Cold Mass Position Sensor Calibration and Programming for Mu2e

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Abstract

The Cold Mass Position Sensor is an important piece of equipment which is used to track the movements of solenoids in the Mu2e experiment. The position of these solenoids must be known within 1000 microns to accurately calculate the momentum of the conversion electrons, but preferably below 100 microns. This project focused on minimizing the error of measurement, determining how to calculate the solenoid positions, and programing the PLC used for this system.

Background

Mu2e is an experiment at Fermi lab which hopes to detect the direct conversion of a muon to an electron without the production of neutrinos. This is known as a charged-lepton flavor violation, and it goes against the current Standard Model. Many theories beyond the Standard Model predict this conversion of muons to electrons at rates that will be measurable by Mu2e [1]. The existence of this conversion would be proof of physics outside of the Standard Model, and so this experiment is crucial to our understanding of the natural world.

Several experiments have been performed already to observe this conversion, but none have succeeded. Mu2e will have a single event sensitivity of neutrino-less muon to electron conversion of 2.5 x 10^{-17}, which is 10,000 more sensitive than the best current experiment. The Standard Model predicts that the likeliness of this event is 10^{-50}, while models of new-physics - those which aren't the Standard Model – predicts rates as high as 10^{-14}. This extreme difference in probability between the models means that it will be easy to tell if the Standard Model holds up, or falls flat [1].

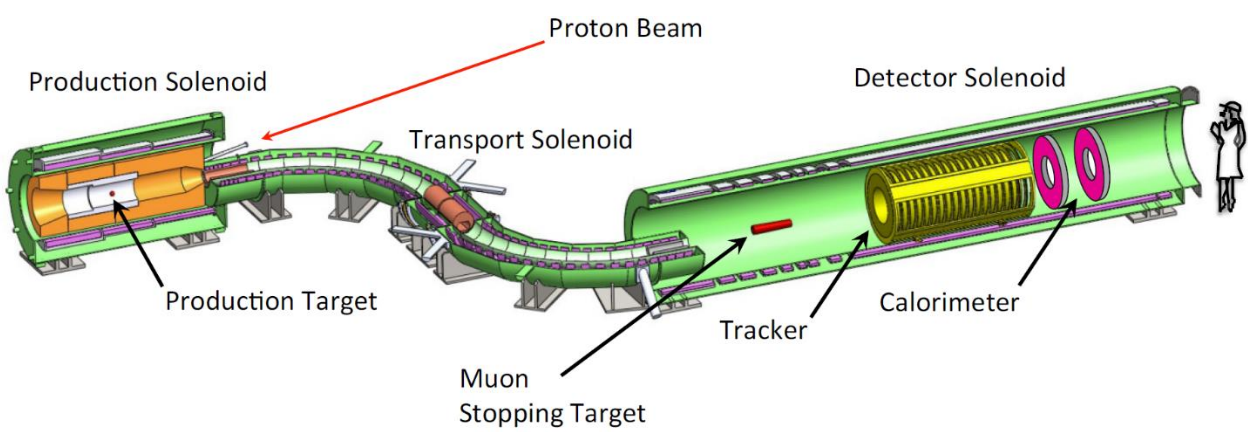

Figure one: The Mu2e Experiment Design

Protons arrive at Mu2e from the accelerator, and they then enter the production solenoid. At the production solenoid, they strike a tungsten target, which causes for the protons to decay into pions, which then decay into muons. The muons are then moved to the detector solenoid using a controlled magnetic field inside the transport solenoid. Once these muons arrive at the detector solenoid, they hit an aluminum stopping target, where they will be captured. Once in orbit around an aluminum nucleus, the muon will quickly decay. An electron will be produced from this decay, and the momentum of the electron is measured in the to determine whether a charged lepton flavor violation has occurred. The energy of an electron from this conversion is predicted to be 105 MeV, which is considerably more excited than a muon to electron conversion that also produces neutrinos. Those electrons have an energy of approximately 53 MeV, and so if a high-energy electron is detected, it will be a sign of a neutrino-less conversion.

