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Development of an Additively Manufactured Capacitive Humidity Sensor for the International Space Station

K.T. Chang, A.T. Rogers, J.A. Colby, F.V. Thompson, and T.D. Rolin
Marshall Space Flight Center, Huntsville, Alabama

March 2019

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LIST OF ACRONYMS AND SYMBOLS

BHC	big honeycomb
KOH	potassium hydroxide
NaCl	sodium chloride

NOMENCLATURE

A	cross sectional area of overlapping electrodes
C	capacitance
d	electrode spacing
RH	percent relative humidity
ε_0	permittivity of free space
κ	dielectric constant

Subscripts

aq	aqueous ion
s	spectator ion

TECHNICAL MEMORANDUM

DEVELOPMENT OF AN ADDITIVELY MANUFACTURED CAPACITIVE HUMIDITY SENSOR FOR THE INTERNATIONAL SPACE STATION

1. INTRODUCTION

The ability to measure humidity on the International Space Station and other long-duration spaceflight missions is a crucial part of the onboard systems. For example, the Environmental Control and Life Support System (ECLSS) needs to know the amount of humidity in the air to make decisions about whether it should spend power to run the dehumidifier systems to attempt to reclaim that water. Other issues can arise if the humidity reaches too high of levels and condensation builds up on electrical components. With that in mind, it is vital that the spacecraft keeps spare sensors on board or has the ability to manufacture new sensors on demand. An additively manufactured sensor would be additionally beneficial because it would save space onboard that would normally be taken up by spares, save money from costly resupply missions, and allow the sensor to be constantly updated with the most effective design. This Technical Memorandum outlines a development process carried out to design, manufacture, and test an additively manufactured humidity sensor.

2. BACKGROUND

To comprehend how to create such a sensor, one must first have an in-depth understanding of electronic sensing techniques and of additive manufacturing technology. Humidity is a measurement of how much water vapor is in the air. Absolute humidity is the mass of water per given volume of air. Absolute humidity is difficult to measure directly; therefore, we express it as 'percent relative humidity,' *RH*. That is the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. Relative humidity can be found in several ways, depending on which values are known.

There are two main electrical properties used for sensing changes in pressure, humidity, or temperature—resistance and capacitance. If the change in the electrical property can be directly linked to the change in the physical property, then if one value is known, the other can be found. In this fashion, hygroscopic, or water-absorbing materials, can be used as either a resistor or capacitor in a circuit and indirectly indicate the humidity of the current atmosphere.

With capacitive sensors, the change in humidity is attributed to water molecules bonding to the dielectric and changing the capacitance. The conductive electrodes are porous to allow moisture to reach the dielectric sandwiched between the two electrodes. There are many *RH* sensors already on the market today, and they are produced by many different electronics companies. With this diversity comes a comparable variety of different dielectric materials used for sensing humidity; aluminum, tantalum, silicon, polymers, and potassium hydroxide are all being used in capacitive humidity sensors.[1]

Another way is to use potassium hydroxide (KOH) powder as the dielectric, which was great for responding to a step increase in humidity.[2] KOH retains moisture well, which makes it great for moisture detection. However, once the humidity decreases again, the dielectric remains saturated (holds onto the water molecules too well), and takes much longer to stabilize at the new humidity level. The dielectric material[3,4] used in this project was developed in house, and sensors built from the material have demonstrated excellent recovery properties after saturation.

Some of the many benefits of using capacitive sensors is the ability to operate well in wet environments for an extended period of time and their low maintenance requirements; and they have low hysteresis and high stability. The general form of calculating the capacitance C is as shown in Eq. (1).

$$C = \varepsilon_0 \, \kappa \, A/d \tag{1}$$

where

C = capacitance
ε_0 = permittivity of free space
κ = dielectric constant
A = cross-sectional area of overlapping electrodes
d = electrode spacing.

3. METHODOLOGY

The methodology to develop the sensors consists of designing, building, and testing.

3.1 Design

The design phase began by envisioning several electrode design patterns following an interdigitated arrangement. Since the interdigitated design maximizes surface area, requires less printing than parallel plates, and allows moisture to penetrate into all of the dielectric, it was chosen as the capacitor style used in this project. Some of the most notable designs included spiral, zigzag, and honeycomb patterns (fig. 1).

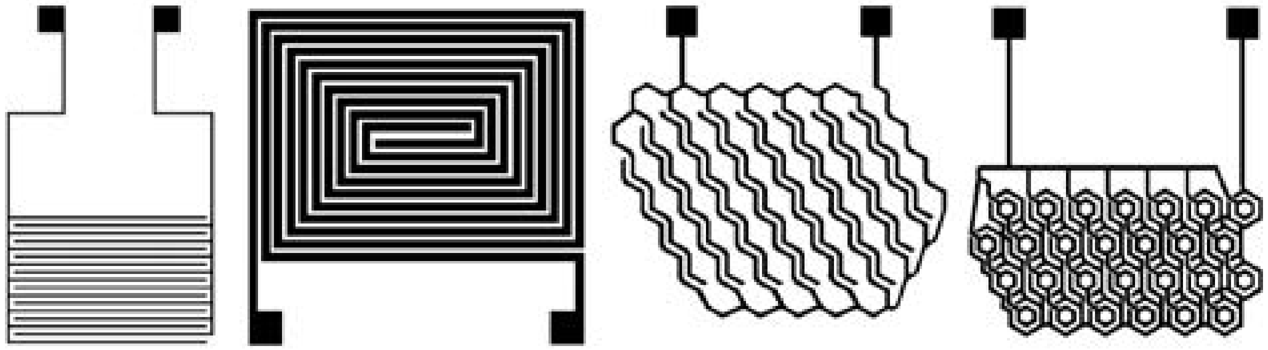

Figure 1. Interdigitated, spiral, zigzag, and honeycomb electrode patterns.

