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A CAPACITIVE DISPLACEMENT MEASURING SYSTEM FOR THE DELPHI MICROVERTEX DETECTOR.

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ABSTRACT

The physical and technical motivations and the working principles of a Capacitive Displacement Measuring System (CDMS) for the Delphi Microvertex Detector are presented. The design, based on a Monte Carlo simulation, is illustrated.

Experimental tests, performed both in laboratory and during a test beam, show the system should be able to monitor the displacements of the detector in space within a few microns accuracy.

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1. - PHYSICAL AND TECHNICAL MOTIVATIONS FOR THE SYSTEM

The use of silicon microstrip detectors as very precise tools for tracks recontruction in fixed target experiments has nowadays a long and estabilished tradition. The fully exploitation of their high geometrical resolution (≤ 5 μm) relies also on alignment techniques essentially based on a two steps procedure. The first step consists in mounting the detectors on high precision and stable mechanical structures [1], while in the second step an off -line alignment is performed by means of particle tracks.

In a collider experiment the different geometry introduces new problems one has to cope with. Microstrip detectors are in some case the core of the detector, constructed according a cylindrical onion-like structure [2 - 4].

In order not to waste the spatial and momentum resolution of the whole tracking apparatus, the support structure, together with the microstrip detectors themselves, must get a minimum amount of material, while still being stiff.

For the Delphi Microvertex Detector (μVD), carbon fiber has to be used in order to garantee stiffness to the detector, while representing only 0.3 % of radiation length [2]. The mechanical construction of the whole detector is accurately done, and mechanical measurements of the system will be done with a few μm precision [5]. However the position of the μVD " in situ ", i.e. once installed in Delphi, will be mechanically determinated only within about 0.100 mm.

Off-line alignment by means of tracks can be employed but takes a few days because of the rate of useful interactions [6 - 7]. Movements over a short time scale could waste the effectiveness of this method.

Following these considerations a fast " in situ " hardware alignment is strongly recommended.

We think of some ways of implementing such a system: 1) Inductive; 2) Optical; 3) Capacitive.

The first one is ruled out by the presence of a high magnetic field (1.2 T) in Delphi. The second one makes use of light spots that are detected by the microstrip detectors themselves [8]. Thus it is direct, but has the disadvantage of being able to monitor mainly only displacements along the coordinate measured by the strips.

The capacitive system seems to be able to fully monitor the movements of the detector in space. In the following sections we will present the design and some experimental results of a Capacitive Displacements Monitoring System (CDMS) for the μVD.

2. - BASIC WORKING PRINCIPLES

The concept of a capacitive system for measuring displacements lays on the well-known law of the capacitance C_0 of a parallel-plate capacitor:

$$C_0 = \frac{\varepsilon S}{d} \tag{1}$$

where ε is the permettivity of the dielectric filling the space between the two plates, whose surface is S, d is the distance (gap) between the two plates.

This formula tell us we can calculate the gap between the two plates by measuring C_0 once ε and S are known. On the other hand, if the gap d is known, toghether with ε, we can get S measuring C_0.

Let us consider a capacitor composed by two electrodes: one, the "target" is mounted on a reference frame; the other, the "sensor" is mounted on the object, whose displacements with respect to the reference frame we want to measure.

In the simplest situation, the two electrodes overlap each other (fig. 1a) and, if S is known, a measure of their capacitance corresponds to a measure of the gap d. In the case where the two electrodes partially overlap (fig 1b) their lateral displacement can be measured, once the gap is known, by measuring their capacitance.

Some tests were done with a sensor constructed by us [9], showing the effectiveness of the method. Then, lackness of time (LEP startup is scheduled for July 14th, 1989) has forced us to reaserch commercially available systems.

After a careful search we found a firm, Capacitec [10], was able to produce systems with the requested characteristics (in particular sensors must be small for the problem of multiple scattering and a few micron resolution must be achievable).

The firm produces the sensors and also the readout electronics. As a target, any conducting object can be used. The sensor itself is actually composed in two parts: one, the "true" sensor, is a circular plate and it is surrounded by the second one, the guard-ring, which produces an electric field in phase with the one produced by the central electrode. This allows the reduction of edge effects and the C - d relation is quite close to that expressed in (1).

