RoyalFlush: Non-Invasive Water Level Monitor to Prevent Toilet Overflows

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ABSTRACT

Neglected toilet overflow can cost thousands of dollars through mold growth and damage to furniture, upholstery, electronics, and household appliances. We propose RoyalFlush: a novel non-invasive overflow system meant to detect such events in their early stages and prevent them from escalating. RoyalFlush uses a floating capacitive sensing technique that relies on the sizable difference between the dielectric constants of water and air for tracking changes in the water level. Capacitive sensing in this way does not require any hardware inside the toilet bowl. RoyalFlush consumes only 150 μW of continuous power, allowing it to operate for a couple of years on a 9 volt 625 mA h alkaline battery. We evaluate RoyalFlush on 10 different toilets in a controlled 60-minute experiment to validate its functionality. Additionally, we deployed RoyalFlush into 5 homes for 24 hours to test in real-world scenarios. During the real-world deployment, RoyalFlush identified overflow events with a precision of 98.16% and a recall of 100%.

CCS Concepts

•**Hardware** → **Sensor applications and deployments;** *Digital signal processing;* •**Human-centered computing** → *Ubiquitous and mobile computing;*

Author Keywords

Real World Application,Toilet Overflow detection, Capacitive sensing

INTRODUCTION

Water overflow damage is a problem that most property owners dread. Water overflow can cause thousands of dollars worth of damage by destroying wooden furniture, upholstery, electronics, household appliances, and plumbing equipment. Water damage also increases the risk of mold growth, which is an expensive problem to remedy[1]. Water overflows in toilets are one of the most common causes for water damage within

[1]http://www.homeadvisor.com/cost/environmental-safety/remove-mold-and-toxic-materials/

IoT 2018, Oct 15–18, 2018, Santa Barbara, CA, USA

ISBN 123-4567-24-567/08/06. . . $15.00
DOI: http://dx.doi.org/10.475/123_4

Figure 1. The RoyalFlush prototype, which has two adhesive copper plates that are attached onto the back of the toilet bowl.

the home and can occur for a number of different reasons. Children may flush toys down the toilet, septic tanks may stop draining properly, a sewer backup can occur due to a heavy rain, and clogs may even occur from normal usage. A review by the Insurance Institute for Business and Home Safety (IBHS) estimates that toilet failure incidents cost $5,584 on average, even after the deductible has been paid; one-third of those incidents were the result of an overflowing or clogged toilet[2].

With the advancement in Wireless Sensor Network, a new trend in the era of ubiquity is being realized. Using these sensors, we are able to collect different types of data regarding humans everyday objects and automatically take the necessary actions to reach an intelligent home automation system. To this end we try to design a system that could detect and automatically prevent water overflows in toilets.

Liquid level sensing in general could be done with numerous viable methods. Optical fiber-based techniques [7, 15], although extremely accurate, are not well suited for toilets because they require either transparent containers or direct liquid contact; standard toilets are made with opaque porcelain, and direct contact with toilet water raises sanitation concerns. Mechanical vibration-based approaches [13] are best suited to

[2]https://disastersafety.org/ibhs/water-damage-studies/

situations when vibration is predictable and always a direct result of liquid motion, such as in industrial settings. In the case of a toilet, users can easily introduce unpredictable vibrations that may trigger false events. Ultrasonic sensors [17] can be excellent at water level detection, but require ideal acoustic environments and are not well suited to the large variation in toilet designs. Finally, RFID has been shown to be applicable to water-level sensing by examining the RSSI and phase shift of tag data [1]; however, an RFID reader is expensive and bulky.

To overcome these challenges, we propose RoyalFlush, a novel water-level measurement system for detecting water overflow events in a toilet without needing to place anything inside the toilet bowl. This system relies on a floating capacitive sensing technique for water-level measurement. Since direct contact is not required, RoyalFlush is easier to install and more sanitary than other systems. It also does not rely on ambient vibration or a transparent bowl, making it easy to install onto most existing toilets. Furthermore, the entire sensing system is ultra-low power and inexpensive.This paper focuses on the sensing approach underlying RoyalFlush. Once an overflow event is detected, a number of different mechanisms can be activated to stop water coming into the bowl from the tank. For instance, a small solenoid locking device can be added to the toilet tank to close the flapper and prevent additional water from entering the bowl. Once the flapper is closed, the user can address the issue causing the overflow and then reset the lock once it is remedied.

The key contributions of this work are:

- A novel floating capacitive sensing technique for water-level measurement,
- The design and implementation of the RoyalFlush system: a sanitary method for detecting water overflow in a toilet,
- An analysis of the trade-offs associated with different design variables associated with RoyalFlush, and
- An evaluation of the RoyalFlush system on 15 different toilets with a variety of flush mechanisms.

