Interdigitated Capacitive Sensor for Great Lunar Expedition for Everyone Applications

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The Great Lunar Expedition for Everyone expanded on a goal from the National Aeronautics and Space Program Decadal Survey regarding determining the physical properties of the Lunar Regolith. For the past few years, the team has worked on developing an in-house capacitive sensor to achieve this goal. It measures changes in the capacitance of dielectric materials it comes in contact with, using interdigitated traces. Interdigitated traces allow the sensor to have a higher sensitivity and expand the sensing range. The latest version is called the LUNA-CAP and has been under redesign since February 2023. LUNA-CAP has two parts: the circuit that measures the capacitance change and the pad design that detects the capacitance of the dielectric material it comes in contact with. The team individually tested each part of LUNA-CAP to ensure the sensor behaved the way it was intended to before making a printed circuit board version of the sensor to do further testing. From these initial tests, the science team hypothesized that the measurement circuit would be able to measure small values of capacitance with small percent error, and the pad design would measure capacitance changes of less than one picofarad (pf), along with a vertical distance of at least 100 mils. From there, the team tested the printed circuit board version of LUNA-CAP in February 2024 and concluded that the sensor can measure a vertical distance of at least 100 mils and can measure changes in capacitance of less than one pf. Overall, this sensor will allow the team to measure changes in capacitance and determine the physical properties of the Lunar Regolith.

I. Nomenclature

R_A = Resistor A
R_B = Resistor B
C = Capacitor
f = Frequency
T = Period

II. Introduction

The Great Lunar Expedition for Everyone (GLEE) in regards to the capacitive sensor plans to solve a goal from the National Aeronautics and Space Administration (NASA) Decadal Survey "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023 to 2032". The goal GLEE aims to achieve with the capacitive sensor is to determine the physical properties of the Lunar Regolith. The capacitive sensor will collect local and distributive data on the Lunar surface by GLEE dispersing around 250 LunaSats using the deployment module developed by the structures team onto the surface. LunaSats are sticky note size CubeSats that contain an accelerometer, magnetometer, temperature sensor, capacitive sensor, solar panels, antenna, Long Range (LoRa) communication, and a microcontroller. The capacitive sensor is an in-house sensor that consists of two parts: the circuit that measures the capacitance change and the pad design that detects the capacitance of the dielectric material it encounters. The measurement circuit uses a 555 timer and astable operations that consist of two 500 kilo-ohms ($k\Omega s$) resistors, two pull-up capacitors of 22 micro-farads (μfs), and a capacitor, which in this case is the pad design. The two parts together can be shown in Fig. 1 with the pad design labeled C.

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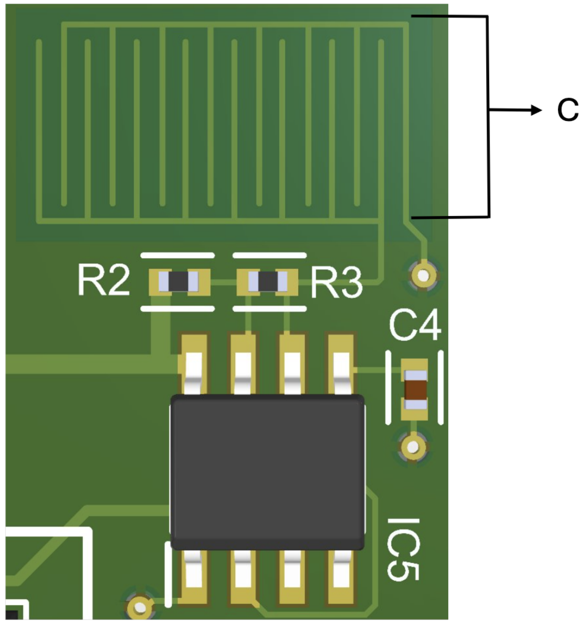

Fig. 1 Capacitive Sensor on LunaSat V7

The pad design incorporates interdigitated traces to measure a capacitance change. Interdigitated traces are planar capacitive sensors that spread out the electrodes, boosting the fringe field. When an electric field penetrates through a medium, it creates an electric displacement that alters the charge stored between the electrodes, which is what is being measured when measuring the changes in capacitance. Additionally, interdigitated traces increase the sensitivity and expand the sensing range of the sensor. [1]

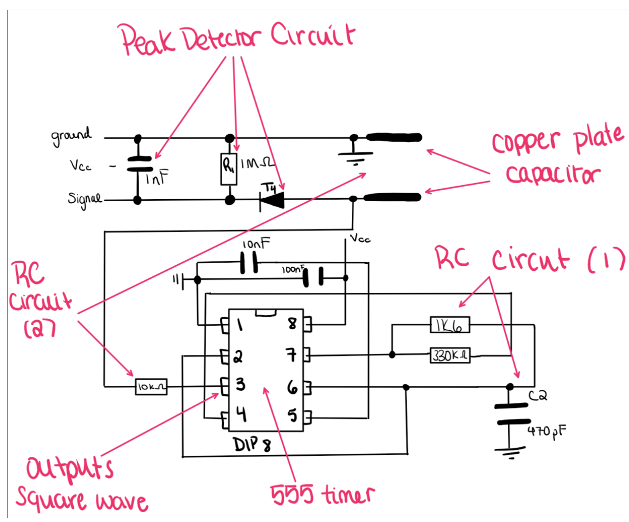

Fig. 2 Schematic for Measurement Circuit by Natalie Alvarado

The in-house capacitive sensor has gone through several iterations before the latest one. Thus, the following information will outline what has been done to the sensor previously. A previous science team member, Natalie Alvarado, introduced the idea of using an interdigitated capacitive sensor for our system. She reached this conclusion by conducting a series of tests with off-the-shelf capacitive sensors and determining that the sensor's sensitivity did not meet the team's objectives. At the time, this sensor used a measurement circuit, shown in the schematic in Fig. 2, that incorporated a peak detector circuit alongside the timer circuit. The pad design had different dimensions but the same shape as the current version. Her team built and tested this version of the capacitive sensor in Spring 2022 and discovered that the sensor was misbehaving and performing as a temperature sensor. That caused them to retake a look at the capacitive sensor design and begin to re-design the sensor.

