RESULTS OF 3D PHOTOGRAMMETRY
ON THE CMS BARREL YOKE

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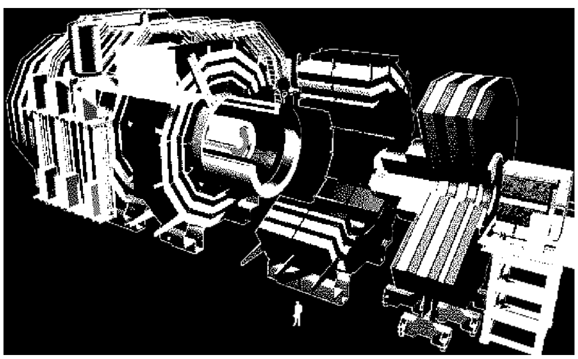
1. INTRODUCTION

Compact Muon Solenoid (CMS) is one of the four new experiments to operate at the Large Hadron Collider (LHC) at CERN (the European Laboratory for Particles Physics) from 2005. The CMS experiment aims to study very high energy collisions of proton beams with the best precision possible. The detector will be built by many separate pieces of structure from the Central Tracker to the End Caps closing both detector heads. This typical onion layout for detectors is shown in figure 1. This paper focuses on the supporting structures called the Barrel Yoke rings [1] that give a magnet of 15 m diameter and 2.5 m width, and their survey by using photogrammetry and the Kodak DCS 460 camera interfaced to the Rollei CDW (Close-range Digital Workstation) software. Also the results of a real photogrammetric measurement of the first full ring in September 1999 in Deggendorf are shown.



Diam : 14.60 m
Length : 21.60 m
Total Weight : ~ 14 600 tonnes
5 Barrel Yoke rings

Figure 1 - The CMS experiment

The precision of the particle tracks reconstruction by a detector like CMS depends on the intrinsic precision of sub-detectors and the precise positioning of those sub-detectors within their supporting structures. At CERN, digital photogrammetry has been taken as a main tool for solving the survey problem of the five Barrel Yokes of the CMS magnet. The precision required for one ring is better than 1 mm. The survey is first done at factory in Deggendorf, Germany (*Deggendorfer Werft und Eisenbau GmbH*) and afterwards at CERN to determine the

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geometrical validation during the construction and transportation. An important preliminary work has been done for analyzing all constraints and finding the best suitable photographing method and configuration for the Barrel Yoke survey project.

The first part of this paper will focus on the preliminary work that has helped to answer to the question: “ How can one validate a method of carrying out the measurements for this large object ? ”. Afterwards, before conclusions, there will be a summarizing of the last results obtained for the measurement of the first CMS Barrel Yoke ring.

2. USE OF MODELS FOR PRACTICAL SIMULATION OF A BARREL RING

Until 2005 and the start of LHC, there should be 45 geometrical measurements of the Barrel rings, at least in this point of the research. Three layers for five Barrel Yoke rings implies 15 surveys and these has to be done first in the factory (Deggendorf, Germany) and afterwards twice at CERN. The survey of the rings will be done by digital photogrammetry using the Kodak® DCS460 CCD Nikkon camera box and lenses and the CDW software by Aicon-Rollei. [3]

Conditions and constraints of the measurements had to be studied in advance and working procedure must be repeatable with the highest reliability possible. In order to define the achievable precision in reality and all the values like the size of the targets, the distance measurements, people, time needed and working conditions, there has been built two structural models to simulate one Barrel Yoke ring. These models are shown and summary for the final geometrical measurements told below.

2.1. First model

The first model was built and measured during the summer 1998. The goal of the first model was to validate the capability of the CERN digital photogrammetric system for the Barrel Yoke survey by taking into account all the known constraints. The other goal was to find the approximate values for the number of targets, minimal number of photos and to define the working conditions. The model was in scale of 90 % of the Yoke ring and had the size of $11 \times 4 \times 2.5$ m which is $^{1}/_{3}$ size of the real Barrel ring (figure 2). The reason not to build the model with the size of ring was that there was not enough room at CERN.

