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Abstract

Since restaurants often make much of their profits on drinks, it is critical for servers to offer refills in a timely fashion. We propose wireless liquid level sensing glassware to aid in this task. Specially instrumented glassware detects fluid levels via a high-resolution capacitance measurement. A coil embedded in the table inductively couples power to the glasses, and provides a path for data exchange. Our prototype glass uses a standard microprocessor and a small number of passive components, making it extremely inexpensive.

Keywords

iGlassware, liquid level sensing, capacitance sensor, RFID

INTRODUCTION

It is a common problem – you are in a bar or restaurant with your drink almost gone and you are desperately hoping that one of the staff will notice and offer you a refill. Sometimes they do, and sometimes they don't. If they don't, you leave a little less happy with your experience and are less likely to return, the waiter or waitress gets a lower tip, and the restaurant has lost the chance to sell you a drink. Meanwhile, thirsty customers may stand waiting at the door for lack of a table. Everyone loses. It is such a little thing; yet doing it right or wrong can easily make the difference between economic success or failure.

It is thus critical for servers to offer refills in a timely fashion. We propose wireless level sensing glassware to aid in this task. Ideally, instrumented glassware, or *iGlassware*, should have the following characteristics:

- *Extremely inexpensive*
- *Washable by standard restaurant dishwashing equipment*
- *No maintenance issues (e.g. battery replacement)*
- *Familiar glassware appearance (no wires, not bulky, etc.)*
- *Support multiple glasses per table*
- *Globally unique IDs for each glass*
- *Able to recognize a glass of remaining ice as empty of fluid*
- *Reasonable measurement resolution.*

By using a combination of RFID and capacitance sensing technologies, we are able to achieve these properties.

Level Sensing

Liquid level sensing is a well-established field with many technologies in common use [1]. However, the grand majority of these would be inappropriate for use in restaurant glassware. Unlike typical industrial applications, aesthetics are an issue. It is hard to imagine happy customers drinking from glasses with obvious mechanical float mechanisms.

Another constraint on the system is the need for compatibility with general restaurant operations. A glass that cannot be washed in a commercial dishwasher is of little use. Thus, the mechanism must be able to stand up to complete submergence in hot, soapy water and come out the other end clean and undamaged. Realistically, this will require sealing all electronics in either the base or the side of the glass.

Rather than directly measuring fluid level, one might consider measuring a related quantity such as weight. The problem with this approach is that glasses often contain more than just fluid. Ice, straws, spoons, etc. can all make a glass that has been completely drained of fluid be heavier than an empty glass. Fluid level, despite these volumetric additions, is the quantity of interest to both restaurants and their customers. There is little point in attempting to refill a glass that is already filled to the brim, even if ¾ of the volume is ice.

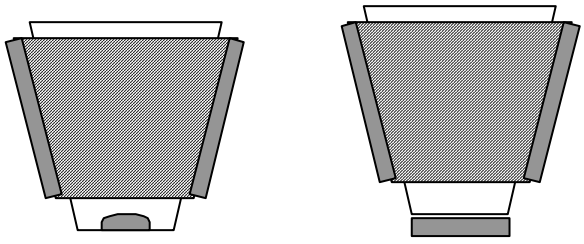

Figure 1. Two electrode configurations for liquid level sensing. "Contact" version requires electrical contact with the fluid. "Contactless" does not.

Power is another key concern. Although battery operated cups have been designed [2], battery replacement, charging, and the lack of robustness to temperature extremes make them impractical for day-to-day restaurant

use. In our system, power is provided via inductive coupling. Thus microwatt sensing is absolutely essential.

Our solution is to use capacitive sensing. Appropriate electrodes can easily be embedded in glassware at low cost, without significantly changing the shape or appearance of the glass. In addition, extremely low-power techniques can be used to perform the capacitance measurement.

We have examined a number of electrode designs for instrumented glassware. Two basic types are shown in figure 1. In the "contact" version, a small electrode inside the glass makes electrical contact with the fluid. The other electrode completely wraps around the sidewall, and is insulated from the fluid by the thickness of the glass. For a cylindrical glass, this gives a roughly linear change in capacitance with respect to fluid height.

