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HAND-HELD UNDERWATER LEAK DETECTOR

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Abstract

Existing technology for detecting leaks in aboveground swimming pools is currently very expensive and cumbersome to use. The purpose of this project is to design a hand-held underwater leak detector for aboveground swimming pools that is low in cost and simple to operate. This device detects the acoustic vibrations of the leak with a hydrophone (a submersible microphone) and displays the proximity to the leak with an LED display panel through the use of filtering and amplification circuits. All components of the detection system are encased in a waterproof plastic housing designed to be held comfortably and operated by the user with one hand.

Introduction

Locating leaks in an aboveground pool can often be difficult and time consuming. The surface area of an average sized pool is large enough where finding a leak with no technological assistance can take as long as two hours. Some leaks are small enough that they are not easily visible to the human eye while others are in challenging locations to access. All of these inconveniences manifest themselves through wasted time and cost to the pool repairman and customer.

This project is the first design iteration of this concept, meaning that the primary focus of this project is to confirm the functionality of the proposed device. A fully functioning prototype model was constructed with all of the required components in place. Schematics of the plastic housing and circuitry were created, along with future plans for improved housing designs, circuit improvements and upgraded performance of the device.

Design Process

The device is required to detect and adequately display an acoustic leak signal emanating from a ¼ inch hole in vinyl pool lining up to one foot from the hydrophone. "Adequate display" entails the ability to see the LED display from two feet while underwater. The device must be completely waterproof to a nominal depth of 6 feet (2 meters) in chlorinated pool water ranging from 50 to 100° F (10 - 38° C). The device is to weigh no more than 3 lb. (1.4 kg) and must sink when released from the diver's grasp. Power for the detector is intended to be drawn from up to two 9-volt batteries and must have a lifespan of one hour without necessitating a battery change. Batteries must be simple and quick to remove, taking no more than two minutes to remove and replace. User comfort is a major priority, which is achieved through rounded corners, soft rubber coating and a comfortable grip design. The cost of the unit, assuming it has been manufactured in medium to high volume, is not to exceed $100.

Acoustic vibration sensing was determined to offer the highest consistency in leak detection while maintaining a low overall cost of manufacturing and upkeep. The employment of a hydrophone guarantees full submergibility of the detector source to the user-required depth of 6 feet (2 meters) with a watertight seal. Acoustic signals are best detected while the hydrophone is at rest, although motion up to approximately 1 foot per second (0.31 m/s) in any direction does not degrade the quality of the incoming signal.

A single, waterproof unit containing all of the system components allows the user to easily maneuver underwater without sacrificing visibility and mobility. Users are able to clearly see and comprehend the LED display panel while operating the device. The LED display panel can be best viewed while the diver holds their breath due to the gaseous exhaust from scuba gear. This exhaust occurs in the form of large bubbles emanating from the mouthpiece when the diver exhales. In addition to the visual impedance of the exhaust, gaseous output from scuba gear also creates noise that disturbs the signal detection. Figure 1 illustrates these features of the developed concept.

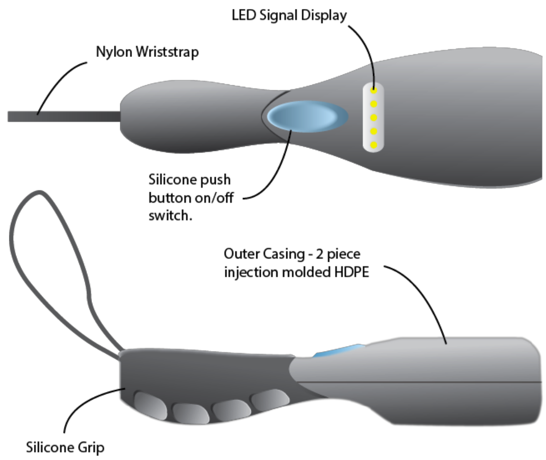

Figure 1 - Conceptual design of leak detector detailing interactive features

Leak Detection System Flow Path

The leak detection system follows a linear flow path where all functions occur in series. The acoustic leak signal is detected by the hydrophone and converted into an AC signal that is sent to the PCB. On the PCB, the AC signal is amplified and put through a low pass filter to bring it to a usable level by the next components. After flowing through the AC/DC converter, the now DC signal is sent to the LED driver which, depending on the signal strength, illuminates a corresponding number of LED indicators (from left to right). The LED indicators are the last step of the detection system flow path before the usage again relies on the operator.

