Disposable, Paper-Based Sensors to Detect Leaks

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Abstract

Metalized paper, standard wood-pulp paper coated with aluminum, is commonly used in many forms of packaging. Recently, recognition of metalized paper as a medium for innovative new applications is growing since it is an extremely affordable, conductive medium. In this project, gridded metalized paper substrates act as the separate plates of a capacitor and are used to detect water leakage. An Arduino Uno unit monitors the increase in capacitance caused by water touching the metalized plates, and thus locates water leakage. The Arduino then sends data to a computer that conveys the location of the leak to the user. Using these paper-based, water-detecting sensors, leaks can be discovered in private, public, and military spaces to avoid irreversible water damage.

1. Introduction

Paper is a disposable and extremely affordable material, made of thin sheets of wood pulp, which is easily mass-produced. Once certain substrates and chemicals are added to paper, there are countless new and innovative possibilities for technological application. One such modification to paper is the application of a micrometer-thin layer of aluminum to one face of the paper. This results in metalized paper. In 2013, researchers used such a technique and developed a paper-based electro-analytical device that greatly increased the accessibility of diagnostic testing for the analysis of glucose, lactate, and uric acid. In this study, a paper-based device has an advantage over traditional leak detection devices due to its ease of mass-production and distribution. Specifically, the flexibility of the material means there is almost no risk of damaging the product during transportation.

Such paper-based capacitive touch pads, made of metalized paper, have even been used in disposable games, interactive packaging, and theft alarms. This study uses the latent capacitance in metalized paper in order to detect the location of water leakages. A leak-detection system based on the capacitive properties of water constructed from metalized paper would make leak-detection more widely available and affordable to the general public.

2. Background

2.1 Water Damage

According to a study conducted by Verisk Analytics ISO, one fifth to a quarter of all property damage between 2009 and 2013 was water damage. Further research has shown that these figures are only rising.
Outdated roof designs retain water beyond their capacity; poor maintenance can lead to blockage and overflow, which makes water leak back into the building. This results in higher risk of leakage. Appliances not constantly in use may be more prone to intermittent leakages, which are harder to detect and slowly build up over time. Additionally, large volumes of water are being introduced to new construction everywhere including plant rooms, boiler rooms, and HVAC systems, making water leakage throughout multiple floors increasingly likely. Thus, the need for highly-sensitive, informative, and affordable leak prevention systems to monitor residential and industrial roofing is greater than ever.

2.2 Cost Analysis

Installing current leak-detection systems throughout a user’s home is generally costly. Commonly available systems cost anywhere from about $50 to several hundred dollars. The cost of the metalized paper in the sensors we describe is less than one dollar per square meter, and the Arduino controlling the sensor is only $29.40 as seen in Figure 1. This means that this system is highly scalable and affordable, since the only part requiring replacement is the paper. Additionally, many current systems are programmed to automatically override home water systems, reducing the user’s control over home appliances. Since most homeowners and homebuilders do not install sensor systems in the roofing of their homes during construction, installing systems later is significantly inconvenient. This indicates that an easily maintainable, affordable, and user-friendly interface is needed to ensure that water leakage detection is more accessible to the general public. Such a system would help homeowners and business owners detect leaks closer to the initial onset. Early detection is essential for maintaining the integrity of a building and preventing the buildup of significant damage. The paper-based sensor system proposed in this paper could potentially account for these needs. Users are able to easily view the system’s data on their computers because the model discussed in this paper logs the precise location of leaks, making it easier for homeowners to find leaks and properly address them quickly.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost per unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metalized paper</td>
<td>&lt; $ 1.00</td>
</tr>
<tr>
<td>Arduino Uno unit</td>
<td>$ 29.40</td>
</tr>
<tr>
<td>Breadboard</td>
<td>$ 7.00</td>
</tr>
<tr>
<td>Total:</td>
<td>~$37.00</td>
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</tbody>
</table>

*Figure 1: Cost tables*

2.2 How the Sensor Functions

This elegant, cost-effective solution takes advantage of the capacitive properties of water. Capacitance is the ratio of storable charge to the applied electric potential that changes when water is dropped onto the sensor buttons. The equation for capacitance is \( Q = C \times V \), where \( Q, C \) and \( V \) are charge, capacitance, and voltage, respectively. This means that a drop in capacitance will increase the voltage while the charge remains the same. The equation, also shows that voltage is inversely proportional to capacitance \( (C = \frac{Q}{V}) \). In the conventional capacitor, the electromagnetic field is between the two plates. Meanwhile, in planar plate capacitors, the electromagnetic field is in the shape of a rainbow, as shown in Figure 2.
When water is dropped to fill the gaps between the prongs of the sensors, capacitance increases. The goal is to figure out how much water has leaked from the roof as well as the location of the leakage using the change in capacitance detected by the sensors. If this apparatus is hooked up to a light bulb which should have a constant resistance, a voltage increase would lead to a current increase since $I = V/R$.

