internal parameters needed for a correct measurement of the LED holders.

3. Applying mathematical transformations the positions of the LED holders can be determined in the chamber's frame. As a byproduct the localization of all the Super Layers in the chamber's frame can also be performed.

The number of muon chambers to be measured was 264, therefore this calibration step also requires a reliable data handling strategy. Since during LED holder calibration the previously mentioned strategy has proved its strength a similar system has been built: data are stored primarily in ASCII files and later uploaded automatically into a MySQL database. As soon as the data are uploaded a data analysis could be started on the survey data to determine the chamber's internal parameters. This calibration process is equipped with a Perl-based web reporting system.

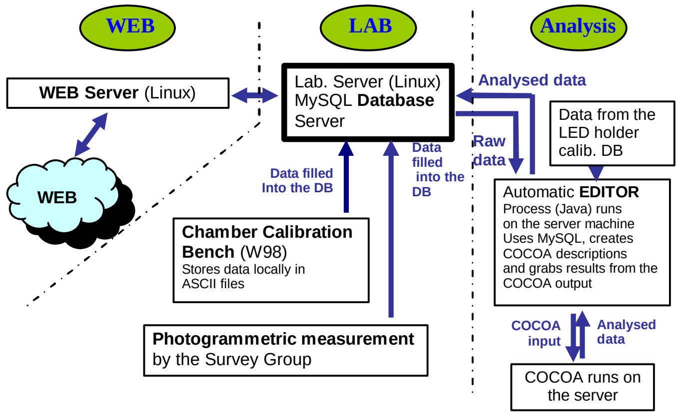

Figure 4. Data flow during the muon chamber calibration

The reporting system is also able to perform a fast check on the LED holder centroids. It fits the LED holder calibration data to the centroids recorded during chamber calibration. Despite the fit is done only in two dimensions (this is much faster than trying to fit the values in 3-D) it is enough to pinpoint if the centroid recognition fails and accidentally identifies a reflection as a direct spot.

B. Camera –related objects

The second most fundamental devices in the Barrel Muon Alignment System are the cameras. The number of these devices is in the range of 600, therefore only a cheap device could be taken as an economically reasonable solution. As a result a very cheap black-and-white one-chip video sensor has been chosen. However, to ensure the reliability of the data recorded by this type of camera every single sensor has to be studied, this is called sensor quality control. During this study gains of all pixels have to be recorded. During this process both the "dead" and "hot" pixels have to be discovered. In order to meet these requirements a device has been constructed where an array of specially selected LEDs and an optical diffusor can produce a uniform illumination on the sensor. Array of LEDs is necessary because uniform light must be provided on a relatively large area. LEDs are driven by a 16-channel 12 bit ADC controlled current generator between 0 and 60 mA. To ensure the comparability of different measurements a monitoring semiconductor sensor has also been installed on this bench.

During the sensor quality control several images are taken at different light intensities and stored as uncompressed bitmap images (Fig. 5). As the measurement finishes, average, sigma and noise images are calculated from the recorded images and stored next to the raw images. Only the numerical results are stored in the database. However the Perl-based web reporting system can retrieve both the raw or calculated images together with the numerical values.

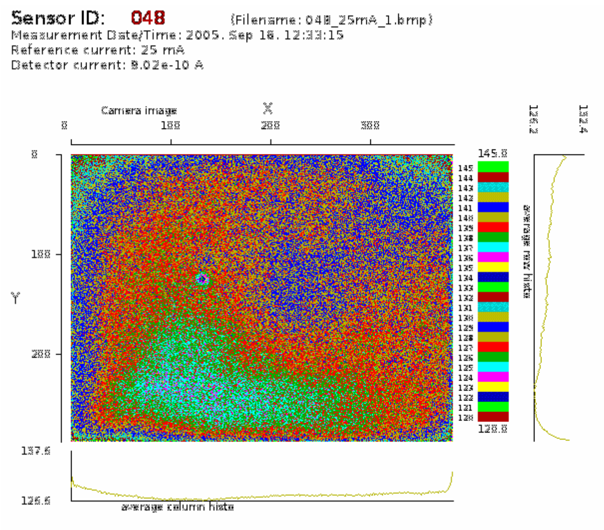

Figure 5. Result of a camera quality measurement

On this figure a dirty spot can be seen at position X~120, Y~120. As a result of this quality control this sensor has been sent back for further cleaning

After the camera quality check sensors are built together with a small lens and the housing to form a very simple pinhole camera. Internal parameters of this camera to be determined are the distance between the pinhole and the sensor center and the tilt angles of the sensor with respect to the axes perpendicular to the line connecting the pinhole and the sensor center. These values can be determined using a bench where plates equipped with optical fiber light sources are installed (see Fig. 6).