The initial design requirements were that there be two electrodes separated by a gap such that they form a capacitor without any electrical shorts, that each pattern had a pair of probe points from which testing equipment could be connected, and that each pattern fit within a 1-in^2 area. Each pattern was drawn in computer-aided design (CAD) software and then converted to a monochrome bitmap file to send to the printer.

Once the best electrode designs made it through the build and testing stages, the requirements were tightened to standardize the designs so the sensor's housing could be developed accordingly. By designing each layout to have connecting pads in the same spot, the different versions of the housing were designed in a single configuration rather than having to develop separately for each electrode layout.

After printing, the electrodes were meticulously inspected both visually and electrically for print quality and electrical separation using a microscope and the multimeter, respectively. The prints needed to be clean and have good resolution, be free of electrical shorts, and be able to produce a low resistance value. Failed prints were photographed and learned from with each new iteration. The sheer volume of failures was a testament to how precisely the inkjet printer must be calibrated to work correctly. Each of the electrode prints were observed under the microscope for quality resolutions. This includes clean edges, no overspray, and consistent electrode spacing. Figures 2–4 are electrode prints that failed inspection for different reasons.

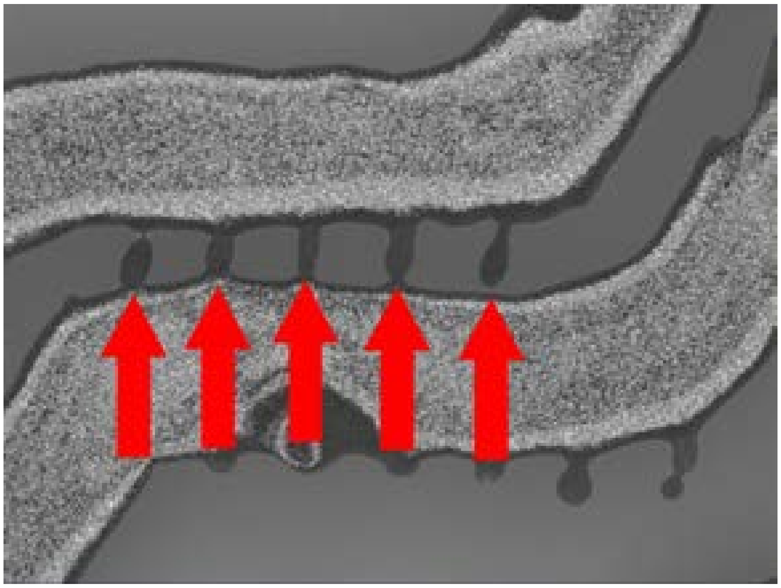

Figure 2. Failure by overspray.

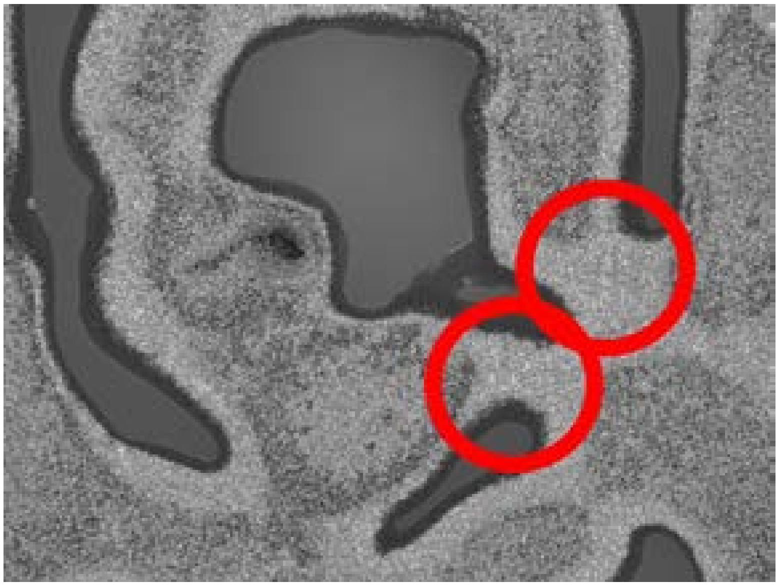

Figure 3. Failure by electrical shorts—poor resolution.

