Capacitance Measurement with a Sigma Delta Converter for 3D Electrical Capacitance Tomography

Mark Nurge

Abstract—**This paper will explore suitability of a newly available capacitance to digital converter for use in a 3D Electrical Capacitance Tomography system. A switch design is presented along with circuitry needed to extend the range of the capacitance to digital converter. Results are then discussed for a 15+ hour drift and noise test.**

I. INTRODUCTION

ELECTRICAL Capacitance Tomography (ECT) has been used since the late 1980s within the petrochemical industry to reconstruct the dielectric profile of material located in a cross section of non-conductive pipe [1]. The sensing elements typically consist of 8-12 electrodes and an overall guard ring surrounding the circumference of the pipe. Mutual capacitance measurements are made on the different pairs of conductors in the system. This capacitance data is then inverted through a variety of methods to reproduce a two dimensional image corresponding to the dielectric constant of the material in the field of view.

The usual measurement technique is to raise one of the electrodes to some fixed non-zero potential while keeping the others at ground. Since charge is proportional to capacitance, the charge is measured on each of the grounded conductors to get the mutual capacitances with respect the driven electrode. All of the possible mutual capacitances can be found by repeating the process, raising each electrode in turn to the same non-zero potential. Performing these measurements both with and without dielectric present allows for a comparison of the change in charge on each electrode due to the presence of the dielectric.

Ideally, electronics capable of resolving a single charge change would be desirable for the best image reproduction. For a 2.5 volt excitation, this corresponds to a change in capacitance of 0.06408 attofarads (aF). This is well below the detection limit of today's capacitance measurement circuits. However, Analog Devices, Inc. has recently released a sigma-delta converter capable of resolving down to 4 aF. This paper will explore the application of this new chip in a 3D ECT system. NASA has an interest in pursuing ECT for use in several applications that may better be implemented with non-cylindrical electrode geometries. For this effort, two parallel 4×4 arrays of electrodes were used.

Manuscript received ?;
M. Nurge is with NASA at the Kennedy Space Center Applied Physics Laboratory, Florida (e-mail:Mark.A.Nurge@nasa.gov

II. REVIEW OF CAPACITANCE

In general, the charges, q_i, on a system of conductors are related to the potentials applied to those conductors, V_j, by a matrix of coefficients, C_{ij}, via the well known equation $q_i = \sum_j C_{ij} V_j$. Self capacitance is defined [2] as the total charge on a conductor when it is maintained at unit potential, while all other conductors are held at zero potential. These self capacitances are carried in the coefficient matrix along the main diagonal, corresponding to the coefficients C_{ii}. The off axis elements, $C_{ij}, i \neq j$, are called the coefficients of induction or more commonly, mutual capacitances. Physically, these mutual capacitances correspond to the charge needed to maintain conductor j at zero potential, while conductor i is maintained at unit potential and all others at zero potential. Some properties of the matrix are as follows [3]:

- The self capacitances are positive.
- The mutual capacitances are negative.
- The matrix is symmetric about the main axis with $C_{ij} = C_{ji}$.
- For a closed system, each row and column in this capacitance matrix will sum to zero due to conservation of charge.

In practice, a closed system is difficult to achieve because some field lines will end on the guard or go to infinity [4]. If these field lines run through the imaging region, they contain information helpful to image reconstruction. Since measurement of the mutual capacitance with respect to the guard is not usually performed, the only source of this additional position information is in the self capacitance readings. Therefore, this paper will show how this measurement system can be used to measure both the self and mutual capacitances.

III. ECT MEASUREMENT SYSTEM

The EVAL-AD7746 evaluation kit became available from Analog Devices, Inc. in May 2005 and was used as the cornerstone for measuring and populating the capacitance matrix for the 3D ECT system. The AD7746 is a capacitance to digital converter chip based on the class of devices referred to as sigma delta converters.

