Beyond Touch Panels: Appliance Solutions Using Electric Field Sensors

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ABSTRACT

When an object comes in contact with an electric field (E-Field), certain properties of the object can be measured. For example, the difference between water and ice can be determined by observing the change in the dielectric constant. This information might be useful to improve performance of automatic ice makers or to increase the efficiency of the refrigeration defrost cycle. Changes in the dielectric constant of water might be useful to determine when a water filter needs changing, or if there are cleaning agents present. Using electric fields to detect the presence and makeup of the object has many unique applications for proximity detection and switch sensors as well. E-Field sensors can determine if refrigerator door seals are properly seated or detect when food has boiled over on an oven range top. E-Field sensors can measure speed and wobble of motors and drums, and water levels. Other potential applications include sensors for mechanical positioning, moisture detection, and safety systems.

ELECTRIC FIELDS

An electric field is a force vector (magnitude & direction) that's present in any region where a charged object experiences an electrostatic force by other charged objects. Almost any object which is somewhat conductive and/or has a different dielectric constant than its surroundings can be sensed by its effect on the E-Field. Almost anything conductive can be part of an electric field sensor by being one side of a capacitor. Using multiple electrodes, one can determine the size and shape of an object. An electric field is suitable for detecting objects, fixed or in motion within the field.

A basic block diagram of the sensor mechanism is shown in Figure 1. The effects of an external capacitive load reduces the AC signal and this results in a change of the detected signal. If the object that comes in contact with the E-Field is conductive (forms the other side of the capacitor plate), then current flows from the electrode through the external capacitor to a “virtual ground”, which is any point in space that has a different electric charge from the electrode. The amount of change is directly proportional to the “E-Field Capacitance”. The MC33794 E-Field sensor IC contains the necessary components to provide up to 11 E-Field sensor channels. An external microprocessor is used to select the desired channel and read the DC level using an analog-to-digital converter.

The system measures the change in the amplitude of the AC signal in response to the external capacitive load applied to the field. This is quite different from other types of traditional capacitive sensing methods. Typically, these systems employ a loosely-coupled oscillator to the external electrode and rely on the electrode capacitance to change the oscillator frequency. The change in frequency is proportional to the external capacitance applied.