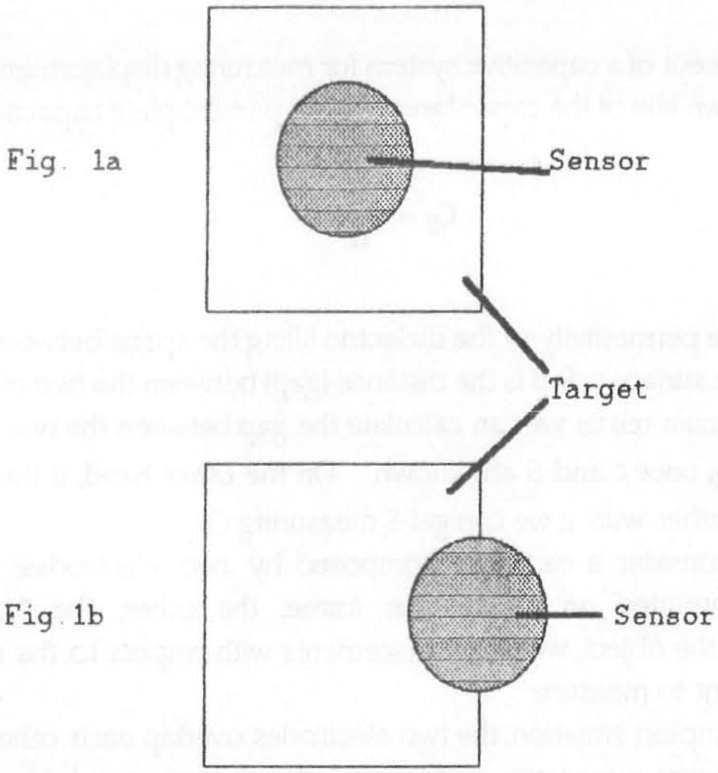


Fig. 1. The two used geometries for the sensor and the target electrodes are shown. Fig. 1a: the sensor completly overlaps the target. Thus it is sensitive only to change in the gap. Fig. 1b: the sensor partially overlaps the target, so being sensitive also to lateral displacements. Once the gap is known the lateral position can be measured.

The way the system works is the following. An AC constant current of fixed frequency (about 15 kHz) and adjustable amplitude is generated and sent to a sensor via a double screened coaxial cable. The voltage drop on the capacitor is sensed by a low input capacitance preamplifier then rectified and filtered. The output of the module is a DC-level inversely proportional to the capacitance, i. e. directly proportional to the gap d in the simplest case of complete overlap. This DC-level can be followingly digitized. The accuracy of the system, as limited by the noise of the available electronics, is 0.01%.

The -3 dB frequency can be up to 5 kHz; this sets a limit on the minimum time scale over which movements can be detected.

3. - MONTE CARLO SIMULATION OF THE CDMS

Starting from the basic commercial components, we thought of using a set of sensors, opportunely placed, for monitoring the movements of each half-shell of the μVD (the μVD is composed by two indipendent half-shells), thought as rigid bodies. The rigidity of one half-shell of the μVD has been tested on a full scale module with dummy silicon detectors and showed to be quite good. In order to properly design the system a Monte-Carlo simulation has been developed [11].

In the simulation the response of the sensors is calculated according to the following scheme. First, the capacitance of sensors which completely overlap the target is calculated with (1). In the case of partial overlap we used the expression:

$$C = \frac{\varepsilon S_{over}}{d} \tag{2}$$

where S_{over} is the overlapping area. Edge effects are not taken into account because their importance is reduced by the presence of the guard-ring.

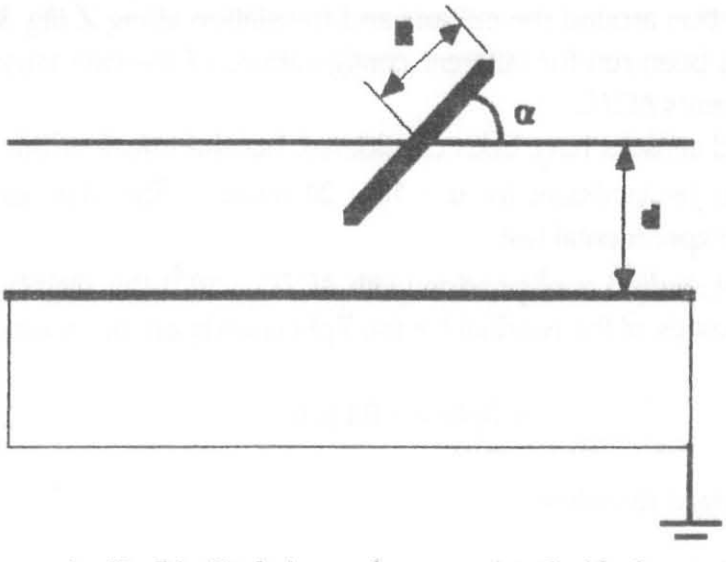


Fig. 2. The sensor of radius R is tilted of an angle α respect to the ideal geometry. d is the distance between the center of the sensor and the target ground.

The effect of the tilt of the sensor (fig. 2) is taken into account by a correction factor F, given by

$$F(X) = \left(\frac{2}{X}\right)(1 - \sqrt{1 - X}) \tag{3}$$

where $X = (R \sin \alpha / d)^2$, R is the sensor radius and α is the tilt angle.

For R = 1.90 mm (radius of the chosen sensor) and d = 2 mm (nominal gap in DELPHI), this effect is about 0.01 % for α = 15 mrad. The effect of the cylindrical geometry of the target has not to be considered because of the large ratio between the radius of the ground electrode (118 mm) and the gap (2 mm). Laboratory tests have followingly proved the correctness of this hypotesis.

The electronic noise is simulated by smearing the value of the capacitance calculated according to the geometry with a gaussian distribution of zero mean and standard deviation $\Delta C / C$.

Movements of the detector from the nominal position are randomly generated. The capacitances measured by the sensors are calculated according to the new geometry and following the above described scheme. From these capacitances the movements of the detector are reconstructed. The "measured" displacements are compared with the generated ones and residual distribution for every degree of freedom are plotted.

In the simulation the µVD has been constrained to the bottom rail, over which it will stand. In these way only two degrees of freedom remained: rotation around the rail axis and translation along Z (fig. 3). The simulation has been run for different configurations of the two sensor used and with differents $\Delta C / C$.

Also tilted sensors have been considered, but the effect of the tilt has been found to be ininfluent for $\alpha = 10 \div 20$ mrad. This has also been confirmed by experimental test.