The subsequent sections expand on these contributions. We begin with an overview of related work, followed by sensing principle, system design, analysis and evaluation.

RELATED WORK

In this section, we first present an overview of existing methods for liquid-level detection, particularly capacitive techniques that may be comparable to our own. We also list commercially available products for measuring water-level in toilets or detecting toilet overflows and outline their limitations. Finally, we briefly go over our proposed system and outline how it addresses some of the limitations with existing techniques, facilitating an easy-to-deploy, out-of-bowl, low-cost toilet overflow detection system.

Liquid-level Sensing

Liquid-level sensing is an extensively researched topic in both industrial and domestic segments [1, 5, 11, 13–15]. Beyond simply monitoring levels, such techniques have been used to detect overflows and leakages in storage tanks, ducts, pipelines, and containers.

Conventional liquid-level sensing methods rely on certain physical phenomena that may or may not be catered to a particular scenario [10]. Optical techniques use fiber optic cables or gratings to measure the time-of-flight of an optical signal as it is emitted and reflected; this technique is also known as time-domain reflectometry [7, 15]. Despite being highly accurate, this technique can only be employed in clear containers or requires mounting fiber optic cables on top of containers which may not be possible in most of the applications [10]. Mechanical vibration sensors leverage the fact that less mechanical vibration occurs as the container fills with liquid. Mechanical vibration sensing only makes sense in containers that are able to vibrate, such as pipes and storage tanks. If the container is too susceptible to ambient vibrations, though, the sensor can pick up a great deal of noise and produce false positives [8, 13].

Like optical sensing, ultrasonic sensors use time-of-flight to estimate liquid-level in pipes and storage tanks. Ultrasonic sensor electrodes must be precisely placed around the container to properly measure the signal of interest [17, 18]. Also, ultrasonic sensors become prohibitively expensive in certain applications[3]. Pressure-sensitive diaphragms can also be placed just below the container or on the exit valve of the container to measure the liquid level; however, installation can be cumbersome for applications where the container has already been installed. Pressures sensors also cannot be used in situations where physical contact with the liquid is not allowed [5, 9].

RFID tags can also be used for liquid-level measurement in containers by exploiting the dielectric constant of the liquid as a dispersive medium that changes phase and RSSI [1]; however, this requires closed loop calibration for precise measurement. Also, RFID sensing requires an expensive, bulky RFID reader[4].

Finally, RADARs employ time-domain reflectrometry or ground penetration radar-based techniques [12, 14]. RADAR does not require physical contact with the liquid in the container and can be placed outside on the container's walls; however, the hardware is expensive and requires a decent amount of power [2]. Our liquid-level sensing solution relies on capacitive sensing. Capacitive sensing addresses most, if not all, of the limitations previously mentioned techniques. However, it also brings forth certain challenges and limitations of its own.

Capacitive Liquid-level Sensing

Like optical, ultrasonic, and RADAR-based sensing, capacitive sensing employs-time domain reflectometry. In capacitive sensing, conductive electrodes could be placed outside the container to perform liquid-level sensing in a non-contact way. Also, the electrodes are typically made out of low-cost copper

[3]https://www.omega.com/kwbld/ultrasonicliquidlevelsensor.html, https://senix.com/general-purpose-ultrasonic-sensors/

[4]https://www.amitracks.com/2013/10/simple-cost-analysis-for-rfid-options/

plates or tapes, making them fairly inexpensive. As capacitive sensing relies on static electric-field sensing for detecting changes in a dielectric medium (*i.e.,* liquid level in this case), this technique is immune to ambient factors such as vibration, sound, and pressure, further expanding the application space that it enables.

Despite the fact that there has been much work in capacitive liquid-level sensing, there has been limited exploration specifically on its application on toilets. Reverter et al. [16] describe the design and implementation of a liquid-level measurement system based on a remote grounded capacitive sensor. Rods of stainless steel and a polytetrafluoroethylene (PTFE)-insulated wire are used as the system's electrodes. Since these sensors need to be inside of the liquid, their approach is not suited for detecting toilet overflows. Chetpattananondh et al. [4] uses an interdigital capacitive sensor to measure water level. The capacitance between their comb electrodes is measured via their discharge time as the water level changes. Although their system is very accurate, its power consumption is order of magnitude higher than RoyalFlush. Their work is also not applicable to toilets due to the system's bulky design. Canbolat et al. [3] uses three capacitive sensors for measuring liquid level. Placement of their sensor is very critical to accurately measure the liquid level, which is very restrictive when a non-expert is deploying the device. Although capacitive water sensing itself is not novel(FDC1004EVM)[5], there is very little literature focusing on its application, and to our knowledge, none regarding overflow sensing. This work thus differentiates itself by detailing the comprehensive design and analysis of an effective solution to overflow detection.