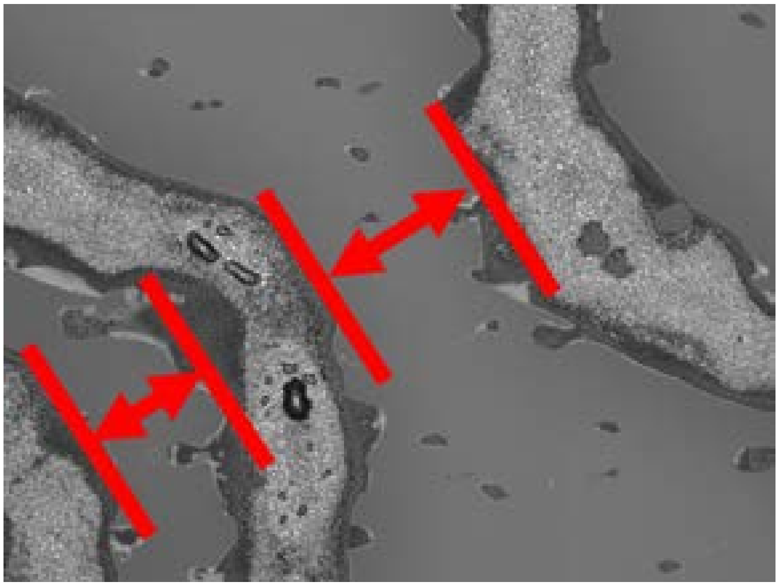

Figure 4. Failure by overspray and inconsistent electrode spacing.

After the first round of testing, the honeycomb pattern was selected as the best candidate for an additively manufactured humidity sensor. The pattern was then designed with different numbers of honeycombs to see if that would vary the sensor's ability to perform correctly. These two variations were affectionately called 'Big Honey' and 'Little Honey.'

In the final optimization of the honeycomb design, the layout was scaled up and down to three target electrode spacings for testing—275 µ, 350 µ, and 400 µ. Using the printer's Graphical User Interface (GUI), various print settings were chosen, such as number of ink layers, which inkjets to use, cartridge and platen heights, and temperatures. Through extensive trial and error, the optimal print settings were found such that the prints came out with high resolution. Frequently, the cartridges were replaced or refilled, so the inkjets had to be checked with the camera for proper jetting. The ink is piezoelectric, so the voltages for each nozzle could be adjusted to cause the ink to jet in different volumes (or different-sized droplets).

3.2 Build

In constructing a quality print, the inkjet setting calibrations had to be varied. Printing variables to consider included substrate thickness, jet voltages, number of ink layers, the height of the cartridge, amount of jets used, and platen temperature. Some of the settings and their respective results are shown in table 1.

Table 1. Example print settings chart.

Inkjet Setting							
Substrate Glass	Substrate Thickness (Microns)	Volts	Layer	Cartridge Height (mm)	Jets	Temperature (°C)	Results
Quartz	1,000	17	1	1	4	33	No
Quartz	1,000	17	1	1.15	4	33	No
Quartz	1,000	17	1	1.15	6	33	Ok
Quartz	1,000	17	1	1.1	6	33	Good, no blending in gap
Big quartz	1,700	17	1	1.3	5	33	Good
Big quartz	1,700	16	2	1.35	5	33	Minimum overspray through
Big quartz	1,700	16	2	1	9	33	Good
Big quartz	1,700	17	3	0.5	9	33	Too thick
Big quartz	1,700	16	1	0.5	9	33	Good
Quartz	1,000	16	2	0.9	5	50	Great and clean
Quartz	1,000	17	2	0.9	5	50	Good, minimum fuzz
Quartz	1,000	19	2	0.9	5	50	Fuzzy
Quartz	1,000	16	2	0.8	5	50	Two lines that overspray through gap

The inkjet printer has 16 ports that allows ink to jet through. The built-in camera viewer, known as drop watcher, allows for the viewing of each port to determine if any are malfunctioning or are blocked. (See fig. 5.) An important consideration is that the higher the jetting voltage, the faster the inks are jetted out, resulting in overspray of ink, which leads to poor quality resolutions. If the voltage is too low, printing will result in inconsistent electrode spacing and insufficient ink deposition, leading to an electrical open.

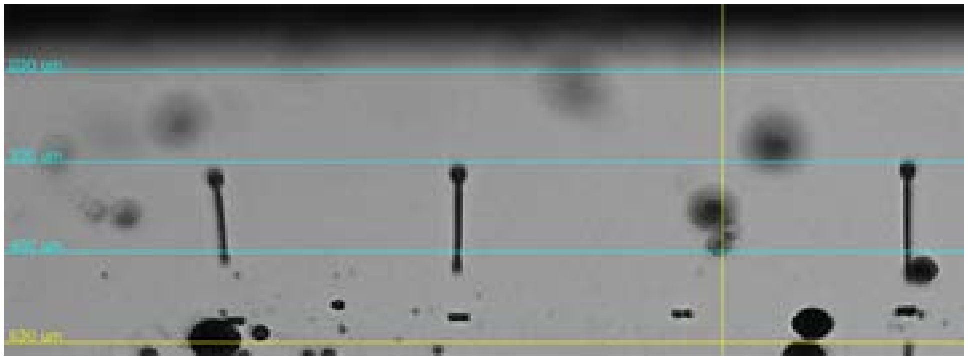

Figure 5. Drop watcher screenshot.