In the best studied configuration (with $\Delta C / C = 10^{-4}$) the distribution of the absolute values of the residual for the Rphi coordinate has mean

$$< Rphi > = 0.4\ \mu m$$

and with standard deviation

$$\sigma_{Rphi} = 0.3\ \mu m$$

while for the Z coordinate we get

$$< Z > = 0.06\ \mu m$$

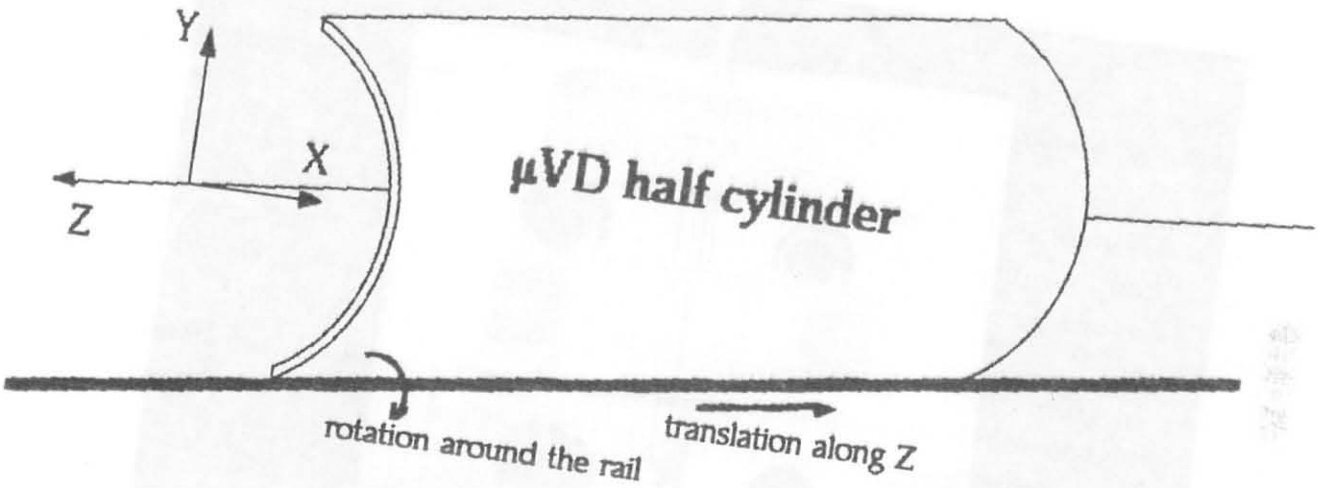


Fig.3. The geometry and the movements allowed in the simulation are shown. The Delphi reference frame is indicated. The Z axis coincides with the axis of the half cylinder in the vertical position.