There are a number potential problems with a directly contacting design. First, the electrode must be able to withstand immersion in various, corrosive beverages. Second, since the contact electrode must be isolated from the rest of the cup, there is necessarily an electrode/glass interface that may leak, or be a cleaning nuisance.

An alternative "contactless" design is also shown in figure 1. This electrode style does not allow any fluid to come in contact with either electrode. The bottom electrode capacitively couples to the fluid in a fashion that is largely independent of fluid level above a minimum height. Unfortunately, this bottom coupling capacitance is effectively in series with the sidewall capacitance. If the bottom capacitance is large compared to the sidewall capacitance, the series combination will be approximately the sidewall capacitance, giving a roughly linear response for a cylindrical glass. However, the bottom area of a glass is typically smaller than the sidewall area, and it may be difficult to achieve a relatively high capacitance. In this case, the series bottom coupling capacitance places a limit on the possible total capacitance, which will be asymptotically approached with increasing fluid level. For higher fluid levels, this results in a severe loss in accuracy. A good production design should try to maximize the bottom coupling capacitance by embedding this electrode as close to the surface as possible.

Many other electrode designs are possible, but one must keep in mind several practical constraints. In use, people will frequently be touching the glasses while the capacitance measurement is in progress. Thus, the design should shield the measurement appropriately. For example, one might consider using a stripe of conductor on the side of the glass rather than covering the entire sidewall. If this is not properly shielded, grasping the glass will dramatically impact the effective area of this electrode, ruining the measurement. Another advantage of the fully wrapped designs is that for a cylindrical glass, the measurement is somewhat independent of tilt. A single stripe would lose this feature.

Up to this point, we have tacitly assumed that the fluid in the glass is a fairly ideal conductor. Since the capacitance measurement is accomplished via a charge pump circuit, the resistance will be insignificant so long as the resulting time constants are short compared to the charging time. This is on the order of 10^{-4} seconds. Given capacitances on the order of 10^{-11} farads, we require resistances less than 10^{7} ohms. This does not pose a significant restriction for common beverages, with the possible exception of distilled water. This also means that the resistivity of the electrodes can be fairly high, allowing us to use clear conductors (e.g. indium-tin oxide) to improve the aesthetics of the glass.

Ice and carbonation present some interesting issues. An "empty" glass with remaining ice should read as empty. In fact, in our experiments, we have found ice to provide very little coupling. The bumpy nature of ice tends to minimize the contact area with the glass. Typically, a glass filled with crushed ice but no fluid reads akin to a very small amount of fluid.

Carbonation is more complex. The main issue is the bubbles that form on the sides of the glass. These do lessen the coupling, but typically less than 5%. They also can cause a rather odd oscillatory effect as the bubbles form, merge, escape and then reform.

CAPACITANCE MEASUREMENT

Common circuits for high-resolution capacitance measurements are too cumbersome for use in glassware. In particular, we would like a technique that is extremely low power, uses few components, and is easily compatible with low-end microcontrollers. For this, we turn to the most basic of switched-capacitor circuits – the switched-capacitor version of an RC circuit [3].

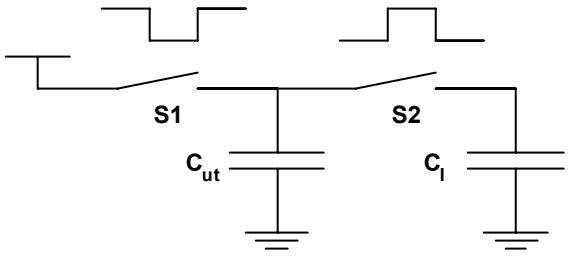

Figure 2. A Switched-capacitor "RC" circuit.

The well-known [4] technique of using an RC circuit to measure an unknown C is impractical in this case. Our microcontroller is running at an approximately 30kHz instruction rate. Assuming we want at least 8-bit resolution, we will need a time constant on the order of 10 ms. Given a capacitance on the order of 10^{-10} farads, yields a resistance of 10^{8} ohms. While such resistors exist, they are expensive and require special handling to maintain their high value.