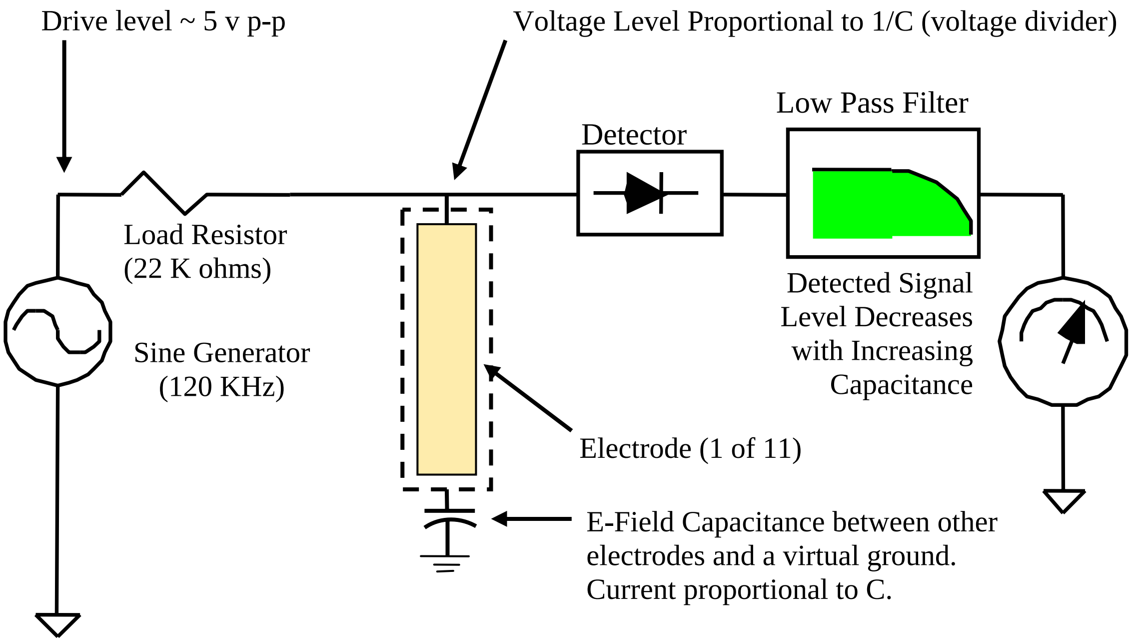


Figure 1. Basic E-Field sensor block diagram.

CAPACITOR BASICS

Before getting to the applications portion of this paper, it is a good idea to cover the basic physics of a capacitor. With this knowledge, the designer will have a better feel for how to use E-Fields as a sensor.

E-Field detection works on a simple concept: the object you are trying to detect forms a capacitor to some virtual ground. The diagram to the right (Figure 2) is a model of a parallel plate capacitor. The total capacitance, C is calculated as:

$$C = \frac{k\varepsilon_0}{d}$$

Equation (1)

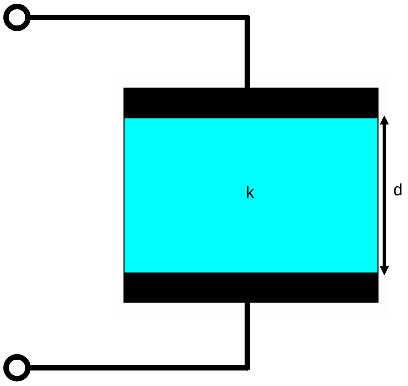


Figure 2. Capacitor Model

where,

A = area of the two plates
d = distance between the plates
k = dielectric constant of the material between the plates
ε_0 = permittivity of free space

The dielectric constant, k, becomes important when we want to detect the presence of water or ice. The variable, d, becomes important if we wish to measure distances between objects, such as refrigerator doors, or detecting wobble in a spinning object. The area, A, improves our sensitivity—the larger the electrode is, the bigger the capacitance, and changes in capacitance are easier to detect. Note that the only dependence on temperature is with the dielectric material chosen for the application.

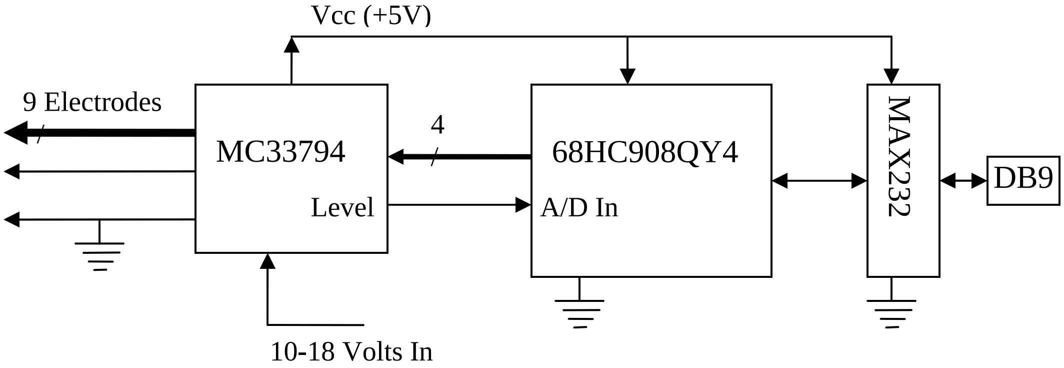


Figure 4. MC33794 E-Field Evaluation Board Block Diagram

Here's a good example of exploiting the changes of the dielectric constant as a function of temperature. Consider the application of detecting the difference between water and ice. Place an electrode in a container as shown below in Figure 3.