3. Experimental Procedure

3.1 Materials and Software Used

The paper-based sensor system is composed of a grid of sensors, an Arduino circuit, and a computer (provided by the user) that is connected to the Arduino in order to process the sensor output. The sensor grid is made from metalized paper, regular paper that has aluminum ablated to one side of it. The metalized paper is the medium through which the capacitance is changing and being monitored.

In order to create the sensors used in this experiment, SolidWorks was utilized to design a multitude of capacitor layouts. SolidWorks allows the user to draw lines and shapes that can be extruded to create three-dimensional models of different parts and objects.

The extruded Solidworks images were saved as .dxf files and then converted to Inkscape files. Inkscape is an OpenSource vector graphics editor, and was used to convert the SolidWorks design into a format compatible with the laser cutter whose model name was VersaLaser 2.30. It uses a red laser to cut the 5 cm by 5 cm designs into the metalized paper. Acrylic was the backing onto which the sensors were ultimately mounted.

3.2 Initial Uni-Layer Design

To achieve the main goal of designing and fabricating an affordable, disposable leak detection system, the first step was to create different designs for the capacitive sensor. It needed to have two separate plates, which would be charged to create the capacitance, and the gaps between the plates had to be maximized in order to maximize the probability of water landing on the gap. The sensitivity of the system depends on the probability of water dropping on the gaps—water that does not bridge the gaps between plates does not affect capacitance and is not detected. Therefore, the best sensor should maximize the probability that water hitting it will drop on the gaps. Accordingly, a generic comb-like design was drawn, with square prongs that interlocked, to take full advantage of each sensor grid. The designs were created to maximize the probability that water...
Other prong designs created were triangular and rounded. Prongs with squared-off ends were initially chosen for their ease of design and production: the squared edges are easy to draw in SolidWorks (Figure 4).

Triangular prongs were also designed to see if they would augment the capillary action of regular paper (Figure 5). It was hypothesized that this could increase the surface area of gaps the water bridged. Later, curved prongs were tested, because the curved prongs keep the gap width uniform throughout the sensor so that a leak registers equally regardless of its landing location (Figure 6). For each design, prototypes were made with 1.5 mm gaps with 2.5 mm prongs, 3 mm gaps with 3 mm prongs, 0.5 mm gaps with 1.5 mm prongs, and 1 mm gaps with 1 mm prongs, with side lengths of 5 cm (Figure 4-6). The curved design with 1 mm gaps and 1 mm prongs proved to be the most sensitive after testing and thus it was chosen as the final design to be integrated with Arduino. Testing comprised of hooking up each sensor to an impedance analyzer and dropping water on it. Ideally, capacitance would increase sharply after each additional drop, making it easier for our system to detect leaks with accuracy.

The initial setup of the entire sensor system was envisioned to be one large metalized paper square connected to an
Arduino with LEDs that would light up at varying frequencies depending on how much water leaked. More water leakage would initiate a faster flashing, indicating to the user that the problem was more urgent.

For each design, prototypes were made with 1.5 mm gaps with 2.5 mm prongs, 3 mm gaps with 3 mm prongs, 0.5 mm gaps with 1.5 mm prongs, and 1 mm gaps with 1 mm prongs, with side lengths of 5 cm.

### 3.3 Fabrication of Initial Designs

The fabrication process was a trial-and-error cycle during which the procedure was perfected. First, metalized paper was taped using double-sided tape to regular paper and cut by the laser cutter. Both layers of paper were cut through, so the sensor required another piece of regular paper as a backing to mount it on.

![Figure 8: Triangular-pronged sensor that was destroyed during mounting](image)

This procedure was faulty, because the metalized sheet couldn’t be completely adhered to the backing paper, though it did help determine the correct intensity of the laser cutter. The next procedure tried involved cutting a single layer of metalized paper into the sensor design, then mounting it onto acrylic using double-sided tape. Ultimately, this procedure was the one used for further fabrication.