A better way of implementing an effective high resistance is via a switched-capacitor circuit as shown in figure

2. In this case, there are now two capacitors, either of which can be varied to alter the effective time constant. Since the operation of this circuit requires $C_{ut} << C_I$, C_{ut} should be chosen as the small variable cup capacitance to be measured.

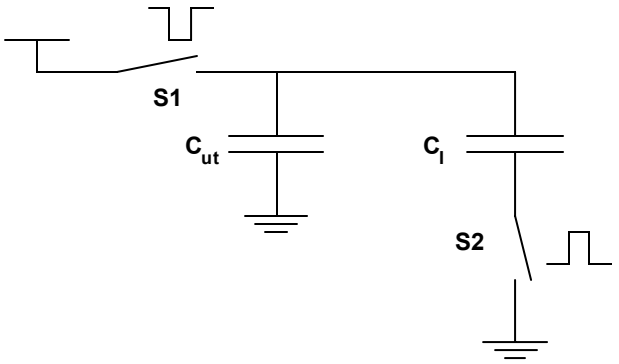

Figure 3. A Switched-capacitor "RC" circuit with S2 moved to the bottom plate.

While this switched-capacitor circuit could be implemented with discrete switches, a simpler solution is to use the inherent switching available on digital CMOS I/O pins. Such I/O pins are really three-state devices: switched to VDD, switched to Ground, or floating (i.e. an input). On first inspection, it appears that the middle switch between the two capacitors is the only one that cannot be implemented via an I/O pin. However, a minor rearrangement of the circuit, shown in figure 3 moves this switch to the bottom plate of C_I. From this position, it still functions to prevent current flow, and has the added side benefit of removing the signal dependence of the charge injection when that switch is turned off.

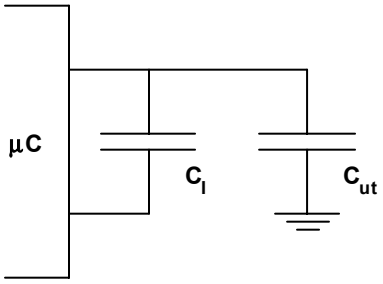

Figure 4. The microcontroller-based capacitance measurement circuit.

The complete capacitance measurement circuit is shown in figure 4. It uses only two digital I/O pins and a single integrating capacitor. Operation is shown in figure 5. To begin a measurement cycle, both pins are brought low, discharging the capacitors. The second pin is set to be an input, and the first is brought high. This rapidly charges C_{ut} to VDD without affecting C_I. Next both pins are set to input, and then the second is set to output ground. This causes the two capacitors to share their charge. By repeating the charge/share cycle, C_{ut} exponentially charges C_I to VDD at a rate proportional to C_{ut}/C_I.

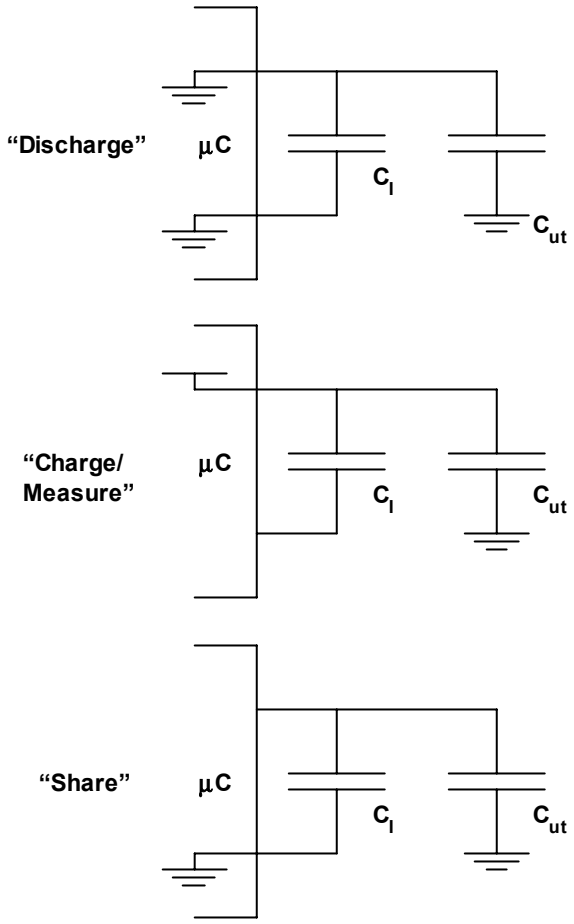

Figure 5. I/O sequence for capacitance measurement. "Charge/Measure" and "Share" are repeated until the input reads low during "Chrage/Measure". Note that the I/O pins should be set to input between steps.