with

$$\sigma_Z = 0.06\ \mu m$$

Even with $\Delta C / C$ of 10^{-3} we found

$$< Rphi > = 3.5\ \mu m \qquad \sigma_{Rphi} = 2.7\ \mu m$$

$$< Z > = 0.6\ \mu m \qquad \sigma_Z = 0.6\ \mu m.$$

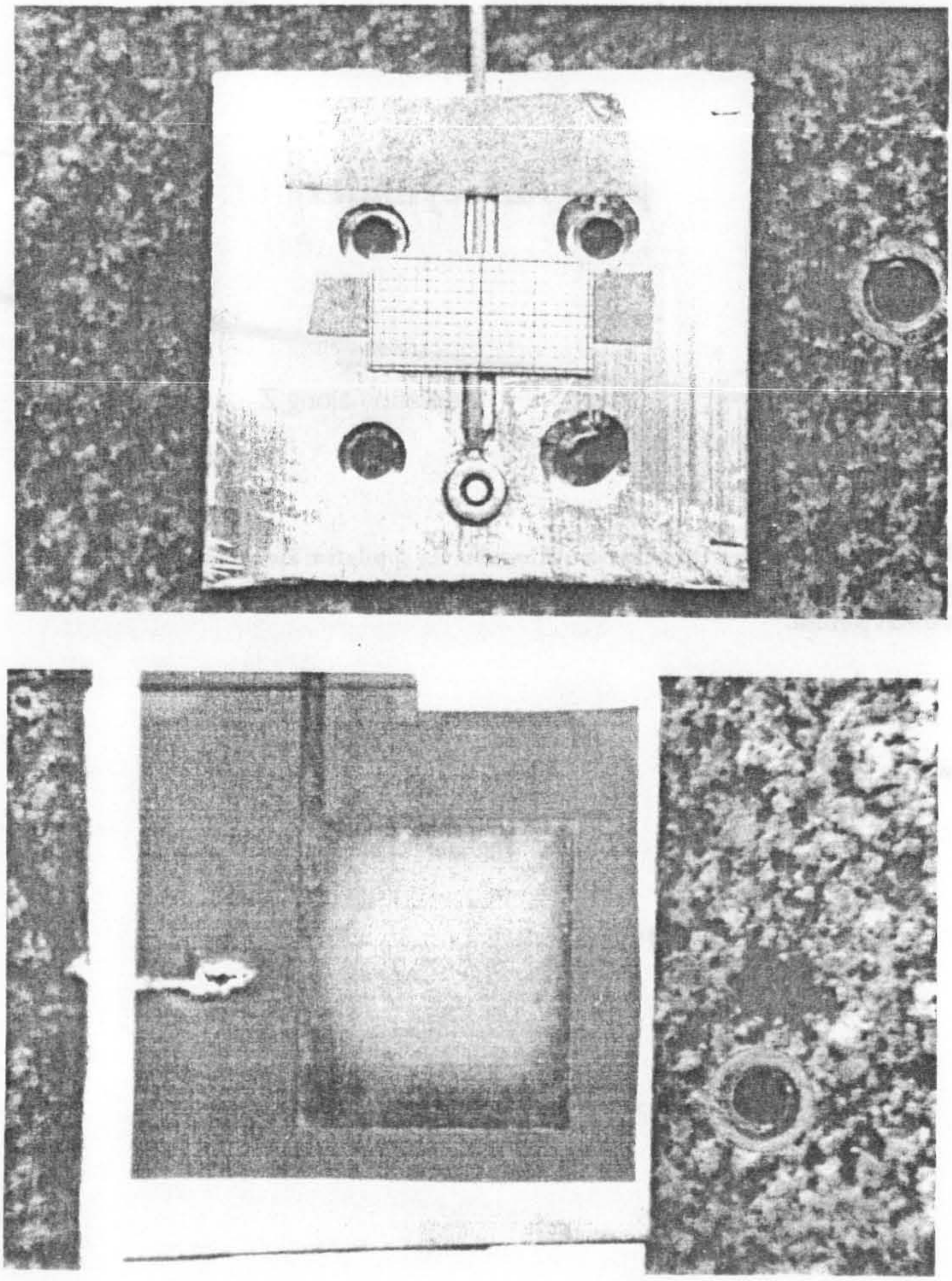


Fig. 4. One of the target electrodes and a sensor.

4. - LAYOUT OF THE CDMS

According to the results described in the previous section, we decided to design a system able to fully monitor the displacements of the µVD in space.

Since a rigid body has 6 degrees of freedom, a set up of at least 6 sensors is required to monitor the movements of each half shell of the µVD. Following [12] we plan to use 7 sensors, where two sensors are thought to monitor rotations along Z. This should allow to have a better control of the Rphi movement, that we want to measure with a high accuracy. The movements of the µVD are referenced to the Inner Detector (ID) inner wall.

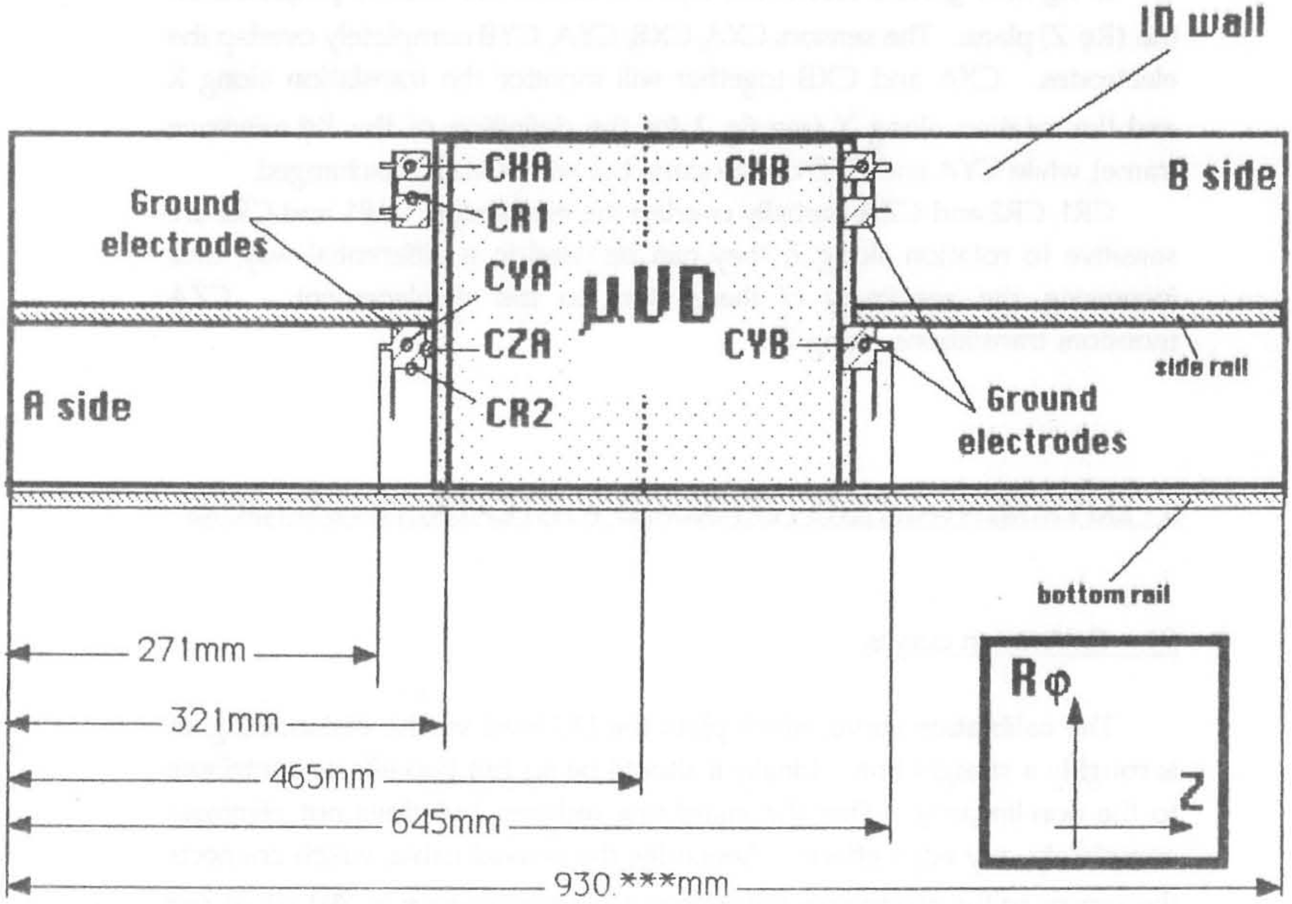


Fig. 5. The µVD and the inner wall of the ID, together with the ground electrodes and the sensors are projected onto the (Rφ-Z) plane. The support rails for the µVD are also shown. The drawing is in scale 1:5. Some dimensions are indicated.