Julia Claxton, another previous science team member, took on the re-design of the capacitive sensor and began to look over the existing schematics and explanations of the sensor created by Natalie. From there, Julia researched interdigitated capacitive sensors and came across a paper that explained how the design parameters impact the capacitive sensor readings [1]. Julia developed a MATLAB script based on this paper that would tell them how changing some physical dimensions of the pads would alter the metrics the paper mentioned. Based on the results of that script, they selected four pads for testing. Toward the end of Spring 2023, Julia and Angelina (another science team member) tested these four pad designs. From these tests, the pad design with the area of the pad optimized performed the best as it had the most change in capacitance.

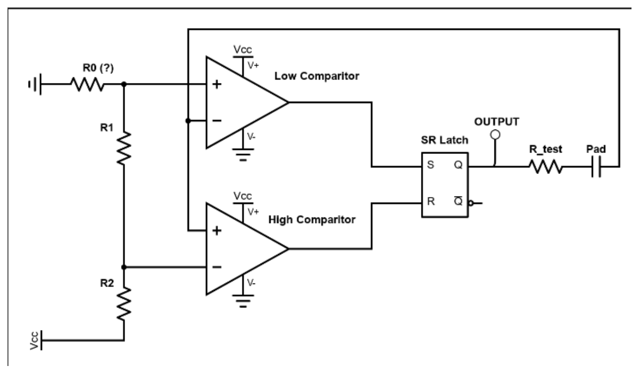

Fig. 3 Schematic for Measurement Circuit by Julia C.

In addition, Julia and Angelina simulated the measurement circuit designed by Natalie and a measurement circuit designed by Julia in software called Multisim. The measurement circuit designed by Natalie focused on constant time, and the one by Julia focused on constant voltage. They found that the initial circuit behaved poorly, and the other circuit showed potential in the simulation. Thus, at the beginning of Summer 2023, Angelina built the constant voltage circuit using a breadboard, SR latch, and comparators, as shown in Fig. 3, with the help of the Integrated Teaching and Learning Laboratory (ITLL). Overall, the initial circuit did not work as intended and Angelina had to work with the ITLL to make changes to the circuit to try to make it work. However, they were not able to get the circuit to work. Fortunately, the LunaSat team of GLEE was in contact with a professor at the University of Colorado Boulder, who teaches the practical printed circuit board (PCB) course and the senior design capstone course. His research is primarily focused on circuit design and analysis, rapid prototyping of circuits, and signal integrity. Thus, the LunaSat team was able to introduce the science team to him and have a meeting about the current state of the capacitive sensor. From that meeting, the science team learned that they could use the measurement circuit created by Natalie but needed to make the following changes. He suggested removing the peak detector and making simplifications to the timer circuit. In addition, he explained that measuring frequency to achieve capacitance values is way more accurate and precise than analog values (which is how the team was calculating capacitance at the time). Furthermore, he advised the science team on a better way to evaluate the pad design dimensions, which is in section 3 of this paper. Lastly, he mentioned that the capacitive sensor will not be able to calculate the dielectric constant of soils as that is very tricky. Therefore, the team changed its original goal of measuring dielectrics to trying to measure the change in capacitance of materials on the Lunar Surface, since he was very confident that the team would be able to do that. Overall, this leads to the current version of the capacitive sensor, Luna-CAP.

III. Materials and Methods

As mentioned before, the function of our system can be broken into two parts: the circuit that measures the capacitance change and the pad design that detects the capacitance of the dielectric material it encounters. To ensure that the re-design of the sensor would behave the same as intended, Angelina individually tested each part of the LUNA-CAP by using a breadboard version of the new measurement circuit and ANSYS Electronic Desktop to test the theoretical pad design before combining the two parts onto its own PCB version.

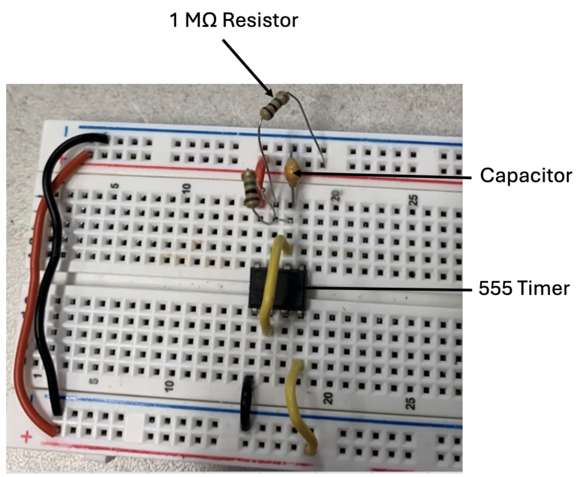

Fig. 4   Measurement Circuit Used During Testing

Testing the measurement circuit consisted of building the circuit, shown in Fig. 4, using two $1M\Omega$ resistors and changing the capacitor value to create a frequency versus capacitance graph and a period versus capacitance graph to verify future results of when the two parts of the capacitive sensor are together. Materials used to create the breadboard version of the circuit were pliers, wire cutters, a Plusivo hook-up wire kit, a solder-less breadboard, a capacitor kit, a resistor kit, and 555 timers (both the NE555 and TLC555). Materials used to test the measurement circuit were an anti-static wrist strap, static electricity discharge (ESD) mat, 9V AC/DC adapter, micro-USB to USB, and an Analog 2 Discovery Diligent Scope. Additionally, to test the measurement circuit for accuracy and range, Angelina used Eq. 1 to calculate the expected input frequency for each of the different capacitor values used (10 pf, 15 pf, 22 pf, 33 pf, 47 pf, 68 pf, 100 pf, 220 pf, 470 pf, 680 pf, 1000 pF, 10000 pF, 100000 pF) to compare to the tested frequency value obtained.