The steps discussed allow C_I to accumulate charge, but we still need a mechanism for determining when it reaches a predefined level. Fortunately, when the I/O pins are set to input, they can be used to determine if the signal exceeds a digital input threshold. At first glance, it might appear that an obvious time to make this measurement is during the "share" part of the cycle. While this works, it is not the best choice. Since the capacitance being measured will typically be exposed to the world, there can be significant noise. A better choice is to measure during the "charge" part of the cycle. From the perspective of the second I/O pin, as C_I charges up, the voltage level on this pin will drop. At this point, the capacitance being measured is tied directly across the power supply rails, thus shielding the measurement from extraneous noise sources.

The end result is that we measure how many charge/share cycles it takes for C_I to charge up to VDD minus the digital input threshold. The number of cycles

will be directly proportional to C_I/C_{ut}. This technique allows high-resolution measurement of picoFarad-level capacitances. Absolute accuracy depends upon a number of factors, especially temperature and supply variations of the digital logic threshold and integration capacitor stability.

RFID

Our instrumented glass needs both a source of power, and a way of transmitting data. Radio Frequency Identification, or RFID, techniques address both of these issues simultaneously.

The basics of RFID techniques are described in [5]. Power is inductively coupled from a large reader coil to a smaller transponder coil embedded in the tag. Typically, the transponder coil is placed in parallel with an appropriate value capacitor to resonate at the base frequency of the system. A full wave bridge rectifier then converts this to a DC voltage that is some how regulated and used to drive the transponder circuitry. The regulation is important because the voltage available varies widely with distance between the coils. Data is transmitted from the transponder to the reader coil by briefly loading the transponder coil. This change in loading can be seen at the reader coil. A number of different modulation schemes for this loading are in common use, including ASK, PSK and FSK.

When implementing RFID systems, one typically uses a custom IC designed explicitly for this purpose. However, we were unable to locate a combined RFID/general purpose microcontroller that would suit our needs. Given the untested nature of a market for instrumented glassware, we did not feel a custom design was appropriate at this time.

The solution to our dilemma lay buried in an obscure application note from Microchip [6]. Ignatov describes a technique for using standard microprocessors to implement RFID systems. Given the high volume nature of low-end microcontrollers, they can be considerably less expensive than specialized RFID parts. By exploiting the general-purpose nature of the microcontroller in Ignatov's system, we extend his technique beyond simple identification tasks to include high resolution sensing.

Ignatov's system is remarkably clever. Rather than using a discrete bridge rectifier, he exploits the internal protection diodes typically used on CMOS inputs. These diodes generally connect the input to the supply rails in such fashion as to conduct current to the rails when the input exceeds the rails in either direction. This is half of a full wave bridge rectifier. By connecting the transponder tank circuit across any two inputs, we create a full wave bridge rectifier to the chip's supply rails. Of course, we must be careful to limit the current (I_{MAX}=20mA), or the chip can go in to latch-up. However, given the degree of coupling easily achievable, this turns out to be an easily met requirement. To regulate and smooth out the supply, a 5.1V zener diode and a capacitor are placed across the supply pins. The result is a powered processor.

Because the power supply is rather erratic, it is difficult to guarantee that the processor will come out of reset properly. Ignatov suggests using the watchdog timer to force a reset. Worst case, this might take a couple of seconds, but this is perfectly adequate for our application.

While it would be possible to use a crystal or RC-based clock for the processor, Ignatov provides another clever insight. He uses the clock input as one of the tank circuit inputs. Given the structure of the clock circuit on the PIC12C508, this forces the clock to run in synchrony with the coil frequency, providing accurate clocking with no extra components in the transponder.

