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J. Huth and C. D. Moore
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510 U.S.A.

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THREE-DIMENSIONAL SURVEY TECHNIQUES FOR LARGE DETECTOR SYSTEMS

J. Huth, C. D. Moore

Fermi National Accelerator Laboratory*
P. O. Box 500, Batavia, IL 60510

This paper describes several novel survey techniques which have been developed for the Collider Detector at Ferm ilab (CDF).[1] These techniques include the collection and manipulation of survey data from a large multipurpose colliding beams detector.

The CDF Detector has been described in detail elsewhere.[1] The detector, Fig. 1, consists of a central detector weighing 2400 tons with approximate dimensions 320 x 320 x 320 (inches), and a forward/backward system which consists of two mirror image components flanking the central detector, each weighing ~1040 tons with approximate dimensions 200 x 200 x 200 (inches).

The central detector consists of a tracking system inside a 1.5 T solenoidal magnetic field. Surrounding the solenoid are four "C" shaped calorimeter arches. Each arch consists of 12 wedges of a combination of lead and iron calorimeters. In addition, an iron magnetic flux return yoke forms the mechanical framework of the central detector. A cone-shaped end plug calorimeer fills the region at the end of the solenoidal field.

The forward detector consists of both EM and hadronic calorimetry and a pair of magnetized iron toroids (three feet thick, outer diameter 250").

Survey Requirements

In order to perform various physics analyses, the positions of the active detector elements must be determined to precisions varying from 0.1" to 0.015". For example, the relative positions of the wedges in the arches must be known to an accuracy of 0.04" in order to reconstruct electrons by matching a calorimeter shower position to a stiff charged track in the central tracking.

In most cases, full three-dimensional survey information is required, however, there are various constraints imposed upon the survey procedure. In some cases the points to be surveyed are hidden by obstructions, when in a final location. In other cases, conventional survey techniques cannot be used because the high magnetic fields prohibit the introduction of equipment, such as tooling bars, etc., into the high field region. Also, the number of three-dimensional data points (roughly 1000) is large, and the data points must be collected in the short time period (1 - 1 1/2 weeks) after the central detector has been rolled into place and before the beginning of the accelerator startup periods. The survey data must then be verified for accuracy in a relatively short time.

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Use of Electronic Triangulation Systems

A major recent advancement in optical tooling is the advent of electronic triangulation systems. Firms such as Wild,[2] Brunsen,[3] and Kern[4] have developed equipment and software for electronic triangulation. Such systems typically consist of a pair of electronically read-out theodolites, each connected to a central mini-computer equipped with disk drives and printers as peripherals.

The operation of the system requires an initial calibration of the pair of theodolites to establish their orientation relative to each other, including a baseline distance. The theodolites are first leveled and a pair of angles are determined for each theodolite to the other theodolite using a collimation of the two. At this time a distance scale must be introduced to calibrate the baseline distance between theodolites. This is done using a precisely machined material with a low thermal coefficient of expansion, such as Invar. The theodolites simultaneously focus on each end of the rod. From the length of the rod and from the angles to the ends, resection is used to determine the baseline distance.

The coordinate system is thus arbitrarily determined. From external survey references a unique coordinate system can be determined, and a transformation from the theodolite system to the system defined by the survey workers can be achieved by appropriate coordinate transformation.

In the specific case of the survey of large 4π detector systems, a global system must be established. For CDF, the global system is referenced to the Fermilab Tevatron control network. The origin is set at the midpoint of the low-β quadrupoles in the Collision Hall, and the three orthogonal axes are oriented using gravity and the direction of the proton beam. Before the central detector occupies the Collision Hall, a large number of targets on the walls, ceiling, and floor are surveyed, and their coordinates are determined relative to the coordinate system origin (defined above).

Targeting

When the detector occupies the Collision Hall the auxiliary targets are used to orient the electronic triangulation system into the global coordinate system. The Collision Hall targets include cross hair type patches and tooling balls on rods anchored in the walls.

The coordinates of the tooling balls are determined by pointing the theodolite at the reflection of a source of light collimated along the theodolite against the tooling ball. Although the accuracy of this targeting is less than crosshair-type targets in a direct shot, it is more precise when viewed at steep angles, as is often the case in the Collision Hall containing obstructed views and shallow angles. Ideally, a system of targets forming a series of roughly equilateral triangles with the theodolite will yield the best results.

