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Monitoring of absolute mirror alignment at COMPASS RICH-1 detector

M. Alexeev [a,b], R. Birsa [j], F. Bradamante [i], A. Bressan [i], M. Chiosso [g], P. Ciliberti [i], S. Dalla Torre [j], O. Denisov [h], V. Duic [i], A. Ferrero [g], M. Finger [f,k], M. Finger Jr.[f,k], J.Ch. Gayde [e], M. Giorgi [i], B. Gobbo [j], S. Levorato [j], A. Maggiora [h], A. Martin [i], G. Menon [j], D. Panzieri [a], G. Pesaro [i], J. Polak [c,d], E. Rocco [g], G. Sbrizzai [i], P. Schiavon [i], M. Slunecka [f,k], F. Sozzi [i], L. Steiger [c,d,*], M. Sulc [c,d], S. Takekawa [i], F. Tessarotto [j]

[a] INFN, Sezione di Torino and University of East Piemonte, Alessandria, Italy
[b] INFN, Sezione di Trieste and University of Bari, Bari, Italy
[c] Technical University of Liberec, Liberec, Czech Republic
[d] Regional Centre for Special Optics and Optoelectronic Systems (TOPTEC), Institute of Plasma Physics ASCR, Turnov, Czech Republic
[e] CERN, European Organization for Nuclear Research, Geneva, Switzerland
[f] Charles University, Prague, Czech Republic
[g] INFN, Sezione di Torino and University of Torino, Torino, Italy
[h] INFN, Sezione di Torino, Torino, Italy
[i] INFN, Sezione di Trieste and University of Trieste, Trieste, Italy
[j] INFN, Sezione di Trieste, Trieste, Italy
[k] JINR, Dubna, Russia

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ABSTRACT

The gaseous COMPASS RICH-1 detector uses two spherical mirror surfaces, segmented into 116 individual mirrors, to focus the Cherenkov photons onto the detector plane. Any mirror misalignment directly affects the detector resolution. The on-line Continuous Line Alignment and Monitoring (CLAM) photogrammetry-based method has been implemented to measure the alignment of individual mirrors which can be characterized by the center of curvature. The mirror wall reflects a regular grid of retroreflective strips placed inside the detector vessel. Then, the position of each mirror is determined from the image of the grid reflection. The images are collected by four cameras. Any small mirror misalignment results in changes of the grid lines' positions in the image. The accuracy limits of the CLAM method were checked by laser interferometry and are below 0.1 mrad.

1. Introduction

The Ring Imaging CHerenkov detector, RICH-1, is designed to cover the acceptance of the first stage of the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS), achieving charged hadrons separation above three standard deviation levels (pions, kaons and protons) of particle momentum up to 60 GeV/*c* [1]. Large volume vessel of the RICH-1 detector is filled with heavy fluorocarbon radiator gas C_4F_{10}.

Cherenkov photons emitted in the gas are reflected by two spherical mirror surfaces of total area larger than 21 m^2 towards the photon detection chambers. The chambers are placed outside the COMPASS spectrometer acceptance. Such arrangement focuses the cone of light, produced by particle crossing the radiator, towards the detector plane, where it generates image of a ring, regardless of the photon emission point along the trajectory of the particle.

The mirror wall is formed by a mosaic arrangement of 116 spherical UV mirror elements and is split into two parts by the horizontal plane on the beam axis. The radius of curvature of 6606 $\pm$ 20 mm is equal for both spheres [2].