$$f = \frac{1.44}{(R_A + 2R_B)C} \tag{1}$$

This input frequency ideally should be the same frequency that gets outputted from the output pin of the 555 timer. Thus, comparing the output frequency to the predicted input frequency determines the accuracy of the measurement circuit. In addition to comparing the output to the input frequency, Angelina calculated the percent error to discover which values have a smaller or larger percent error to determine the capacitance range the measurement circuit can measure accurately. Furthermore, the team wanted to test different 555 timers for the measurement circuit to find what type of 555 timers would ensure higher sensitivity for our sensor. The two types of timers that Angelina tested with were a bipolar version (the one used in Natalie's measurement circuit) and a CMOS version that theoretically could provide a low power consumption and large noise tolerance. The bipolar version was the NE555, and the CMOS version was the TLC555. Overall, this test helped validate and verify that the modifications to the measurement circuit worked as intended.

Fig. 5   Label Definitions

As for the pad design, the test consisted of Angelina using software called ANSYS Electronic Desktop and a feature within the software called Q3D to simulate how the sensor would behave in the real world. The main objective of the test is to determine what pitch the sensor can achieve within its constraints. Pitch is defined as the center-to-center distance between the fingers, as shown in Fig. 5, and is assumed to be proportional to the vertical range (penetration depth). In other words, the pitch determines how far away the sensor can measure a substance. The primary design constraint for the sensor is the footprint area, as there is limited space on the LunaSat. Therefore, the test will look at the relationship and trade-off between capacitance versus pitch and depth versus pitch to find the most optimal design parameters for the mission.

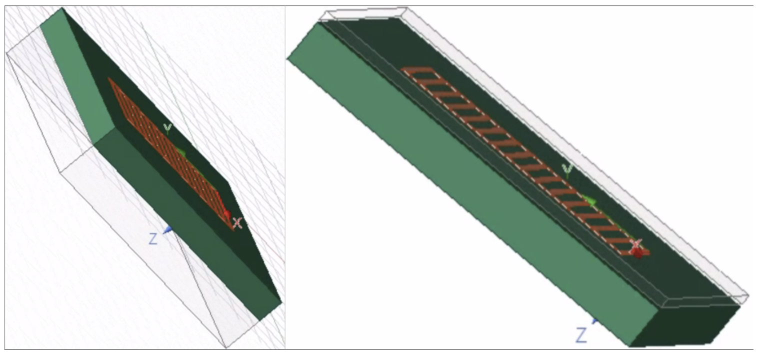

Fig. 6 Pad Design Test Set-Up

In the software, Angelina computer aid designed (CAD) the pad on top of a PCB and created boxes made of dielectric materials to put onto the sensor to determine how small it can measure changes in capacitance and how far the sensor can be away from the dielectric material it is measuring. As shown in Fig. 6, the clear box on the bottom and top of the pad represents the box made of dielectric material, and the green box simulates the PCB. Overall, Fig. 6 shows the test set-up to determine the best optimal pad design. Using the Q3D feature in the ANSYS Electronic Desktop, Angelina measured the changes in capacitance by testing different dielectric materials and increasing the thickness of the clear boxes until the capacitance stopped changing to determine the range of the sensor.

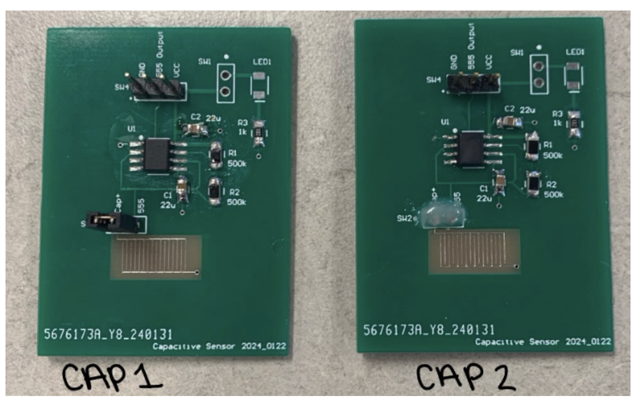

Fig. 7 Identify Printed Circuit Boards Used During Test

In Spring 2024, the LunaSat team integrated both parts of the capacitive sensor using Altium to manufacture them with JLCPCB. After that, the LunaSat team soldered on the components to provide the science team with a complete capacitive sensor. The PCB version of the capacitive sensor is to test the behavior of the measurement circuit and pad design together, as shown in Fig. 7. Equipment used for this test was an oscilloscope, AD2 scope, digital multimeter (DMM), anti-static mat, anti-static wrist strap, probes, sand, distilled water, scoop spatula, droppers, and bowls. The measurement circuit on the PCB consists of two 500 $k\Omega$ resistors, two pull-up capacitors of 22 μfs, a TLC555 timer, and a capacitive pad. The test was completed in total, two times, with variations between them. CAP 1, as defined in Fig. 7, was tested using an oscilloscope to calculate the frequency using Eq. 2, to then put into Eq. 3, and calculate the capacitance throughout the test. The range was determined by holding the capacitive sensor above a pile of sand and slowly moving the sensor down by a defined measurement.