A. Sigma Delta Converter Overview

A sigma delta converter is essentially a one bit analog to digital converter formed by running the measurement signal through an integrator and then a comparator. Feedback is

routed to a summing node on the input to the integrator to try and balance the input leads to the comparator. The difference (delta) between the reference and input signals is coded by the comparator. The output of the comparator is tied to a counter to keep track of the number of times the comparator has a logic 1 output. Another counter is used to keep track of the number of clock cycles. This is the sigma or summing part of the name. The measure of the input signal is the ratio of the two counters times the reference voltage. So, for an input voltage that is one half of the reference, the comparator will output a logic 1 half of the time. Extensive digital signal processing is done on the output to remove noise and extend the resolution. The benefit of this technology is the high resolutions that are achievable, albeit at the price of slower sample rates. A more detailed description can be found in the paper by Aziz [5].

When configured to receive a voltage input, a sigma delta converter uses a reference capacitor in series with the reference voltage and another in series with the input signal. It was noted in a paper by Brytcha [6] that the design could be altered to measure capacitance by applying a known input voltage and allowing the input capacitor to vary instead of the reverse. The resulting simplified circuit is shown in Figure 1 . Further information on the AD7746 and EVAL-AD7746 used in this design and sigma delta converters in general is available through Analog Devices website [7].

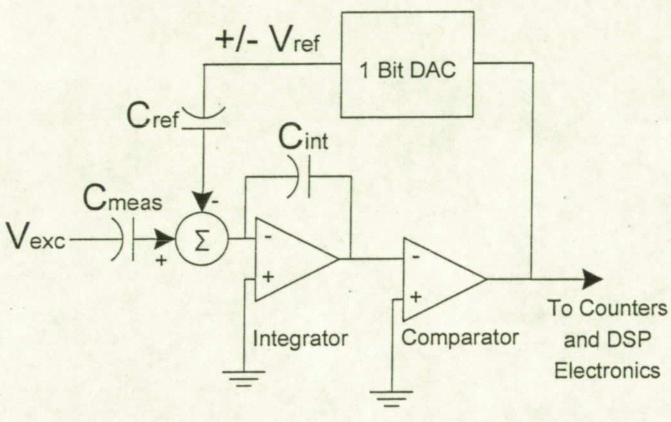

Fig. 1. Simplified diagram of sigma-delta converter for capacitance measurement

B. Electrode Design

Two 4×4 arrays of electrodes were constructed from square sections of copper tape mounted on a .0254 m thick piece of glass filled plastic. The glass filled plastic backing was cut to approximately square shapes, 0.1 m on a side. Each electrode is .019 m on a side, placed on 0.02 m centers. The parallel arrays were mounted with the electrode arrays 0.04 m apart. The open ends were surrounded by a mu metal guard to reduce the sensitivity of the electrodes to outside interference and to help maintain the spacing between the arrays. Figure 2 shows this configuration, with a front view of one of the arrays on the left and a side view containing both arrays and the guard. Wire wrap wire was used to connect each of the electrodes through a a penetration in the guard to a connector on the edge of the plastic. A ribbon cable was used to then connect each array to the switch network.

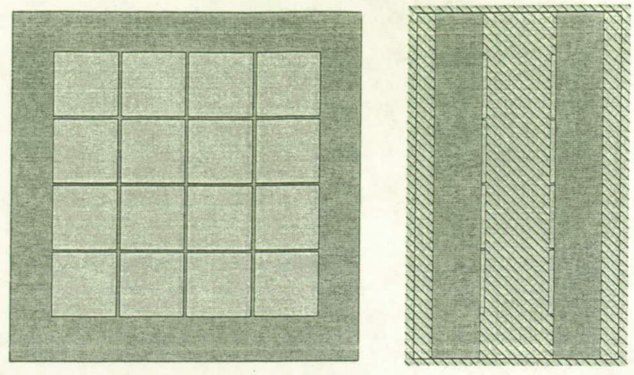

Fig. 2. A front view is shown for one of the two electrode arrays on the left. The diagram on the right shows a side view of both arrays and the surrounding guard.

C. Switch Network Design

A switch network was designed and fabricated to switch each conductor to either the excitation side of the AD7746 or the input side. Figure 3 shows a simplified version of the electronics for switching 3 conductors. This pattern is then repeated for the other conductors. The 74HCT4053 analog multiplexer was selected to perform the switching due to the small parasitic capacitances, 5 pF in the off state and 8 pF in the on state. However, with all 32 electrodes connected, only around 150 pF of offset was seen in practice.