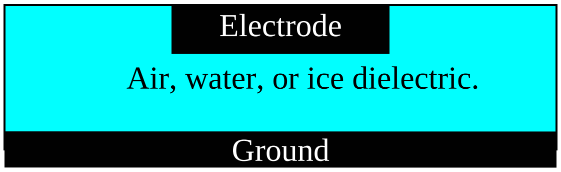


Figure 3. Example Electrode Configuration

One side is connected to a virtual ground. The distance between them is fixed. This forms a basic capacitor. If the container is filled with air, (k=1) then we will measure a value C_{AIR}. Now let's fill the container with pure water, which has a dielectric constant of around 80. The result is a different capacitance of C_{WATER} which is about 80 times larger according to Equation 1. The increased capacitance lowers the detected voltage. When we freeze the water, the dielectric again changes. As water becomes a crystal, the molecules have more space between them and the dielectric again changes, this time to around k= 5, and forms a capacitor C_{ICE}. (The dielectric constant for snow or frost is about 3.2.) In this case, we expect the voltage to rise back up, near the C_{AIR} value. Note that all these values are different and are all directly proportional to the presence or state of the water. Referring back to Figure 1, as you alter the "E-Field Capacitance", you change the voltage reading. Hence, here is a reliable way to determine if a container is filled with water, ice, frost, or air.

HARDWARE SETUP

Photo 1 shows the KIT33794DWBEVM evaluation module (EVM). Figure 4 is the block diagram of the EVM. This small

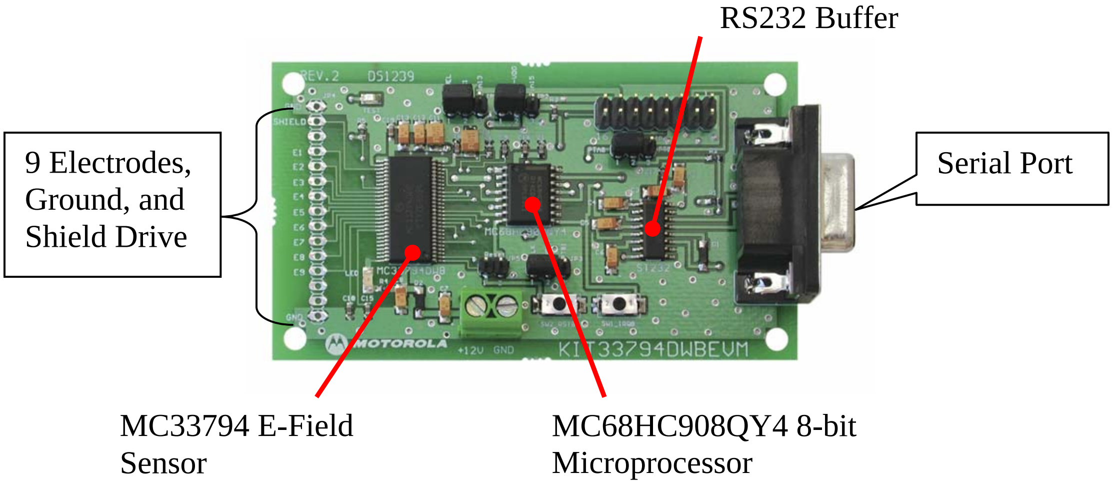
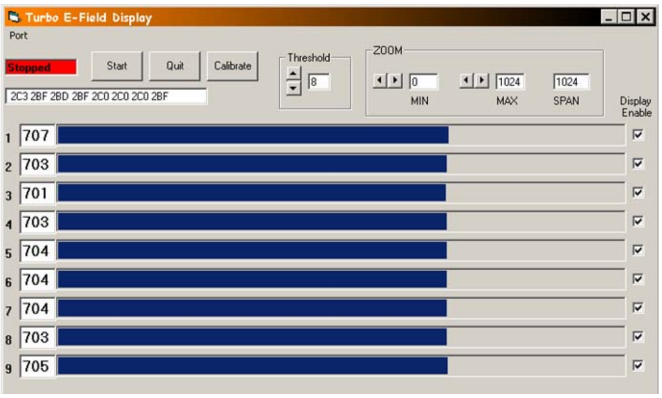