Ground "target" electrodes have been designed and built (fig. 4) with 100 μm thick polyammide covered by a 50 μm thick layer of copper and gold in order to have the necessary conductive surface. A 1.2 mm thick layer of plexiglass has been added under the kapton layer in order to reduce the gap and to increase the sensitivity for lateral displacements (see next section).

The so assembled ground electrodes have been glued on the ID wall that is covered by a 100 μm thick grounded Al foil, used for screening from e. m. interferences (LEP r. f., inductions from electron-positron bunches, ...).

The sensors will be glued to an Al support placed to the edges of the mechanical structure of the μVD. Since the guard-ring, who completely surrounds the real sensor, drives a sinusoidal signal, different from one sensor to the other, each guard-ring has to be electrically insulated from the others, and also form the grounded support structure. Actually we foresee to glue a thin (100 μm) mylar layer between the supports and the sensors.

In fig. 5the ground electrodes and the sensor are shown, projected on the ($R\varphi$-Z) plane. The sensors CXA, CXB, CYA, CYB completely overlap the electrodes. CXA and CXB together will monitor the translation along X and the rotation along Y (see fig. 3 for the definition of the $R\varphi$ reference frame), while CYA and CYB do the same but with X and Y exchanged.

CR1, CR2 and CZA partially overlap the electrodes. CR1 and CR2 are sensitive to rotation along Z; they can be used in a differential way, thus increasing the sensitivity of the system to this displacement. CZA monitors translations along Z.

5. - EXPERIMENTAL TESTS PERFORMED WITH CAPACITIVE SENSORS

5.1. - Calibration curves

The calibration curve, which plots the DC-level vs. the distance (fig. 6), is roughly a straight line. Ideally it should be so, but two effects contribute to the non-linearity. First the guard-ring reduces, but does not eliminate completely, any edge-effects. Secondly, the coaxial cable, which connects the sensor to the electronics introduces a big capacitance (≈ 700 pF in our case) that could waste the measurement of the small capacitor: ≈ 50 fF at a distance of 2.00 mm (at this distance a 10 μm change in the distance between the sensor and the target ground corresponds to a change in capacitance of only about 0.2 fF !). The designed electronics actually allows the measurements of such a small change in capacitance, but we have observed that a long cable reduces

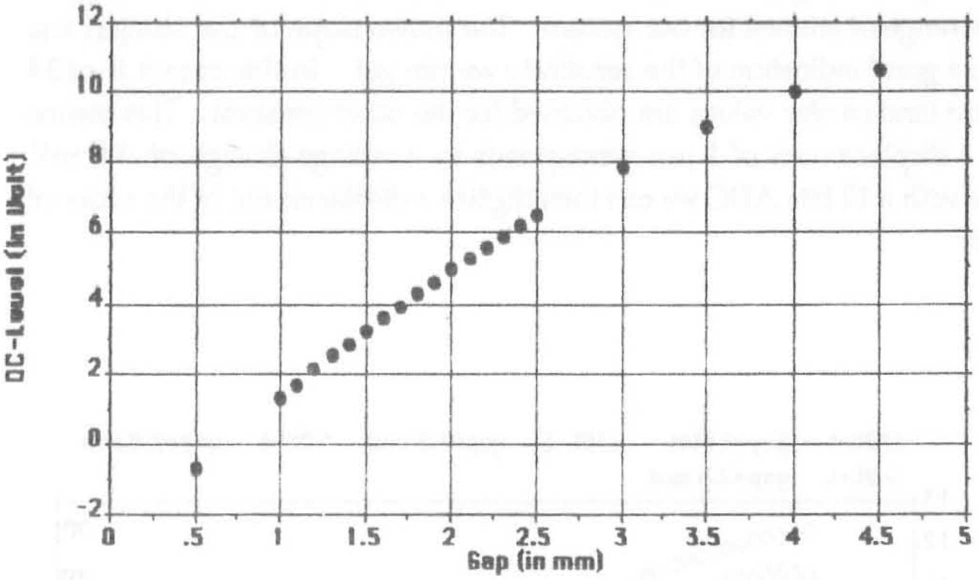


Fig. 6. The calibration curve for sensor # 3191. In abscissa there is the gap, in ordinate there is the DC output of the electronics measured with a high precision voltmeter.