Data Manipulation

All data taken using the theodolite system are written into a database on a VAX cluster for further manipulation and retrieval. Each entry in the database is for a given survey target and includes nine discrete pieces of information. Three numbers give the ideal coordinates (x,y,z) determined either from engineering drawings or previous surveys, three numbers are the "real" coordinates as determined by field measurements with the theolodite system, and there are three errors on the real coordinates.

Both the accuracy of the survey and the location of hidden points can be determined through the use of a coordinate transformation matrix. It is assumed that the detector system can be described in terms of a set of rigid bodies. With this assumption, database entries can be grouped together to define the orientation of each rigid body.

If the points of a rigid body are measured in different orientations, the differences between the data can be expressed in terms of a coordinate transformation. The most general transformation consists of a rotation and a translation. Let the column vector (x_i, y_i, z_i) represent the coordinates of the i^{th} point on a rigid body. The general transformation we have used is a rotation followed by a translation. If (x_i', y_i', z_i') are the coordinates on a transformed rigid body, then there exists a transformation that takes (x_i, y_i, z_i) into (x_i', y_i', z_i').

$$\begin{pmatrix} x_i' \\ y_i' \\ z_i' \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} + \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix}$$

where (x_o, y_o, z_o) is the translation vector, and r_{ij} are the elements of the rotation matrix. The r_{ij}'s are:

$$\begin{aligned}
r_{11} &= \cos\psi \cos\theta - \sin\psi \sin\theta \sin\phi \\
r_{12} &= 1(\cos\psi \sin\phi - \sin\psi \sin\theta \cos\phi) \\
r_{13} &= \sin\psi \cos\theta \\
r_{21} &= \cos\theta \sin\phi \\
r_{22} &= \cos\theta \cos\phi \\
r_{23} &= \sin\theta \\
r_{31} &= -1(\sin\psi \cos\phi - \cos\psi \sin\theta \sin\phi) \\
r_{32} &= \sin\psi \sin\phi - \cos\psi \sin\theta \cos\phi \\
r_{33} &= \cos\psi \cos\theta
\end{aligned}$$

Here ψ, θ, and ϕ describe rotation angles about each of the original axes (y,x,z). These are generally referred to as yaw, pitch and roll. Given the above set of ideal, real, and error data for a rigid body, a coordinate transformation can be uniquely fit using a χ^2 estimator, which is to be minimized. Given the set of transformed points (real) and the original (ideal) points, we form a χ^2 as:

$$\chi^2 \equiv \sum_{j=1}^{N_{pts}} \frac{(x_j^r - x_j^i)^2}{\sigma_x^2} + \frac{(y_j^r - y_j^i)^2}{\sigma_y^2} + \frac{(z_j^r - x_j^i)^2}{\sigma_z^2}$$

where the $(\sigma_x, \sigma_y, \sigma_z)$ are the errors on the coordinates.

The χ^2 is minimized by allowing the parameters x_o, y_o, z_o, ψ, θ, ϕ to vary until a minimum in χ^2 is found by the computer package MINUIT.[5] The sum of the squares of the residuals then serve as a measure of the reliability of the survey data.

This technique is useful for determining the accuracy of surveys. Over the dimensions of the CDF Collision Hall, using the BETS [3] system, a typical resolution of 0.03 inches was obtained. For objects such as the CDF central calorimeter arches, accuracies of 0.01 to 0.02 inches were typical.

Example: survey of the central calorimeters.

The use of the fitted coordinate transformations is a powerful tool to locate the position of hidden points on a rigid object. The detector is built in discrete pieces each of which can usually be surveyed by itself in the open. Once the detector is assembled, many of the points of interest are hidden from view. One can determine these points from a set of reference points. When the detector is disassembled, coordinates of the hidden points and a set of fiducial markers are determined. The fiducial markers must be visible when the detector is assembled.

After assembly, the fiducial points are then surveyed in the Collision Hall coordinate system. From these data, a unique coordinate transformation can be determined for the object. The same transformation can be applied to obtain the positions of the hidden points.