Existing Toilet Overflow Solutions

Several products designed to prevent overflow are already on the market, but each has a significant drawback addressed by RoyalFlush. Toilet Guardian[6] detects an abnormally high water level using sensors in the toilet bowl. However, placing a sensor inside the bowl leads to sanitation issues and cleaning the bowl could lead to permanent damage to the sensor. Other products like Wally[7] can detect an overflow by detecting water on the floor or in contact with conductivity sensors that are placed on the outside of the bowl. Such methods either suffer from sanitation issues or detect the overflow after the water is already out of the bowl and on the floor.

There are also sophisticated mechanical designs such as Penguin Toilets[8] that have a secondary drain system to add protection to the toilet against overflow. The FlushIQ toilet by Delta[9] uses a dedicated sensor placed outside the bowl; their sensor technology and performance validations are proprietary. Although such designs might prevent overflows, they require the purchase and installation of an entirely new toilet.

RoyalFlush advances the state-of-the-art by being minimally intrusive, inexpensive, compatible with all porcelain toilets, and having a well documented and available design and evaluation study. There is no other product or solution that properly addresses these considerations.

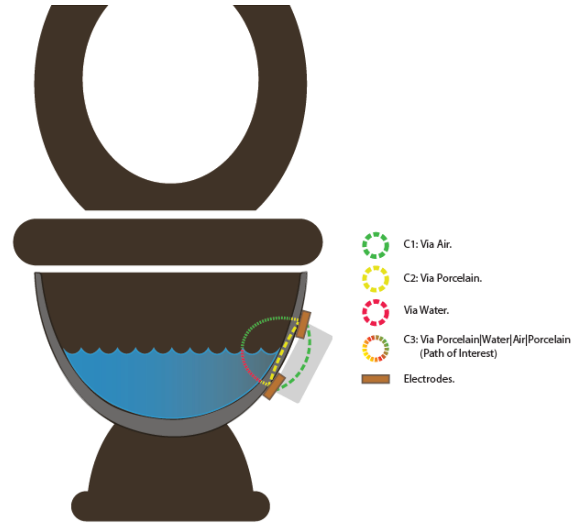

Figure 2. Sensing principle of RoyalFlush.

SENSING PRINCIPLE

As shown in Figure 1, RoyalFlush has two adhesive copper plates that are stuck onto the back of the toilet bowl. Figure 2 illustrates the theory of operation behind RoyalFlush. We model the contents of a toilet as a variable dielectric between two plates of a capacitor. The working principle of this setup is the "parallel fringing effect" [6], in which a fringing capacitance appears between two electrodes arranged side-by-side on the same plane. There are three major electric field paths between the two electrodes of the device: through the air (C_1), directly through the porcelain of the toilet bowl (C_2), and through the porcelain, water, air, and back through the porcelain again (C_3). Since these capacitances are in parallel, the total capacitance between the two plates is the sum of the three. Because the shape and material of the toilet are constant, all measurable variation in capacitance is a function of the water height inside the bowl. Although humidity and other factors may have some effect, the dielectric constant of water is so much higher than that of porcelain and air that they are negligible (80 vs. 6 and 1, respectively[10]). Thus, measuring the capacitance between RoyalFlush's plates is a relatively direct proxy for the height of water in the bowl. As shown in Figure 2, C_{water}, C_{air} and C_{por} is the measured capacitance inside the bowl due to water, air, and porcelain, respectively. Equation 1 gives these capacitances:

$$C_{water} = \frac{\varepsilon_0 \cdot \varepsilon_w \cdot A}{h_w} \quad C_{air} = \frac{\varepsilon_0 \cdot \varepsilon_a \cdot A}{h_a} \quad C_{por} = \frac{\varepsilon_0 \cdot \varepsilon_p \cdot A}{h_p} \quad (1)$$

In these equations, h_w is the height of the water in the bowl, h_a is the height of the air in the bowl from the top plate, and h_p is the thickness of the porcelain. Also $\varepsilon_w, \varepsilon_a, and\ \varepsilon_p$ are the

[5]http://www.ti.com/lit/ug/tidu736a/tidu736a.pdf
[6]http://www.aquamanagers.com/h2orb.html
[7]https://www.wallyhome.com/
[8]http://www.penguintoilets.com/
[9]https://www.deltafaucet.com/bathroom/product/c43903t-wh
[10]http://www.clippercontrols.com/pages/Dielectric-Constant-Values.html