The mechanical structure supporting the mirror wall has a net-like configuration with spherical design made from aluminum. Each mirror is coupled to a fine thread screw which allows it to rotate around two orthogonal axes. During the RICH-1 particle trajectory reconstruction, the dispersion that comes from the mirror optical imperfections results in a contribution to the error on the measured Cherenkov angle of 0.1 mrad; the error contribution caused by the misalignment adds in quadrature [3]. The mirrors' misalignments can be caused during initial installation and they can vary with temperature changes (material dilatation), pressure changes or mechanical vibrations. To eliminate the

* Corresponding author at: Technical University of Liberec, Liberec, Czech Republic.
E-mail address: steigerl@seznam.cz.(L. Steiger)

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alignment errors, and consequently to maximize the angular resolution of the RICH-1 detector, it is suitable to monitor the alignment of individual mirrors. More details about the angular resolution of the detector and other effects that influence particle identification by the detector can be found in Ref. [4].

Several methods were developed for the measurement of the mirrors misalignments in RICH detectors in the past. They have some limitations in the case of usage in the COMPASS RICH-1.

In the case of the alignment of the optical system with data collected by the spectrometer [5], position of a selected reference mirror has to be known precisely in advance. Moreover, a large statistics is needed, hence the information is averaged over long time intervals. In the case of COMPASS RICH-1 detector, not more than about one quarter of the mirrors, those, which are placed in the most populated areas, can be monitored with this approach.

The laser alignment monitoring system (LAMS) [6] could be adopted to ensure correct alignment of the reference mirror. The LAMS system is properly working in the RICH2 detector at the LHCb experiment [7]. Because of large number of components needed by the LAMS, the method can be used to monitor only a few mirror segments.

The most advanced method, surveying the mirrors with the theodolite in autocollimation mode [8], has one main disadvantage – the need of direct access to the mirror setup. Thus, the surveying can be performed only when the spectrometer is not in operation mode.

In 2001, the initial alignment of the whole mirror wall of the RICH-1 was performed and then remeasured using the autocollimation technique [9]. At the end of the measurement, residual misalignments showed a standard deviation of 0.06 mrad. Later, the alignment of selected mirrors was measured several times between the experiment data taking periods, typically once per year. It takes one day to measure ten mirrors. Misalignments with a random distribution in the range of 0–1.5 mrad were observed. The origin of the misalignments detected after the initial alignment procedure is not known yet.

Almost realtime monitoring for all the mirrors of the mirror wall is not implemented so far. The first proposal of the on-line monitoring method, named Continuous Line Alignment Monitoring method for RICH mirrors (CLAM), was written by Sergio Costa and Jean-Christophe Gayde in 2005 [10]. In 2007, hardware parts of the CLAM were installed in the COMPASS experiment in the RICH-1 detector. In our previous work [11] we have presented details of the relative measurement used by the CLAM system. We have also shortly introduced an idea for the absolute measurement method.

The paper is focused on the study of possibilities to monitor the alignment of a large set of spherical mirrors by the use of the CLAM digital photogrammetry-based method with the emphasis on the absolute measurement attitude.

2. CLAM method

The idea behind the CLAM method is as follows: if adjacent mirror segments are not coherently aligned, the image of an object reflected by these mirrors appears broken, not consistent. Thus, any discontinuity in the image of a rectangular grid of continuous lines corresponds to a relative mirrors' misalignment.

The basic hardware components include four digital cameras for the monitoring of four different segments of the mirror wall, a regular grid of retroreflective strips illuminated by light emitting diodes. The two LEDs are placed close to each camera. All the parts of the system were properly chosen to achieve resolution of mirror misalignment of 0.1 mrad [10].

In the arrangement designed for the CLAM system, the retroreflective strips of the width of 10 mm form a square grid with a pitch of 100 mm. Circular photogrammetric reflective targets, each 10 mm in diameter, are placed on the strips intersections. To avoid mechanical deformations of the grid, the grid is glued to an aluminum support. The grid is fixed only at the top and bottom parts and it is not stabilized in the middle part, a movement towards the mirror-wall may occur. Another photogrammetry targets are mounted on the mirror wall frame. They are used to calculate the position of the camera.

The regular retroreflective grid is reflected off the mirror wall and on the account, that the mirrors are spherical, the reflection image of the lines taken by the camera will be an image with the conic sections instead of the straight lines. Then, the mirror misalignment is detected as a discontinuity of conics.