As an example, the CDF central arch is defined by the positions of the discrete wedges (Fig. 2). The fiducial markers on the wedges are only visible when the arches are in the disassembled position. In an initial survey, all of the wedges were surveyed relative to a set of fiducial markers on the outside of the wedge. Using conventional survey techniques, this job would take roughly 1.5 weeks for two surveyors. Using electronic triangulation the same job can be performed by the same crew in an 8-hour shift. Figure 3 shows schematically the displacement vectors derived for one of the arches, using the above analysis.

Once the detector is positioned in the Collision Hall, the markers on the rear of the arches are surveyed and a transformation is determined to take the arches from the initial survey into the Collision Hall coordinate system. This transformation is then applied to the wedge data, and the positions of the wedges are determined in the Collision Hall coordinate system.

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5. MINUIT, a function minimization package produced by CERN. Computer Physics Communications (10) 1975 343-367.

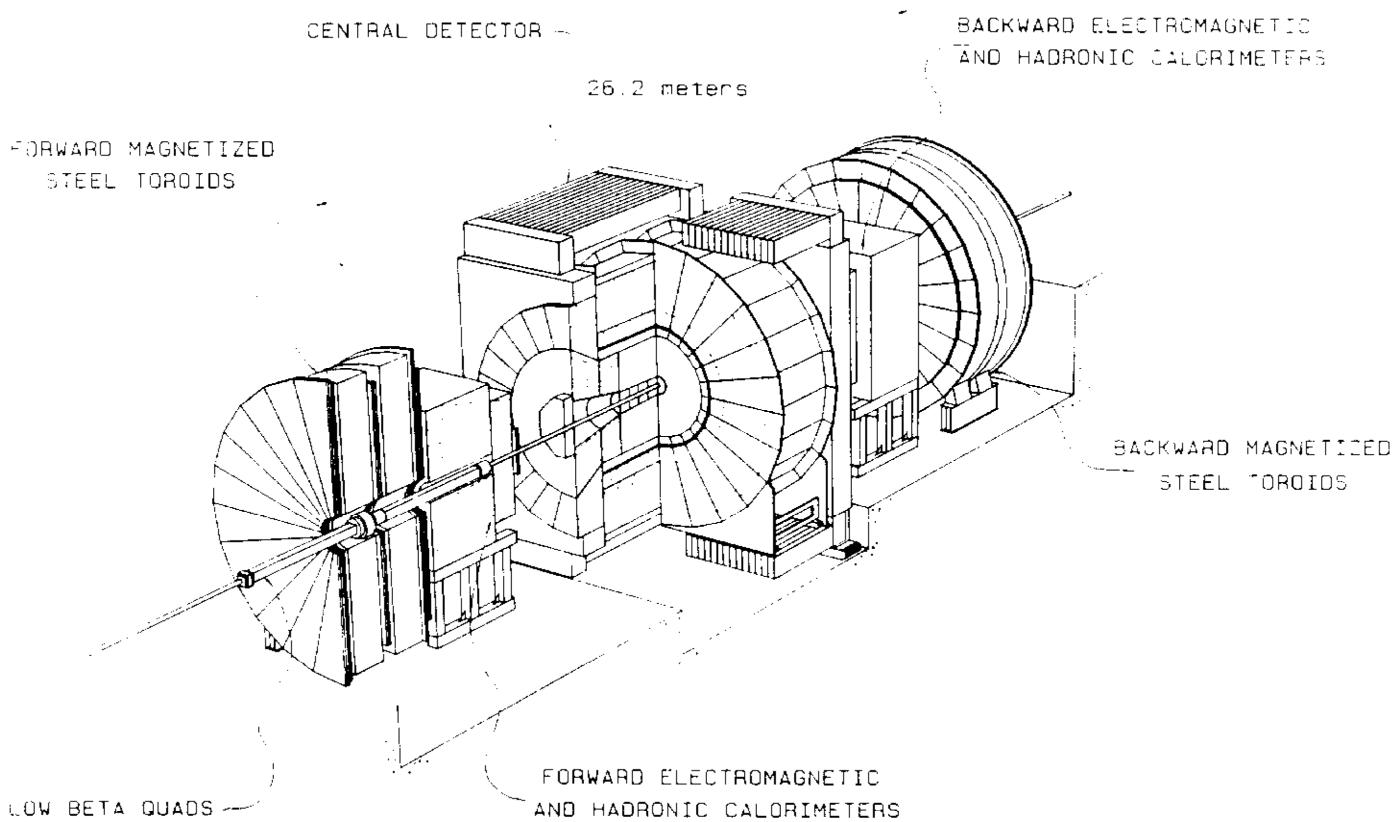

Figure 1. CDF detector. A central detector consisting of calorimeters, a superconducting solenoid, and charged particle tracking is flanked by a forward/backward system of detectors.