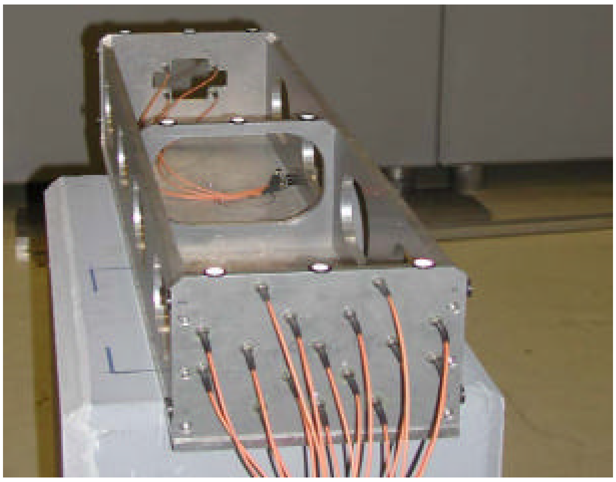

Figure 6. Camera calibration bench

It has been proven from the preceding simulations that two well designed plates can help to find the above mentioned parameters if they are located precisely (~ 20-30 microns) in the laboratory frame and their internal parameters (fiber positions) are known down to the 3 micron level. In order to localize these plates they need to have holes that can accept photogrammery targets. These holes should be localized with the same precision as the fibers are. Measurement technique is very similar to that of the chamber measurement's that is cameras observe the centroids of spots created by the fibers. This process is still under development therefore it is still not equipped with all the database and web reporting techniques as the above mentioned ones, but it is desired as these measurements are started.

As soon as the camera internal parameters are determined the camera gets mounted on the rigid supporting structure called MAB. The main role of the MAB is not only to support the cameras but also to define a coordinate system where these cameras can be located. The structure of the MABs has been chosen to be as rigid as possible, to have the smallest thermal expansion constant and have the smallest weight in order to prevent the geometrical distortion due to the gravity. The material that meets these conditions is the carbon-fiber structure. Since it defines a local frame of reference for every object it incorporates must be localized within it. The camera localization process is very similar to the processes mentioned so far: it makes use of a specially designed plates having optical fibers attached and mapped in a high precision metrology lab. The measurement process is also very similar, centroids of spots created by the fibers must be measured and then a geometrical reconstruction is to be performed to get the camera positions in the laboratory frame. In the meantime the carbon fiber structure of the MAB is localized in the same frame by common survey methods therefore the transformation of the cameras from the laboratory frame to the MAB's frame can be done. This is also a method under development therefore all the database and web reporting tools are not yet ready, but will be finalized by the start of the mass measurements.

Figure 7. MAB calibration bench

III. Application of the Calibration Data

Data recorded during the various calibration processes are used on one hand during the already described successive calibration phases and on other hand serve as input data to the main geometrical reconstruction process called COCOA [3],[4]. Result of this reconstruction gives the positions of the muon chambers at the end.

In order to allow the reconstruction process to use the calibration data, they should be uploaded to the main CMS databases. Since the reconstruction uses these data in POOL-ORA format and stores the values in an Oracle database, all data have to be converted during the upload. Test of this data conversion have already been done. However, the upload of the full data set has not yet been done.

IV. Summary

Each piece of all element types in the CMS Barrel Muon Alignment System have to be identified, calibrated and the position of each embedded element on the enveloping object must be known and followed.

Given the large number of elements and the complexity of the system, the data handling procedures of the calibration and assembly was automated as much as possible.

Five calibration facilities have been built to calibrate the LED holders, the chambers, the sensors, the camera-boxes and the MABs. They are very different in size and complexity but similar in nature: in all of them LED-type light sources have to be switched on and off and driven with given current and their images have to be captured by camera-boxes. These functions are complemented -depending on the task- by other control and DAQ functions like 2D-motion table control, video-multiplexing or environmental (temperature and humidity) measurements.

Therefore all the facilities are also similar from control, data acquisition and data handling point of view.

The core hardware elements of the control and data acquisition system are the microcontroller-based modular units [6] that - together with the control software - can easily be adapted to any particular calibration step. As the primary result of all the measurements are either full video-images or light spots, the image processing and transfer solutions can be reused at each calibration step.

The direct database connection is providing a correct, reliable and searchable storage of raw and processed data also in view of the fact that the validation and processing for the given calibration process is using the results of the preceding calibration steps. A dynamic WEB-based reporting tool makes it possible to follow the status of calibration and assembly and to search for any data in an easy way without direct database-operations. In the paper these points are discussed in detail.

The intermediate and final calibration values are stored in a relational database. Each step of the calibration procedure heavily relies on the results obtained in the previous steps, so the online query and update features offered by the database system are vital to our design.

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V. References

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