![Figure 9: The sensor being cut out on the laser cutter bed](image)

Other problems encountered during initial fabrication include the flimsiness of the triangular prong design and the difficulty of using the silver adhesive. The silver adhesive was used to attach the wires to the plates of the sensor, because it conducts current. However, gluing the wires was difficult since the wires easily came detached. In the end, the procedure developed for handling the silver adhesive was to weigh down the wires so they lay flat on the sensor, apply some adhesive, wait ten minutes until it dried partially, apply some more adhesive and finally tape over the wire. The iterations of trial and error ultimately concluded with the decision to use 1 mm prongs and 1 mm gaps.

### 3.4 Water Testing

Individual water droplets were dropped onto the paper from varying heights to observe the difference in area covered. When dropped from about a 1 cm height, the water drops did not lose their cohesion or break its surface tension; they remained near-hemispherical on the paper.

Water dropped from heights greater than or equal to 10.0 cm made contact with the paper in a circular shape. That made surface area covered by the drop easier to measure, thus allowing uniformity to be ensured. Increasing the height from which
water was dropped increased the area each drop covered. When the height surpassed 10.0 cm, the drop began to expand into irregular shapes on the paper. Thus, 10.0 cm was decided as the testing height.

The sensor testing process used a standardized method of water-dropping to discover which sensor best detected small capacitance changes. First, the sensor designs were laser-cut and positioned under a syringe. Double-sided tape was used to glue the metalized paper to an acrylic base during testing.

Two wires were attached to each 5 cm x 5 cm sensor, one on each adjacent plate, using Silver Adhesive 503, a metal-based conductive liquid that strips the thin coating off of the metalized paper in order to expose the aluminum directly to the metal wires as well as attach the wires to the sensors. The sensors were then connected to the impedance analyzer with these wires, and the analyzer was set to 100 kHz of frequency to monitor the change in capacitance.

A rod-and-arm setup held the 5.0 mL syringe to ensure that water would be dropped from a set height of 10.0 centimeters. The syringe has a needle-thin nozzle able to drop single consistent droplets of water. The data from each sensor’s test was graphed and analyzed to find the relationship between number of water droplets and resulting capacitance (Appendix A). This data was analyzed to find the most sensitive sensor: the one whose capacitance increased at the most rapid rate per drop added. Following these guidelines, the curved sensor with 1mm prong width and 1mm gap width was the most sensitive and chosen as the final sensor design.

### 3.5 Objective Change

After testing, the objective of determining volume of water leaked was changed to identifying the location of the leak. This change was made because it was realized that location would be more useful to the user of the system, especially seeing that the system is ultimately designed to reduce water costs. As a result, the general setup that was initially envisioned was drastically altered. The flashing LED was abandoned for a grid setup that would be displayed on a computer connected to the Arduino. That meant that the code had to be changed to now identify location. However, the graphs of change in capacitance to number of water drops were kept in order to decide on a sensor design to pick.

### 3.6 Final Setup

The final sensor grid was an eight-by-eight coordinate plane formed with two paper sensor layers laid over each other perpendicularly.

![Figure 10: One layer of engraved sensor](image)

The bottom sensor was the “x-coordinate” sensor. It was responsible for sensing the horizontal location of the water drops. It consisted of eight elongated plates that were all paired with one opposite plate to form a single sensor. An identical “y-coordinate” sensor was added on top, with its prongs positioned perpendicular to the underlying one. It was responsible for sensing the vertical location of the water drops. Both capacitors are oriented so that their wood paper sides are touching and
their metalized sides face outward. This positioning is to prevent the circuit from shorting, which would happen if the plates overlapped and the gaps were bridged. Together, the two sensors provide both an x-coordinate and y-coordinate location on the sensor grid, which Arduino uses to notify the user of the exact water leakage location.

The same process used for the initial fabrication of different sensor designs (Section 3.3 Initial Fabrication) was used for final fabrication. However, in the final procedure, the sensor designs were engraved rather than fully cut out because engraving removes only the top layer of metal, leaving the underlying paper intact. (On the engrave setting, the laser cutter heats targeted sections of the metalized paper until the aluminum evaporates.) It would have been significantly more labor-intensive to manufacture the sensor system if the laser completely cut through the paper—each sensor would have to be fitted together and mounted onto another surface, keeping gap widths constant to fractions of a millimeter. Engraving ensures that the distance between consecutive prongs is exactly 1 mm. Before, the gaps between the plates had to be manually removed, which was difficult after the sensor was glued to the acrylic. It was easy to move the plates and scratch the edges, which would change gap width unpredictably and significantly skew results.

