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University of Pittsburgh

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16. Abstract

From 1966 to 2005, a total of 1,502 bridge failures occurred in the United States with approximately 60\% of those failures due to hydraulic conditions, i.e. bridge scour. Bridge scour is the erosion of riverbed material as a result of flow conditions surrounding abutments and piers supporting bridges. During Phase 1, a conceptual prototype float-out device bridge scour monitoring system was developed. Multiple float-out devices are buried at various locations around a bridge structure. During a scour event, a float-out device is released due to removal of sediment around the bridge abutment and floats to the surface transmitting a unique identifier over radio frequencies. A radio frequency receiver located near the bridge waits for communication from each float-out device and displays the current scour depth via light indicators. A float-out device monitoring system provides an initial indication of scour severity for further investigation. This system is designed to allow real-time monitoring of scouring without the need for inspectors to physically access the foundation areas during the scour event.

The objective of Phase 2 is the verification and development of a production ready float-out device bridge scour monitoring system based on the research of Phase 1. The float-out device was re-designed and tested to the specifications agreed upon by PennDOT. The radio frequency receiver and multiple light indicators were combined into a single enclosure referred to as the receiver unit. Initial investigation into solar and battery backup to power the receiver unit in the event that AC power is not available at the bridge has been performed. A float-out device arm switch was developed that allows the float-out device to remain off until the installation procedure. A receiver unit housing was researched that allows the light indicators to be viewed from outside of the enclosure at a distance of 200 feet with binoculars. The installation instructions outline the suggested location and activation for the receiver unit as well as the arming and installation of the float-out devices. The operation instructions detail the procedure for communicating with the receiver unit to visualize the current scour status and retrieve the float-out device serial numbers through the USB connection.

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1 Executive Summary

From 1966 to 2005, a total of 1,502 bridge failures occurred in the United States with approximately 60% of those failures due to hydraulic conditions, i.e. bridge scour. Bridge scour is the erosion of riverbed material as a result of flow conditions surrounding abutments and piers supporting bridges. During Phase 1, a conceptual prototype float-out device bridge scour monitoring system was developed. Multiple float-out devices are buried at various locations around a bridge structure. During a scour event, a float-out device is released due to removal of sediment around the bridge abutment and floats to the surface transmitting a unique identifier over radio frequencies. A radio frequency receiver located near the bridge waits for communication from each float-out device and displays the current scour depth via light indicators. A float-out device monitoring system provides an initial indication of scour severity for further investigation. This system is designed to allow real-time monitoring of scouring without the need for inspectors to physically access the foundation areas during the scour event.

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2 Requirements

A prototype float-out device bridge scour monitoring system is illustrated in Figure 1 with the focus on a single substructure member. Other substructure members are simple replications of Figure 1. The float-out device is fabricated into a watertight Radio Frequency (RF) friendly cylindrical container capable of being deployed through a standard NX sized hollow stem auger.