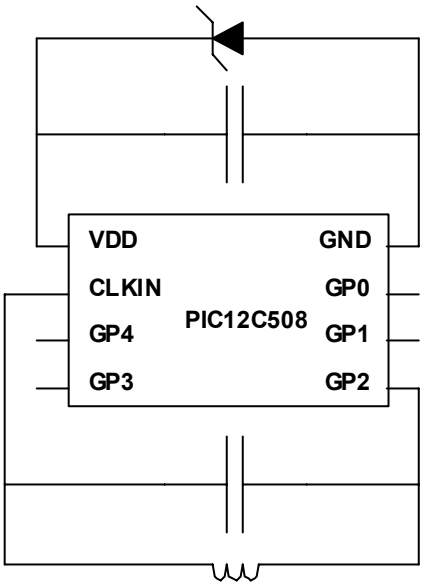

Figure 6. Ignatov's PIC-based RFID tag [6].

Finally, to send data back, Ignatov needed a way of changing the loading on the transponder coil. He accomplished this by setting the other tank circuit input momentarily to an output. The result is an RFID transponder that uses a standard PIC12C508, two capacitors, a coil (i.e. a trace on the printed circuit board), and a zener diode. The complete transponder circuit is shown in figure 6.

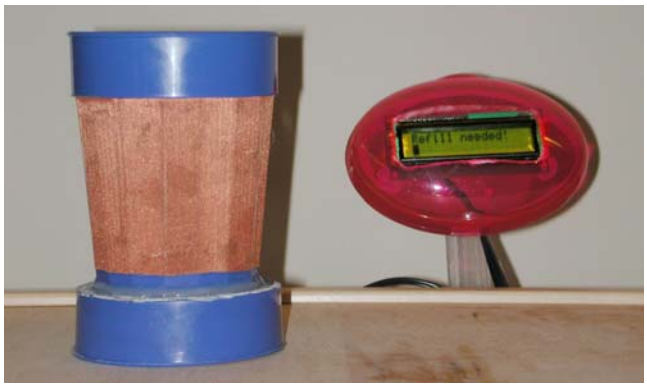

Figure 7. The prototype iGlassware system.

THE PROTOTYPE

We constructed the prototype wireless liquid level sensing system shown in figure 7. This early version ran at 100kHz, but our latest generation system runs slightly faster at 125kHz, a standard RFID frequency. Our transponder circuit is shown in figures 8 and 9. Compared to figure 6, we have added only a single capacitor to perform the sensing function. The transponder performs the capacitance measurement on the "contactless" glass, and then transmits back a data packet. The data packet contains the cup ID number, the measurement data, and a checksum for validating proper transmission.

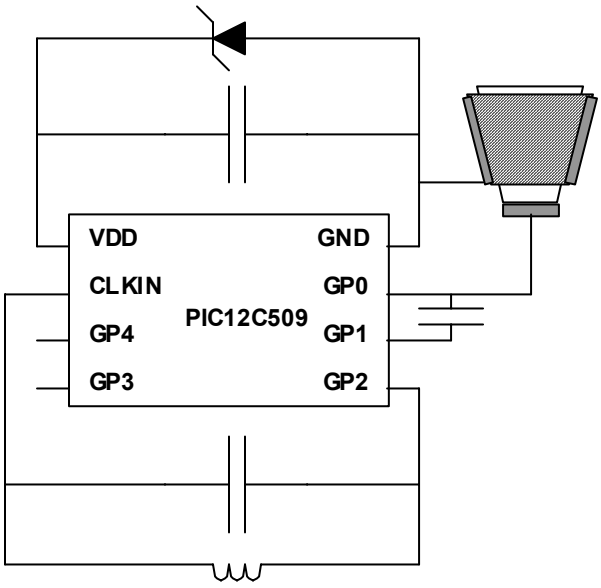

Figure 8. The iGlassware glass schematic.

A reader coil is embedded in the table and has approximately 40 turns of 26-gauge magnet wire. The circuit, shown in figure 10, is similar to those described in [5]. With careful tuning, the L-C tank driven at 5V resonates at over 100Vp-p.