Two approaches are considered when one needs to evaluate the mirrors' misalignments – relative and absolute measurement. During the relative measurement, the positions of the grid lines reflected by the mirrors are evaluated from images taken at different times. The first image serves as a reference. Then, the other images are subtracted from the reference one. Consequently the change of mirror tilt is indicated in the subtracted image by arised line. The width of the grid lines in the subtracted image is proportional to the tilt of the mirror [11].

Eventually, one could compare each mirror with its neighbouring mirrors using just one picture. This would work on the assumption that surrounding mirrors are perfectly aligned. Unfortunately, several mirrors were misaligned since the beginning when the CLAM data collection started.

3. Mirror misalignment measurement

The aim of the absolute measurement method is to determine directly the mirror tilt/orientation using only one picture. Every mirror segment is originally defined by its ideal position and its orientation according to the centre of curvature C_k of the top or bottom part of the spherical mirror wall. The coordinates of both centres are given in the COMPASS coordinate system. The picture taken by the camera is a result of a projection of the measured scene (3D→2D). In the absolute method, the mirror position and its orientation is estimated using only the image of the retroreflective grid reflected of the mirror taken by the camera.

The process to obtain a relation between the image coordinates and the real world coordinates can be divided into two basic steps: interior orientation of the camera which provides the camera calibration and the exterior orientation of the camera which provides the position of the camera [12].

The interior orientation parameters are the principal point, the principal distance and the parameters of functions describing imaging errors. The imaging errors represent aberrations and distortions of the ideal central perspective model of the camera. The interior parameters were obtained by the self-calibrating bundle adjustment method [13]. As a reference, a plate with circular photogrammetry targets placed in well defined regular positions was used. The plate was photographed by the camera in several positions.

The position of each camera was obtained by the space resection algorithm [13] using images of the photogrammetric targets mounted on the mirror wall supporting structure [12]. Since each camera is placed outside the detector, separated from monitored mirrors by 10 mm thick glass window, the change of the refractive index between camera environment and environment inside the detector has to be included in the measurements. The calculation is based on the light-ray path through the system.

The idea behind the algorithm of finding the misalignments of individual mirror segments is simple. It assumes that the position of the centre of curvature of a mirror changes with the mirror misalignment. The principle of the algorithm is shown in Fig. 1. P is the principal point of the CLAM camera, E is point of the retroreflective rectangular grid and D is the image of the point E on the camera sensor. The position of E was measured with the precision of 0.5 mm in every coordinate. The reflection point S on the mirror surface is not known while only the *ideal* centre of curvature C_{id} is known. Also, the ideal radius of curvature R_{id} of the spherical mirror is known. We search for the centres of curvature C of individual mirrors.

Since points P, E, D are theoretically coplanar, it is possible to define the 2D rectangular coordinate system, where the origin is set in the point P, i.e. $P=(0,0)$, and the x-axis is defined by the direction of the vector $\overrightarrow{DP}$. E_x and E_y are 2D coordinates of the point E. According to the given geometric system, $S=(u,0)$, where $u=|\overrightarrow{PS}|$. Then, C can be expressed as

$$C=\overrightarrow{PS}+\overrightarrow{SC}=(u,0)+(-R\cos\beta, R\sin\beta), \tag{1}$$

where β stands for the reflection angle of the mirror surface. There are two unknown variables, u and β. Using the law of sines, the