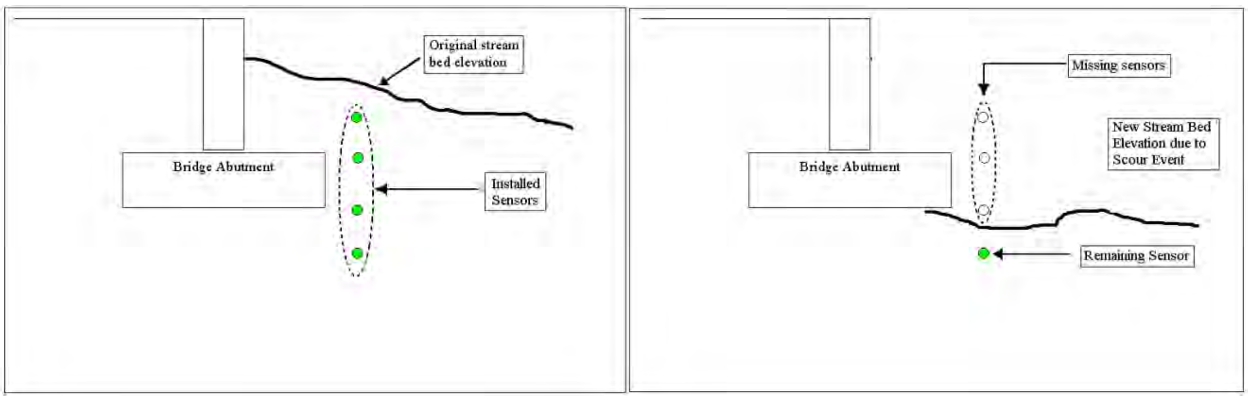

Figure 1: Bridge Scour Float-out Device Monitor System

The objective of Phase 1 was the development of a scour monitoring system that is capable of producing a visual indication to an inspector in the vicinity of the bridge that scour has occurred and to what depth. The proposed solution, a float-out device, was fabricated in a cylindrical container that is Radio Frequency (RF) friendly and watertight. The float-out device will contain an RF transmitter, operating in the ISM (Industrial, Scientific, and Medical) Band, orientation sensitive power circuitry and a microcontroller. Once the float-out device is activated, any deviation from the vertical orientation will activate the orientation sensitive switch and create a physical connection between the battery and microcontroller. The microcontroller will continuously communicate data to an RF transmitter, which transmits the bridge identification number, the float-out device serial number, scour depth and scour location. The float-out device is lowered into a hole drilled with a standard NX3-3/16 inch inner diameter hollow stem auger and covered with sediment. As scour occurs at the pier or abutment, the float-out device is released and relative buoyancy causes the float-out device to rise to the surface and activate the orientation sensitive switch. The radio frequency receiver continuously waits for a packet to be received from a float-out device. Once a packet is received, the microcontroller verifies that the data has not been corrupted during transmission and converts the scour information received to a corresponding light indicator LED. The light indicators are activated and the LEDs are enabled to provide an up-to-date status of the scour locations and depths.

The float-out device requirements include the following:

- Software that remains resident on the float-out device for 20 years after programming.
- An enclosure that maintains water tight integrity after being subjected to a simulated water pressure equivalent of 50 PSI for a period of 48 hours.
- An enclosure that withstands the impact of four (4) free falls onto a concrete pad from a height of 10 ft. After each free fall, the float-out device is tested to ensure the electronics transmit, at which point the float-out device will be reset for the next test.
- A battery system capable of operating the float-out device for at least 20 years after deployment of the float-out device.
- Wireless transmission capabilities up to 1000 feet in open air.
- Wireless transmission capabilities for 1 hour after release depending on the battery supply and lifetime capabilities.
- Broadcasting abilities of the float-out device that can be tested prior to installation with the ability to reset the float-out device.
- A reset switch that is used to reset the float-out device after the functionality test.
- An enclosure with an outside diameter no larger than 3-1/16 inches. This allows the float-out device to fit inside a NX hollow stem auger with a 3-1/16 inch inside diameter.

The receiver and light indicator requirements include the following:

- The ability to be powered from AC power, DC batteries, and/or solar power.
- The ability to switch to DC battery power in the event of a power outage.
- An enclosure for the receiver and the light indicators that can provide protection against water, ice, and snow and contains a key lock to prevent tampering.
- A receiver design that simplifies the addition of wireless data transmitting capabilities.
- A light indicator with sixteen (16) LEDs viewable from 200 feet in daylight ($\sim$ 110,000 lux) using binoculars.
  - One LED indicates that the receiver and light indicators are powered.
  - Fifteen (15) LEDs divided into five (5) groups of three (3) lights.
  - One LED periodically indicates that the receiver software is executing properly.

- The groups of three (3) LEDs are assigned to a specific sub-structure on the bridge.

During Phase 1, an investigation of float-out devices was performed and a proof-of-concept prototype was developed that adhered with the requirements agreed upon by PennDOT. During Phase 2, the focus of the research was to modify the Phase 1 prototype for a production ready system and verification testing. This document details the requirements for the float-out devices, the receiver unit and the light indicators, as specified by the work order.

3 Modifications to Phase 1 Prototype

During Phase 2 Task 1, the objective was to evaluate the Phase 1 proof-of-concept prototype and determine the required adjustments and testing needed to deliver a production prototype system. The following section covers the suggested changes to the Phase 1 prototype system.

3.1 Receiver Unit

Due to changes in the design from Phase 1 to Phase 2, multiple adjustments have been made to the topology and corresponding nomenclature of each component in the system. The Phase 1 receiver unit is now referred to as the radio frequency receiver. The Phase 2 light indicator unit is now comprised of a group of light indicators. Each light indicator refers to a single group of four LEDs under a focusing lens. A light indicator printed circuit board refers to a group of two light indicators on one printed circuit board with corresponding control electronics. The radio frequency receiver and light indicator unit are housed in one enclosure and are collectively referred to as the receiver unit.