Hydrophone

In order to achieve the maximum signal detection at a minimum cost, the hydrophone was carefully selected in order to meet the final design requirements. The hydrophone is essential to the first step of the system process flow: converting the acoustic vibrations generated by the leak into an AC electrical signal. Several factors were considered when selecting a hydrophone including operating depth, polar response and frequency detection range and cost. After examining these factors, the prototype hydrophone was chosen to be the H1C Aquarian Audio Hydrophone (Fig. 2).

Figure 2 - H1C Aquarian Audio Hydrophone.

As previously stated, the hydrophone is completely waterproof up to 80 meters, which far exceeds the customer requirement of a watertight seal up to 6 feet (2 meters). The unit has a stainless steel base with a rubber cap that protects the internal microphone components. The stainless steel base is machined to a ¼ NPT threading, making it easily mountable. A shielded and waterproof cable carries the mono signal from the hydrophone to the PCB. Because the location of a leak is assumed to be unknown when using this device, a flexible polar response of the hydrophone is highly desired. The H1C model offers an omnidirectional polar response, which gives the detection system design a high margin for error when scanning for the leak. The user will have the ability to detect an acoustic leak signal even if the device is not trained directly on the source of the signal.

Sensitivity requirements of the leak detection system called for -60 dB in order to adequately detect the leak signal. From the supplied data sheets for the H1C hydrophone, the device is capable of achieving a sensitivity of -190 dB, which far surpasses the engineering specification previously stated. This flexibility allows for leaks with weak signal levels to be potentially detected, while visual inspection would easily miss the location of the leak.

The frequency detection range of the H1C hydrophone is a crucial aspect of the leak detector. Frequencies of approximately 1 to 5 kHz were determined through testing to be the target frequencies emanating from a leak. The H1C hydrophone is designed with the ability to detect frequencies from approximately 1 Hz to 100 kHz. Although this range is only approximated by developmental research, it well encompasses any frequency that is usable for the leak detector. Any frequencies detected from sources other than the leak due to the wide capability of the hydrophone are later filtered and eliminated by the PCB.

The cost of the hydrophone does not entirely reflect the pricing of an underwater leak detector being manufactured at a medium to high volume production scale. One unit was set at the price of $150, which was a major purchase from the team budget of $1000. Although this price is 50% higher than the customer required price for a working lead detector, it was determined that the purchase of high-quality hydrophone was a higher priority than reducing the unit cost in early developmental stages. It was assumed that the bulk price of hydrophones in full production of leak detector would be low enough to accommodate for the customer requirement of a final cost of $100.

PCB and LED Display Layout

When the AC leak signal reaches the PCB, it is both unfiltered and low in magnitude. The PCB is 2.5"x5.0" made of mainly passive components including seven resistors and two capacitors. A separate board that mounts ten LEDs is designed to be a separate entity from the main PCB. The two integrated chips used in the PCB design include one LM324 quad operational amplifier (op-amp) and one LM3914 LED driver. An amplifier, low-pass filter, AC/DC converter and LED driver receive and alter the signal. The newly filtered and amplified signal is then sent through the LED driver to the ten LEDs. Depending on the strength of the signal being sent to the LEDs, a corresponding number of LEDs will be illuminated. For example, when the detector is one inch from the leak, all ten LEDs will be illuminated. However, when the detector is one foot from the leak, only one to three LEDs will be illuminated. Data sheets for each device and component yielded the necessary worst-case consumption rates. Calculations showed that the amplifier circuit consumes 5 mA of current at its maximum consumption point and the LED driver circuit consumes a maximum of 100 mA of current. Also note that each of the ten LEDs consumes 15 mA or current. From this data, it is clear that the LED driver is the main source of power consumption. Figure 3 below shows the schematic for the entire electrical system. Figures 4 and 5 illustrate the final board designs that fabricated for the mock-up detector.