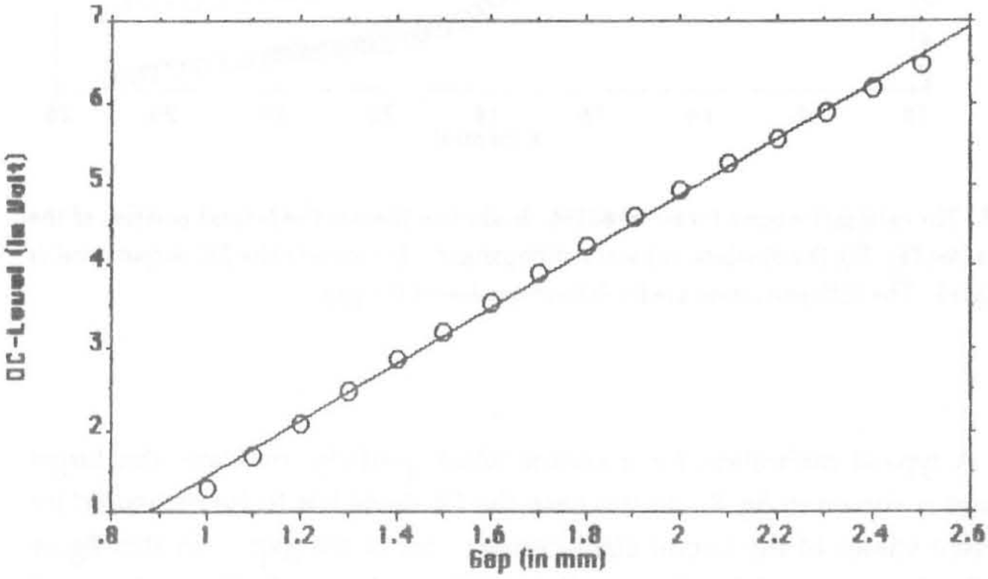


Fig. 7. Magnification of the curve shown in Fig. 6 in the region between 1 and 2.5 mm. The results of a straight line fit is also indicated showing that a displacements of 1 μm corresponds to a 3.4 mV change in voltage.

the range over which displacements could be measured and also reduces the linearity of the calibration curve.

In fig. 6 a calibration curve in the range 0 - 4.5 mm is shown, while in fig. 7 only the range 1 - 2.5 mm of the same calibration curve is shown: this is the range of interest for our system. The shown slope of the straigth line gives a good indication of the sensitivity we can get. In this case it is of 3.4 V/mm (and similar values are obtained for the other sensors). This means that a displacement of 1 µm corresponds to a voltage change of 3.4 mV. Thus with a 12 bits ADC we can then digitize a displacement of the order of 1 µm.

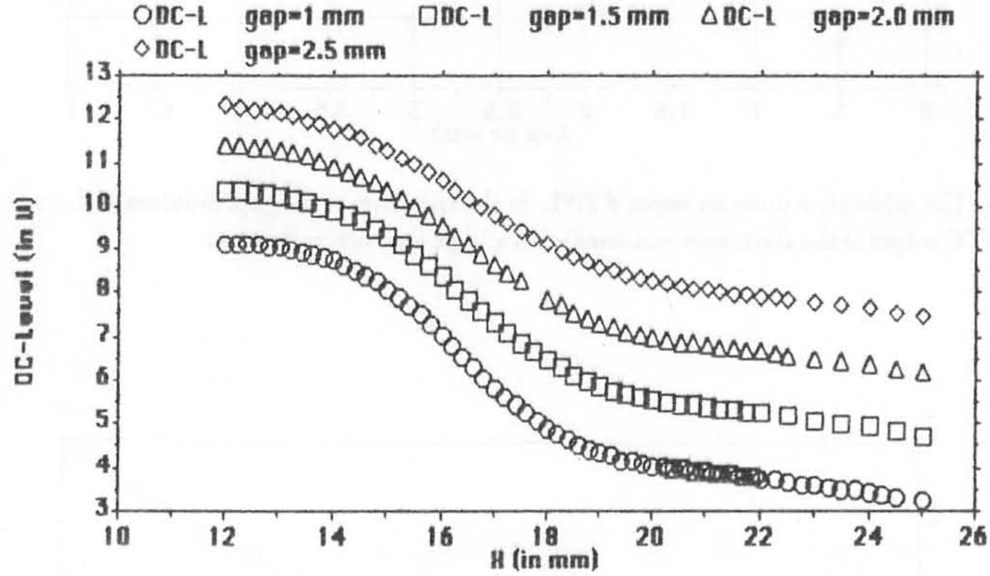


Fig. 8. The calibration curve for sensor #3194. In abscissa there is the lateral position of the sensor (see Fig. 1b); the absolute value is not important. In ordinate the DC output level is indicated. The different curves are for different values of the gap.

A typical calibration for a sensor which partially overlaps the target ground is shown in fig. 8. In this case the DC-level has to be measured for different values of the lateral displacement and of the gap. In this figure the absolute value of the abscissa X is not important. In the region of X ranging between 15.00 and 17.00 mm, which corresponds to the region where the central part of the sensor passes over the edge of the ground electrode, the response of the sensor depends roughly linearly on the lateral displacements. Here we have also the maximum sensitivity. If we do a straigth line fit in this region and then we plot the calculated slope (lateral sensitivity) as a function of the gap, we obtain a linear dependence of the lateral sensitivity on the gap (fig. 9). In particular, the lateral sensitivity is decreasing for increasing gaps.