Before the experiment begins, the magnetic field which the muons and electrons will travel through is precisely mapped so that their momentum will be able to be calculated. The solenoids used to create the magnetic field are not rigidly fixed, and so they are able to shift when they are cooled down, and when they are powered on. Through simulation, the maximum such shift that could occur is 37 mm, which is considerably large when trying to track a single particle. The Cold Mass Position Sensor (CMPS) is what is used to track the movements of the solenoids, which allows for the experimenters to precisely know the location of the magnetic field. Each CMPS must be able to withstand a vacuum of 10^{-7} torr, an overpressure of 15 psig in case of vacuum loss and subsequent overpressure due to a leak in the liquid helium or nitrogen cooling circuits, and be able to withstand radiation of 1 kGray/year. A side note - the term 'Cold Mass' refers to any of the solenoids which are being tracked.

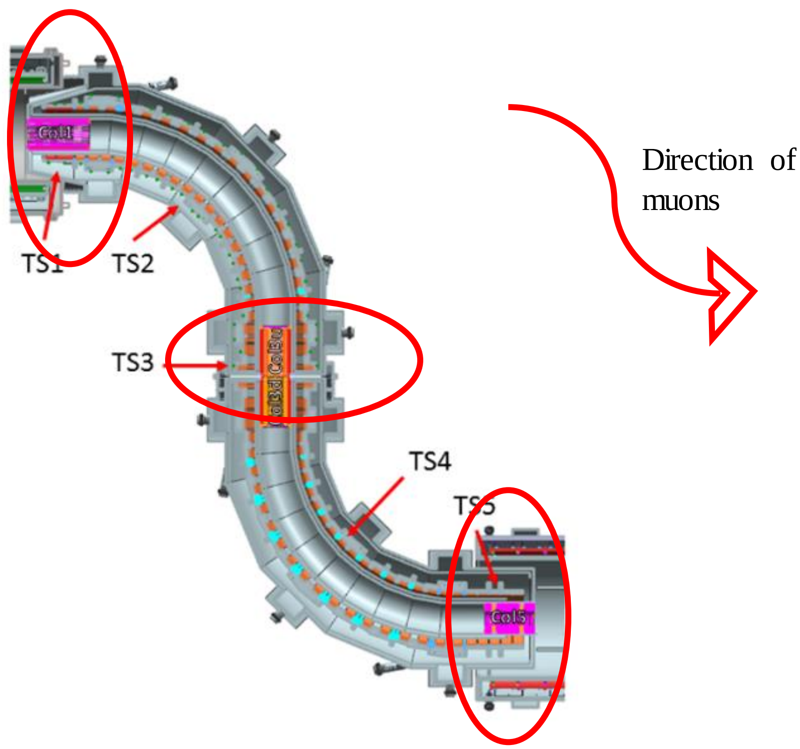

Figure two: Aerial view of the transport solenoid, general location of CMPS's circled in red

These Cold Mass Position Sensors are in three areas along the transport solenoid, as shown above in figure two. All the sensors relay the data they collect to a Siemens programmable logic circuit (PLC) which processes the information, and sends the determined location of the Cold Masses to scientists, where that data will then be recorded and used appropriately.