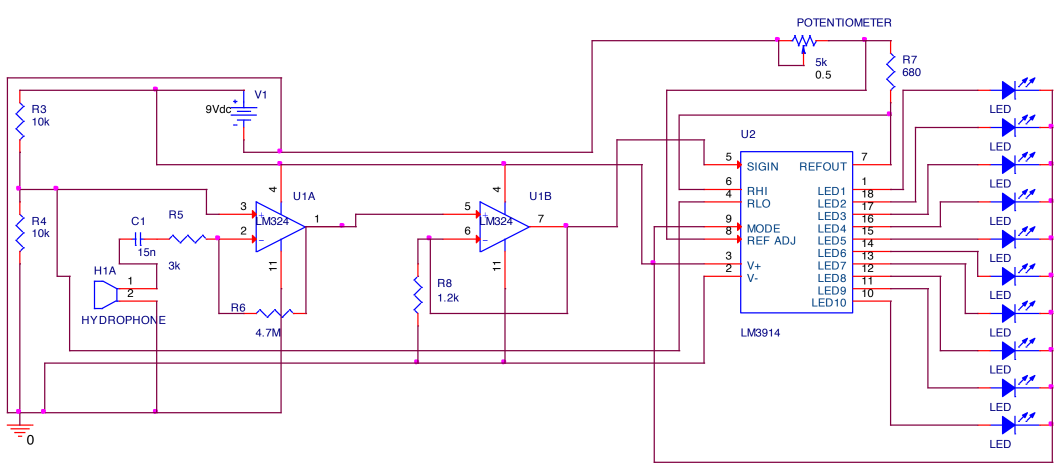

Figure 4 - Electrical system schematic

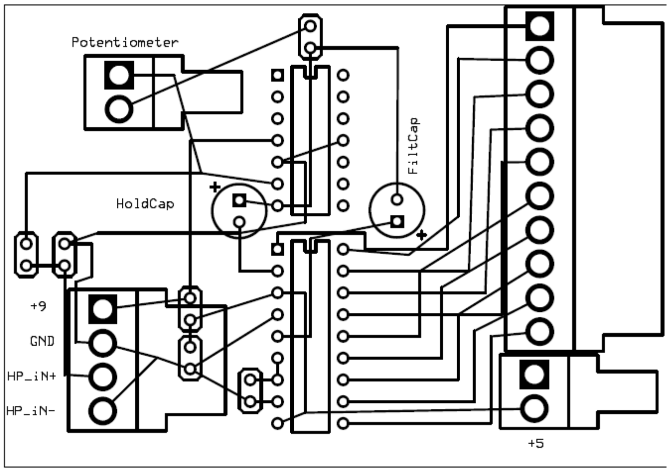

Figure 4 - Final PCB layout

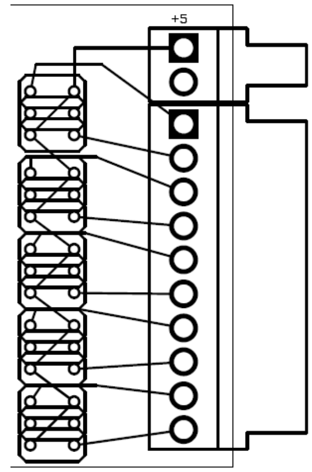

Figure 5 - Final LED Display layout

Power Supply

Power for the entire electrical system was calculated by adding the maximum power draw from each portion of the circuit. Due to the requirement of all system components being internalized, a small battery was the only option for a power source. In order to compensate for any excessive and unforeseen power use, a 100% factor of safety was chosen as a minimum power consumption rate for the selection of a power source.

The initial circuit design called for only one standard alkaline 9-volt battery to power the device. After extensive testing of the circuit's power consumption tendencies, it was determined that two batteries would in fact be required. The use of two batteries supplies the circuit components with a higher consistency of power, thus making the detection results more reliable. One 9-volt battery allows approximately 1000 mA hours of life, which translates to an approximate battery life of 10 hours per battery at most. The customer requirement of the device lasting for one hour is easily achieved according to the factor of safety previously stated. Each battery has an approximate weight of 0.7 ounces and is 0.5x1.0x1.75" allowing two batteries fit end-to-end in the easily accessible screw-cap handle of the device.

Waterproof Housing

All components of the leak detection system are encased in a waterproof plastic housing. Due to the nature of this project, a preliminary mock-up was created along with first-draft plans for future developments to the concept an opposed to a full-production housing design. The current mock-up is intended to successfully house the fully functioning detection system components (hydrophone, PCB, and power source) with a watertight seal while allowing components to be regularly removed, altered and replaced without and damage to the housing. The design concept shown in Fig. 1 illustrates the housing design that was fabricated. Vacuum-form molding was used as to create the shell of the mock-up housing, although full-scale production would be achieved through injection or blow molding.