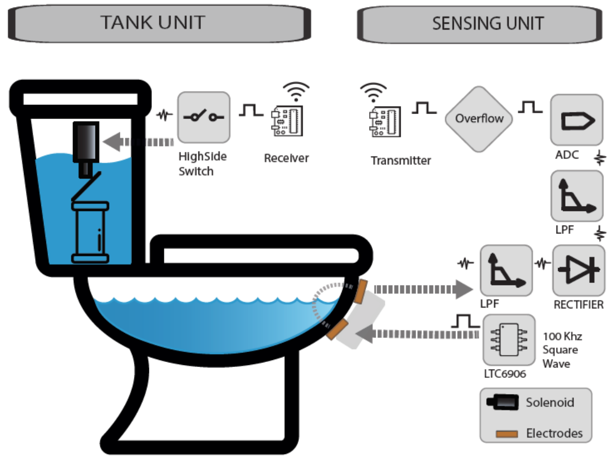

Figure 3. Block diagram of RoyalFlush.

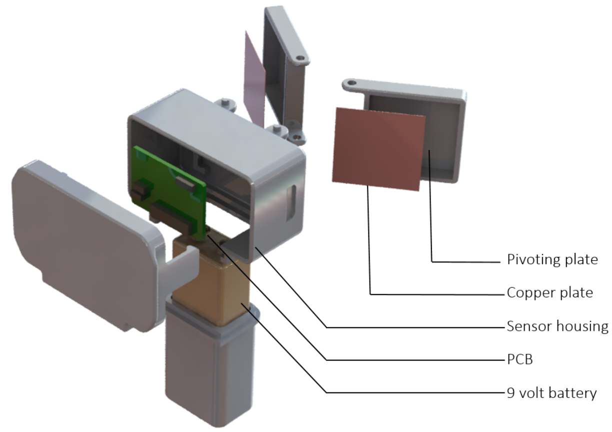

Figure 4. An exploded view of RoyalFlush prototype, showing all the different layers in the design. RoyalFlush has two adhesive copper plates that are stuck onto the back of the toilet bowl.

relative permittivities of water, air, and porcelain, respectively. ε_0 is the permittivity of free space, and A is the area of the electrodes. Because the dielectrics are stacked in series, the total capacitance becomes

$$C_3 = \frac{1}{\frac{1}{C_{por}} + \frac{1}{C_{water}} + \frac{1}{C_{air}} + \frac{1}{C_{por}}} \tag{2}$$

$$= \frac{\varepsilon_0 \cdot \varepsilon_w \cdot \varepsilon_a \cdot A \cdot C_{por}}{C_{por}(h_a \cdot \varepsilon_w + h_w \varepsilon_a) + 2\varepsilon_0 \cdot \varepsilon_w \cdot \varepsilon_a \cdot A} \tag{3}$$

Let D be the vertical distance between the electrodes inside the bowl. Taking into account that $D = h_a + h_w$, we could rewrite equation 3 as below:

$$\frac{\varepsilon_0 \cdot \varepsilon_w \cdot \varepsilon_a \cdot A \cdot C_{por}}{C_{por}(D \cdot \varepsilon_w - h_w(\varepsilon_w - \varepsilon_a)) + 2\varepsilon_0 \cdot \varepsilon_w \cdot \varepsilon_a \cdot A} \tag{4}$$

Since ε_w is an order of magnitude larger than ε_0, we can estimate $(\varepsilon_w - \varepsilon_a)$ with ε_w. Letting $\alpha = \varepsilon_0 \cdot \varepsilon_a \cdot A$ leads to equation 5:

$$C_3 = \frac{\alpha \cdot C_{por}}{C_{por} \cdot (D - h_w) + 2 \cdot \alpha} \tag{5}$$

Since C_{por}, D, and α are constant, the effective capacitance of the system varies due to the change in the height of water. As the height of the water (h_w) increases, C_3 also increases and therefore the total capacitance between the two plates increases, allowing more AC current to pass and reach the other plate.

HARDWARE DESIGN

This section covers the hardware choices, the architecture, and the power consumption of the RoyalFlush . Figure 3 illustrates the block diagram of the entire system and the different components that comprise RoyalFlush.

We propose a design for a capacitive water overflow detector that can be applied to a toilet of any shape. Figure 4 shows the RoyalFlush sensing unit exploded view. Both electrodes are built using copper foil tape (3M 45J589). The electrode holders have the capability to pivot so they can conform easier to any toilet bowl. The sensing unit is contained in a plastic housing. (Figure 4).