Photo 1. E-Field Evaluation Board.

board connects to a host PC via a standard RS232 serial port. Up to 9 electrodes are available, each one selected by a 4-bit value from the microcontroller (the other two electrodes are used internally). When an electrode is enabled, the rectified and filtered DC output is multiplexed and measured by the 8-bit microcontroller. The results are then sent to the PC via the serial port in standard ASCII format. (You can access the board using a standard terminal program.) This particular microcontroller has an integrated 8-bit A/D converter to measure the DC output level. For many applications, the 8-bits of A/D resolution are adequate. But when it's necessary to detect small changes in external E-Fields, 10-bits or more of A/D resolution is preferred. However, external DC amplification or "over-sampling" software techniques can be used to help make up for the 8-bit limitation. For this setup, software over-sampling provides10-bit results, thereby improving sensitivity. The MC33794 has an integrated 5 volt regulator which is used to provide power to both the microprocessor and the MAX232 interface.

HOST PC SOFTWARE

Figure 5 is a screen shot of the program that runs on a Windows PC and communicates with the EVM. There are 9 bar graphs that are updated approximately 40 times per second. Although the device can support up to 11 electrodes, only 9 are available with this particular evaluation board. Each reading goes from zero to 1023 (10-bits). The software was written in Microsoft Visual Basic.



2C3 2BF 2BD 2BF 2C0 2C0 2C0 2BF

Threshold: 8

MIN: 0
MAX: 1024
SPAN: 1024

1 707 ☑
2 703 ☑
3 701 ☑
4 703 ☑
5 704 ☑
6 704 ☑
7 704 ☑
8 703 ☑
9 705 ☑

Figure 5. Screen shot of PC hosted software that displays real-time changes of 9 electrodes with 10-bits of resolution.

ELECTRODE DESIGN AND THE SHIELD DRIVE

Thus far, we have shown how to form sensing electrodes based upon a capacitor model. What happens if we run a wire to the electrode? Wouldn't it also become a capacitor sensor? The answer is yes. This becomes more of an issue in applications where wiring harnesses must be used to connect up the electrodes. By the time the signal finally arrives to the electrode, much of the E-Field might be shorted to virtual grounds along the way (such as other wires). But there is a solution.

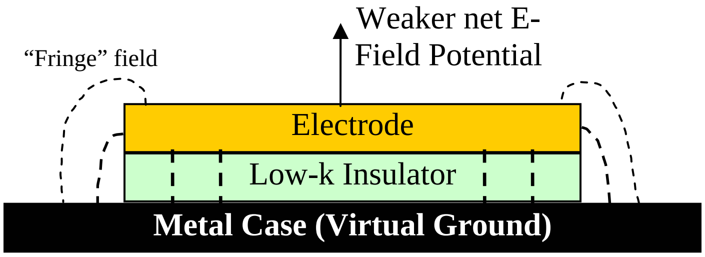


Figure 6. An electrode is placed next to a virtual ground. Much of E-Field can be shorted to ground through the insulator.

The shield drive output of the MC33794 is one of the most powerful and unique aspect of this E-Field sensor. It can effectively isolate the radiated E-Field from other virtual ground sources. Typically, an electrode is connected to the sensor chip using a thin gauge coaxial cable. The electrode signal is connected to the center wire, and the shield drive is connected to the coax shield. It works as follows: The shield drive signal and the electrode signal are essentially the same signal; the only difference is that the shield drive is buffered (i.e. it has more output drive). So at any instant, there is a very small net voltage difference between the two signals. If the two sources are near the same potential, the resulting E-Field is quite small. The larger the voltage difference, the stronger the E-Field. With both voltages nearly the same, little or no current will flow between any electrode capacitance that might be present.

