MAGNET FIDUCIALIZATION WITH COORDINATE MEASURING MACHINES

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Introduction

One of the fundamental alignment problems encountered when building a particle accelerator is the transfer of a component's magnetic centerline position to external fiducials. This operation, dubbed fiducialization, is critical because it can contribute significantly to the alignment error budget. The fiducialization process requires two measurements:

1. from magnetic centerline to mechanical centerline, and
2. from mechanical centerline to external fiducials.

This paper will focus on methods for observing the second measurement. Two Stanford Linear Collider (SLC) examples are presented.

Goals

The object of magnet fiducialization is to relate the magnet-defined beamline position to exterior reference surfaces. To be useful for later component alignment, this relationship must be established in a manner consistent with overall positioning tolerances. The error budget for the SLC's $\pm 100\mu\mathrm{m}$ component to component alignment tolerance is as follows:

magnetic centerline to mechanical centerline	$\sigma = \pm 30\mu\mathrm{m}$
mechanical centerline to fiducial marks	$\sigma = \pm 50\mu\mathrm{m}$
fiducial marks to adjacent components	$\sigma = \pm 80\mu\mathrm{m}$
TOTAL	$\sigma = \pm 100\mu\mathrm{m}$

The offset between the mechanical and magnetic centerlines of well-known magnets is generally smaller than the $\pm 30\mu\mathrm{m}$ measurement tolerance. It is commonly assumed to be zero without measurement. When this tiny value must be measured, extreme care is necessary to avoid obscuring the offset with measurement tool registration errors. In contrast, the mechanical centerline to fiducial measurement must be performed on every magnet. The $50\mu\mathrm{m}$ tolerance for this operation is only slightly larger and pushes conventional surveying technology to its limit.

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This has forced the search for other means of measuring these quantities reliably and accurately.

Methodology

To complete the transfer for mechanical centerline to the fiducials, a magnet coordinate system must be defined. This includes establishing its origin and the three orientation angles of the rigid body. Often the X and Y origins are determined by the centerline of the pole tips while the zero coordinate for Z is the longitudinal center of the magnet. Roll is set by the midplane of symmetry and yaw and pitch are defined by locating the center of the pole tips at both ends of the magnet.

All measurement systems used to make this transfer establish this coordinate system. Then all fiducial coordinates are defined within this coordinate system.

Tools

The measurement tools for transferring the pole-defined centerline to outside reference marks must have some basic capabilities. They must be able to measure the size and shape of the poles as well as the midplane of symmetry. The length of the magnet and the fiducials must also be inspected by the same tool. The method should be quick and reliable providing accuracy better than $\pm 50\mu m$. 'The inspection services should be nearby to provide for a timely delivery of results. Three methods which utilize existing hardware and software systems are available. Each has its limitations as well as its strengths.

Optical tooling provides a tried and proven fiducialization technology. It is simple and well understood. The equipment is readily available and reasonably priced. However, the reliability of optical tooling is questionable. This stems from the lack of redundant, independent observations inherent to the process. Therefore, no statistical calculations or blunder checks are possible. Also, magnet features must be targeted, thus mechanically approximating the actual surface or center. Given a case with no blunders, the limitations of human observers, instruments, and targeting hold the system's intrinsic accuracy to ± 50 to $75\mu m$.

Theodolite-based industrial measurement systems (IMS) provide an optical alternative to optical tooling. This system is highly accurate (25 - $50\mu m$) with reliability provided by redundant observations and least squares data processing. The hardware and software if available to industry. However, magnet features must still be targeted, which limits the measurement accuracy. Intimate knowledge of a complex software is also required.

Coordinate measuring machines (CMM) (Figure 1) provide a third alternative. These highly accurate machines ($\pm 3\mu m$ to $\pm 5\mu m$) can measure magnet features directly using a touch probe system. They are fast and reliable if used correctly.

Form fit quality checks are available, but the user is required to provide a global "common sense" check.

On the other hand, CMMs are powerful, complex systems whose operators require extensive training. They are also quite costly. Hourly rates at local inspection shops can be quite reasonable, however.

All three of these methods are used at SLAC. Optical tooling continues to take most of the load with CMM measurements used only for special components. The IMS systems are used for components which are too large for a CMM but require the redundancy checks not provided by optical tooling. Two SLAC CMM experiences are outlined below.