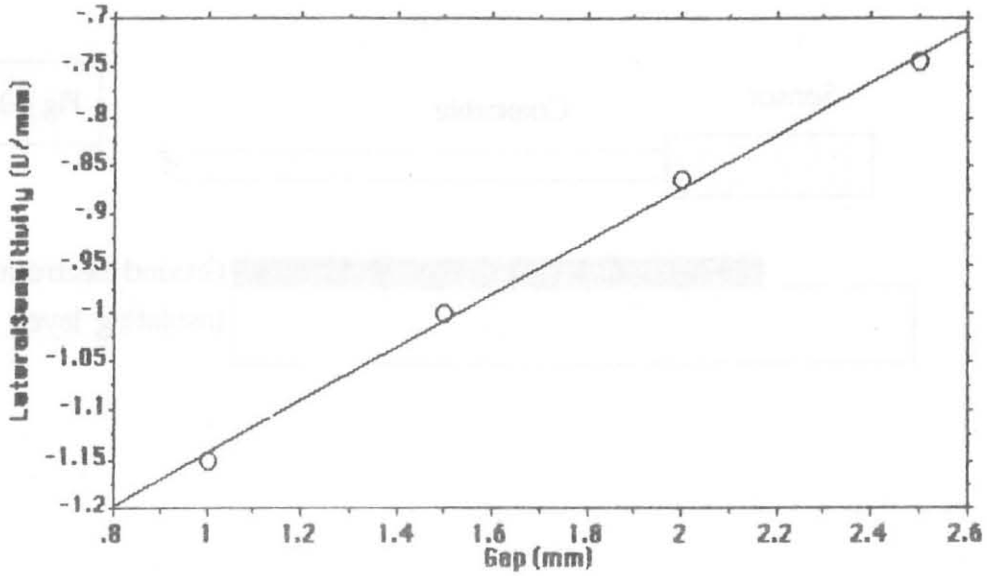


Fig. 9. The lateral sensitivity, as calculated by a straight line fit in the region of maximum sensitivity to lateral displacements (15 mm < X < 17 mm, see Fig. 8) is plotted versus the gap.

In summary for a lateral displacement ΔX the corresponding change ΔV in the DC-level is given by

$$\frac{\Delta V}{\Delta X} = B\,d + C \qquad (4)$$

where d is the gap and C and B are constants. In this case:

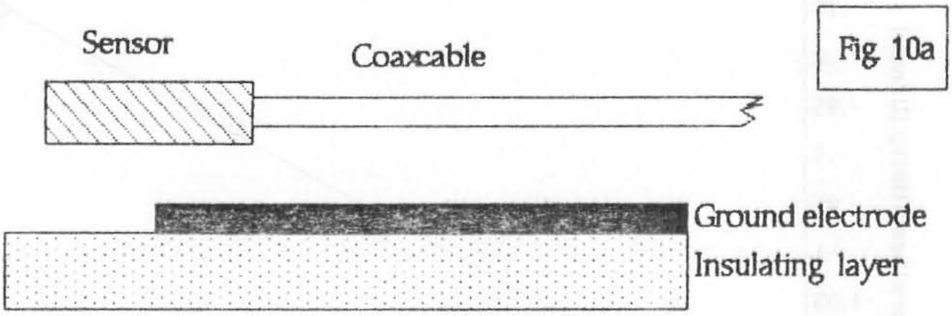
$$B = 0.271 \quad V/\,mm^2$$

$$C = -1.414 \; V/mm.$$

This means that, if d = 2 mm, we get

$$\frac{\Delta V}{\Delta X} = -\,0.872\ \mathrm{V/mm}$$

In analyzing this figure we should notice that these data were taken in the situation illustrated in fig. 10a, while the real situation is shown in fig. 10b.



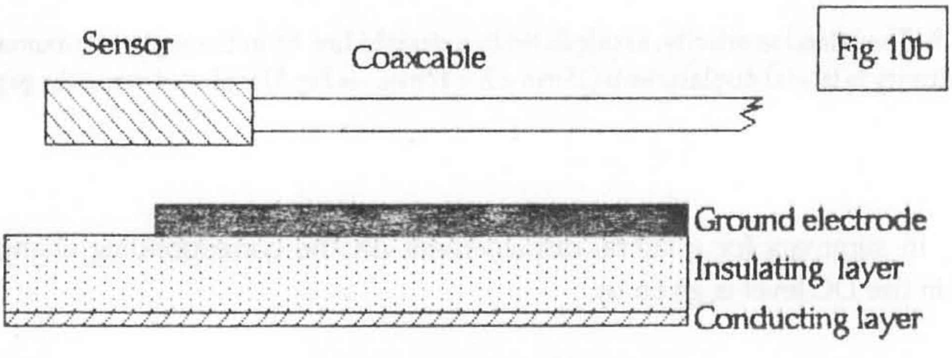


Fig. 10. In Fig. 10a the target electrode is simply supported by an insulator while in Fig. 10b another conducting layer is placed behind the insulated support. If the insulated layer is too thin, the presence of the conducting surface, which modifies the field of the capacitor, can dramatically reduce the sensitivity to lateral displacements.

The presence of the ground Al foil can affect the sensitivity of lateral displacements because the electric field is modified by the presence of the conducting surface while the sensor passes over the edge of the ground electrode. The overall result is a decreasing in the value of $\Delta V/\Delta X$.

However the choice of a thick insulated spacer between the ground electrode and the screen should allow to keep the sensitivity in an acceptable range. This conclusion is supported by experimental tests.

5.2. - Noise measurements

Noise measurements done in laboratory are shown in fig. 11, where the ratio of the noise of the electronics module is plotted vs. the corresponding DC-level. The noise measurements here reported have been done using a sensor smaller (radius = 0.95 mm) than the ones designed, but similar results have been obtained for these last ones.