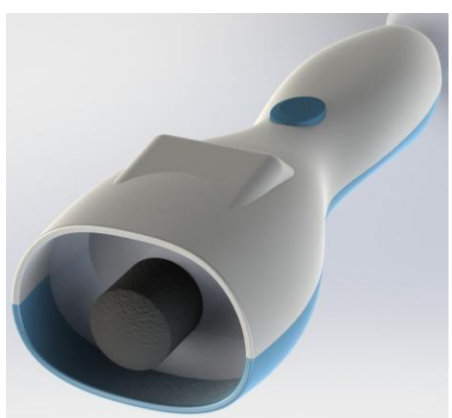

Figure 6 - Solid model of full-production leak detector concept (front view)

The vacuum-form molded mock-up was fabricated in two halves from 25 mm clear acrylic and permanently adhered together to form the base of the working prototype. Features of the intended final design that were fabricated into the working prototype include a comfortable one-handed handle, an angled LED display window, and flat inside surfaces for mounting the PCB and LED display board. The mock-up measures 12 inches in length with the hydrophone actively attached, 3 inches wide and 2 inches deep at the largest point of the profile. The PCB and LED boards are mounted with removable glue on the respective inner lower and inner upper surfaces of the plastic shell. When held at arm's length, the LED panel is approximately normal with the user's line of sight, yielding maximum visibility of the LED indicators. Users are able to operate the mock-up by holding the ergonomically designed handle with either the left or right hand. Batteries are housed in the handle of the device inside of a waterproof match case in which the batteries fit snug while remaining protected from being submerged underwater. In order to access the PCB and make necessary alterations, the front of the plastic housing was cut off and replaced with two aluminum pressure plates. These plates are sealed with an internal silicone gasket and are held together with four #8-32 bolts. Due to the low power consumption of the detection circuits, no air vents or heat sinks are required in the design.

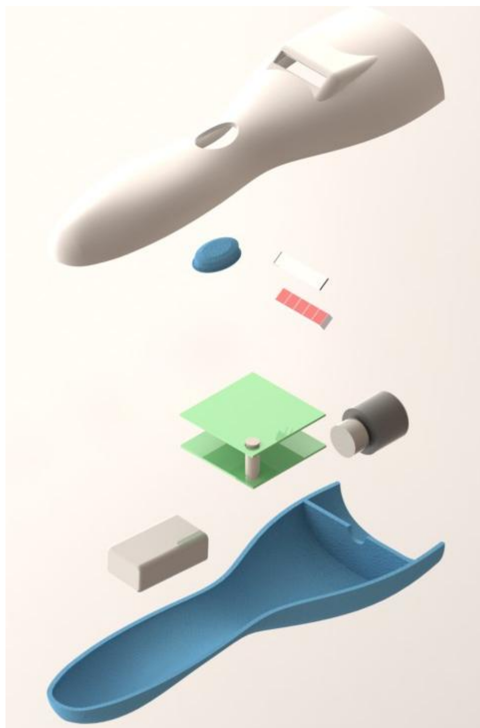

Figure 7 - Solid model of full-production leak detector concept (exploded view)

Full production of the leak detector waterproof housing is based around the same general design of the mock-up. However, certain features would be altered or added to accommodate for lower cost, stronger materials and a more user-friendly overall design. In full production, the upper and lower halves of the casing would be injection molded due to its high repeatability and low cost. The two halves would be either screwed together or be attached with multiple snap-together tabs. In any situation, a gasket would be placed in between the two halves in order to create the imperative waterproof seal. By using two detachable halves, the user will be able to access the internal components without damaging the device. The hydrophone mount is intended to be molded into the lower and upper half of the housing shell. A gasket will seal any potential spaces between the hydrophone and the hydrophone mount. Mounting posts for the PCB and the LED board will molded into the lower and upper inside surfaces of the shell halves, respectively. Self-tapping mounting screws are intended to be used for the plastic mounting posts. This will safely secure the circuit boards to the device and add internal rigidity and strength to the device. The battery compartment will be molded with a rectangular profile to seat the 9-volt batteries while holding them motionless. The concept of the threaded end-cap is a design feature of the mock-up that could possibly be carried through to the full production model. An additional feature that could possibly be integrated into a full production model is a power on/off switch. The switch would be located at the resting position of the thumb on the top of the handle, giving the user complete control over the system power without sacrificing any comfort. These feature additions and improvements will be explored in further iterations of this concept.