$$f = \frac{1}{T} \quad (2)$$

$$C = \frac{1.44}{(R_A + 2R_B)f} \quad (3)$$

The experimental data collected using the oscilloscope was time and voltage. However, after discussing the results with Professor Bogatin, he suggested using an AD2 scope instead, as it has a higher resolution than the Keysight DSOX1102G oscilloscope, and he provided a better way to measure the range of the sensor. He proposed to stack the same dielectric material on top of the sensor until the sensor stops changing capacitance to determine the range of the sensor. Therefore, Angelina modified the test procedure to reflect these changes and re-tested CAP 1 to get better-resolution results. While re-testing CAP 1, the LunaSat team realized how they built the circuit in Altium could create additional capacitance on the sensor. Thus, the LunaSat team provided a similar capacitive sensor PCB that has no bridge connector and has them soldered together with epoxy on top, as shown in Fig. 7 labeled CAP 2. The reason for this is they wanted to see if the bridge connector is impacting the capacitance measurements. Thus, Angelina tested CAP 2 using the same new version of the test procedure. The experimental data collected using the AD2 scope was period, frequency, time, and voltage. The AD2 scope can collect more information than the Keysight oscilloscope, resulting in fewer calculations and only using Eq 3. to calculate the capacitance. Overall, this test procedure used sand and paper as our dielectric material, varied moisture levels, and determined the range of the sensor.

IV. Results – Angelina

The measurement circuit test procedure started with gathering data on the NE555 and TLC555 timers with no capacitor in the circuit to measure the internal capacitance of the 555 timers to provide more accurate results. The internal capacitance measured for the NE555 and TLC555 timers was 14 pF and 16 pF, respectively. With this knowledge, the external capacitance gets added to the respective capacitance value throughout the test to determine an accurate expected frequency. The average findings for the NE555 timer can be found in Table 1, revealing an average percent error of 2.96. The average findings for the TLC555 timer can be found in Table 1, revealing an average percent error of 3.32. The full findings for the NE555 and TLC555 timers can be found in Table 3 and 4 in the appendix. Towards the end of the measurement circuit test procedure, the 1 $M\Omega$ were replaced with $10M\Omega$ to determine how the resistor value impacts the accuracy of the circuit. Table 2. shows the results gathered from that test.

Table 1 Average Results Found for Both Timers

Timer	% Error
NE555	2.96
TLC555	3.32

Table 2 Results Found for $10M\Omega$

Timer	Cap Values	Calculated f	Output f	% Error
NE555	10	2.00 kHz	2.17 kHz	8.2
TLC555	10	1.85 kHz	2.03 kHz	9.51

The pad design test procedure had the top and bottom of the pad tested for each of the different thicknesses of the clear block as listed: 5, 10, 15, 25, 35, 45, 55, 65, 75, 85, 95, 100, 110, 120, and 200 mils. The clear block has a dielectric constant of 4, and the FR4 block has a dielectric constant of 5 (simulates the dielectric constant of a PCB). The thickness of the FR4 block is 1.6 mm (62.9921 mils), which means that for the bottom tests, the thickness of the FR4 block gets added to the vertical measurement of the sensor. Under the results tab in the Q3D feature, Angelina created individual graphs for each thickness and orientation (top or bottom). Those graphs measured capacitance versus frequency and were used to find the average capacitance value at each thickness to create a capacitance versus thickness graph. Figures 8 and 9 show the average capacitance values taken by each test to create a capacitance versus thickness graph for the top and bottom tests. The red line represents the values collected from one side of the fringes, and the green line is the other side of the fringes. In this context, "fringes" refer to a grouping where each set of fingers is interconnected.