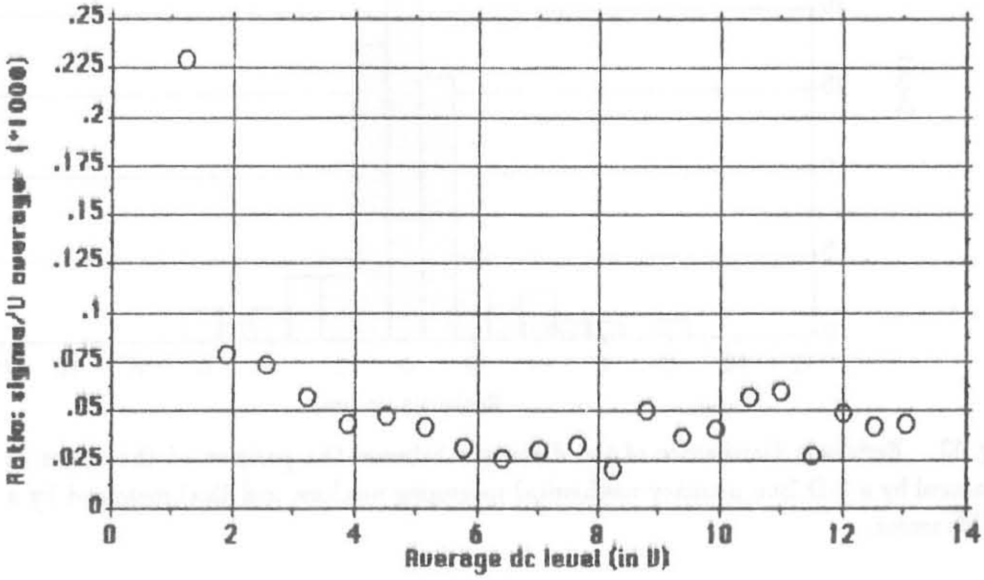


Fig 12. For different values of the average DC - output level, that is for different gaps, the ratio between the standard deviation of this DC level and the average value is shown, indicating the good noise performance of the electronics.

5.3. - Resolution measurements

A first test has been done in order to study the displacement monitoring capability of the CDMS. In this test the sensor has been attached to a high precision 3-dimensional mechanical measuring machine [13] allowing to move the sensor with a 1 µm accuracy.

The sensor has been randomly moved and at each step the DC-level and the position of the sensor has been read. With the DC-level value, using the calibration curve, we could measure the displacements via the CDM sensor. The distribution of the residuals (defined as the difference between the position measured by the CDM sensor and the position given by the 3-D machine) is plotted in fig. 13. The mean value is 0.046 µm, and the σ is 2.204 µm.

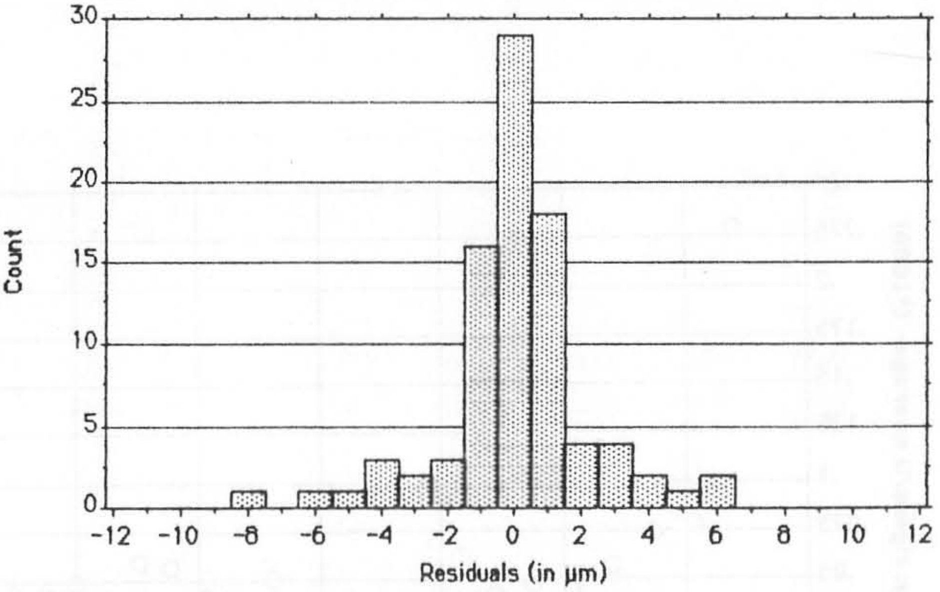


Fig. 13. Residuals distribution of the difference between the position of the sensor as measured by a 3-D 1µm accuracy mechanical measuring machine and that measured by a CDMS sensor.

The result is worse than that indicated by the simulation but this can be explained by the fact that non-linearity were not considered and calibration curves in the simulation were known with infinite precision.

In order to study the behaviour of the CDMS in 3D we plan to build a model of the µVD allowing the control of all the 6 degrees of freedom.

6.- CONCLUSION

We have presented the development and some experimental results of a CDMS. From these results we are confident to build a system able to monitor the displacements of the DELPHI µVD (thought as a rigid body) in space with an accuracy of a few microns.

The CDMS system is now under construction and the ground electrodes have been already placed on the ID wall.

7.- ACKNOWLEDGEMENTS

We wish to warmly acknowledge the precious collaboration of Dr. A. Breakstone, University of Hawaii, who first designed a CDMS for the Mark II/SLC Silicon Strip Detector.

Dr. A Stocchi has set up the on-line monitor software; Dr. W. Kucewitz gave us his useful collaboration; M. Battaglia and W. Bonvicini, while working on their degree thesis, have given substantial contributions to the measurements described in this paper.

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