D. Range Extension

The dynamic range of AD7746 is ± 4 pF, which is well suited to ECT measurement. It can also compensate 17 pF of common mode capacitance, but this is too small for the 3D ECT system due to the added capacitances from switches and cabling. However, both ranges can be extended by adding a circuit to scale the excitation. This technique is explained in a preliminary technical note available through the manufacturer [8]. A low noise op amp, TLC2272, and the two 1% resistors shown in Figure 3 were selected to expand each of the ranges by a factor of 10.57, allowing for common mode compensation of 179.7 pF and a range of ± 42.3 pF.

Each AD7746 contains two capacitance measurement circuits and identical but separate excitation sources (Excitation A and B). This range extension technique requires both excitation sources on the AD7746, disabling one of the capacitance measurement circuits. Excitation A is inverted by writing to the appropriate register and run through one leg of a voltage divider. Excitation B is run through the other leg, providing the summation of the two signals at the input to the buffer amplifier. This has the effect of reducing the amplitude of the excitation signal by a factor of 10.57. The down side of reducing the excitation voltage is that the noise is increased by the same factor. The resolution is also changed from 4 aF to 42 aF.

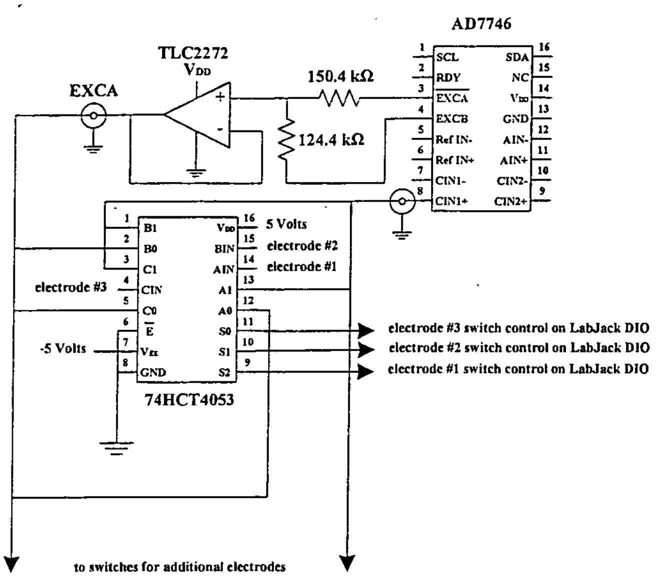

Fig. 3. This simplified circuit diagram shows the basic element of the switch network for the electrodes, the amplifier and resistor components needed to expand the range and offset compensation by a factor of 10.57, and the interface to the AD7746 Capacitance to Digital Converter

E. Control and Measurement Description

Two LabJack U12 modules were used to provide the digital control signals for the switches. Both the LabJack U12 and EVAL-AD7746 interface to the computer via a universal serial bus link. To help with communications and coding, the manufacturers each provided a data link library and code examples in National Instruments LabVIEW software. Overall control was therefore accomplished with virtual instruments created with LabVIEW software.

Self capacitance values are obtained by switching each electrode in turn to the CIN+ side of the EVAL-AD7746 while the others (including the guard) are connected to the excitation. The EVAL-AD7746 is set up to acquire data in a single ended configuration. Digital to analog converters are present on the AD7746 to provide compensation for offset capacitances present in the transducer and cabling. These are used to remove the offset capacitance in order to provide the maximum dynamic range to the ECT system.

Mutual capacitances are obtained by switching two electrodes at a time to the CIN+ side of the EVAL-AD7746 while the others (including the guard) are connected to the excitation. The mutual capacitances are then calculated by subtracting the self capacitances for each electrode and dividing by 2 as shown by

$$C_{1,2} = (C_{measured} - C_{1,1} - C_{2,2})/2. \quad (1)$$

The actual self capacitance of each electrode with no sample present is on the order of 2 pF on top of an offset of roughly 150 pF. For ECT image reconstruction, only the changes in capacitance caused by the dielectric material are important. These changes are found by taking a set of readings without a sample and subtracting it from a set with the sample. As a result, the 4 fF (42 fF with the added gain circuitry) absolute accuracy of the AD7746 becomes less important.