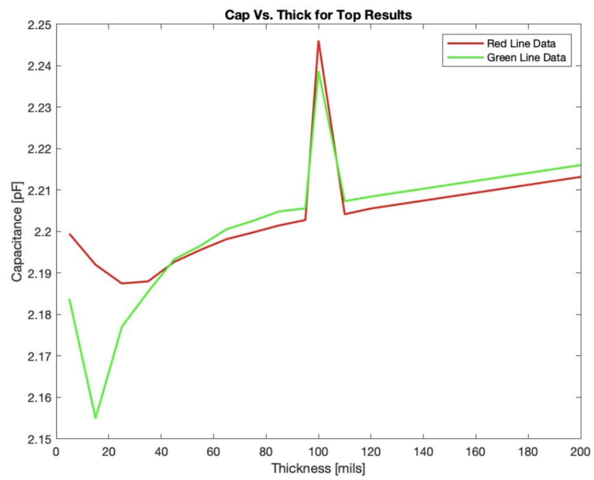

Fig. 8 Capacitance versus Thickness for the Top Results

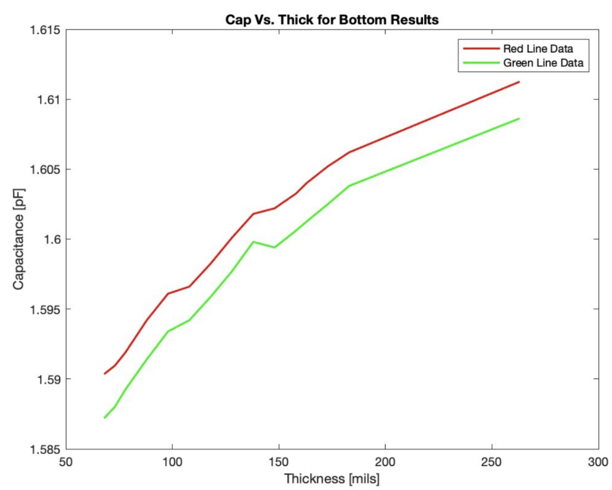

Fig. 9 Capacitance versus Thickness for the Bottom Results

Performing a baseline test on the PCBs by placing no dielectric material onto the pad and just having the pad exposed to the air found the internal capacitance of the measurement and pad design together as 19.4805 pF and 19.3221 pf for Cap 1 and 2, respectively. The findings for the original and new versions of the PCB test procedure performed on CAP 1 and CAP 2 are shown in Tables 5 and 6 and the corresponding graphs in the appendix. Ultimately, in both versions of the test procedures, Angelina found that the capacitive sensor can measure changes in capacitance between 0 and 1 centimeter. Lastly, Fig. 10 shows the test values directly on the expected period versus capacitance line created in the measurement circuit test.

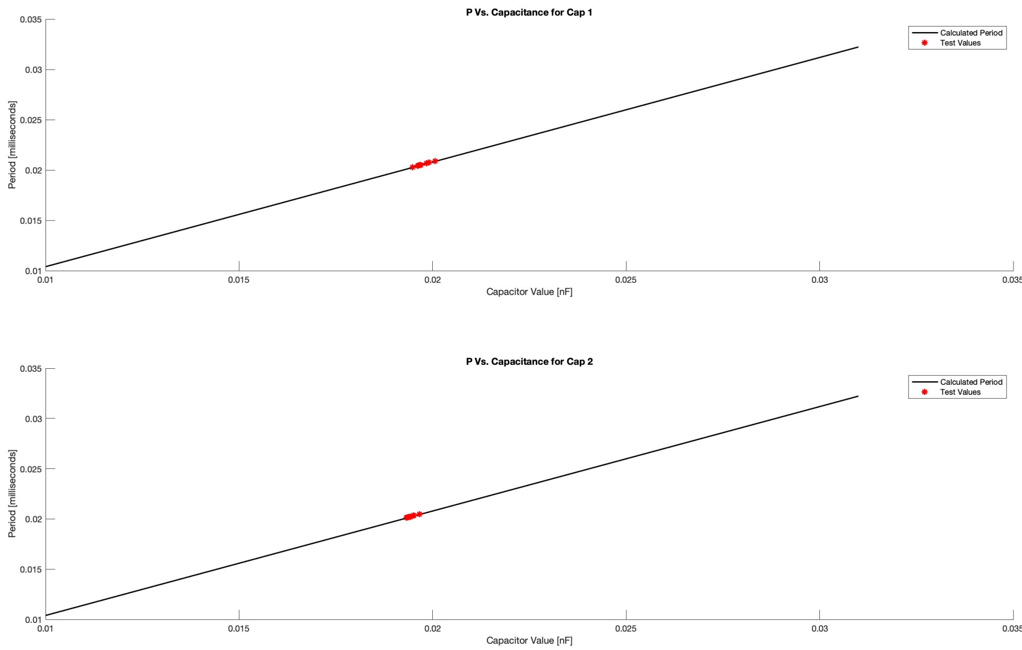

Fig. 10 Period versus Capacitance with PCB Results

V. Discussion and Conclusions – Angelina

In the measurement circuit test for both timers, Angelina determined that the measurement circuit is more accurate for smaller values than larger values of capacitance. Thus, the range of the measurement circuit according to those used during the test is between 10 and 500 pf for better accuracy. Additionally, switching the 1 $M\Omega$ to 10 $M\Omega$, Angelina found that larger resistance values have larger percent errors for smaller capacitance values and vice versa. Angelina also found that the average percent error is lower for the NE555 timer than for the TLC555 timer. Thus, the NE555 timer is slightly more accurate than the TLC555 timer. Despite this observation, either timer can effectively operate within this circuit and yield accurate results. Overall, from this initial test, the science team concluded that the measurement circuit would be able to measure small values of capacitance with a small percent error with either timer.

Figures 8 and 9 conclude that the sensor can measure a distance of at least 100 mils on the top part of the pad due to changes in capacitance still occurring at a thickness of 100 mils. Figure 9 concludes that the sensor can measure less than 100 mils on the bottom part of the pad since the capacitance value is the same capacitance value obtained for the individual block with a dielectric constant of 5, which means that the pad is not measuring past the FR4 block. The bottom part of the pad will only be able to measure the capacitance of the PCB. However, the bottom portion of the sensor does not matter as much as the dielectric material will be going onto the top of the sensor and measure the capacitance of this dielectric material. In a vacuum, the pad design shows a capacitance of about 0.7 pF, and at a dielectric of five, the pad design shows a capacitance of about 1.6 pF. This means that our capacitive pad can measure capacitance changes of less than one pF. Fortunately, the first pitch dimension chosen had great results and is the one the GLEE team is using. Therefore, from this initial test, the team hypothesized that the pad design would measure capacitance changes of less than one (pF) and a vertical distance of at least 100 mils.

The timer chosen to build the capacitive sensor on its own PCB was the TLC555 timer, as it worked better for our LunaSat team. Additionally, the LunaSat team wanted to use 500 $k\Omega$ resistors for the same reason, and since it should ideally make the circuit more accurate, the science team approved those changes. The conclusion that can be drawn from the original version of the test procedure is that the results for coverage of the pad impact the changes in capacitance. For example, when the pad is fully covered, it has a capacitance of 19.5456 pf, barely covered (sprinkle) at 19.3536 pf, and partially covered at 19.4688 pf. The changes in capacitance show how coverage impacts the results. Additionally, the sensor can measure a range between 0 and 1 cm and determine small changes in capacitance that are less than one pf.

