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General alignment concept of the CMS

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Abstract

Efficient and accurate track reconstruction requires proper alignment of the tracking devices used. Here, we describe the general alignment strategy envisaged for the CMS experiment. The hardware alignment devices of the CMS are presented as well as the different track-based alignment approaches.

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1. Introduction

Individual sensors of the CMS tracking devices have an excellent intrinsic spatial resolution. For the ~20 000 silicon sensors of the CMS tracker, it is in the range of 10–50 μm [1], and for the ~1400 muon chambers and drift tubes in the range of 75–100 μm [2]. The intrinsic resolution is, however, degraded by *alignment uncertainties*, the imperfect knowledge of the positions and orientations of the individual sensors. These uncertainties are expected to be in the range of 100–500 μm after installation [3], and they are one of the largest potential sources for tracking uncertainties. Specific *alignment* procedures are needed to decrease alignment uncertainties.

It is required for the CMS tracker that the alignment procedure decreases alignment uncertainties to a level negligible compared to the intrinsic sensor resolution [4]. Thus, the alignment accuracy has to be equal to, or preferably better than, the intrinsic sensor resolution. A similar requirement is imposed to the muon system [2].

Additional alignment requirements arise from specific physics goals. For instance, to measure the mass of the $W^{\pm}$ boson with the required precision of $\sigma(M_W) < 15$–20 MeV, the momentum scale has to be known with an accuracy of 0.020–0.025%. This implies for the tracker that the positions of individual sensors have to be known with an accuracy better than 10 μm in the $r\phi$ plane [2].

The required level of alignment precision can only be achieved with a track-based alignment (TBA) procedure. However, other methods are also needed, since the pattern recognition of the first track reconstruction requires an accuracy better than the placement precision of the assembly.

2. General alignment strategy

The general alignment strategy of the CMS utilizes three approaches:

(1) precise position measurements during the assembly of tracking devices;
(2) measurements of relative positions of sub-detectors with a dedicated hardware alignment system, and
(3) TBA.

The first two approaches are used to reach a level of about 100 μm for the alignment uncertainties in the very beginning of data taking. This level is required by the pattern recognition. Later on, TBA will be used to further improve the alignment of individual sensors. For the tracker, it is foreseen to improve the alignment below 10 μm in the $r\phi$ plane.

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The general alignment strategy proceeds with TBA as follows: first, the tracker will be aligned stand-alone, beginning with the pixel detector, then covering the strip detector. Thereafter, the muon system will be aligned with the tracker, and finally the calorimeter modules will be adjusted to the aligned tracking devices.

3. Assembly tolerances and misalignments

During the assembly of the CMS Tracker, positions and orientations of tracker detector components are measured and stored in databases. Measurements are carried out with e.g. coordinate measurement machines or photogrammetry. If measurements are carried out for all silicon detectors, they are saved in a database, and used as corrections to the ideal tracker geometry. If only a sample is measured, the standard deviation of the measurements can be used as an estimate of the corresponding mounting uncertainty, and this error is taken into account in the initial track reconstruction.

The estimated mounting precisions are shown in Table 1. For the muon system, uncertainties of several mm are expected due to displacements caused by the magnetic forces.

Misalignments have also been introduced into the reconstruction software to study their impact on physics variables as well as to enable alignment studies. The effect of misalignments on track and vertex reconstruction is discussed further in Ref. [5].

4. Hardware alignment

The hardware alignment system of the CMS consists of independent alignment systems for the tracker and the muon system and a link system connecting these together. The tracker is equipped with a laser alignment system (LAS), which uses infrared laser beams to monitor the positions of selected detector modules. The muon detector alignment system consists of optical devices, which are used to align the muon barrel and the endcaps (some laser devices are also used). The link system relates the muon and tracker alignment systems and allows a simultaneous monitoring of these devices.

Hardware alignment is especially important for the muon system, which is mounted on the iron rings and disks, subjected to displacements ranging from a few mm to 1–2 cm when the magnetic field is activated [6]. These correlated displacements can be corrected for the most part with the hardware alignment system. TBA is used to further improve the alignment of individual muon chambers. To ensure an optimal performance over the entire momentum range up to 1 TeV, an accuracy of 100–500 μm, internally and with respect to the central tracking system, is necessary [7].