After the Dimatix inkjet printer setup was completed, the electrode pattern was printed on quartz substrate using conductive ink. An example is shown in figure 6. Once completed and inspected (fig. 7), the ink was then sintered in an eight-zone furnace at up to 850 °C. Using an ultraviolet lamp to sinter the ink was also attempted but tended to result in an uneven curing of the ink.

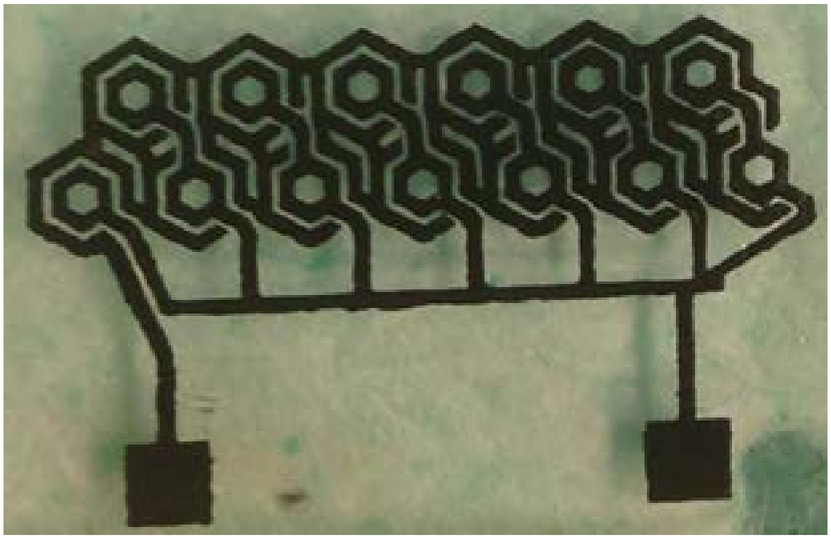

Figure 6. Completed print (fresh ink).

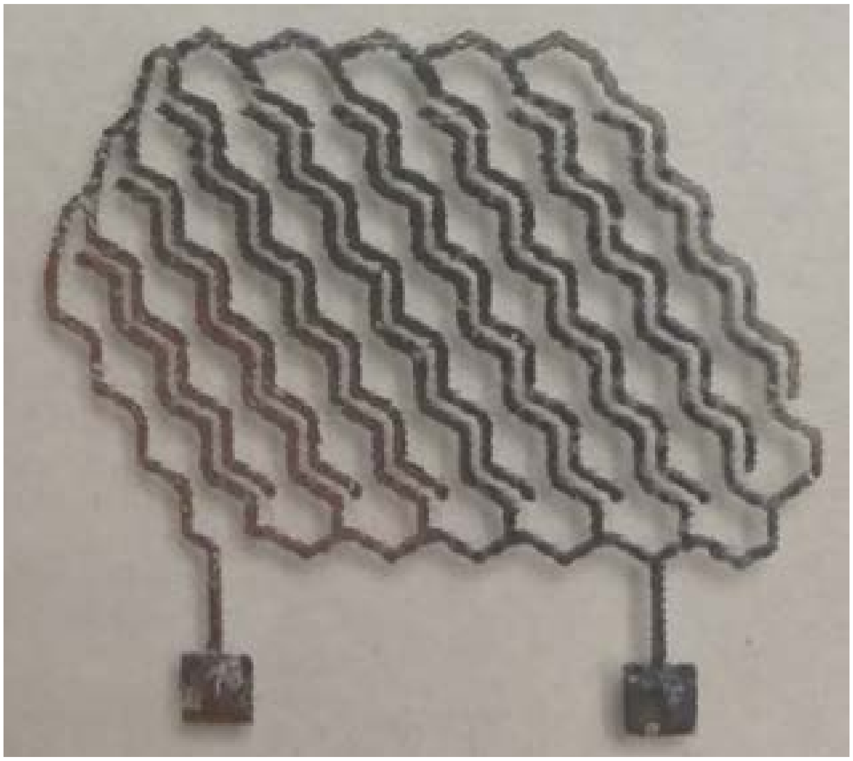

Figure 7. Post-sintering electrode.

After the ink was sintered and the electrodes were inspected for electrical shorts, a dielectric material was screen printed over the electrode pattern, and the entire sensor was post-processed in the burnout furnaces. The process of screen printing the dielectric material was carried out one to three times, depending on how many layers of dielectric was desired. Once the dielectric was completed (fig. 8), the sensor was ready for testing.