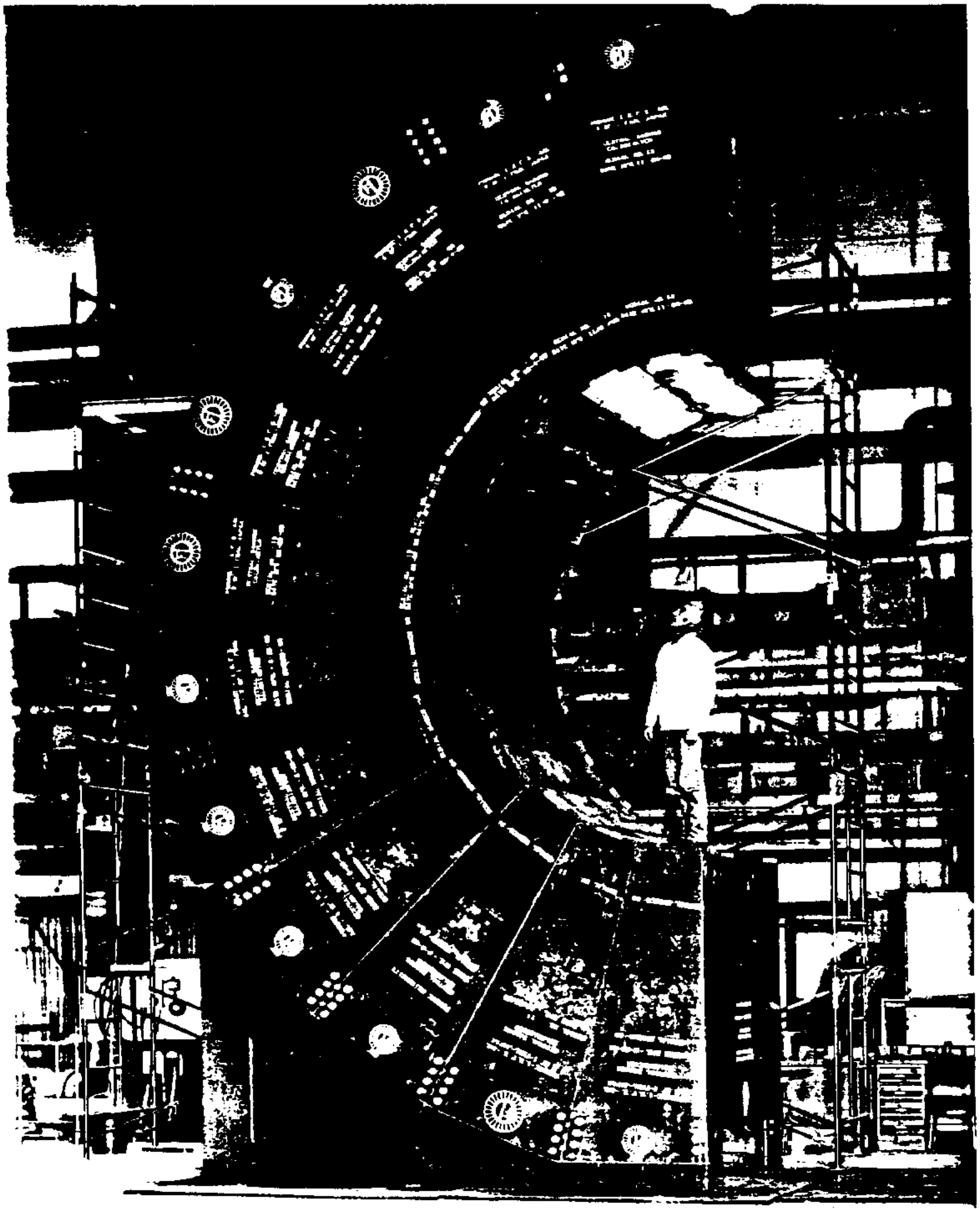

Figure 2. CDF central arch. Precision dowel pin holes are used to locate the position of the wedges. These coordinates are hidden when the arches are installed, and a rigid body transformation is employed to determine their location.