Further, the initial sensors were individual squares, but in the final setup, they were elongated and one sensor would include eight separate plates on one side and one plate that serviced all eight on the other side. This simplified the setup and made mass-production easier. The end goal was to find the coordinates of a leak, so two of the rounded-prong sensors were engraved and overlapped to form a grid that could send signals for x and y coordinates. Once two full sensors were engraved, they had to be aligned and attached to each other in this grid formation setup. Since the prongs were elongated, the actual sensor area was rectangular, posing a problem when the two layers were overlapped. To account for this, the edges of the prongs on both layers were lined up exactly to maximize overlap, then a square was cut (as opposed to cutting along the white paper revealed by engraving, as shown in Figure 12.)

Figure 11: Schematic of the final circuit

Figure 12: The sensor being engraved on the laser cutter bed
The bi-layer design was chosen to make production more efficient and the product more durable. It is inefficient to create a grid of sixty-four separate sensors, and two sets of eight elongated prongs are more durable than one set of sixty-four. Also, there was a shortage of Arduino sensor ports which was accommodated for by hooking up two multiplexers to the circuit. Multiplexers are Arduino switches that compress information coming from multiple ports by converting them into binary. One multiplexer controlled the x-coordinates of the grid, and the other controlled the y-coordinates. The multiplexer is able to take inputs from eight buttons and transfer them to the Arduino through one port because each row is named in a 3-digit binary number. This bi-layer design was then connected to the Arduino breadboard with wires attached to each of the eight prongs on both layers.

3.7 Coding

Each button of the paper sensor had to be initialized in the Arduino code and named separately using the multiplexer. In the bilayer sensor, the top layer logs x-coordinates and the bottom layer logs y-coordinates. Each has 8 rows, X1, X2, and so on up to X8. The same goes for the Y-sensor. Because the Arduino does not have enough ports to individually connect each button directly, a multiplexer is used that converts each sensor row into a three-digit binary number so all the sensors can be logged with only three ports. The Arduino code detects when capacitance increases above a certain threshold for any particular button, and logs that data to its console where it can be viewed by the end user. The threshold was determined by testing the sensor’s average default capacitance, when there was no leak present. If the capacitance changes by more than a factor of 2, the user is alerted.

Figure 13: Bi-layer circuit connected to the Arduino

Figure 14: final circuit setup hooked up to the laptop

Figure 15: code creating one button, repeated 16 times in the code with different variable names/initializers
4. Data and Data Analysis

4.1 Calculations

Initially, diametric measurements were taken of water droplets ranging from sizes 1 drop to 5 drops, all released from 10 cm above the sensor. The mean diameter of each droplet size was then calculated to provide a number to from which to calculate the average area of each droplet size, using the equation:

\[ A = \pi \times r^2 \]

This provided confirmation that the drops of each size category were approximately uniform.

The graphs created from the sampling of the different prong shapes to find the sensor related the number of drops of water to the change in capacitance, measured by the impedance analyzer (Figure 7). These graphs were fitted with a regression line to compare which prong type and size had the steepest change in capacitance. This regression usually followed a linear path, except in the case of the model with 1.5 mm-thick prongs and 2.5 mm-wide gaps, although this could be due to another error when too great a volume of water falls onto the sensor (Appendix A).

4.2 Further Applications of Paper-Based Leak Detectors

The final design of the paper-based sensor system described in this paper was intended to detect leaks in household roofs. The grid system made up of the bi-layer of metalized paper could be adhered to the underside of the wood layer to which the tiles are nailed. Wires would connect the grid system to the Arduino, which also uses wires to connect to the user’s home desktop. The desktop would display a running account of the data collected by the Arduino and will notify the user of any disturbances using the x- and y-coordinates of the grid on which water is detected.

The concepts explored in this research project could be applied to many situations and locations other than residential buildings. These water sensors could potentially be useful in warehouses or food storage locations that are susceptible to unmonitored leaks. Further research could yield paper sensors able to detect non-water leaks, such as alcohol, acid, or oil. The paper sensors and corresponding code would be recalibrated to detect leaks of different substances. These sensors could send alerts about fires and other dangerous situations that result from leakage of perilous substances. One such potential application is in the medicinal packaging industry. Pre-filled syringes often bubble at the tips, causing unwanted leakages that could dangerously alter the proper dosages of medicine. During transportation and shipment, pre-filled syringes are especially susceptible to such leakage, and these easily portable, disposable, and lightweight sensors can in such situations. They can be used to detect leaks and alert the user to defective syringes.

5. Conclusion

Since the results of this experiment prove that a paper-based leak detection system is feasible, it should be noted that metalized paper is an especially effective material for fulfilling the main purpose. Paper-based sensors can be applied in nearly infinite settings. The placement of the paper-based sensors is not restricted by the shape of the space it is covering, due to paper’s innate flexibility. Many shapes can be
effectively wrapped, including pipes, unique architectural shapes, and support structures.