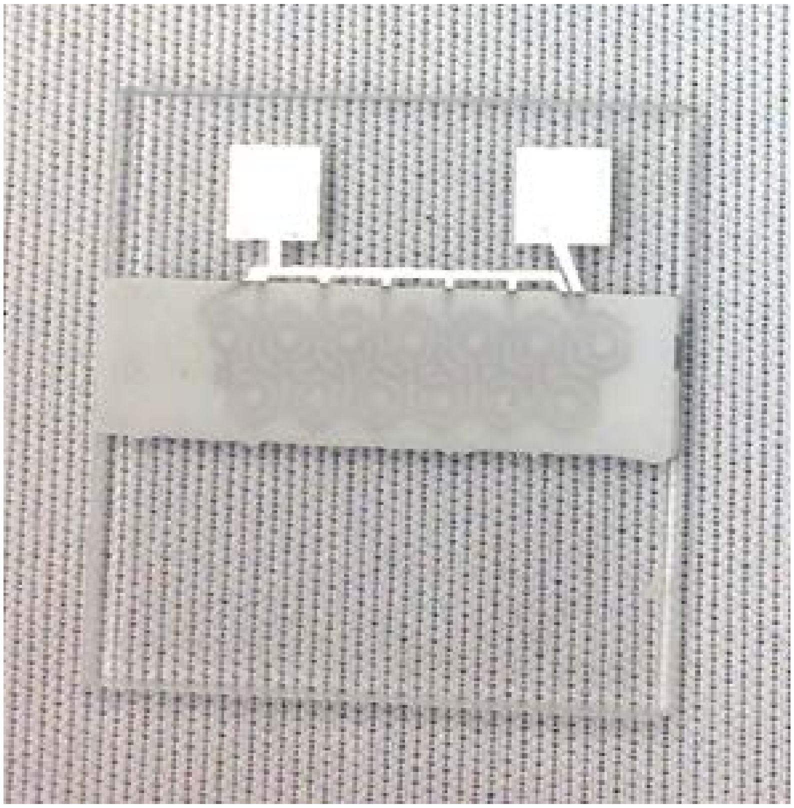

Figure 8. Example of completed sensor.

In addition to manufacturing working humidity sensors, packaging designs for the sensor were also considered in the event that the design was to ever be used outside of NASA in a consumer application. The first step in package design was to create a holder for the sensor that also placed the wire leads onto the sensor's pads. The design shown in figure 9 was created to serve this initial purpose.

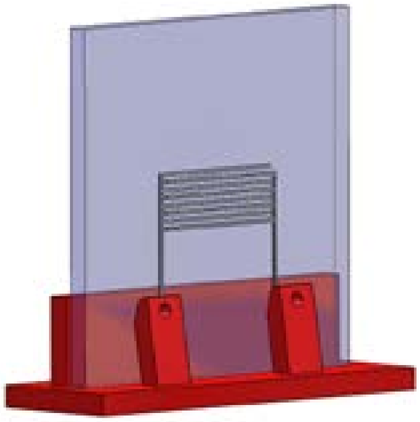

Figure 9. Initial house design.

This design worked well with the exception of the pressure that the base put on the quartz to contact the lead actually would scratch and wear the sensor pads. Additional bases (fig. 10) were then designed to overcome this issue.

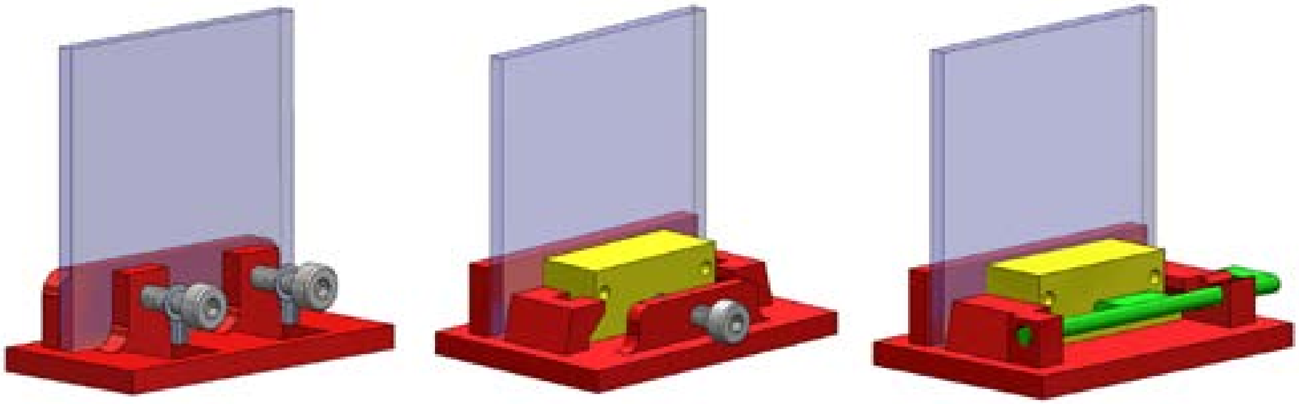

Figure 10. Additional base designs.

All the designs were printed and tested, and each had their own advantages and disadvantages. Additionally, the base could be fitted with a sensor grille to prevent people or objects from coming in contact and damaging the sensor (fig. 11). These packages could eventually be used to create a 'plug and play' style humidity sensor for commercial applications.