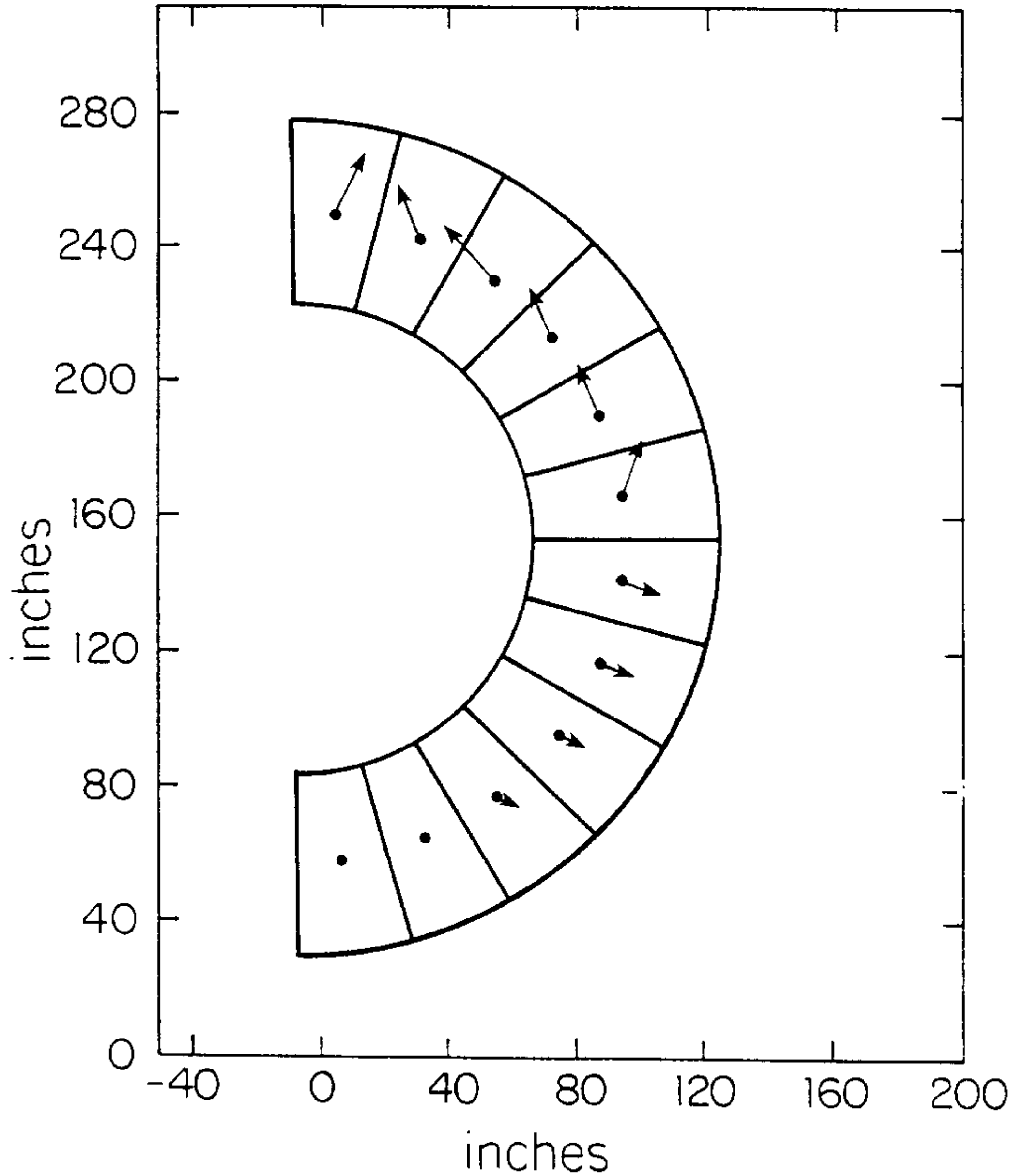

Figure 3. Schematic of the displacement vectors derived for a CDF central calorimeter arch using the techniques described in the text. The arrows represent 70 times the size of the displacement vectors taking each wedge from an ideal to a true location. The discontinuity between vectors in the horizontal position is due to a spacing wedge. The buildup of sag for higher wedges is clearly visible.