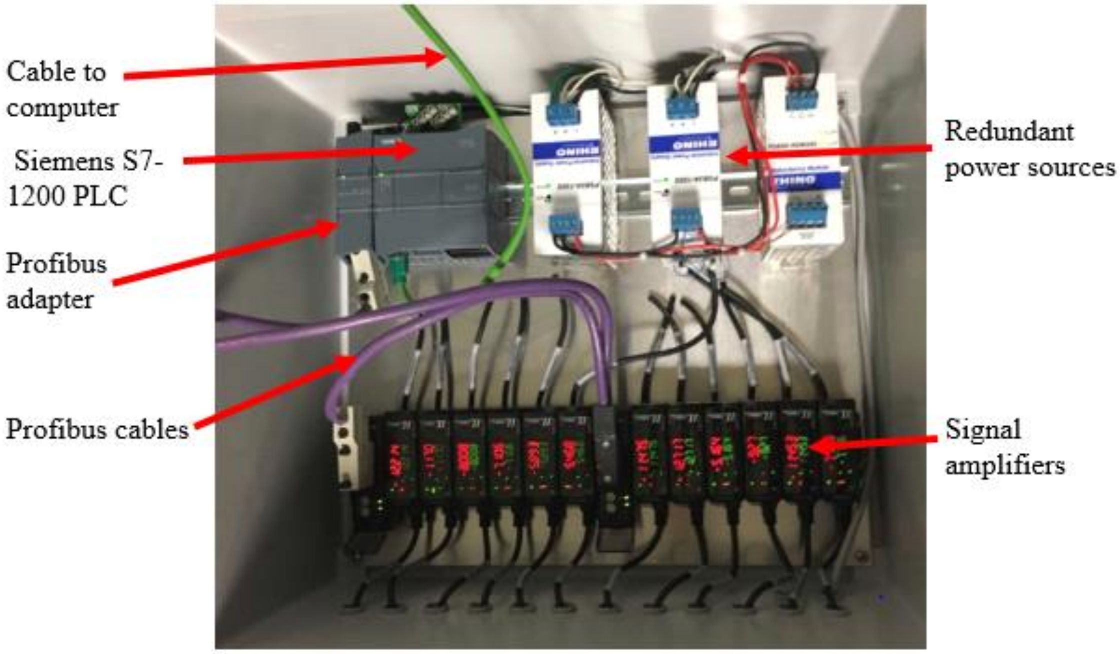

Figure three: Fully assembled equipment housing box

The equipment used to record and interpret the measurements made by each CMPS is shown above. There are three of these housing boxes in total, each receiving data from four CMPSs. Each box contains 12 amplifiers, two data sending units for the amplifiers, and two power supply units (for redundancy). The box nearest the detector solenoid will contain the PLC, since this area has the least amount of radiation. Placement of each component was considered with respect to orderly cabling and logical arrangement. Every cable was labeled three times with a description of what location and sensor head it corresponds to. It was my responsibility to assemble these housing boxes and properly attach all the labels.