The underlying sensing principle of RoyalFlush is to produce an AC signal on one of the plates and observe the change of received signal on the other electrode and decide the water level based on that. To this end, we use a LTC6906 to produce an electric field on the bottom plate (transmit electrode). This electrode is excited with a 5 volt, 50% duty cycle square wave at 100 kHz. A low amount of current proportional to C_{total} passes to the receive electrode. The AC voltage output from the top plate is first filtered and then fed to a small signal Schottky diode (BAV16W) for AC-DC conversion. The signal is sampled at 10 Hz through the analog-to-digital converter of an MSP430FR5969 micro-controller unit. The sampled signal is passed through a low-pass filter where it is processed by a state machine to determine whether an overflow is impending.

When RoyalFlush detects that an overflow is imminent, it turns on the sub 1 GHz transceiver (SPIRIT1) and sends a signal to the tank unit to activate the shut-off mechanism. However when the user addresses the overflow and the water goes down to a safe level again, the RF module on the sensing unit will send a signal to turn off the shutoff mechanism in the tank unit and the microprocessor will turn off the RF module to preserve power.

As stated earlier, one of the requirements for our system is to be as low power as possible so that it could be ran on a battery for a long time. To that end, we optimized the hardware and firmware and measured the power consumption of RoyalFlush using a data acquisition unit[11]. The sensing unit only consumes 150 μW of average continuous power, allowing RoyalFlush to run for several years on a 9 volt 625 mA h alkaline battery.

[11] NI DAQ, USB-6003

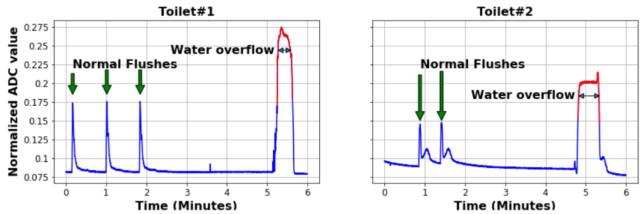

Figure 5. Normal flushes and a water overflow event. When an overflow occurs, the signal shoots above the signal level of a flush.

Although all the evaluations of RoyalFlush were done without the tank unit and the focus of this paper is on sensing and detecting overflow events, we have built the tank unit device to conduct preliminary tests on the end-to-end system. When the sensing unit sends the appropriate signal, the tank unit receives it using the same sub 1 GHz transceiver as the sensing unit. This module is controlled by a MSP430FR5959 that activates every 200 ms. If an impending overflow is detected, the MSP enables a high-side MOSFET driver (LTC1154), which triggers the solenoid (B14HDP). The solenoid then pushes a mechanical structure designed to shut the flapper between the tank and bowl.

We measured the power consumption of the tank auto-shutoff unit when there is no overflow impending using the same method as discussed earlier. The tank unit only consumes 100 μW of average continuous power, allowing the tank unit to also run for several years on a 9 volt 625 mA h alkaline battery.

SIGNAL PROCESSING

The hardware of the RoyalFlush sensor produces an analog value that correlates to the level of water in the toilet bowl. If all toilets were identical, it would be straightforward to determine a specific threshold above which an overflow was occurring. However, there is a huge variation in toilet bowl shape, movement of water in the bowl during flushing and clogging, as well as sensor placement. Figure 5 shows an overflow event after a series of normal flushes for 2 different toilets to illustrate these differences. As you can see, not only is the normalized voltage different for different toilets, but also the shape of the signals are completely different. Furthermore, we have designed are system to be more immune to false negative than false positive since the former results in a costly overflow, whereas a false positives trigger a tank shut-off event which would only happen for a short amount of time and when the water goes down again it would reset itself. Thus, we require a more sophisticated algorithm than simple thresholding.

To account for toilet variation, RoyalFlush requires a short calibration procedure when first deployed on a new toilet. During this procedure, the user is asked to wait 45 seconds and then flush their toilet a couple of times. From this, RoyalFlush calculates the voltage of no activity, the average peak voltage of a flush, and the average duration of a flush and saves these values in nonvolatile memory of the processor.