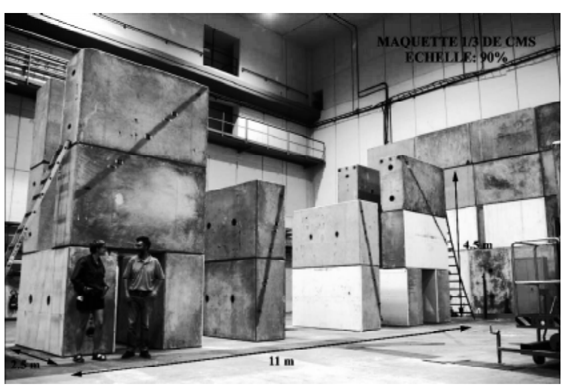

Figure 2 : the model prototype 1, simulating $^{1}/_{3}$ of the CMS Barrel Yoke ring

There were four “target lines” simulating the real target positioning of one Barrel. The maximum shooting distance was considered to be six meters due to the factory environment in Germany. Some measurements were done with different kind of target configurations, amount of photos and photo configuration. Also the importance of the additional coordinates and distance values in calculations was checked.

The most important final conclusion by the first prototype of model was that the digital photogrammetric system at CERN is reliable and precise enough for the Barrel survey. Some adapted tooling has been defined by studying the first model measurements. A set of 516 pieces of coded targets (∅ 40 mm) with magnetic supports and 12 carbon scale bars with lengths of about 1.4 m have been bought. Also the use of precise (0.3 mm) long distance measurements has been studied to be efficient for the Barrel Yoke survey. Connection between the two planes of the ring is the most important part of the project and a lot of targets and known distances should be placed to these difficult places of the object. The minimum amount of images for the precision required should be 150. [6]

2.2. Second model

The first model was replaced by a new, the size of $^2/_3$ of the Barrel ring with a scale of 66%, in January 1999. The second prototype is seen in figure 3.

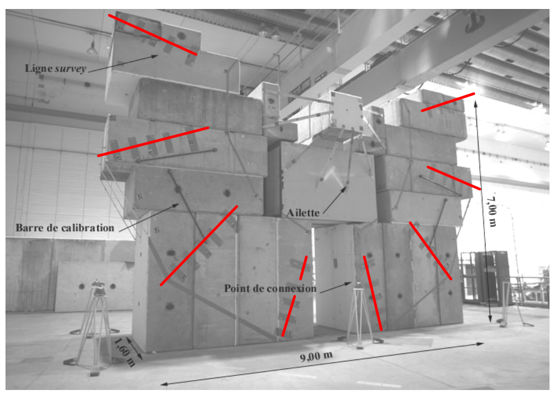

Figure 3: the model prototype 2, simulating $^2/_3$ of the CMS Barrel Yoke ring

2.2.1. Methods

The working method with the second model was similar to the first one. Only the connection between the faces were done by exterior way, not using the middle part of the ring. Different measurement projects were done to precise the project values got by the first model and to find more detailed information for the best possible Barrel survey. Additionally the time needed for one Barrel measurement was to be checked. The company wanted it clearly to be as short as possible for a minimum interruption in their workshops. Thus compromises had to be found between the boundary conditions.

Besides the time, the most important tasks to declare in this point of the research were the influence of the camera calibration and long distance measurements for the calculations and the final results of this object. Especially the connection between two planes of the ring was checked more carefully. More about these points is told below.

2.2.2. Camera calibration

The camera calibration refers to the determination of the parameters of the camera's interior orientation and distortion parameters. Interior orientation includes the coordinates of the principal point, the focal length, affinity and non-orthogonality of the pixel. Distortion parameters are the radial symmetrical, the radial asymmetrical and tangential ones. [4] Generally these parameters are estimated simultaneously with autocalibration during the calculations. In some cases it has been noticed that the use of the camera parameters from a separate calibration improves the precision of the results. Separate calibration was considered to be an important preliminary work of the project.