The shield drive can be used to isolate the electrode from metal surfaces. Consider what happens if the container or the frame is made of metal, and that this metal is at a ground potential. Simply placing an electrode on one side will result in the E-Field becoming shorted to the virtual ground. Some low-k insulation should be placed between electrode and the case. If the insulating material has a low dielectric constant, and the distance between the electrode and metal is as large as practical (i.e. a thick insulator), then less of the generated E-Field will be shorted to ground. In many situations, this may be good enough.

However, by placing a shield electrode between the metal and the sense electrode as shown in Figure 7, you can effectively isolate the generated E-Field from the metal case. Most of the E-Field losses are due to fringing effects from the top of the electrode to the case. In a sense, you are "focusing" the E-Field away from the virtual ground and towards the object you want to detect.

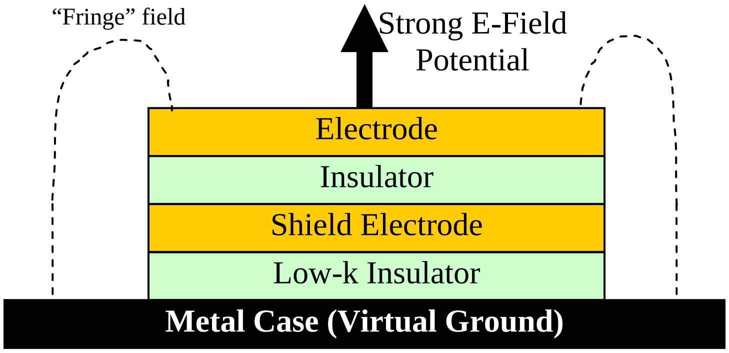


Figure 7. Use of the shield drive to reduce E-Field loses to the chassis ground.

In many instances, the E-Field sensor ground is connected to the chassis ground. If the shield drive is not adequately insulated from the chassis ground, then the shield ground output may be shorted. In most cases, the low-k insulator placed between the shield electrode and the case is sufficient to keep this from happening. One interesting effect you can try is to isolate the E-Field sensor ground and power supply from the appliance power and ground. In my experiments, I simply connected a battery to the EVM. The shield driver now generates a low level signal to the metal case. If you then touch any metal part, the shield drive changes, and all electrode readings will change as well. This might be a useful and novel method for safety systems or to enable the appliance to "know" when the user touches it.

AUTOMATIC ICEMAKER

A typical icemaker used in a refrigerator consists of a mechanism to fill the ice trays, waits until the water becomes ice, heats the tray to loosen the ice, then uses a mechanical arm to push the frozen ice into a container. The control system is mostly open loop. There is no means to detect when the tray is full. There may be a thermostat to detect when the water is frozen, but this is usually set to trigger when the temperature is many degrees below freezing. If the system could reliably detect when the water has actually frozen, and to know exactly how much heat is required to loosen the ice from the tray, some improvement in energy efficiency and improvement in ice production could be realized.

For this experiment, a small single electrode was fabricated using copper foil and double-side sticky tape as shown in Photo 2.

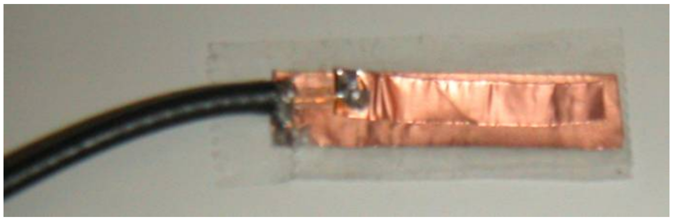


Photo 2. Electrode assembly made from two layers of copper foil and tape.