After calibration, RoyalFlush operates by going into a low power sleep mode, waking once every 0.1 seconds to sample

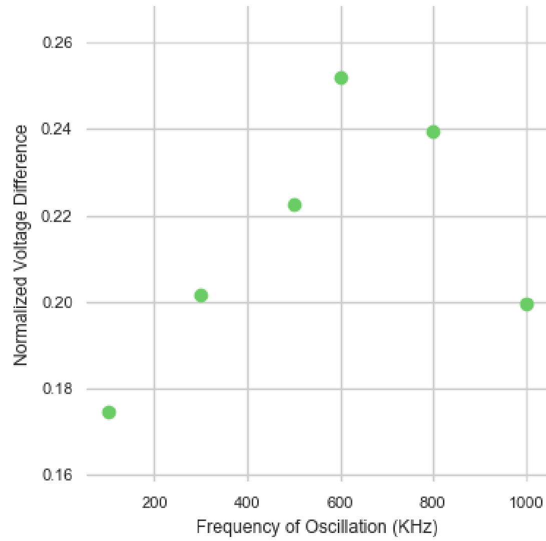

Figure 6. Normalized voltage difference between the base water level and flush water level as a function of the frequency.

the water level voltage. A state machine is used to efficiently monitor for clogging and overflows. The slope of the current point with respect to the previous is calculated. If it is positive, the state machine enters a “rising state”. This continues until either a negative slope is detected or the water level rises above the voltage of an average flush, causing a transition to the “peak state”. In the peak state, a counter begins to keep track of how long the water is at a high level. If the water remains abnormally high for moderately longer than the average flush duration, the toilet is likely clogged and RoyalFlush triggers a shut-off signal to prevent an overflow. If the water level falls below the elevated level at any point in this state, the state machine resets.

In the extreme case that RoyalFlush misses an overflow event, water covers both electrodes simultaneously. An even larger signal spike in the signal occurs in that case, giving RoyalFlush another opportunity to trigger the shut-off mechanism in the toilet.

ANALYSIS

In this section, we discuss some of the choices that went into the design of RoyalFlush and their trade-offs. In the experiments conducted in this section, we show the trade-offs of our choices based on changes in the measured voltage between base and flush levels.

The first is the oscillation frequency that will excite the transmitter electrode. Oscillation frequency has a fundamental relationship with capacitors. The higher frequency a signal is, the more current can be moved between plates. We thus are interested in a frequency which allows enough current to provide a clean detectable signal. However, higher frequency signals require more power to generate due to increased parasitics, so we are motivated to keep the oscillation as low as possible without impacting performance. Figure 6 shows how

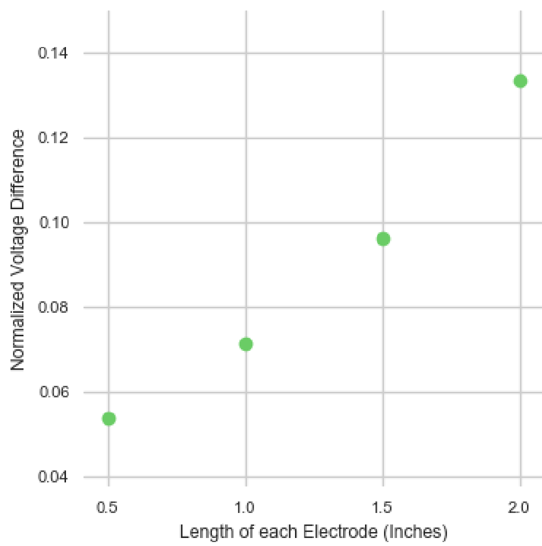

Figure 7. Normalized voltage difference between the base water level and flush water level as a function of the length of each electrode.

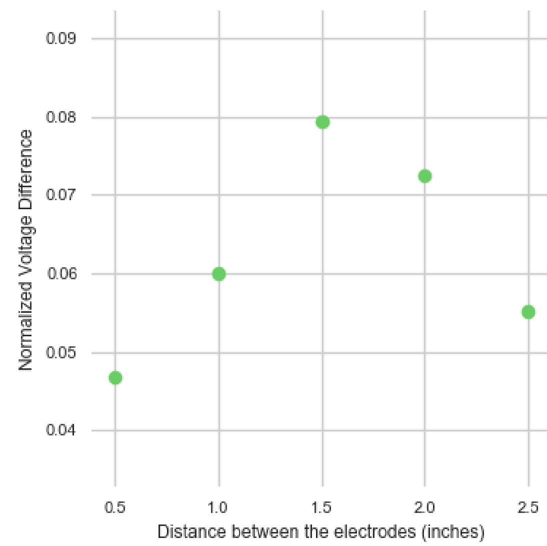

Figure 8. Normalized voltage difference between the base water level and flush water level as a function of the separation of the two electrode.

the oscillation frequency affects the change in the sensed normalized voltage. The dielectric constant of a material tends to vary somewhat with frequency, decreasing up to a certain frequency and beyond that it increasing [19]. The effect of the changing dielectric can be seen in our frequency sweep. As we increase the frequency up to around 600 kHz the dielectric constant of our system decreases resulting in a better coupling and therefore a larger sensed voltage difference. Beyond this frequency, the dielectric constant of our system increases resulting in a worse coupling and lower measured voltage difference. Because we want our system to be as low-power as possible, we choose 100 kHz to be the oscillation frequency in order to minimize power consumption.