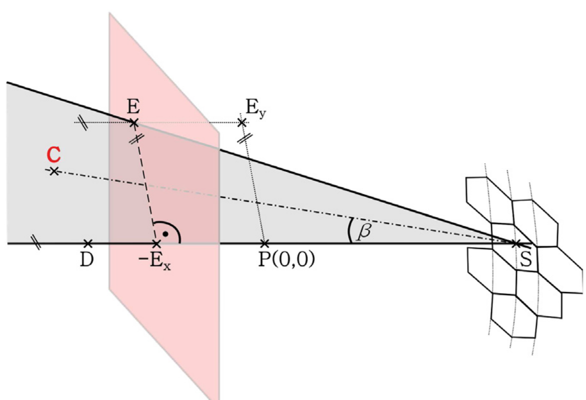

Fig. 1. Determination of mirror orientation – 3D scheme of the geometry used in the algorithm for the absolute measurements of mirrors misalignments. P is the principal point of CLAM camera, E is point of the retroreflective rectangular grid and D is the image of the point E on the camera sensor, S stands for the reflection point on the mirror surface and C for the centre of curvature of the mirror.

position of the point C in 2D can be estimated using the equation:

$$C_{2D}=\left(\frac{|PE|\sin(\alpha)\cos(2\beta)}{\sin(2\beta)}+|PE|\cos(\alpha)-R\cos(\beta),\ R\sin(\beta)\right). \tag{2}$$

For a set of input points P, E, centre of curvature C_{2D} is obtained as a function of parameter β. Back-projection of the C to 3D coordinate system can be resolved using the following considerations:

$$(C-D)\cdot[(P-D)\times(E-P)]=0 \tag{3a}$$

$$|\overrightarrow{SC}|-R=0 \tag{3b}$$

$$\|C-P\|-\|C_{2D}\|=(C-P)\cdot(C-P)-\|C_{2D}\|=0 \tag{3c}$$

$$\frac{(C-P)\cdot(P-D)}{\|C_{2D}\|\,\|P-D\|}-\frac{C_{2D,x}}{\|C_{2D}\|}=0. \tag{3d}$$

The meaning of Eqs. (3a)–(3d) is the following: Eq. (3a): points D, P, E, C are coplanar, Eq. (3b): the distance between points S and C is equal to the radius of curvature of the mirror, Eq. (3c): the distance between the points P and C. In other words, it is the equation of a circle with the centre in P, Eq. (3d): the angle γ are equal in 2D and 3D systems.

The theoretical position of the centre of curvature of every mirror is given in spherical coordinates R, φ, θ relative to the ideal centre of curvature of the top/bottom sphere [14]. The coordinate system is defined as follows: the origin is at the sphere centre, the vertical z-axis is in the upwards direction, the x-axis lies on the vertical symmetry plane of the spheres and y-axis is perpendicular to the zx plane. xyz axes share directions with the COMPASS survey coordinate system. For spherical coordinates, the angle θ is measured from the z-axis towards the polar vector while the angle φ is measured from the x-axis towards the projection of the polar vector into the xy plane.

The absolute misalignments of the mirrors are given as differences of the spherical coordinates $\Delta\varphi, \Delta\theta$. The misalignment is computed from the ideal centre of curvature of the sphere C_{id}, the calculated centre of curvature C of selected mirror and the centre of the mirror M_S. Spherical coordinates of the mirror centre are recalculated according to the calculated centre of curvature C. Finally, the misalignments are calculated by subtraction of the