IV. Test Results

To understand how suitable the electronics are for ECT, one only needs to look at effects the environment has on the system. This was accomplished by configuring the system to measure the self capacitance of one of the electrodes overnight to characterize measurement noise and drift. The first few times this was done, a large amount of noise was present in the capacitance data. This noise was traced to the external power supply for the switch network. Further investigation revealed noise on the chassis ground. As a result of these problems, the power supply was switched to batteries. Additionally, the array assembly, LabJack modules, switch network, batteries, and EVAL-AD7746 were placed in a grounded stainless steel box to further improve the shielding. The major components were further shielded with mu metal. The EVAL-AD7746 was configured to sample at 4.56 Hz, the slowest acquisition rate available, but the greatest noise suppression. LabVIEW was used to acquire the data from the EVAL-AD7746, average every 25 points, and write the result to a data file on a PC laptop.

A Vaisala HMP45A humidity and temperature probe was used to monitor the environment within the stainless steel box. Data was acquired from the sensor via two differential input channels on one of the LabJack U12 modules. A temperature and relative humidity reading were stored with each average capacitance reading.

Figure 4 shows a 50 point centered moving average of the capacitance data. The box temperature varied between 23.7-24.2°C. According to the AD7746 data sheet, this is too small a change to account for the approximate 670 fF change in capacitance seen. However, the sensing arrays were designed with the intent of measuring differences in moisture content. So, it was expected that some variation in capacitance would occur with changes in moisture density of the air. To see if this was the case, the relative humidity data and temperature data were used to find the absolute humidity. This result is shown in Figure 5. From a comparison with Figure 4, it is evident that change in absolute humidity contributed to the change in capacitance.

A one hour slice of data was used to find the noise and its root mean square value. Figure 6 shows both the raw capacitance data along with the 50 point centered moving average. The two curves were then subtracted to examine the noise. This data is presented in Figure 7. The root mean square of this noise was calculated to be 0.545 fF and is plotted as a line on Figure 7.

V. Conclusion

The EVAL-AD7746 showed itself to be an attractive low cost option for use in ECT imaging. A large amount of offset capacitance was produced by the external switch network

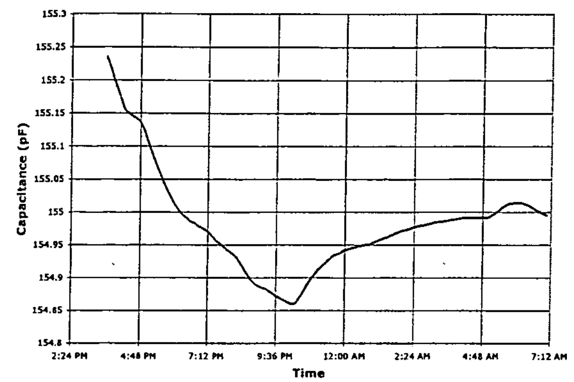

Fig. 4. Overnight drift test of a single self capacitance reading. Each point represents a 50 point centered moving average of the raw data.

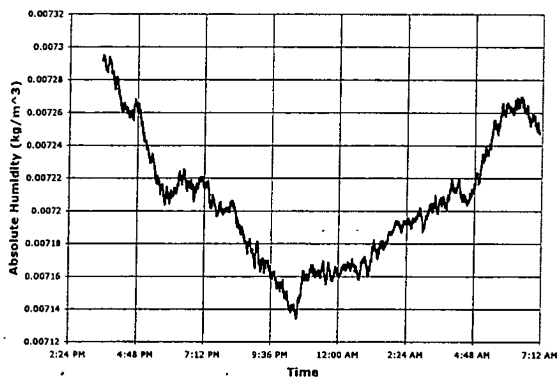

Fig. 5. Plot of the absolute humidity calculated from the relative humidity and temperature. This appears to be the major source of change in the self capacitance.