Table 1
Mounting precisions (μm) for individual sensors as well as for their support structure for pixel barrel (TPB), inner barrel (TIB), outer barrel (TOB), pixel endcaps (TPE), inner disks (TID) and endcaps (TEC)

	TPB	TIB	TOB	TPE	TID	TEC
Modules	130	200	100	25	105	50
Ladders/rods/rings/petals	50	200	100	50	300	100

The goal of the optical alignment system for the muon system is to track large displacements due to the magnetic forces affecting the return yoke, and also to provide long-term supervision of the detector positions and of the changes due to thermal effects. It is expected that the thermal expansion of the chambers and their iron supports are in the sub-millimeter range [8].

The muon alignment system consists of three $r-z$ alignment planes. Linking of muon barrels, endcaps and tracker alignment system is also carried out in these planes. The barrel and endcap monitoring systems can work in stand-alone mode. LEDs and laser beams are used together with precise distance and angle-measuring devices. Each of the 250 drift tube chambers in the barrel is monitored, while only 23 out of the 540 chambers in the four endcap stations are directly monitored. The alignment system provides continuous monitoring of the detector geometry with or without collisions. It can be operated in presence or absence of the magnetic field. A full cycle of measurements can be carried out several times per hour, which is also the time scale of monitoring any movements.

In the tracker, the LAS can monitor most of the composite structures, but the pixel detector as well as the Tracker Inner Disks (TIDs) are out of its reach. The LAS system has two goals: (1) to provide the initial alignment at the level of 100 μm to ensure tracking, and (2) to monitor the larger structures of the CMS on a continuous basis at the level of 10 μm. The LAS is foreseen to operate both in dedicated runs and during physics data taking.

The LAS consists of 16 laser beams parallel to the particle beam and of eight perpendicular to it. The 16 beams are distributed equally in ϕ in the endcaps. These beams cross all nine disks, and allow the internal alignment of the tracker endcap (TEC). The other eight beams are used to align inner and outer barrels (TIB and TOB) and both TECs with respect to each other. A link to the muon system is established by another 12 beams.

5. Track-based alignment

TBA carried out in software is the most accurate method for alignment of large tracking detectors. It has been used and reported in several particle physics experiments, for example, in CDF [9]. The major challenge in CMS is the enormous number of degrees of freedom involved. For the tracker alone, there are 20 000 individual sensors and thus about 100 000 alignment parameters (three translations and three rotations for each sensor). For the muon system, the corresponding numbers are 790 individual chambers and about 5000 alignment parameters.

Whereas the alignment of the muon chambers relies most on the optical alignment system, for the tracker, the TBA is the most important part of alignment.

Several TBA algorithms are developed for the CMS reconstruction software. They use a common software interface, and can utilize data summary tapes (DST) with track refitting to speed up the procedure.

The most prominent data samples for the TBA are $W^{\pm} \rightarrow \mu^{\pm}\nu$ and $Z^0 \rightarrow \mu^+\mu^-$ decays. At low luminosity, about 20 000 Z^0 and 100 000 $W^{\pm}$ events are selected per day by the High-Level Trigger (HLT) [4]. It is estimated that 1–2 million tracks are needed to fully align the tracker [3], which corresponds to 1–2 weeks of data taking at low LHC luminosity ($10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). A few days of running time is sufficient for the muon system alignment [7]. For the Z^0 events, one can use the Z^0 mass constraint. A similar possibility exists for $J/\psi \rightarrow \mu^+\mu^-$ decays, although the resulting muons have a lower momentum and their usefulness for alignment needs to be further studied.

The possibility to use tracks from minimum bias events is also being studied. Especially during the first data taking period with low LHC luminosity, these events might be the only source providing a sufficient amount of tracks for tracker alignment.

As a complementary sample to tracks originating from the collision region, other event samples like cosmic muons as well as beam gas and beam halo muons might be very useful.

Beam halo muons are machine-induced secondary particles which cross the CMS horizontally. They can be very useful for the endcap region as they connect the two ends of the apparatus. However, a specific trigger, e.g. from the TOTEM T1 telescopes [10], is needed. Muon rates exceeding 1 kHz for the whole CMS and 200 Hz for the tracker (with $E_{\mu} > 100\,\mathrm{GeV}$) were estimated in an LHC study [11], where exact values depend strongly on the operational settings of the LHC.

Beam gas events have a large rate already during single beam operation of the LHC. Their event topology is similar to collision events, but they have a softer p_t spectrum and are usually almost parallel to the beam axis. Thus, their use in the alignment is mostly restricted to the innermost part of the CMS (to the tracker). Their triggering is also difficult.