According to the results from the newer version of the test procedure, the sensor can measure changes in capacitance within a range between 0 and 2 cm. However, Angelina can confidently say that the sensor can measure a range between 0 and 1 cm (400 mils) since a couple of the values after 1 cm jump below the capacitance measure at 1 cm when it should increase or stay the same. Additionally, the sensor can measure small changes in capacitance that are less than one pf. Furthermore, Angelina can conclude our sensor is accurate by comparing the output values to the expected period and capacitance graph from the measurement circuit test. The graph of the period versus capacitance shows what the capacitance value should be for a certain period. Therefore, the sensor is accurate because the period and capacitance obtained are relatively close to the respective values. Lastly, the epoxy and header pins did affect the capacitance.

In conclusion, our current version, Luna-CAP, can measure a range of 0 to 1 cm (about 0.39 in) and small changes in capacitance of less than one picofarad (pF). Overall, this sensor will allow the team to measure capacitance changes in the dielectric material and help determine the physical properties of the Lunar Regolith. The intended test plan for the future is to test the capacitive sensor on LunaSat V7 to inform the team of the resolution and range of the sensor. Although, the range should stay the same as the PCB test. However, the resolution will change since that is dependent on the tool used to measure from the output pin of the 555 timer. Lastly, determining the sample rate and testing the software code to ensure the sensor works with the integration onto V7 is the last step towards final integration of the sensor.

Appendix

A. Measurement Circuit Results

Table 3 Results Found for NE555 Timer

Cap Values	Calculated f	Output f	% Error
10	20.04 kHz	20.55 kHz	2.54
15	16.59 kHz	16.82 kHz	1.39
22	13.36 kHz	13.33 kHz	0.26
33	10.23 kHz	10.11 kHz	1.24
47	7.89 kHz	7.90 kHz	0.15
68	5.87 kHz	5.79 kHz	1.35
100	4.22 kHz	4.32 kHz	2.32
220	2.06 kHz	2.08 kHz	1.36
470	993.80 Hz	1 kHz	1.10
680	693.08 Hz	743.6 Hz	7.29
1000	474.36 Hz	515.6 Hz	8.69
10000	48.03 Hz	44.50 Hz	7.37
100000	4.81 Hz	4.64 Hz	3.47
		Average % Error	**2.96**

Table 4 Results Found for TLC555 Timer

Cap Values	Calculated f	Output f	% Error
10	18.5 kHz	19.31 kHz	4.38
15	15.52 kHz	16.21 kHz	4.45
22	12.66 kHz	12.67 kHz	0.09
33	9.82 kHz	9.77 kHz	0.44
47	7.64 kHz	7.62 kHz	0.24
68	5.73 kHz	5.77 kHz	0.83
100	4.15 kHz	4.31 kHz	4.04
220	2.04 kHz	2.05 kHz	0.69
470	989.71 Hz	1 kHz	1.79
680	691.09 Hz	747.65 Hz	8.18
1000	473.43 Hz	514.22 Hz	8.62
10000	48.02 Hz	44.23 Hz	7.9
100000	4.81 Hz	4.74 Hz	1.48
		Average % Error	**3.32**

B. PCB Results

The outcomes from both the previous and updated PCB test methods are detailed in Tables 5 and 6 below. Distilled water was used as the liquid to introduce moisture to the sand; however, excessive contact with the pad led to a short circuit in the sensor. Consequently, while these findings are not extensively utilized, they do illuminate the issue of excessive distilled water causing short circuits in the capacitive sensor circuit.***NEED TO ADD!!!***

Graphed the results for the original test procedure into five different categories: variation in the distance shown in

Table 5 Results Found for Old Version of PCB Test

Test	Material	Avg. Output P (s)	Output Cap Value (pF)
Baseline	Air	2e-5	19.2
2cm	Sand	2e-5	19.2
1.5cm	Sand	2e-5	19.2
1cm	Sand	2.004e-5	19.238
0.5cm	Sand	2.008e-5	19.277
Dry	Sand	2.036e-5	19.546
10 Drops	Distilled Water	2.084e-5	20.0064
20 Drops	Distilled Water	2.516e-5	33.754
30 Drops	Distilled Water	2.996e-5	28.762

Table 6 Results Found for New Version of PCB Test

Cap Version	Test	Material	Avg. Output P (s)	Output Cap Value (pF)
CAP 1	Baseline	Air	2.030e-5	19.481
	Dry	Sand	2.073e-5	19.905
	1 mm	Paper	2.043e-5	19.614
	2 mm	Paper	2.045e-5	19.632
	3 mm	Paper	2.067e-5	19.839
	4 mm	Paper	2.051e-5	19.684
	5 mm	Paper	2.048e-5	19.658
	10 mm	Paper	2.090e-5	20.067
	12 mm	Paper	2.090e-5	20.061
	16 mm	Paper	2.051e-5	19.687
	20 mm	Paper	2.996e-5	19.69
CAP 2	Baseline	Air	2.013e-5	19.322
	Dry	Sand	2.048e-5	19.656
	1 mm	Paper	2.015e-5	19.342
	2 mm	Paper	2.020e-5	19.387
	3 mm	Paper	2.018e-5	19.370
	4 mm	Paper	2.023e-5	19.423
	5 mm	Paper	2.022e-5	19.414
	10 mm	Paper	2.033e-5	19.519
	12 mm	Paper	2.022e-5	19.412
	16 mm	Paper	2.032e-5	19.508
	20 mm	Paper	2.020e-5	19.392

Fig. 11, variation in moisture levels shown in Fig. 12, variation in coverage of the pad shown in Fig 13, verifying the sensor still works after each type of testing shown in Fig. 14, and all the data collected shown in Fig. 15.