5.1 Lab Results

Initial testing found the most sensitive sensor using water-dropping tests with the impedance analyzer. Appendix A shows a depiction of the relationship between water droplets and capacitance for each of the initial sensor designs. The sensor with 1.5 mm thick rectangular prongs and .5 mm gaps followed a trend initially of sharply increasing capacitance reading with each additional drop of water until over five droplets were placed on the sensor. The six drop caused a sharp increase in the capacitance reading that would then quickly drop, eventually leveling out at values lower than the previous drop’s reading. The values of capacitance recorded for these drops were taken during this period of rapid decreasing, and therefore may not accurately represent the sensory results. The 3 mm thick round prongs with 3 mm gaps sensor had a similar design flaw. The graph of the results shows that capacitance decreased on some occasions when additional droplets hit the sensor and increased on others (Appendix A). This problem common problem could possibly be attributed to short circuiting of the sensors due to a great volume of water dropped on the buttons in comparison to their size.

The final two sensors followed an increasing linear trend in amount of water dropped vs. capacitance, as was initially predicted. The model with 1.5 mm thick rectangular prongs with 2.5 mm gaps had a smaller increase in capacitance between drops than the 1 mm thick rounded prongs with 1 mm gaps sensor. This means that the rounded 1 mm thick prong with 1 mm gap sensor was the most sensitive, and was selected as the final button design and recreated on a larger scale to be tested in the circuit.

The final testing of the circuit indicated that the program reads the correct location of water leakage and allows the user to view it on the computer screen, as was expected. This test was done by placing a finger on a certain sensor prong and watching the interface to see the Arduino output a sharp increase in capacitance at that x- and y-coordinate. If there had been more time, water would’ve been dropped on the sensor to hopefully view the same output.

5.2 Error Analysis

In all experimental models, it is important to identify possible reasons for error in data collection and analysis. In regards to this project, an individual decided which readings to take down from the continually fluctuating numbers of the impedance analyzer during the initial tests of the different sensor comb models, introducing the human error in data collection. Humans also manually manufactured the final assembly of the sensor setup, tampering with the precision of the grid dimensions used in the Arduino code. Potential for error also exists in the choice of adhesive material used in manufacturing the sensors.

Natural properties of water also create small inaccuracies in data: water drop sizes all vary and are generally irregular in shape, meaning calculations made assuming that the droplets were perfect circles have some margin of error. Additionally, the testing water used in the lab was tap water, which was chemically imperfect and included many minerals. In real world applications, the water may have different chemical compositions, which would affect the capacitance changes. Furthermore, water evaporation and humidity would alter the capacitance readings and data numbers.
5.3 Final Evaluation

The final design of the metalized paper sensor had 1 mm thick, rounded tip prongs and 1 mm thick gaps. It displayed the greatest linear increase in capacitance per drop of water added onto the sensor; thus it was the most sensitive design. Comparatively, the square design created problems with uniformity of electric field; the distance between the plates at the corners of the prongs was greater than that everywhere else, skewing the field as a result. At the same width of gap and prong (1 mm each), the triangular prong design was too flimsy and impractical. It also did not have a uniform gap width.

6. Discussion

The overall sensor design could be improved by making it functional without a computer. Using an Arduino shield, the sensor could be made to update without a laptop, while using an Arduino Yun could eliminate the use of wires, making mobile device applications possible. Additionally, the program could be altered to make the leakage notification system more user friendly. Instead of outputting visually overwhelming number coordinates, a grid on an LCD screen could be made with squares that correspond to the sensor grid squares. Once a leak is detected on a certain square of the sensor, its corresponding square would light up. This would make the alerts much more readily readable and visually intuitive for the user. It would also make sense to waterproof the system.

7. Acknowledgments

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8. References


Appendix A: Graphs of sensitivity for different sensor designs

- **Sensitivity of 3mm gap/3 mm prong sensor (rounded)**
  - Equation: $y = 3E-13x - 9E-12$
  - $R^2 = 0.9722$

- **Sensitivity of 1.5 mm gap/2.5 mm prong comb (rectangular)**
  - Equation: $y = 3E-12x + 2E-11$
  - $R^2 = 0.9953$

- **Sensitivity of 0.5 mm gap/1.5 mm prong comb (rectangular)**
  - Equation: $y = 3E-12x + 4E-11$
  - $R^2 = 0.9912$

- **Sensitivity of 1 mm gap/1 mm prong sensor (rounded)**
  - Equation: $y = 3E-11x + 5E-11$
  - $R^2 = 0.9919$