Dim : 1600 x 1800 x 1280 mm3
310 targets
7 scale bars

Figure 4 : the calibration bench

The movable "calibration bench" was built at CERN in April 1999. This bench is made with three pieces of 8 mm wide vetronit (low CTE) and has 310 photogrammetric targets. It was made in order to be easily stored and transportable between Germany and CERN. Some adapted fixations allow the use of eight carbon-fiber scale-bars. Several measurements with different optics were done. It was studied that a lens with a 20 mm focal length is the most stable one and should be used for the Barrel Yoke ring survey, too. Measurements of the calibration bench will be performed before and after each measurement of the Barrel Yoke ring.

2.2.3. Connection between two planes

The most difficult part of the Barrel survey is the connection between the two planes of the Barrel Yoke ring. The distance between the two planes is 2.5 m. On the top connection there are only four meters of shooting distance available. Then, there are big structures supporting the ring and many scaffoldings in the field. Those are problematic for using photogrammetry, because they block the view for the survey and connection points in the lower part of the ring.

After different measurement projects it has been decided to use relatively bigger amount of targets for these connection parts like scale bar distances, too. It was studied that a certain number of 30 mm diameter spherical targets (*Géodésie Maintenance Services*) could be really helpful in the connections because it is possible to see the targets from different wide angles. The magnet targets could not be tested with the models but were considered to be the best solution for the connections between the two planes.

2.2.4. Long distance measurements

Distances are needed to determine the scale of the object and to perform the scale control. With a large scale object like the CMS Barrel Yoke ring, the distances should be also long ones depending on the size of the object. This means that the scale bars (with a length of ~1.5 m) are not sufficient as the only distance observations. Some distances should have the longest length possible with a best precision possible and lie in all coordinate directions.

The long distances are measured between survey reference holes where photogrammetric targets can also be assembled. These distances can be measured in different way but the need of the accuracy in case of the Barrel ring should be better than 0.3 mm/10 m. The triangulation with theodolites, calibrated tapes and other special measurement tools (the known tension is achieved with compressed spring device) have been studied carefully for using long distance measurements at CERN and in Deggendorf.

In calculations the distances are used for comparison and checking of photogrammetric results. The distances that are got by photogrammetry are compared to the long distance measurements and the direct control of the quality is done simultaneously during the calculations. With long and precise distance observations the network of the object has better quality.

2.3. Summary of the simulations

The use of the models, the determination of special tooling, the research of camera calibration and long distance measurements have helped to see the practical views with the CMS Barrel Yoke survey. The procedure of the ring survey has been mainly settled and will be used similarly in all projects to achieve the highest reliability possible. Some points of the practical work like the difficulty of seeing the survey points on the lower part of the rings due to the supporting and scaffolding structures were not able to be studied in advance before the first real measurement.

The initial information before the research had started, was applied mostly by the constraints of the working environment in the factory and at CERN. The object size was determined to be 15 m by diameter, the maximum distance to the object 6 m and there was no extra space to put permanent survey stations for the creation of the object network. Time of intervention, immobilization and data collection of the ring was considered to be the shortest possible. The main goal of the research was to find the practical way to use photogrammetry on the site and on the calculations afterwards due to the initial information. The precision required was better than 1 mm.

The measurements of the models, study of calibration and special tooling and long distances defined the practical values for the Barrel Yoke survey. The number of the points were studied to be at least 250 and the size of the magnetic coded targets 40 mm as a diameter. Also some magnetic sphere targets were researched to be efficient for the connection part between two big planes of the object. The approximate time for the photographing part of the project was studied to be about four hours. The best and most stable optics turned to be one with 20 mm focal length and the minimum number of photos that are needed for one Barrel project is 200 with that lens. 20 scale bars with lengths of about 1.5 m around the object with precision of 0.05 mm and 14 long distances with precision of 0.3 mm around the object were studied to be the minimum amount of distance information for reaching the required results. The final estimated precision of the object coordinates turned to be 0.7 mm after the practical work.[2]

3. PHOTOGRAMMETRIC MEASUREMENT OF THE FIRST FULL BARREL YOKE IN DEGGENDORF

The full Barrel ring is supported by a central part called Ferris Wheel having a diameter of seven meters. Around the Ferris Wheel there are three iron layers that are attached to each other by Corner Pieces and Connecting Brackets, which make the final ring having a diameter of 14 m.