The electrode assembly uses the shield driver for the coax shield and to isolate the electrode from the grounded metal ice cube tray as shown in Photo 3.

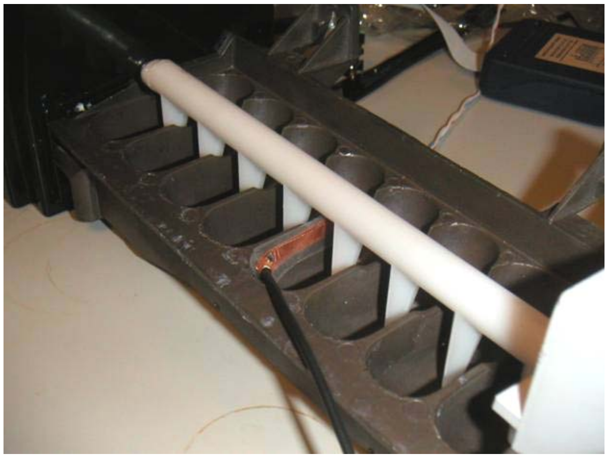


Photo 3. Electrode placed on side of one ice cube tray cavity.

The electrode was connected to the E-Field EVM board. As I started to fill the trays with cold water, the readings began to drop when the tray was full. I then placed the entire assembly in a freezer until the water became frozen as shown in Photo 4.

Photo 4. Water in cavity is frozen.

A new reading was made. As expected, the reading was higher than the liquid state, but less than the dry state.

As the ice began to melt, the readings continued to decrease approaching the liquid state. After about 20 minutes, the ice cubes were sufficiently melted to remove from the tray.

The table below summarizes the results.

Condition	**Value**
Dry	707
Liquid	516
Frozen	682
Thaw – 10 minutes.	638
Thaw – 20 minutes	605
Thaw after 24 hours	517

Note the substantial change in the electrode values when the water changes state. Also note that the value of liquid water before freezing and after fully thawed are within one count. This illustrates how reliable and repeatable the data is, and strongly suggests that using E-Fields for this application has merit.

DEFROST CYCLE

Another refrigerator function that might benefit from an E-Field sensor is the ability to detect the presence of frost buildup on the cooling coils. This would indicate that a defrost cycle needs to begin. A typical defrost cycle turns on a heating element inside the evaporative (cooling) coils to melt the accumulated frost or ice. The heater remains on until a temperature sensor tells the cycle to halt.

Most systems today run open loop in that a defrost cycle is periodically performed whether or not one is required. To improve efficiency, some refrigerators rely on some kind of specialized algorithm that runs in a microcontroller. It may track cumulative compressor usage and manage the defrost cycles based upon a set of rules.

One or more E-Field sensors placed in contact along the evaporative coils could provide measurement data that might result in higher power efficiency and improved performance. We've already shown that E-Fields can reliably determine the presence of water moisture in various states. With this information, the system could begin a defrost cycle when it is truly required, and terminate it once the ice has melted. In theory, this ought to be far more efficient than current methods. The large and potential savings in electricity usage, along with low cost of implementation certainly makes this an attractive application of new technology and is certainly worth further investigation.

DOOR-OPEN/CLOSED DETECTION

Equation (1) discussed earlier shows the relationship between the distance of two plates of a capacitor and the capacitance value, C. If one side of the capacitor is a refrigerator door, and the other side is the refrigerator itself, then a reliable method to determine if a door is closed or open can be realized simply by measuring the total capacitance. This value is inversely proportional to the distance, d, between the door and the frame. The larger the value, the closer they are. Now assume that the gasket normally used in refrigerator doors is configured as one side of a capacitor, and the frame has several electrodes connected around the perimeter. Not only would there be an indication of whether or not the door is closed, but also, a measure of closure "goodness". In other words, the gasket around the entire door could be analyzed to insure a good seal.