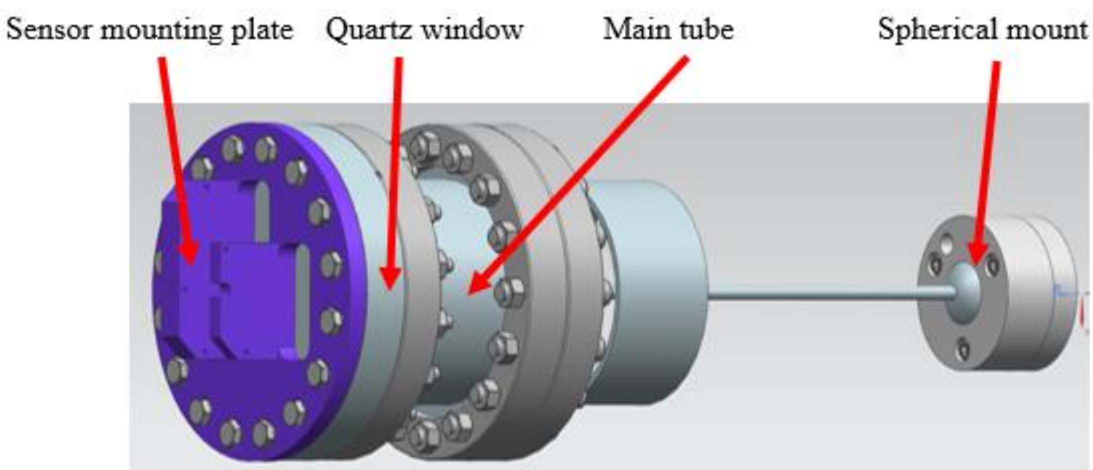

Figure four: External view of the Cold Mass Positon Sensor

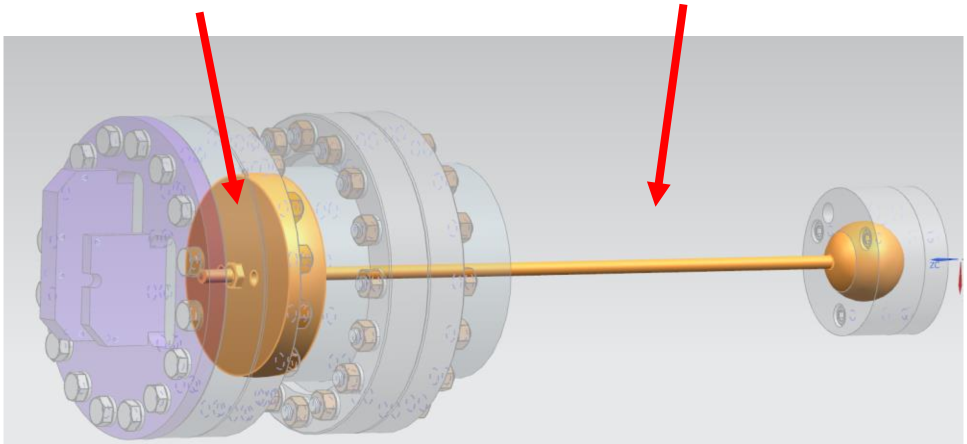

Figure five: Internal view of the Cold Mass Position Sensor

Referencing figure three, the spherical mount is attached to the Cold Mass, while the right side is attached to the external frame work of Mu2e. The two are connected via a long rod, which then connects to a spherical plate within the main tube of the CMPS. The plate's edges have the same curvature as though it were a sphere, which allows it to rotate freely within the main tube. This allows for any movement of the Cold Mass to be translated to a shift in the plate, which is constantly monitored by a set of three Keyence IL-065 lasers. These lasers measure distances within the range of 45-105 mm, and have an accuracy of two microns.

The initial program that was written to test the CMPS relied on the origin of each laser being in its ideal location, and that each laser was perpendicular to the plate which it was attached to. This method of measurement had an error of 800 microns on the actual position of the Cold Mass. While this met the original error requirement of no more than 1000 microns of error, a lower amount of error was still desired. It was estimated that a properly calibrated system would have a factor of 10 less error, and so the efforts to calibrate the CMPS began.

Methodology

Survey Methods

To determine the skewness of the lasers they were attached to their mounting plate, and then three different points along each trajectory were measured. These points were at 5 mm, 75 mm, and 2000 mm from the face of the plate. The first and third point would be used to determine the laser vector, and the second point is used to confirm this vector. During the measurements at 75 mm, the sensor readouts were recorded as well. This was done because the exact origin that each sensor references in unknown, and so it must be inferred using each sensor's own measurements. Additionally, the vector of the port tube axis, the length of the connecting rod, the thickness of the plate, and the skewness of the rod were measured.