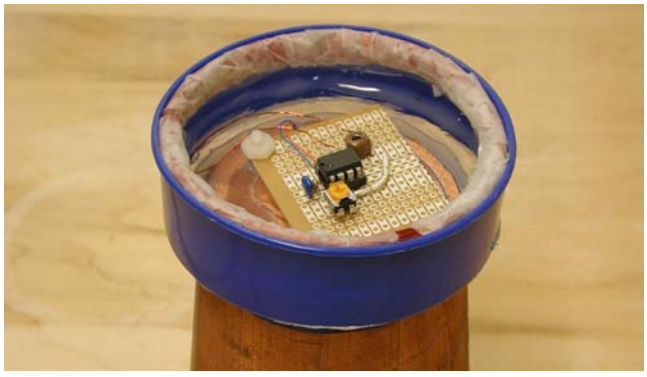

Figure 9. Inside iGlassware.

For our prototype, it was more convenient to perform the calibration and scaling in the reader microprocessor. We observed the measurements at different fluid levels, and generated a crude function to convert to fluid level. This is then displayed on a small LCD display mounted on the table shown in figure 11.

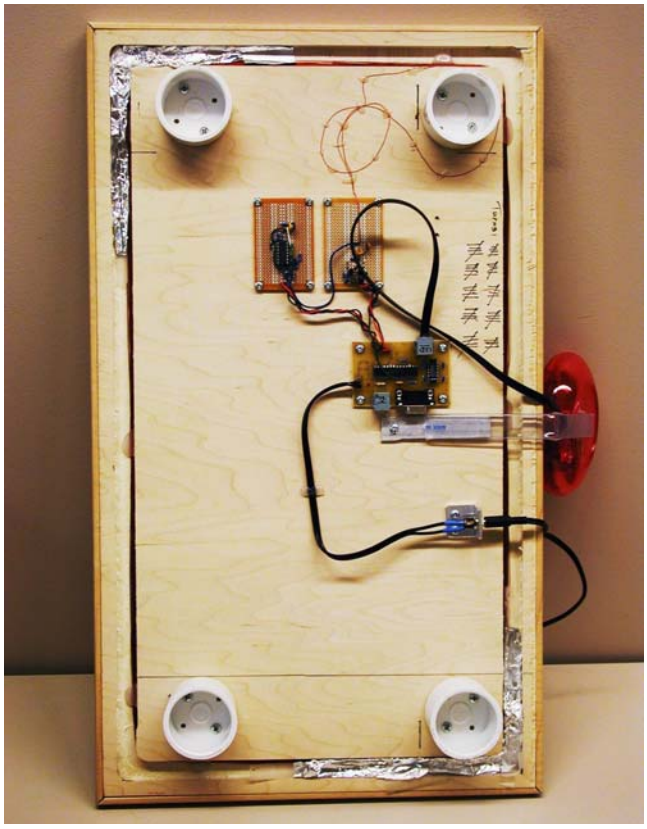

Figure 10. Underneath the iGlassware table.

Overall, the prototype works quite well. As expected, the measurement is essentially unchanged by grasping the glass. While our display only shows 16 levels, the actual measurement resolution runs as high as 0.1%. Unfortunately, the accuracy is considerably lower for a number of reasons. Most significantly, the capacitance measurement is somewhat dependent on the transponder voltage (digital input thresholds do not scale linearly with supply voltage). Since this varies slightly over the extent of the table, somewhat different levels are read in different locations. However, the system is probably sufficiently accurate for its original purpose.

Figure 11. The display indicating a full glass.

CALIBRATION TECHNIQUES

Although it is probably unnecessary for our application, the accuracy of the level measurement can be improved by a number of simple techniques that we are investigating.

Since the measurement is a function of the input threshold, knowing this threshold would give us a way of calibrating out the error. A simple RC circuit can be used for this purpose. By noting the changing time to reach a digital input threshold, we get a calibration coefficient.

An even better technique is to perform a ratiometric measurement. A third electrode is added to the sidewall of the cup, near the base. By comparing the capacitance of this reference electrode to the total sidewall capacitance, a far more accurate measurement can be made.

CONCLUSIONS

By combining RFID and capacitive sensing technologies, we have developed a practical wireless liquid level sensing technique for use in restaurant glassware. The circuit uses only a handful of commonly available parts making it extremely inexpensive.

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