The first full ring was surveyed with different steps. As a first step in the beginning of August 1999, the twelve first Corner Pieces were measured by theodolites to survey their distances to a vertical reference plane within a tolerance of ± 1 mm. The second step was to survey the first iron layer of the Barrel by photogrammetry. The measurement with the second layer was decided to be skipped. The last step was the geometrical validation of the full ring by photogrammetry. The procedure of the last two surveys was based on the practical simulations explained in chapter 2. The final measurement is described in this chapter.

3.1. Installation

The full Barrel Yoke ring (see figure 5) preparation consisted of the installation of calibration bench near the Barrel, points, scale bars and temperature sensors. The wheel was turned slowly (360° in one hour) in order to perform the installation. At the end, the ring was turned and placed in the final experiment position.

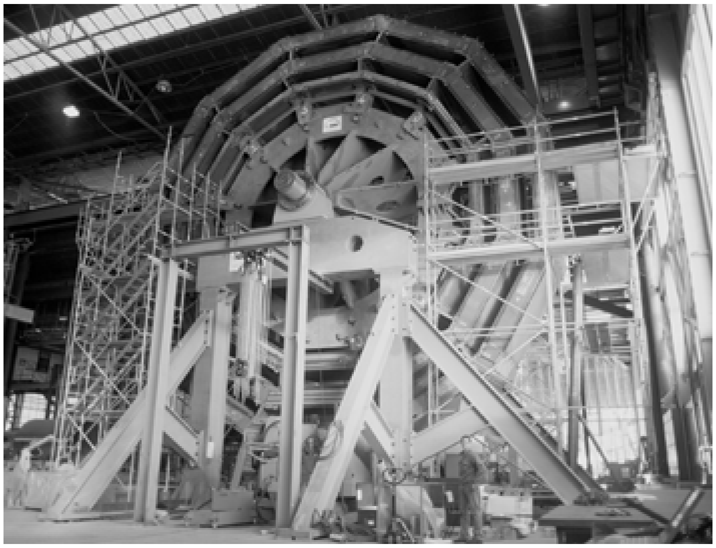

Figure 5 : the full Barrel Yoke ring in Deggendorf

Survey targets were installed in the precise survey holes of the Corner Pieces and Connecting Brackets. Connecting coded points and spheres were also installed all around the object. All points were attached to the Barrel with magnets. In the end, 240 survey points and 300 connecting points were used for this full Barrel Yoke measurement. Twelve scale bars were installed with powerful magnets and eight of them replaced on the other side of the object during the photographing. Since the purpose of the survey is a geometrical validation, six temperature sensors were installed in three different height level around the ring and the effect of the temperature distortion taken into account for long distance measurements.

Installation was studied in advance to be as easy and automated as possible. This research is explained in chapter 2. and the special tooling helped a lot during the work in the factory.

3.2. Measurements

Sixteen long distances were measured between survey holes following from the practical simulation. The final tool used was a calibrated tape with a compressed spring device (see chapter 2.2.4.) which gave the results with a precision of 0.4 mm/10 m. The temperature sensors measured no more than 4.6°C maximum difference between the top and the bottom of the object during the measurement.

A first set of photos was taken from the calibration bench. The horizontal parts of the scaffoldings around the Barrel had to be moved before photographing. The photos of the two parallel faces were taken with six meters distance. The photo taking took 4 h 30 and there was one break of an hour for displacing some of the scale bars and moving the scaffoldings. The photos for the connection of the two faces were taken from the top part twice and from the bottom part once. Due to the Ferris Wheel feet and to the amount of scaffoldings (See figure 6) the image configuration had to be adapted and the number of photo increased from the simulation conclusions. Some points at the bottom part of the Barrel were hidden and extra photos were taken only for these survey points to increase the amount of observations for these points. Finally, 260 photos were taken. The second set of photos was taken from the calibration bench in the end of the measurements.