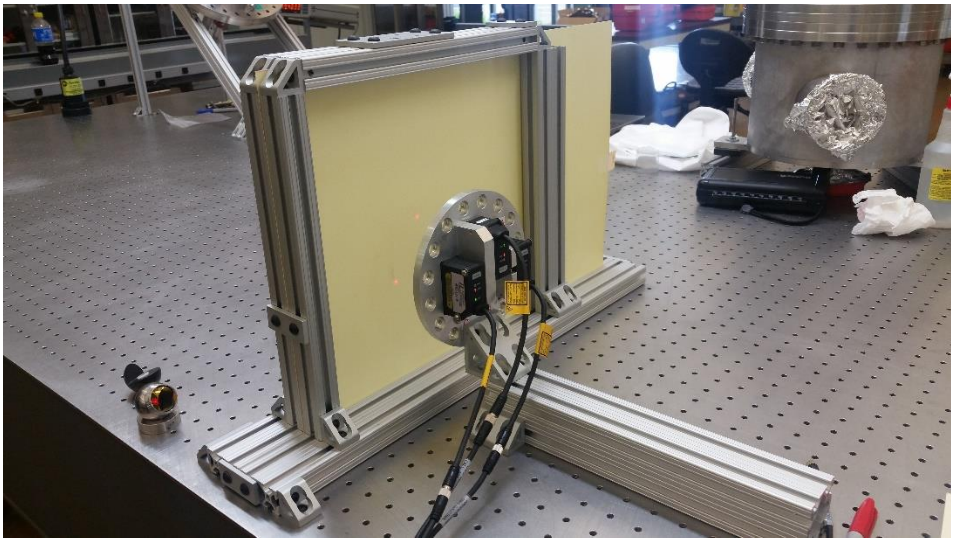

Figure six: Laser calibration setup for 75mm distance measurements

For simplicity, the calculations for each laser's slope and origin were performed in Excel. The inputs for the spreadsheet are the three points along each laser's trajectory, and the sensor readout to point two. Then the slopes and origins for each laser are calculated twice- once using the slope from points one and three, and the other from points two and three. The differences of these values are displayed for user knowledge. The largest origin error calculated based on these slope differences was three microns, which is very close to the expected error of two microns.

Table one: Expected Error of Measurements

Source of Error	**Expected Amount of Error (μm)**
Keyence Laser	2
Laser Origin	2
Port Tube Axis	<25
Rod Length	<25
ANSYS Modeled Rod Cooling	<10
Plate tilt	X: <20, Y: <20, Z: <2
Sphere position	<25
Cumulative Error	**Expected Amount of Error (μm)**
X direction	48
Y direction	48
Z direction	45
Total	**81**

The table above shows the itemized errors expected for the CMPS system. These values were estimated through discussion with the Survey Team, and will be compared to actual error in the results section.

Once all the measurements were taken for the system, it was ready to be tested. The position of the sphere was monitored by a Radian Laser Tracker. The initial position for the sphere was recorded using both the laser tracker and the CMPS. Then the sphere was moved using the xyz adjustment on the test stand to several different locations, and each time both measurements of position were recorded. Since the initial coordinates of the tracker and CMPS are not the same, the accuracy of the CMPS will be determined by comparing the change in position relative to their starting points.

Programming Methods

The software used to program the Siemens PLC was Siemens Totally Integrated Automation V14 (TIA). In this program the physical network of devices is recreated, and then functions are written to the user's specifications. There are two ways that a program can be written in TIA, either using ladder logic, or structured text. Ladder logic is a visual way of programming that involves blocks and gates, while structured text is very similar to C or C++. The CMPS PLC was programmed using structured text since it was much easier to use for complex geometrical calculations. The following constants are stored in a data base with in the PLC: each laser's slope and calculated origin, tube axis vector, thickness of the plate, distance from the center of the plate to the center of the connecting sphere. These constants are used in the function which calculated the Cold Mass position.

Summary of logic structure operations

1. Laser readings are converted to absolute distances
2. The point at which each laser contacts the plate is calculated by traveling along the laser's vector from the origin by the absolute distance to the plate
3. From these three points, the normal unit vector of the plate is determined by crossing the vector from point one to three and the vector from point one to two
4. The equation for the plane midway between the faces of the plate is calculated, and the intersection point between this plane and the central axis of the tube is found
5. The location of the Cold Mass is found by traveling along the vector normal to the plate from the point of intersection mentioned previously by the length from the center of the plate to the center of the connecting sphere on the solenoid
6. The locations of the 12 Cold Masses are stored in a database which can be accessed via Kepware Server software

Results

Table two: Error results from survey

Average Absolute Error	Actual Amount (µm)	Expected Amount (µm)
X direction	155.55	48
Y direction	271.36	48
Z direction	152.03	45
Total	331.81	81

The results above show the amount of absolute error between what the CMPS and the laser tracker measured. The error was considerably larger than what we expected, but it was still much lower than the original 800 microns of error. The cause of this error is that the plate and connecting rod are not exactly perpendicular with one another. During the survey, we found that over the 30 cm length of the rod, it had a horizontal shift of 1 mm. This source of error explains why the CMPS was off by an average of 331 microns.