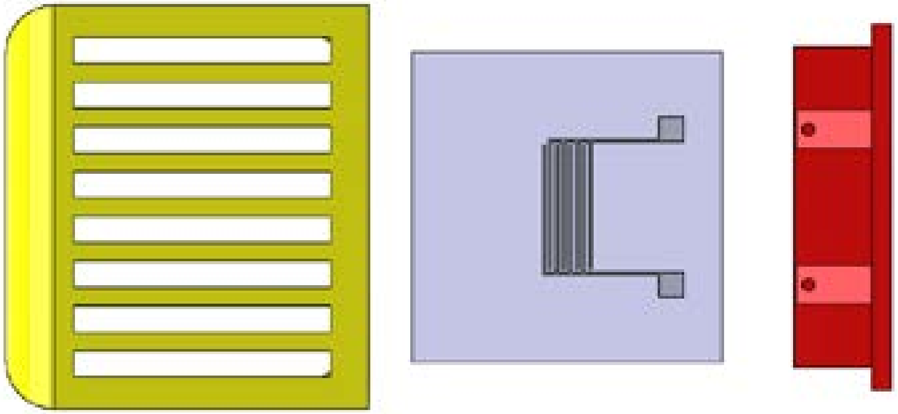

Figure 11. Sensor grille.

3.3 Test

The sensors capacitance (saturation range) was observed real time on an Agilent precision inductance, capacitance, and resistance meter from a short breath blown directly onto the sensor. Sensor recovery response time was observed by visually determining the slope of the capacitance as the sensor recovered to its initial value. After this empirical testing was performed with the different electrode patterns, the data was compiled into a table to be compared. Table 2 shows that the honeycomb pattern excelled in every category.

Table 2. Initial test results.

Design	Shortly After Breath	Several Minutes After Breath	Capacitance Range
Spiral	Quick to respond	Slow to return to nominal	Large range
Rectilinear	Quick to respond	Remains saturated	Large range
Zigzag	Slow to respond	Quick to return to nominal	Small range
Honeycomb	Quick to respond	Quick to return to nominal	Large range

Thus, the honeycomb electrode pattern was selected as the best candidate for an additively manufactured humidity sensor, because of its ability to quickly return to the nominal value after an increase in humidity. As shown in table 2, the other designs failed to match the advantages of the honeycomb design because they were either too slow to respond initially or too slow to return from saturation.

Once the pattern was chosen, two variations of the honeycomb were printed. One was printed with only a few large honeycombs, and the other with several smaller honeycombs. These were both tested using the same method as the initial round of testing. The results are shown in table 3. After testing, it was found that the bigger honeycomb produced more desirable results, and thus it was chosen.

Table 3. Second round of testing results.

Comparing Small and Big HC					
Name	Distance (mm)	Electrodes Layer	Dielectric Layer	CAP. Range Test_1	CAP. Range Test_2
SHC1	0.275	2	1	1–20 nF	1–20 nF
SHC2	0.275	2	1	700 pF–13 nF	700 pF–16 nF
BHC1	0.275	2	1	750 pF–40 nF	800 pF–40 nF
BHC2	0.275	2	1	560 pF–20 nF	560 pF–50 nF

For the third and final round of sensor testing, it was decided that the electrode thickness and spacing should be tested. In addition, a constant-humidity chamber was created using a stirring plate, a saturated sodium chloride (NaCl) solution, and a flask with a stopper. The chamber used for this portion of testing is shown in figure 12. Ionic salt solutions are often used to test humidity sensors because their partial pressure of moisture produces very predictable humidity levels. Therefore, this method was chosen for testing the design variations for its consistency. Saturated NaCl solutions at 20 °C are expected to produce relative humidity conditions of approximately 75.47±0.14%.[4] The sensors were placed in the chamber with this solution and were suspended above the solution where the humidity was constant. The solution was stirred to prevent stratification of the water vapor above the solution. The sensors were observed during initial exposure to the humidity and again during the recovery period when they were taken out of the flask. Equation (2) is the net ionic equation:

$$\mathrm{NaCl}_{(s)} \leftrightarrow \mathrm{NaCl}_{(aq)} \quad . \tag{2}$$

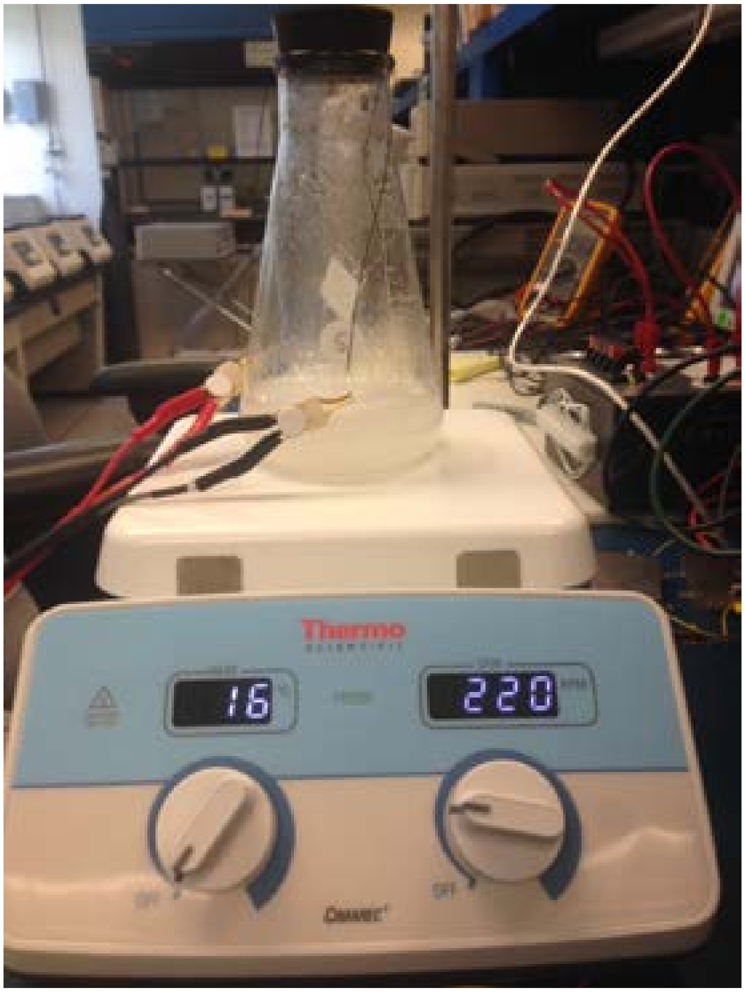

Figure 12. Humidity chamber setup.

4. RESULTS

Due to the favorable performance of the big honeycomb (BHC) pattern, its design was then varied in terms of changing the spacing between the electrodes. Additionally, the number of dielectric layers was tested at the same time. Sensors with three different spacing by three different amounts of dielectric layers resulted in nine different sensors being tested with the salt solution method. As shown in figure 13, the large honeycomb pattern with 0.35-mm spacing between the electrodes (BHC_350_2) approaches the highest value of capacitance, resulting in the widest range of saturation in an hour timeframe. Complete recovery of the sensor is achieved in the same timeframe yielding a printed functional sensor that saturates and recovers as expected (fig. 14).

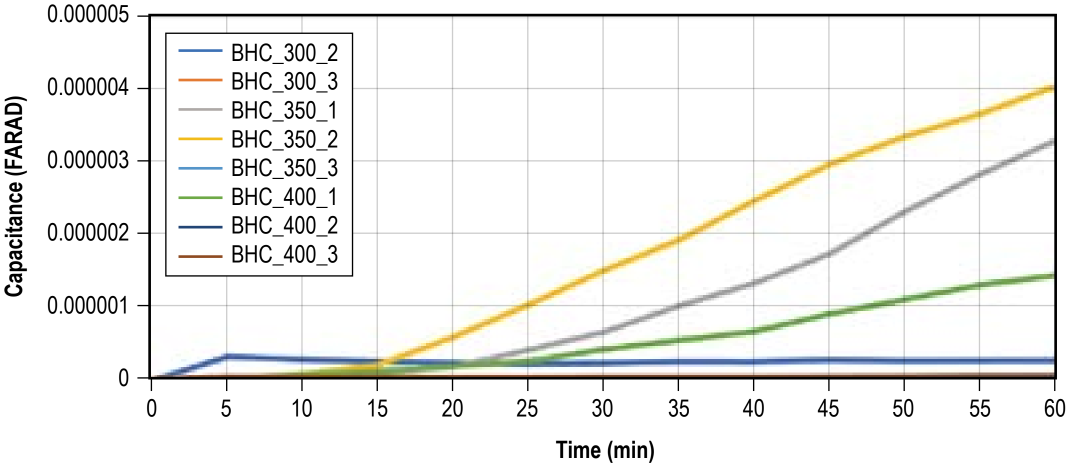

Figure 13. Capacitance testing.

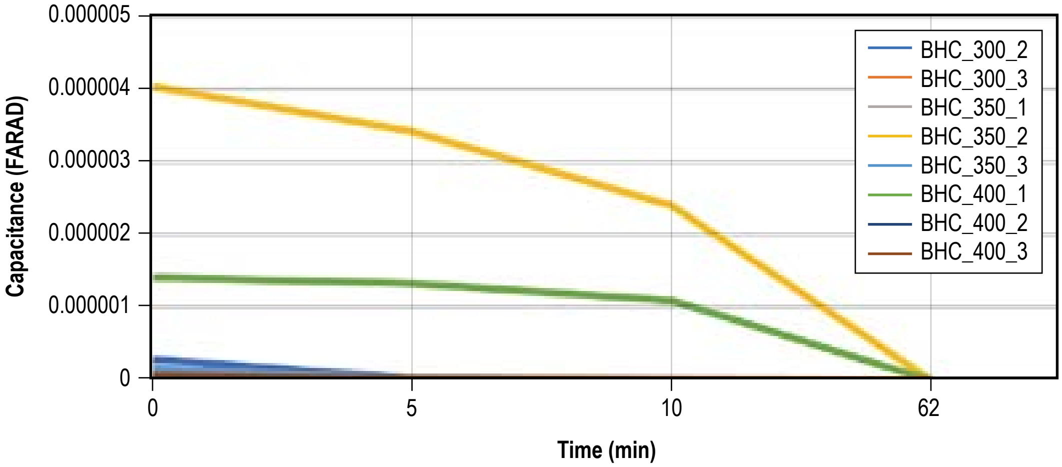

Figure 14. Recovery.