The design of the electrodes is also critical for determining if an overflow is about to occur with high accuracy. There are two parameters of interest: the area of the electrodes and the spacing between them. Figure 7 shows the relationship between the change in normalized voltage as a function of electrode area. In this experiment, all of the electrodes were square-shaped and the distance between them was 1.5 inches. As can be seen, there is a positive correlation between the electrode size and the measured voltage. This is expected since capacitance is a function of plate area; as electrodes get larger, the AC voltage that reaches them increases, thus making the difference between the two water levels more significant. Building larger sensor plates increases the amount of observable capacitance, but also leads to a bulky design that is difficult to place on toilet bowls.

Figure 8 shows the relationship between the change in normalized voltage and the distance between the two electrodes. There is a non-linear relationship between the distance and the voltage. If the distance is very small, the coupling from the two electrodes will be dominated by C_1; in other words, since the two electrodes are very close together, the path across the air between the two electrodes gets more AC voltage and overwhelms the difference that is generated by the change in water level. If the separation between the two electrodes gets too big, the coupling between the two electrodes becomes very small and measurements become noisy. In other words, C_{total} becomes so small that it is harder to differentiate between the base and flush water levels.

After the experiments regarding form factor, we decided that the electrodes in RoyalFlush should be 1.25 inch in height and width and the separation between them should be 1.5 inch.

EVALUATION

In this section, we will describe the experiments that have been conducted to validate RoyalFlush's ability to detect water overflow events. We conducted two different studies. The first was a controlled experiment in which 10 different toilets were manually clogged, flushed, and overflowed. We then deployed RoyalFlush into 5 homes and asked participants to use their toilet as they normally would for 24 hours.

Controlled Study

To validate the consistency of RoyalFlush across toilets, we performed a series of sequential actions on 10 distinct toilets. The actions started with 5 flushes, during which RoyalFlush calibrated itself. After calibration, a random sequence of flushing the toilet, sitting on the toilet, and overflowing the toilet was performed, with an average of 16 flushes, 10 sits, and 8 overflow events per toilet. Due to the difficulty of naturally occurring overflows, we instead simulated them through two methods: (1) clogging the toilet with a plunger and performing several flushes and (2) clogging the toilet with a plunger and filling the toilet bowl with water from a bucket. The flush-based overflow accurately simulates an overflow caused by a routine clog, whereas the bucket overflow is more similar to a pipe or mechanical failure of the toilet. Data was annotated

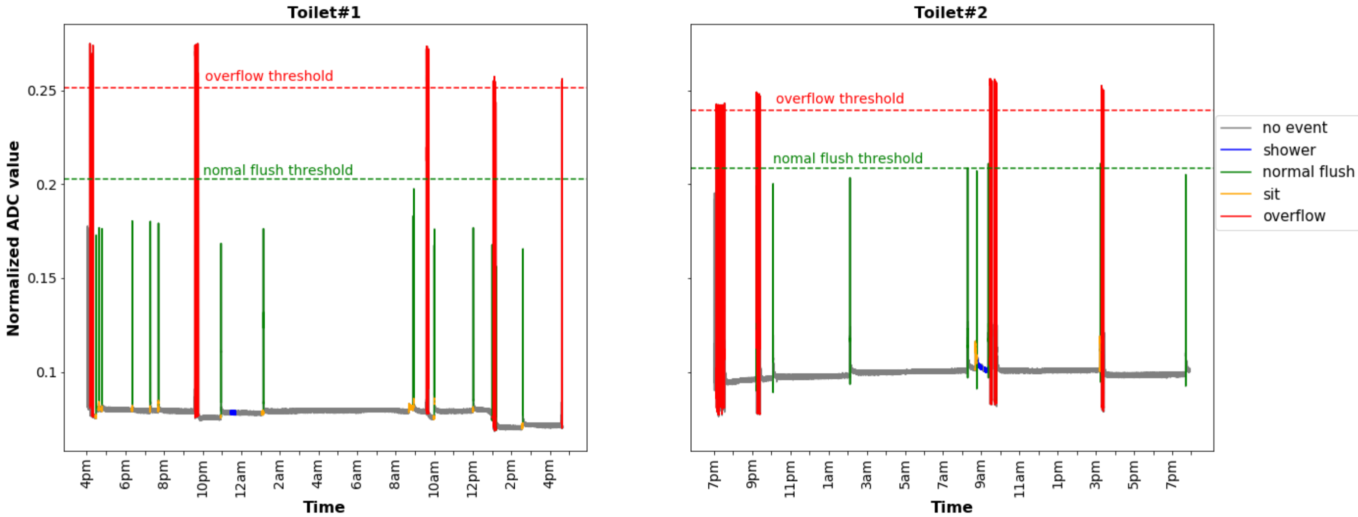

Figure 9. An example of RoyalFlush monitoring two toilets for a 24 hour period. Note every overflow event is higher than the overflow threshold.

manually by the researcher performing the events for ground truth in our analysis. RoyalFlush was able to detect every one of the 80 simulated overflow events with no false negatives or false positives.