Feasibility Testing

In the initial stages of the product design, the behaviors of an actual pool leak were unknown. Feasibility testing was required in order to determine what frequency band a leak in a vinyl pool lining creates. The initial test setup consisted of an inflatable 12 foot diameter pool with a depth of 3.5 feet. The pool walls are made of a durable plastic material that behaves very similarly to vinyl. Testing proceeded by creating a 0.25 inch incision in the pool lining at approximately 3 feet in depth and recording the audio signal from the hydrophone at increasing distances from the leak beginning and ending at one inch and 3 feet, respectively. The leak was then opened up to a 0.5 inch width and the test was repeated. This occurred three more times until the leak was approximately 1.25 inches in width. At this point, the leak could easily be detected with the naked eye. It is important to note that during these test, the leak was amplified using an Eridol® AudioCapture UA-5 pre-amplifier to boost the signal to a usable level.

Feasibility Testing Results

After gathering sufficient data samples from the pool test site, the audio capture was then analyzed using filtering algorithms in Matlab®. It was quickly discovered that the audio signal created from 0 to 1 kHz as well as anything greater than 5 kHz was noise that required filtering. This left a usable frequency of 1 to 5 kHz. There were no significant differences in the location of the frequency band between the various hole sizes and measuring distances. This allowed the circuit to be designed for a constant frequency band pass filtering. The unfiltered leak signal is shown below in Fig. 8 followed by the filtered signal in Fig. 9.

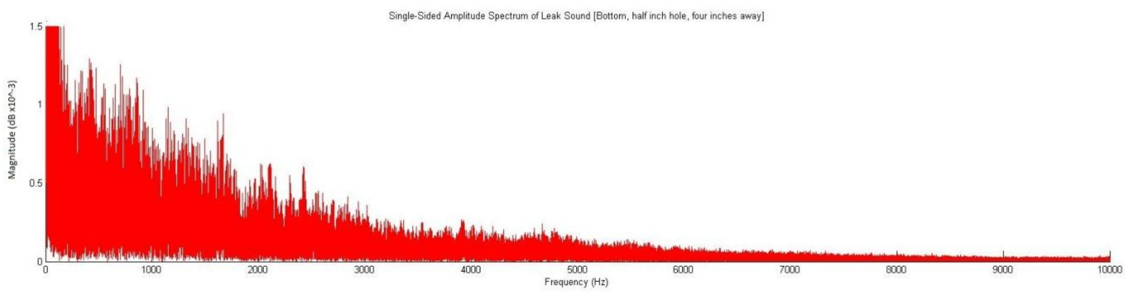

Figure 5 - Unfiltered amplified leak signal from initial testing

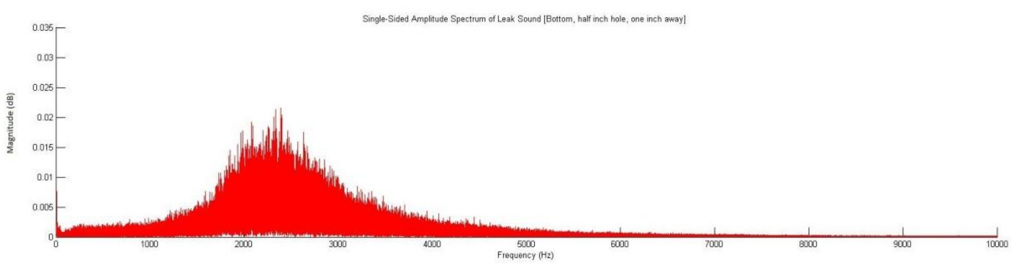

Figure 6 - Filtered amplified leak signal from initial testing

Mock-up System Test Setup

Circuit design and development was based upon the initial research that yielded the detectible frequency band emitted by a pool liner leak. The prototype circuit was built on two breadboards and tested with only the hydrophone held underwater. This allows the circuit board and power source to remain safely above water in order to be altered according to the live testing results. The ultimate goal of the circuit testing is to finalize the circuit design and test it within the waterproof housing with no system components being externally operated. Due to weather conditions, the outdoor pool was no longer available to be used as a test environment. In place of the pool, a scaled-down indoor testing environment was created by filling a large industrial-strength plastic bag with water and supporting is with a plastic barrel in order to simulate the synthetic pool lining. The barrel was perforated on the bottom surface to allow the leaking water from the punctured bag to empty from the barrel at a higher flow rate than that of the leak. Initial testing of this new environment quickly yielded that when the water level submerges the leak, no audible signal is created. Water is pumped into the barrel as during testing to maintain a constant water level of approximately three feet. According to basic fluid mechanics, the hydrostatic pressure increases in a linear proportion to the water depth, thus maintaining the maximum water depth will yield the strongest leak signal.