It is also foreseen to use cosmic muons in the alignment of the tracker and the muon system [8]. Since the CMS cavern is 100 m below ground, most cosmic muons enter the cavern through the maintenance shaft. Their vertical tracks are especially useful for barrel region alignment. It is estimated in Ref. [12] that each hour 700 high-energy cosmic muons cross the entire barrel part of CMS (TOB, TIB and the pixel barrel). Dedicated cosmic runs are foreseen in between LHC machine operations.

6. TBA algorithms

New TBA algorithms are needed for the CMS, since the straightforward way of solving the alignment problem with 100 000 alignment parameters by inverting the corresponding covariance matrix of $100\,000^2$ elements is practically impossible. A comprehensive review of the different alignment algorithms can be found in Ref. [13].

Three different alignment algorithms are implemented and currently studied within the CMS collaboration. Two of the algorithms calculate alignment corrections without solving the large matrix equation, and one algorithm solves it in an iterative way.

The Hits and Impact Points (HIP) method [14,15] is a straightforward and robust way to solve the alignment problem. In this method, all desired sensor modules are aligned independently with a sample of tracks. The track information is updated under consideration of the new module positions and the alignment step is repeated until the system converges. The method has a very low computational cost: for each sensor which is aligned, a maximum 6×6 matrix needs to be inverted. The method has been successfully applied to a test beam setup [3], which acts as a proof of principle for the alignment software in CMS but does not allow strong conclusions concerning alignment on the scale of the CMS.

The Kalman filter [16,17] algorithm is a method for global alignment derived from the Kalman filter. The method keeps track of the correlations of alignment parameters of all sensor modules. Its fundamental idea is to update the correlation list as well as alignment parameters after each track for all modules. The use of a correlation list is computationally easier than the inversion of a huge matrix, but requires some bookkeeping.

The Millepede approach has been used in CDF [9] and other experiments. It is a non-iterative linear least-squares algorithm, in which the huge correlation matrix is solved by inversion (Millepede1). In its original form, it was limited to problems with about 10^4 parameters, and therefore a new version, Millepede2, was developed for the CMS. Millepede2 uses an iterative method to solve the matrix equation instead of matrix inversion [18]. The Millepede method fits both global and local parameters simultaneously and uses the maximum amount of information for solving the alignment problem. A variant of the method has been used for muon alignment studies of the CMS.

The three algorithms have been implemented into the CMS reconstruction software through a common interface. First results of their use can be found in Refs. [3,7].

7. Prospects

Test beam and cosmic data taken with a dedicated test setup as well as simulations are being used to study the performance of the three TBA algorithms. Several different alignment tasks are foreseen: the stand-alone alignment of the pixel or strip detectors in the early data taking, the alignment during normal data taking and the monitoring of time-dependent effects, etc. The muon alignment system, both software and hardware alignment, will be studied with the data recorded in the so-called "Cosmic Challenge", in which a slice of the experiment is operated with cosmics in the CMS surface assembly hall in 2006.

The general alignment strategy will be refined when experience concerning usefullness and required statistics of the different event samples and CPU needs is obtained. Studies of alignment with simulated data are foreseen for the whole tracker or whole CMS as well as comparisons of the different algorithms.

The alignment algorithm will also be developed to take some additional information into account. For example, the overlap of sensors imposes an additional constraint especially for barrel-like structures. The vertex constraint helps especially in the stand-alone alignment of the pixel. The $Z^0 \rightarrow \mu^+\mu^-$ mass constraint and kinematic fit helps to correlate detector parts which are not crossed by a single collision track (e.g. two endcaps), and also to constrain the curvature of the muon tracks.

Alignment with the other event samples (beam gas, beam halo and cosmic muons) will be studied further, since they complement the collision events originating from the vertex region. For these events, the question of triggering has to be addressed. Other important questions are the uncertainties in the magnetic field and in the material budget.

Once realistic alignment studies are completed, the impact of residual alignment uncertainties on physics analyses can be estimated in a reliable way. At the moment, physics analyses are carried out either with ideal geometry or with residual alignment uncertainties estimated on the basis of the assembly precisions.

8. Summary

The alignment of the CMS is based on three components: precision measurements before the installation, laser and optical alignment systems available before and during the operation, and TBA. Whereas most of the alignment of the muon system relies on hardware alignment systems, for the tracker the track-based approach is the most important ingredient.

At present, the CMS possesses the full software infrastructure to realistically misalign the tracking devices and to run alignment algorithms. One alignment algorithm has been developed for the muon system, and three different alignment algorithms for the tracker. First studies of these algorithms have been carried out. Comprehensive studies of the algorithms are planned.

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