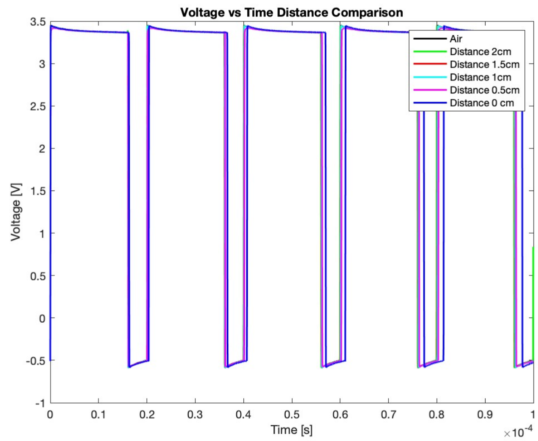

Fig. 11 Variation in Distance

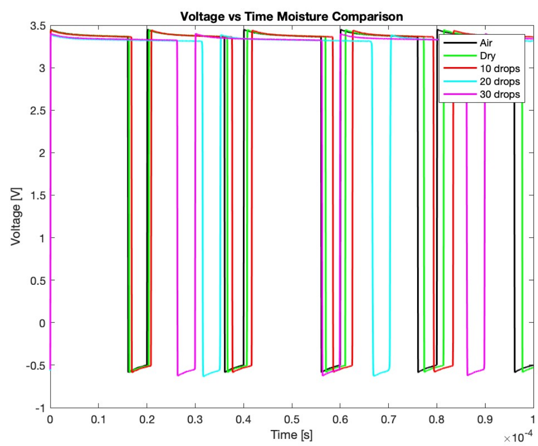

Fig. 12 Variation in Moisture Levels

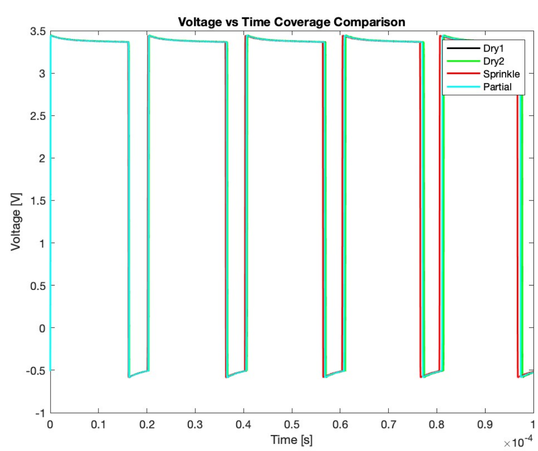

Fig. 13 Variation in Coverage

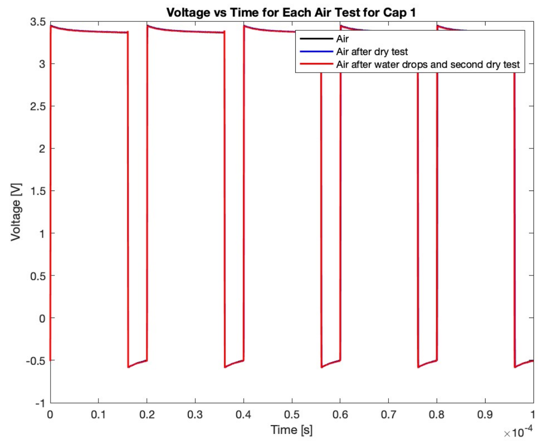

Fig. 14 Verify Sensor Still Works

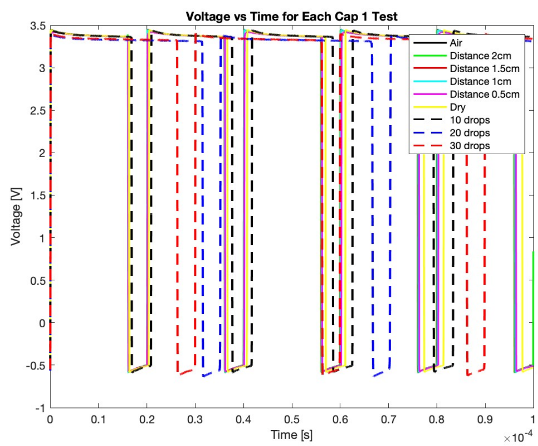

Fig. 15 All Data Collected

Graphed the results into three different categories for the new test procedure: variation in distance shown in Fig. 16, variation in moisture levels shown in Fig. 17, and all the data collected shown in Fig. 18.