In order to test the mock-up housing, certain measures were taken to ensure a watertight seal. Although portions of the housing are not detachable like the full production model would be, the mock-up housing is tested to highest priority customer needs; a watertight seal to protect the internal electronics, a simple and comfortable user experience, and the overall ability to detect the leak. The upper and lower vacuum molded halves of the shell were permanently adhered together using Bondo® to ensure a strong and waterproof seal. After the end of the handle was removed via band saw, the waterproof battery compartment was installed, also using Bondo®. In order to simulate the intended functionality of the battery housing, the threaded end-cap remains fully functional. This allows the user to understand the battery replacement method while allowing for flexibility in the developmental stage of testing. The aluminum pressure plates were sealed with a silicone gasket in the fabricated gasket grooves, allowing the front plate to be removed and replaced if necessary. PTFE tape was used to guarantee a watertight seal between the hydrophone mounting hole and the ¼ NPT hydrophone threading.

The second iteration test setup represents an aboveground pool well due to similar water depths, level regulation and a similar lining material. However, two main concerns with this setup may result in slightly inaccurate data readings. The first concern is that incoming water or external noise, such as music or vibrations of the barrel, may inhibit proper observation of the LED indicators. These external noise sources could trigger the LEDs to indicate a leak in an incorrect location. To mitigate this problem, doors to the test room were closed completely and testing was performed during times when vibration sources such as working machines were not being operated.

A second concern with the second iteration test rig is that the small dimensions relative to those of an average-size aboveground pool may create different acoustic patterns. In the small test tank, noise emanating from a leak may echo from the nearby opposite wall or irregular lining surface while in a large pool, the leak noise will disperse evenly, having a smooth floor surface as the only source of interference. To mitigate this concern, leaks at multiple heights were detected with the hydrophone at various distances and orientation angles relative to the hole. By testing as many cases as possible in such a restricted environment, results may carry more validity.

Mock-up System Test Results

Because the frequency band of the leak was determined in the initial hydrophone testing, four main focal points of the device were examined of the second iteration of testing: waterproofing the mock-up, battery life, properly adjusting the circuit gains, and fine-tuning the LED driver to properly reflect the signal strength at various distances of the device from the leak. The mock-up device was sufficiently built to withstand an underwater environment while enabling the user to access internal components. The battery end-cap and the aluminum face plate successfully provided a watertight seal when the device was held underwater for fifteen minutes at a depth of three feet. Further submersion testing will be conducted to confirm the consistency of the waterproof seal. This result indicates that the mock-up housing is able to sufficiently protect the internal electrical components from water damage.

Battery life testing was performed during all second iteration adjustment of the amplifier gains and LED driver features. While the circuits were examined, the battery remained engaged. On average, a battery change was required every 3 hours that the circuit was turned on. Battery changes were prompted by highly irregular test results as well as complete failure of the circuit to function. This exceeds the customer expectation of a one hour battery life by approximately 300%.

Circuit gain values and LED tuning is being constantly revised to yield more accurate results according to the initial hydrophone testing and to fit the user requirements. Currently the device successfully detects a leak from four inches and sufficiently displays that signal on the LED indicators. The gain values are being altered in order to increase this range of detection. The reference voltages being read by the LED driver are also being altered to create the ultimately desired design scenario; all ten LEDs illuminate at a distance of one inch from the leak and one to three LEDs illuminate when the device is one foot (or ideally two feet) from the leak.

Conclusions

This project was intended to develop a first-draft design of a hand-held underwater leak detector to be used in an average sized aboveground pool. While aesthetics and functionality were researched and developed, the functionality of the concept is the primary concern of this first-iteration project.

Future developments of the detector could be improved circuit performance, designing a less expensive hydrophone, preparing the waterproof housing design for commercial sale, and determining methods to save battery life. These feature improvements would strongly guide the concept towards implementation in the pool repair and maintenance industry. A further application of the concept is for leak detection in frack ponds. Hydrofracking is being used more regularly to harvest natural gas, and leaks in the frack ponds are difficult to detect. This would be an ideal application for the underwater leak detector.

Acknowledgements

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