Experience With CMM Measurements

The Final Focus CQ-SQ Quad Pair

This magnet pair consisted of two 200lb solid steel cored magnets 5 inches long with a width of 10 inches and a height of 12 inches. The bore diameter was 3/4 - inch and four tooling balls at the top corners served as external fiducials (Figure 2). The purpose of the CMM inspection was to check the optical tooling measurements taken before installation. Beam steering studies indicated possible errors in the original fiducials.

The inspected procedure consisted of scanning a sample of 180 points per pole tip to determine the best fit circle for each pole tip surface. Another circle was fitted to the centers of the four pole circles to find a best fit geometric center. (Figure 2). This was repeated at both ends to set the X, Y and Z origins as well as the yaw and pitch angles. Roll was to be defined by the split plane.

The quality of the results were greatly diminished by the configuration of the magnet. Roll could not be accurately set because the split plane was not accessible. Attempts to use the centers of the pole tips to set the orientation proved unsuccessful due to the extremely short lever arm (1.5 inch). Also, tooling the CMM probe could not fully access all balls. The results which could be compared to previous measurements showed discrepancies of up to 400μms. Since the CMM measurements did not repeat well and the geometry was poor, the results were discarded. Repeated optical tooling inspection showed changes in fiducial coordinates of up to 150μm. This illustrates that for this case neither method satisfied the 50μm inspection tolerance.

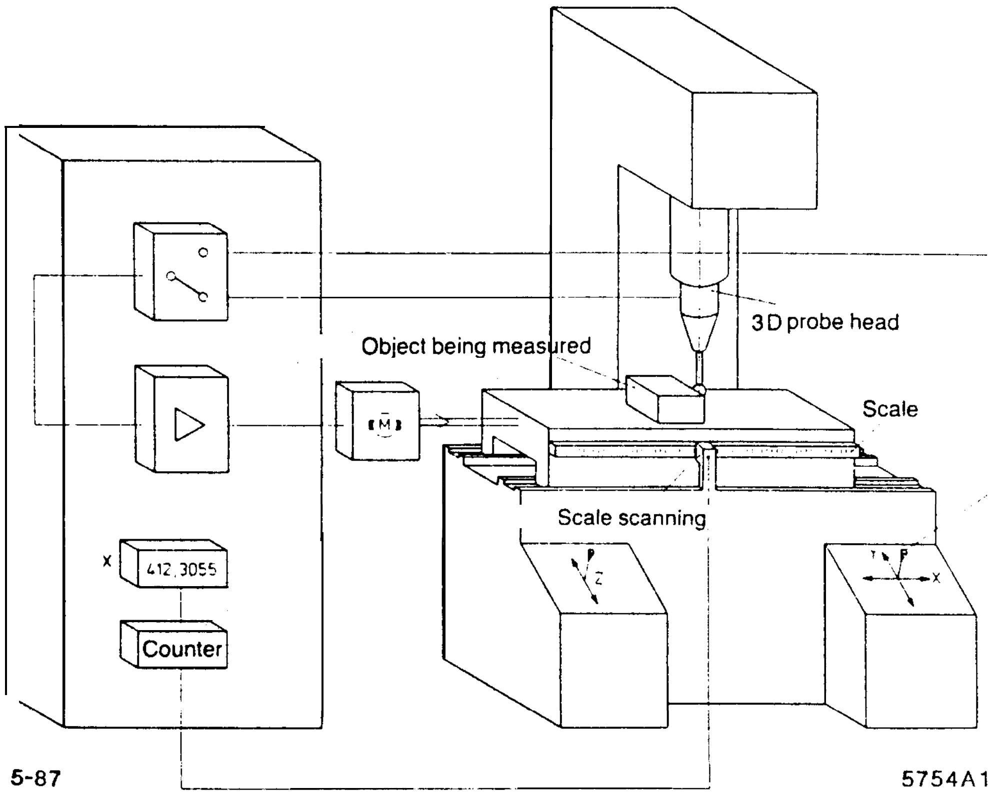
The conclusion is that magnets should be designed with CMM measurable features. "After the fact" fiducialization may be difficult if not, impossible for magnets without them. However, new video systems technology may improve this situation.

The Final Focus Sextupoles

The relative alignment of these 800lb steel cored magnets to their adjacent beam position monitor was extremely critical for producing small spots at the SLC interaction point. The magnets are 12 inches in diameter, 30 inches long, with a bore diameter of 2 inches. 16 tooling balls, 8 at each end of the magnet were pressed into the magnet body to serve as alignment fiducials.