This concept could be extended to oven doors (both conventional and microwave). Another similar application might be to detect if oven racks are properly inserted.

WOBBLE DETECTION

We've seen that changes in capacitance values are due to several factors. As with the previous example of a door closure detector, the small distance changes between electrodes could be used as a wobble detector in a spinning mechanism such as a dryer or washer tub.

Consider the concept drawing in Figure 8. One or more stationary electrodes are mounted around the perimeter of the rotating drum. If the drum is rotating smoothly, the distance, d, between the drum and the electrode will remain relatively constant. Here it is assumed that the drum is made of a material that is conductive. In the case where it may be non-conductive, a small strip of metal foil could be affixed to the perimeter at the same level as the stationary electrode.

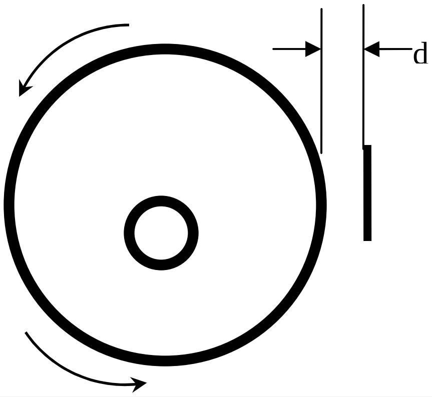


Fig 8. A rotating drum forms one side of a capacitor. The other side is a stationary electrode. Wobble is indicated by a variation in d, which is inversely proportional to capacitance.

Because of the inverse relationship between d and capacitance, the amount of wobble displacement can be measured to within a few thousandths of an inch. The signal reported is a linear DC or low frequency AC level and is a direct dynamic indication of the wobble characteristics. A small software program could analyze the data and determine the harmonic content of the wobble and corrective action would then be called for.

STOVE TOP SPILL-OVER DETECTION

This particular E-Field detection technology is being successfully deployed in touch panels. As a human finger comes within range of a touch pad electrode, the E-Field is disturbed and can be measured to determine if a pad has been touched by a human operator. The human body is mostly water with a large dielectric constant, so it has a large effect on the E-Field.

In a similar fashion, water spilled across electrodes will change the E-Field measurement. As a quick check, a small amount of distilled water was placed on an evaluation touch pad panel as shown in Photo 5.

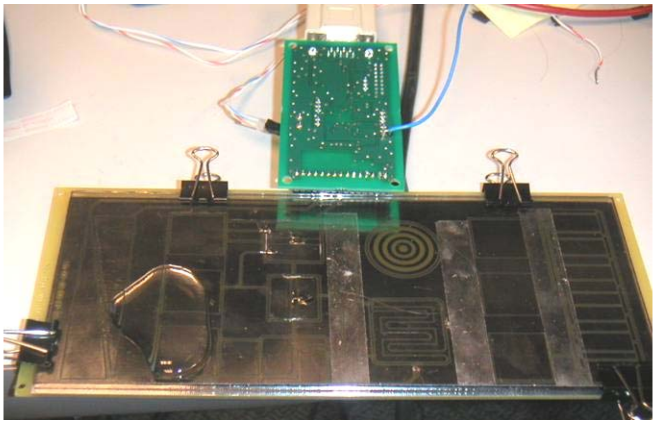
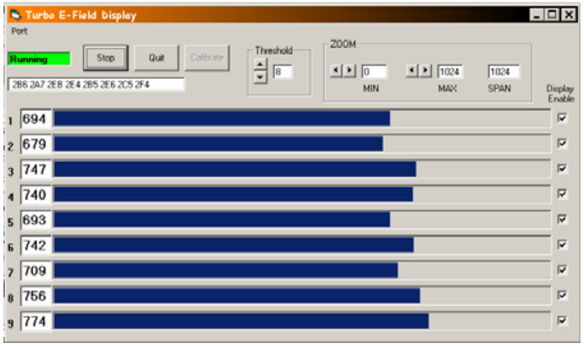


Photo 5. Touch panel evaluation board attached to EVM. A small amount of distilled water is present on the left side. The board is covered by a 1/8 inch thick sheet of glass.