By varying the quantity of printed dielectric layers of the 0.35-mm BHC, the density and porosity of the dielectric between the electrodes change, resulting in varying capacitances. Figure 15 indicates an ideal thickness range around two layers for the highest capacitance. As seen in the figure, three dielectric layers decrease porosity to the point where no moisture is allowed to enter the cross-sectional region between the electrodes. The sensor with one dielectric layer exhibits incompletely filled volume and porosity of dielectric between the electrodes; therefore, the cross-sectional area between the plates is decreased, and a lower capacitance range is the result.

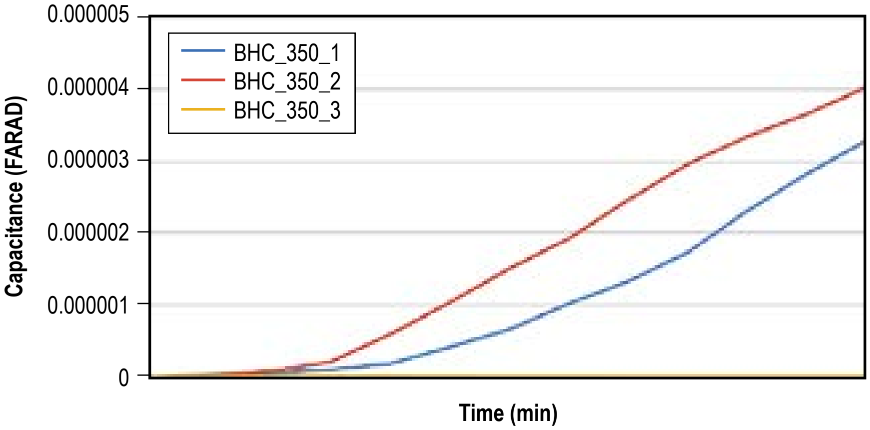

Figure 15. BHC_dielectric comparison.

According to Adafruit Industries, Honeywell, and Texas Instruments, the expected response time for a capacitive sensor on the market today is 5–30 s for a 63% step change in *RH*.[5–7] Honeywell reported a 15-s response time in slow-moving air at 25° C with their thermoset polymer *RH* sensors. Capacitive sensors usually work up to about 200 °C, while a moisture sensor specifically should be used between 10 °C and 70 °C. The optimal range is from 5–80% *RH*, which yields capacitance values in the microfarad range. The honeycomb design easily met response standards of the commercially available humidity sensors observed, taking less than 30 s to reach a 63% step change when tested at 20 °C.

5. CONCLUSION

The large honeycomb pattern, with 0.35-mm spacing between the electrodes and two layers of dielectric, was found to produce an additively manufactured humidity sensor comparable to those that are commercially available. In addition to being an effective sensor, this design allows for the on-demand production of the sensor in a space-based manufacturing environment and allows the sensor to be mass-produced with minimal human input. Additionally, a packaging design was developed in the event that the sensor be made and sold by private industry as a ‘plug and play’ style of sensor.

6. FUTURE GOALS

Future goals of this project would be to test the sensor over greater ranges of both humidity and temperature, as well as known values of humidity, in order to develop a humidity to capacitance curve to calibrate the sensor. Ideally, the integration of an analog front-end signal conditioning chip could be added to the back of the sensor to convert measurements into known formats for use in various instrumentation systems and networks. The signal conditioning chip could also support direct output to a display, providing a standalone sensor product for measuring humidity. The sensor could also be further developed to record the response of the capacitance to other variables such as pressure, temperature, gases, aerosols, radiation, and magnetism to explore the possibility of sensing other phenomena with the in-house-developed sensor. Finally, a future goal would be to further streamline the manufacturing process to allow all printing and integration of the sensor directly into materials or components.

Additionally, the sensor could be refined to be used in the following potential applications:

- detection and characterization of aerosols,
- gas detection systems,
- liquid level sensing,
- wearable environmental sensors in smart watches,
- smart packaging and product tampering detection,
- embedded moisture detection in composites, ceramics, and polymers,
- moisture detection in gasoline and fuels,
- environmental monitoring and control,
- monitoring humidity in oil refineries,
- smart air conditioning and refrigeration systems,
- moisture intrusion detection in electronic devices, and
- humidity monitoring for tobacco storage.

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14. ABSTRACT

This project focuses on highlighting the growing need for alternative on-demand resupply of failed electronic components in space as NASA continues to pursue deep space exploration. In this research, we explore the use of a tabletop Dimatix materials printer as a potentially scalable process to iteratively improve the performance of an in-house developed capacitive humidity sensor. We used inkjet printing technology to digitally iterate through various sensor electrode configurations to observe the differences in performance of a fully printed solid-state humidity sensor. Results proved that the fully printed large honeycomb pattern performed comparably well with commercial humidity sensors available today.

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