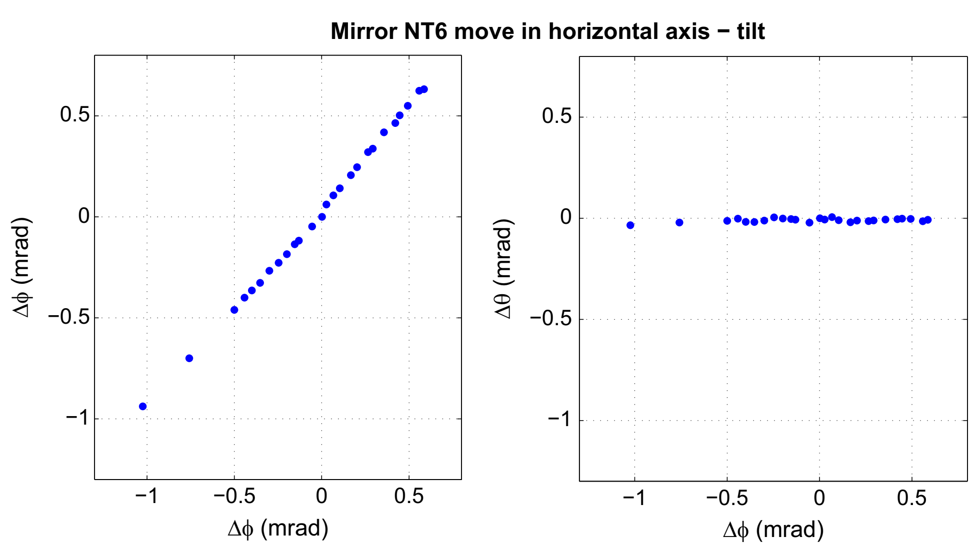

Fig. 2. One of the example of results of the test of the sensitivity of the absolute method when the data measured in the laboratory were used as the input. The algorithm is launched for the mirror NT6 placed in the Jura-Top area of the mirror wall. The mirror is tilted horizontally. Values on x-axes correspond to the mirror tilt in horizontal plane measured by the laser interferometer. Values on the y-axes correspond to the estimated mirror horizontal and vertical tilt.

original spherical coordinates of the mirror centre of the recalculated ones.

4. Results

To prove the concept of the absolute measurement algorithm, laboratory tests were performed.

In laboratory conditions, an activity to find a relation between the shift of the photogrammetry targets in the image (reflections of the grid off the mirror) in horizontal and vertical directions, *hor* and *ver* (in pixels), and the mirror misalignment angles, ϕ and θ (in mrad), was found for each mirror. A laser interferometer was used as a reference measurement instrument. Each mirror was tilted gradually with the least step of 0.05 mrad. Detailed description of the laboratory testing set-up can be found in Ref. [12]. During the laboratory testing, the 30 possibilities of the relative mirror-camera positions of a RICH-1 Jura-Top quadrant were checked.

The plots in Fig. 2 show an example of the results for the mirror NT6. The mirror is tilted horizontally. Values on the x-axes correspond to the mirror misalignment in the horizontal direction measured by the laser interferometer. Values on the y-axes correspond to the estimated horizontal and vertical tilt of the mirror. It can be seen that the CLAM method detects every step of the mirror tilt.

It is clear that the CLAM method is sensitive to the change of the mirror tilt measurement just as the laser interferometry. But in general, the CLAM absolute method results depend on the exact knowledge of the camera position. As a consequence, the accuracy for this method is about 0.1 mrad. This value is still acceptable.

5. Conclusions

It was shown that the use of the CLAM digital photogrammetry-based method can offer an attractive approach to measure the mirror misalignments remotely with sufficient accuracy 0.1 mrad and speed comfort of the procedure.

The new absolute measurement method was developed to determine the mirror tilt/orientation directly using only one picture. The idea, that well aligned mirrors share the same centre of curvature and for a misaligned mirror the centre of curvature differs from its ideal position, was adopted. The process to obtain the mirrors misalignments involves mainly image processing and digital photogrammetry techniques.

The information about the mirror alignment can be used in the reconstruction and analysis package for the RICH-1 detector, called RICHONE. The corrections could be also applied directly to the mirrors if the mirror wall is equipped by remotely driven actuators.

The possibility to correct the mirror misalignments without accessing the radiator vessel has other advantages: if the vessel is always closed, the mirror segments can be constantly kept in a dry, clean atmosphere, thus preventing the degradation of the reflecting surface by moisture and dust. Finally, the CLAM system is the only method that can be used to monitor variations in the misalignments of all the mirrors caused by temperature changes, gas circulation system of the detector or another unpredicted events in almost real time.

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