The results are shown in Figure 9a and 9b.



2B6 2A7 2E8 2E4 2B5 2E6 2C5 2F4

Threshold: 8

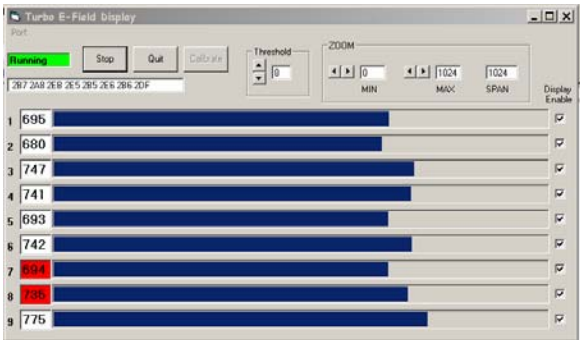
MIN: 0

MAX: 1024

SPAN: 1024

1 694 ☑
2 679 ☑
3 747 ☑
4 740 ☑
5 693 ☑
6 742 ☑
7 709 ☑
8 756 ☑
9 774 ☑

Fig 9a. Electrode readings from dry evaluation touch panel. Note readings of electrodes 7 & 8 are 709 and 756, respectively.



287 2A8 2E8 2E5 2B5 2E6 2B6 2DF

Threshold: 0

MIN: 0

MAX: 1024

SPAN: 1024

1 695
2 680
3 747
4 741
5 693
6 742
7 694
8 735
9 775

Fig 9b. Electrode readings with spilled distilled water. Note the significant drop in the readings of electrodes 7 & 8 (694 and 735).

In a real-world situation, the liquid that is spilled would likely have a substantial sodium chloride content (salt) which would result in even more of a change. This is because the dielectric constant of water with salt is higher than pure water. And from Equation 1, capacitance is proportional to the dielectric constant.

A practical schematic of using electrodes on a range top is shown in Figure 10.

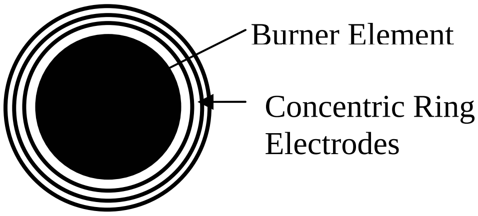


Fig 10. Range top burner surrounded by circular electrodes.

In this case, assume that the entire surface of the range is covered by a low-dielectric glass material. The electrodes consist of thin metallic foils such as etched circuit board or deposits of a thin-film conductive metal on the back side of the glass.

CONCLUSION

Touch sensor technology is quickly finding many uses in the appliance industry. Most of these technologies use electric fields modulated in some fashion to detect the presence of a finger. But E-Field technology can go beyond simple touch panels. I have shown some simple examples and simple experiments that illustrate the potential of E-Fields for detection of ice, frost, water, and distance for applications such as ice makers, refrigerator defrost cycle energy management, range-top cooking spill-over detection, wobble detection, and door open/closed detection. E-Fields have many performance and cost advantages compared to traditional sensors using temperature or light. It's time to begin applying this usable and economic technology for more than just touch.

AUTHOR'S BIOGRAPHY

Brad Stewart joined Freescale Semiconductor Analog Products Division in 2004 as a Principal Applications Engineer. Mr. Stewart has 30 years of analog and digital systems design and applications experience. He has developed numerous consumer electronics products, electronic toys, PC peripherals, military electronics, and embedded systems. He has several patents and design awards. Mr. Stewart has a BSEE degree from the University of California at Santa Barbara. In his spare time, he enjoys skiing, flying, and riding his Harley Davidson Super-Glide.