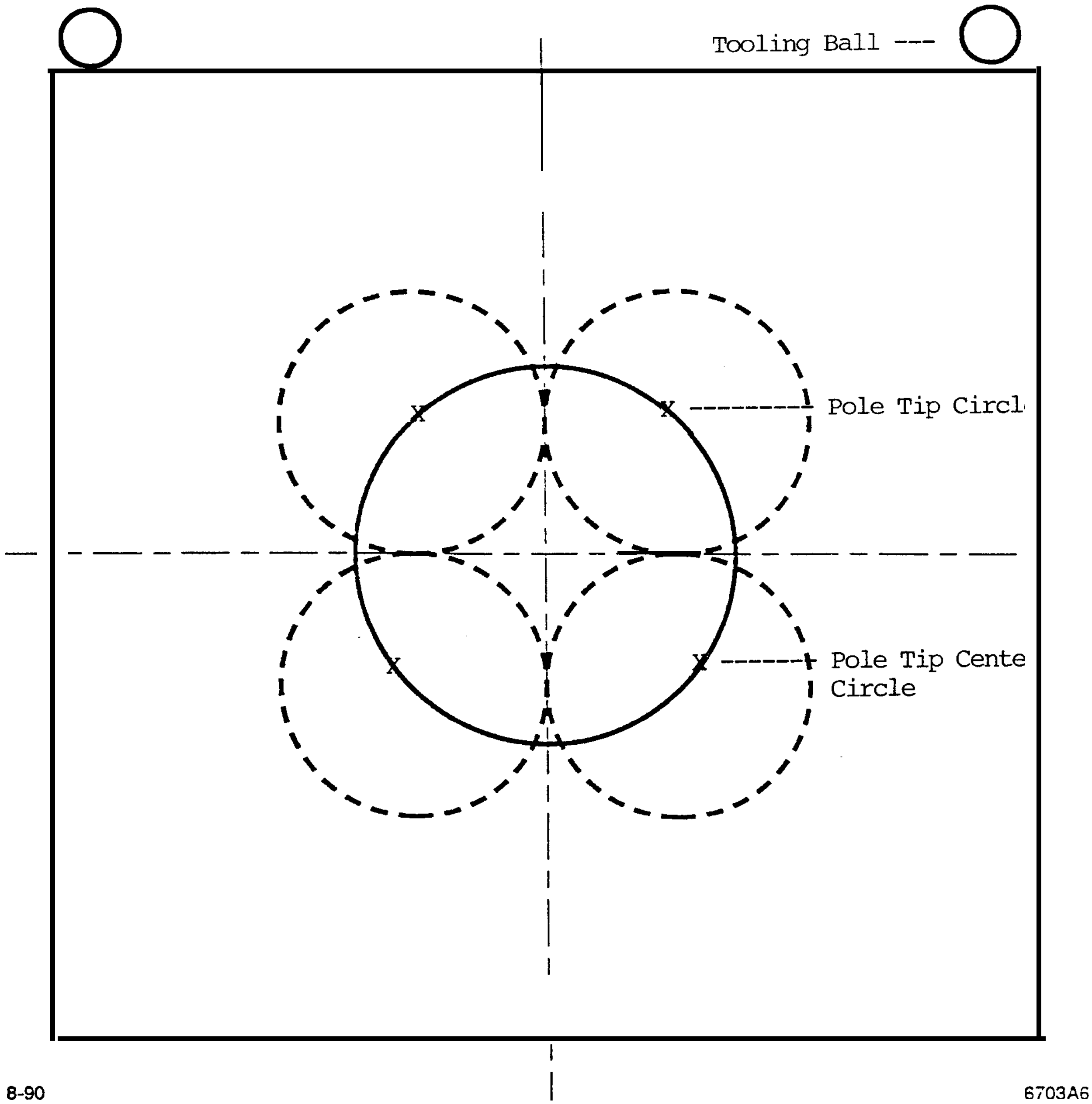
The CMM measurement routine was almost identical to the one used for the CQ-SQ quadrupole pair. The pole tips were probed at each end and circles were fit to determine the mechanical centerline (Figure 3). The roll of the magnet was defined by a tooling ball placed at the "top center" of the magnet. Precise roll orientation was not critical to the measurements, however, a second measurement was made to check the assumption that the mechanical and magnetic centerlines were coincident. Optical tooling target registration pins were measured during the CMM inspection. This provided a method to tie the mechanical centerline to the magnetic probe location mechanical probe location (Figure 4). Wire targets were mounted on the target registration pins. An alignment scope was bucked in on the line between the targets. The magnetic probe was then inserted and electronically loaded on the magnetic centerline. The distance from the remaining target to the probe was observed. This measurement combined with the target pin locations provided the magnetic centerline offset.