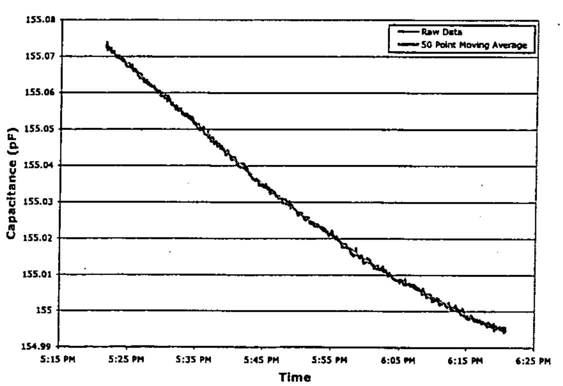

Fig. 6. Overnight drift test of a single self capacitance reading. Each point represents a 50 point centered moving average of the raw data.

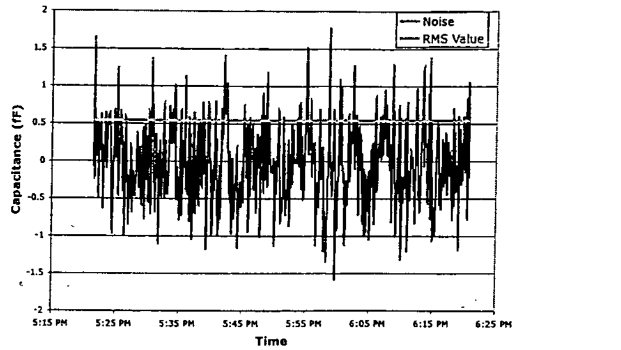

Fig. 7. Noise calculated by subtracting the two curves in Figure 6. The RMS value of the resulting noise is shown as the light line

needed to change the electrode configuration. The EVAL-AD7746 was able to compensate for this by adding circuitry to divide the excitation signal by a factor of 10.57. The drift and noise test revealed that the noise level is acceptable and can be adequately reduced by employing a moving average. For ECT, the 0.38 fF variation in self capacitance would greatly impair the ability to resolve image detail. However, the moisture level can be easily controlled with a dry nitrogen purge.

ACKNOWLEDGMENT

The author would like to thank Robert C. Youngquist for his encouragement and insightful comments regarding this work.

REFERENCES

[1] S. M. Huang, A. B. Plaskowski, C. G. Xie, and M. S. Beck, "Tomographic imaging of two-component flow using capacitance sensors," *J. Phys. E: Sci. Instrum.*, no. 22, pp. 173–177, 1989.

[2] J. D. Jackson, *Classical Electrodynamics*, 3rd ed. John Wiley and Sons, Inc., 1998.

[3] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, 2nd ed. Butterworth-Heinemann, 1984, vol. 8.

[4] Y. Hua, S. FuQun, X. Hui, and W. Shi, "Three-dimensional analysis of electrical capacitance tomography sensing fields," *Meas. Sci. Technol.*, no. 10, pp. 717–725, 1999.

[5] P. M. Aziz, H. V. Sorensen, and J. V. D. Spiegel, "An overview of sigma-delta converters," *IEEE Signal Processing Magazine*, pp. 61–84, January 1996.

[6] *Measure Capacitive Sensors With A Sigma-Delta Modulator*, 2005. [Online]. Available: http://www.elecdesign.com/Articles/ArticleID/10185/10185.html

[7] "Data sheet for analog devices ad7746 24-bit, 2 channel capacitance to digital converter." [Online]. Available: http://www.analog.com/UploadedFiles/Data_Sheets/21450359AD7745_6_0.pdf

[8] M. Brychta, "Extended capacitive range," analog Devices Preliminary Technical Information, AD7745/46.

PLACE
PHOTO
HERE

Mark Nurge is a physicist and electrical engineer at NASA's John F. Kennedy Space Center Applied Physics Laboratory. He has earned Bachelor and Master of Science degrees in electrical engineering from Georgia Institute of Technology in 1985 and 1986, respectively. He also has M. S. degrees in engineering management (1992) and physics (2003) from the University of Central Florida. He is presently a doctoral candidate at the University of Central Florida in physics, researching 3D electrical capacitance tomography.