Real World Study

In this study, RoyalFlush was deployed on 5 different toilets in 5 separate homes for 24 hours. Upon installing RoyalFlush, the participants performed 5 calibration flushes just as before. After the calibration, participants were asked to use their toilets as they normally would. They were also asked to log the start and end of the following events by pressing a key on an accompanying laptop: sitting on the toilet, flushing the toilet, and taking a shower. Additionally, because a natural overflow is unlikely to occur in a 24 hour period, a researcher would occasionally visit the home and simulate overflow events in the methods previously described.

Table 1 shows the results from our real world deployment. In these 5 toilets, there were 273 events, including 107 simulated overflows. Figure 9 shows the normalized ADC value for two of the five toilets that was in the study in the span of 24 hours. The red lines indicate overflow events whereas the green lines indicate normal flushes. As seen in figure 9, the voltage peaks and the signal shape of these two events are easily distinguishable.

Table 1. Number of each event in the span of 24 hours in 5 different toilets in the real world study.

Toilet#	#(Sits)	#(Flushes)	#(Showers)	#(Overflows)
1	14	17	1	23
2	2	17	2	33
3	14	41	1	20
4	1	17	0	8
5	4	31	4	23

We evaluated the performance of RoyalFlush with and without the calibration process. Without calibration, we used a global threshold for an average flush voltage and duration; RoyalFlush had a 50.63% precision and 92.98% recall. Precision indicates how often RoyalFlush was correct when it detected an overflow event, whereas recall indicates how often RoyalFlush correctly detected an overflow event when one actually occurred. RoyalFlush improved significantly with the calibration process, reaching a precision and recall of 98.16% and 100% respectively. In other words, RoyalFlush missed no overflow events and falsely classified only two events as overflow out of the total 273 events.

DISCUSSION AND FUTURE WORK

We note that even though the results are promising, more false positives occurred during the real-world deployment. After a review of our data, we noticed that one of the false positives happened when the toilet was flushed during a long shower in a small bathroom. It is possible that condensation may have formed on the electrodes as steam built up in the confined space, leading to a bigger spike in the measured voltage. After this observation from our studies, we note similar sensor behavior when water is splashed on the electrode. As a future improvement for RoyalFlush, a better casing for the electrodes could help provide better shielding from these issues.

One of the other limitations that was observed from our initial tests was that if someones urinates directly on the side where the sensor is being placed for more than our calibrated overflow time, RoyalFlush would detect that as an overflow event. Our system is immune to that since we place the sensing unit on the side of the bowl and nobody would typically urinate toward the side of toilet bowl.

As stated in Evaluation section, RoyalFlush requires the user to do a calibration process to make our system work. As a future work, this process could be automated and potentially RoyalFlush could find these parameters from usual use of the toilet. In this way, RoyalFlush could learn all the normal events that is being done to the toilet and when it goes into monitoring state it could detect all the abnormalities.

Water back flow can also lead to overflow events. In such scenarios, RoyalFlush can still raise an alarm to notify the user; however, it can not take any preventive action. As another avenue of future work, RoyalFlush could be used to track the amount of water being used on a daily bases by counting the number of flushes. Keeping track of this data could feed a larger system that tracks water consumption in the home.

CONCLUSION

This paper presents RoyalFlush, a toilet overflow detection system that efficiently solves a common and costly household problem. Although the core technology of capacitive dielectric water sensing is not novel, the refinement needed to translate it into this particular application was nontrivial. To validate RoyalFlush, we conducted two extensive studies. In a controlled study, RoyalFlush achieved 100% precision and recall of overflow events on 10 different toilets. In the real-world study, RoyalFlush achieved 98.16% precision and 100% recall on toilets from 5 homes. This excellent accuracy coupled with RoyalFlush's extremely low power usage allow it to prevent virtually all overflow events with no maintenance for years at a time.

ACKNOWLEDGMENTS

We thank Dennis Repp and Daniel Corbin for their funding on this project. The authors also thank Matthew Ibarra for his mechanical design ideas.

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