The results indicated that the mechanical and magnetic axes, coincided within the total measurement accuracy of 50 microns. This shows that high precision connections between fiducial marks and magnetic axes can be achieved. However, optical tooling observations remain the largest error source in the procedure and must be eliminated to reduce the measurement uncertainty.



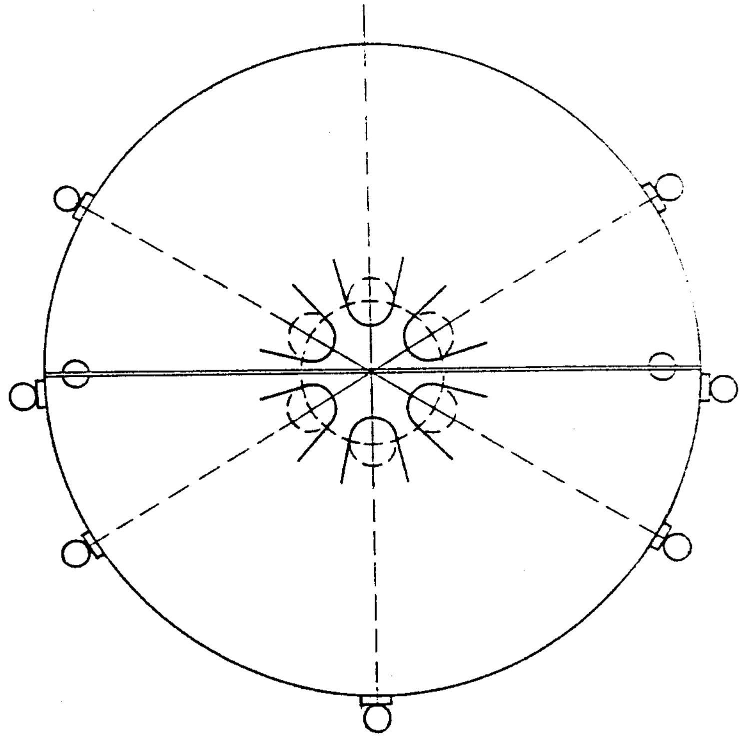
Basic Components of a Coordinate Measuring Machine

Figure 1.

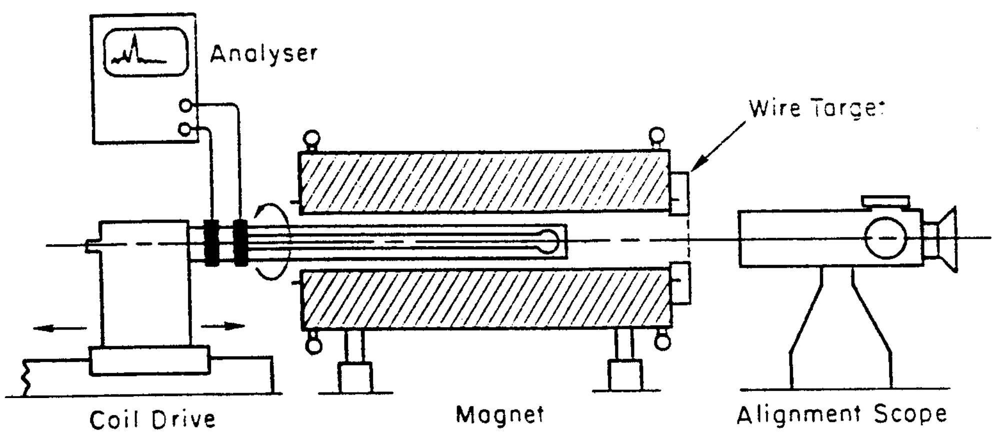


Sketch of a Final Focus CQ-SQ Quadrupole

Figure 2.



Sketch of a Sextupole
Figure 3.



Setup for the Determination of the Magnetic Centerline
Figure 4.