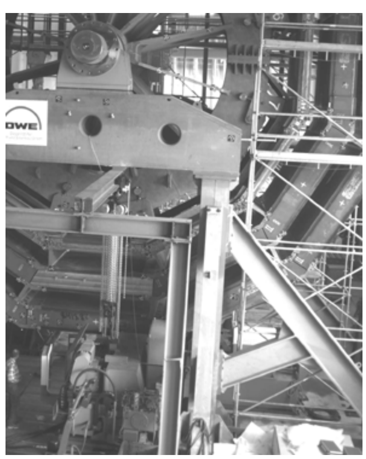

Figure 6 : Barrel Yoke with supporting feet and scaffoldings

3.3 Results

Photogrammetric calculations were made with self-calibration of the camera as a consequences of a good connection of the two faces with the spherical targets. The used co-ordinate system is seen in figure 7.

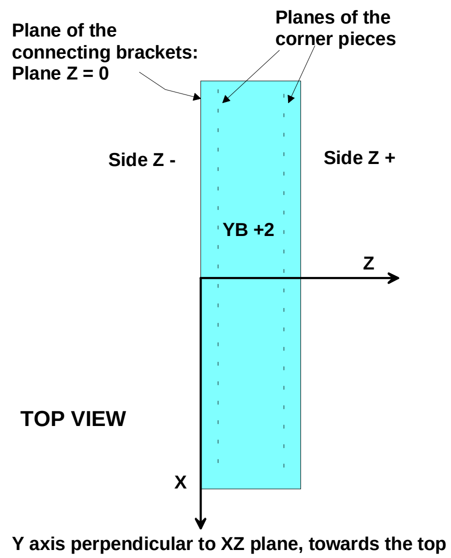

Figure 7 : the used co-ordinate system –top view

Finally, the calculation gave the three dimensional co-ordinates of 500 points with an average RMS (one sigma) of 0.5 mm, which is better than 1 mm asked in advance. Three different geometrical calculations were done in order to validate the construction and the results are seen in Table 1. [5]

Table 1 : Geometrical results of the first full Barrel Yoke
** Z mean planes = 4 mean planes calculated by least square method, using the respective set of measured points*

Range of the differences in XYZ compared to the theoretical co-ordinates
Delta X max = from + 2.0 to -1.7 mm
Delta Y max = from + 2.7 to -2.3 mm
Delta Z max = from + 1.0 to -1.8 mm
Range of distances point to Z mean planes*:
from + 1.0 to - 1.0 mm
Maximal difference between the measured distance separating the Z planes, along Z axis for X=Y=0 and the theoretical one:
0.3 mm

The time schedule given by the factory was respected with the help of photogrammetry.

The precision of the first real measurement of the fourteen meters diameter Barrel Yoke was done within 0.5 mm on the object co-ordinates. The geometrical results showed that the Barrel Yoke construction was made inside the 5 mm tolerance.

4. CONCLUSION

The CMS detector of the new LHC will be built till 2005 at CERN in Geneva. The Barrel Yoke survey has been decided to be done mostly by photogrammetry. After this first measurement, it has been proved that a practical simulation and a study of adapted tools and procedures were helpful for measurement on such a large object.

Using only conventional surveying methods would have been impossible with such constraints. The most important points were the high required accuracy compared to the size of the object, the connection of the two planes, the time intervention, the restricted factory environment and the impossibility for having any outside network. The photogrammetric method was considered to be the best way to survey the Barrel Yoke ring.

Since the required precision has been reached at all levels with the first full Barrel measurements, the procedure is validated for the four remaining Barrels in the factory and afterwards again at CERN. This project was challenging due to the size of the object, the required accuracy and the lack of practical references in the field of digital industrial photogrammetry. This method is a new step for using the three dimensional photogrammetric measurements on large objects.

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