The future direction of the CMPS will be to first address the error caused by the rod and plate not being perpendicular to one another. Another survey will take place to determine if it is the rod which is bent, or if the tapped hole in the plate isn't straight. After this, the data gathered from the CMPSs will be used to determine the final location of each solenoid, which will be used to adjust the momentum calculations for the conversion electrons.

Conclusion

The effort to calibrate the Cold Mass Position Sensor was a success, and can still be improved upon in the near future. Originally, the error in measurement was 800 microns, and it is currently 331 microns. This is a significant improvement, and can be made even better by correcting the perpendicularity of the plate and rod.

Acknowledgements

I'm very grateful for the time I've been able to work at FNAL, and I would like to thank the Department of Energy for providing this opportunity. Everyone who worked to organize the SIST program - Elliott McCrory, Sandra Charles, Judy Nunez, Charlie Orozco, Dave Peterson, and Donovan Tooke – did a phenomenal job. My supervisor, Thomas Strauss, was very supportive and his door was always open to me when I had questions on my project. Lastly, I would like to thank everyone else I've come to know along the way – the other SIST and GEM interns, and everyone in the Magnetic Sector Department.

References

[1] Glenzinski, Douglas, and James Miller. "The Mu2e Experiment: a Rare Opportunity." *CERN Courier*, CERN Courier, 2 June 2015, cerncourier.com/cws/article/cern/61266.

Appendix

Structured text from PLC program

```
#num := 0;
FOR #num := 0 TO 2 DO
    #s1_point[#num] := #s1_origin[#num] + #s1_slope[#num] * (65000 -
#s1_reading);
    #s2_point[#num] := #s2_origin[#num] + #s2_slope[#num] * (65000 -
#s2_reading);
    #s3_point[#num] := #s3_origin[#num] + #s3_slope[#num] * (65000 -
#s3_reading);
END_FOR;
#num := 0;
FOR #num := 0 TO 2 DO
    #vector_a[#num] := #s2_point[#num] - #s1_point[#num];
    #vector_b[#num] := #s3_point[#num] - #s1_point[#num];
END_FOR;
#vector_norm[0] := (#vector_b[1] * #vector_a[2]) - (#vector_a[1] *
#vector_b[2]);
#vector_norm[1] := (#vector_b[2] * #vector_a[0]) - (#vector_a[2] *
#vector_b[0]);
#vector_norm[2] := (#vector_b[0] * #vector_a[1]) - (#vector_a[0] *
#vector_b[1]);
#unitlength := SQRT(SQR(#vector_norm[0]) + SQR(#vector_norm[1]) +
SQR(#vector_norm[2]));
#num := 0;
FOR #num := 0 TO 2 DO
    #vector_norm[#num] := #vector_norm[#num] / #unitlength;
END_FOR;
#num := 0;
FOR #num := 0 TO 2 DO
    #plane_eqn[#num] := #s1_point[#num] +
#vector_norm[#num]*(#plate_thickness/2);
END_FOR;
#plane_eqn[3] := (#vector_norm[0] * #s1_point[0]) + (#vector_norm[1] *
#s1_point[1]) + (#vector_norm[2] * #s1_point[2]);
#plate_temp := ((#vector_norm[0] * (#axis_point[0] - #s1_point[0])) +
(#vector_norm[1] * (#axis_point[1] - #s1_point[1])) + (#vector_norm[2]
* (#axis_point[2] - #s1_point[2]))) / (-1 * (#vector_norm[0] *
#axis_vector[0] + #vector_norm[1] * #axis_vector[1] + #vector_norm[2]
* #axis_vector[2]));
#num := 0;
FOR #num := 0 TO 2 DO
    #plate_center[#num] := #axis_point[#num] + #axis_vector[#num] *
#plate_temp;
END_FOR;
#num := 0;
FOR #num := 0 TO 2 DO
    #coldmass[#num] := #plate_center[#num] + #vector_norm[#num] *
(#center_ball_to_front_plate_length-(#plate_thickness/2));
END_FOR;
```