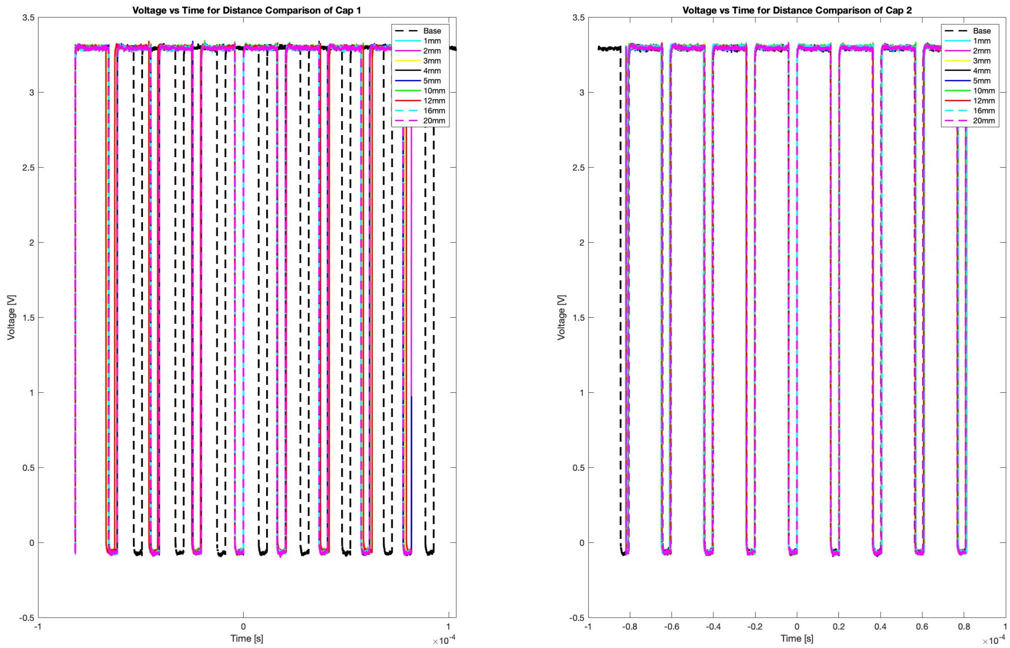

Fig. 16 Variation in Distance

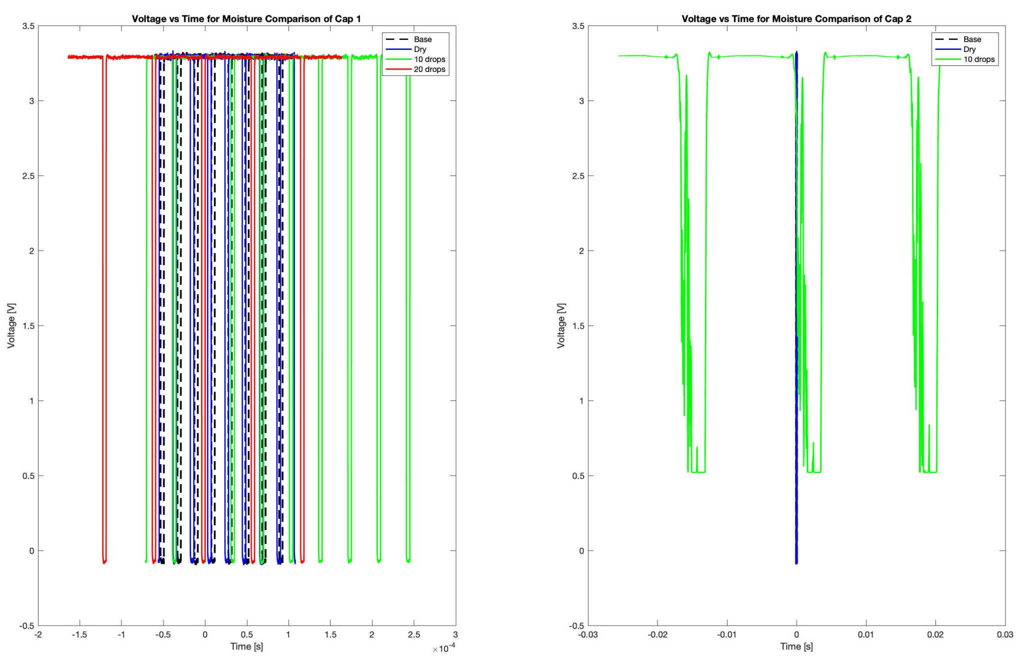

Fig. 17 Variation in Moisture Levels

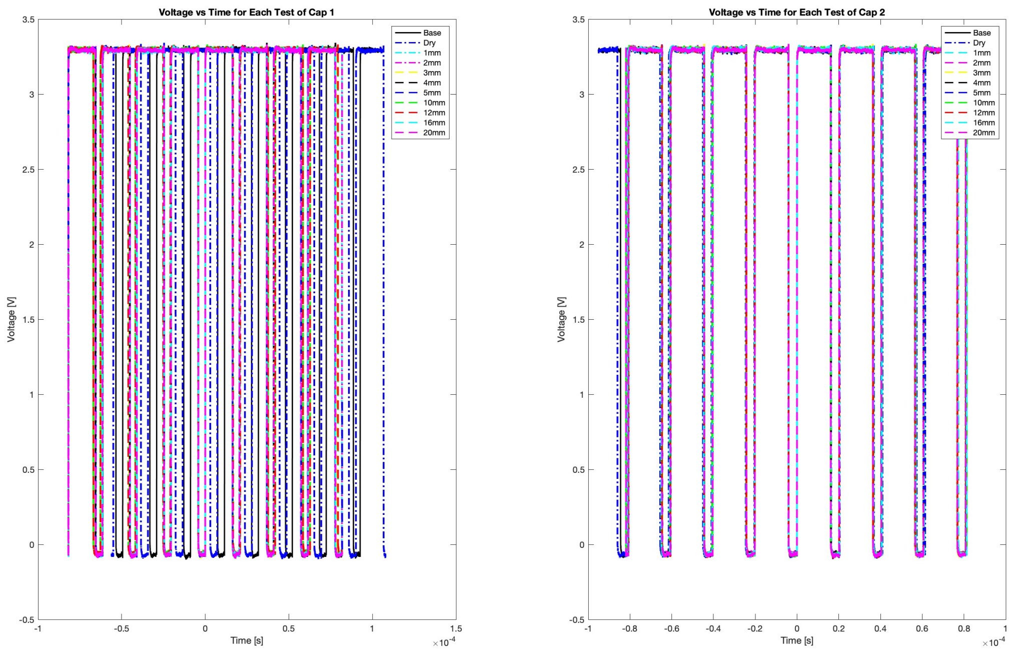

Fig. 18 All the Data Collected

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