3.1.1 Radio Frequency Receiver

In Phase 1, the float-out device prototype was developed around the Texas Instrument MSP430 microcontroller and the Linx Technologies RXM-433-LR radio frequency receiver. The combination of these two integrated circuits is obsolete in processing efficiency and power management when compared with currently available integrated circuits. The Phase 2 design of the radio frequency receiver is based on the Texas Instruments CC1111F32. This is a low-power System-on-Chip (SoC) that combines an 8051 microcontroller, 32kB flash memory, a hardware USB controller and sub-1GHz RF transceiver in a 6mm by 6mm QFN package. The Texas Instruments CC1111F32 microcontroller directly controls each of the light indicator printed circuit boards without the need for a communication protocol to be developed and additional control electronics. The Texas Instruments CC1111F32 is code and hardware compatible with the Texas Instruments CC1110F32. The code compatibility makes the design and debugging of the embedded software a simple procedure.

The hardware USB controller allows a PennDOT employee to connect to and communicate via a laptop to the radio frequency receiver to retrieve a list of current float-out devices that have been released. This will be useful in the event that the float-out device bridge scour monitoring system is deployed to multiple bridges along the same river. A float-out device can communicate with any of the receiver units along that river. A hardware reset has also been implemented, allowing a PennDOT employee to manually reset the receiver unit after the initial installation. The receiver unit is initially used to test the operation of each float-out device before installation occurs. Four status LEDs are present on the radio frequency receiver that provide a visual indication of scour to the PennDOT employee. These status LEDs are separate from the light indicators and provide information concerning the operation of the radio frequency receiver include power, radio and light indicator status. The USB control and status LEDs are covered in-depth in Section 7.

3.1.2 Light Indicators and Light Indicator Printed Circuit Boards

The Phase 1 Light Indicator prototype was designed to be mounted to a substructure in a separate enclosure with the receiver unit transmitting power and control signals to each light indicator unit. Because of the location of the light indicator unit, the LEDs need to be viewable from 200 feet in daylight using binoculars, approximately 100,000 lux. The Phase 1 design is more expensive, power inefficient and complicates the installation of the scour monitoring system. During Phase 2, the receiver unit and light indicator unit were combined into a single enclosure. The Phase 2 requirements state that five groups of three LEDs will indicate three separate scour depths. The light indicators have been designed with four LEDs that indicate the current scour depth. The Luxeon Rebel High Power SMD LEDs were selected because they can be driven with 500mA, are compact in size and are available in a variety of colors. The Luxeon Rebel LEDs on each light indicator are green, white (6500K), amber and red. The green LED indicates that no float-out device has been released at a given location. The white, amber and red LEDs indicate each of the three float-out devices that have been buried at specific depths. The four LEDs are placed in a close proximity below a quad-LED lens, Khatod PL115125, that provides a 20^o beam width for each LED.

The Texas Instruments TL4242 adjustable LED driver is used to drive up to 500mA through the LED. The current is determined by a 0.25W resistor ranging between 0.25Ω to 2Ω or 600mA and 90mA, respectively. A 0.75Ω resistor was used in the design corresponding to an approximate drive current of 250mA. The pulse width modulation (PWM) pin on the Texas Instruments allows for the LED to be toggled on and off to conserver power. Each LED driver is controlled by a NXP HEF4555B dual 2-to-4 decoder. The decoder interprets a 2-bit binary signal from the radio frequency receiver and toggles one of four output pins to a high logic voltage. Each of the output pins on the decoder connects to the enable pin on the LED driver. With this configuration, only one of the Luxeon Rebel LEDs can be on for a given light indicator.

Each light indicator printed circuit board has a single decoder that controls two light indicators. The decoder also contains an enable, that when forced low, will turn off all of the light indicators. Each decoder enable is connected to the same general-purpose input output (GPIO) pin on the radio frequency receiver's microcontroller. This allows the embedded software to easily turn on and turn off all of the light indicators with a single control signal. Each light indicator printed circuit board contains two light indicators and one decoder. Each light indicator contains four Luxeon Rebel LEDs and four LED drivers. Figure 2 shows the schematic for a light indicator printed circuit board. Each output of the decoder has a 100Ω resistor placed in series to reduce the amount of external noise coupled into the long traces.

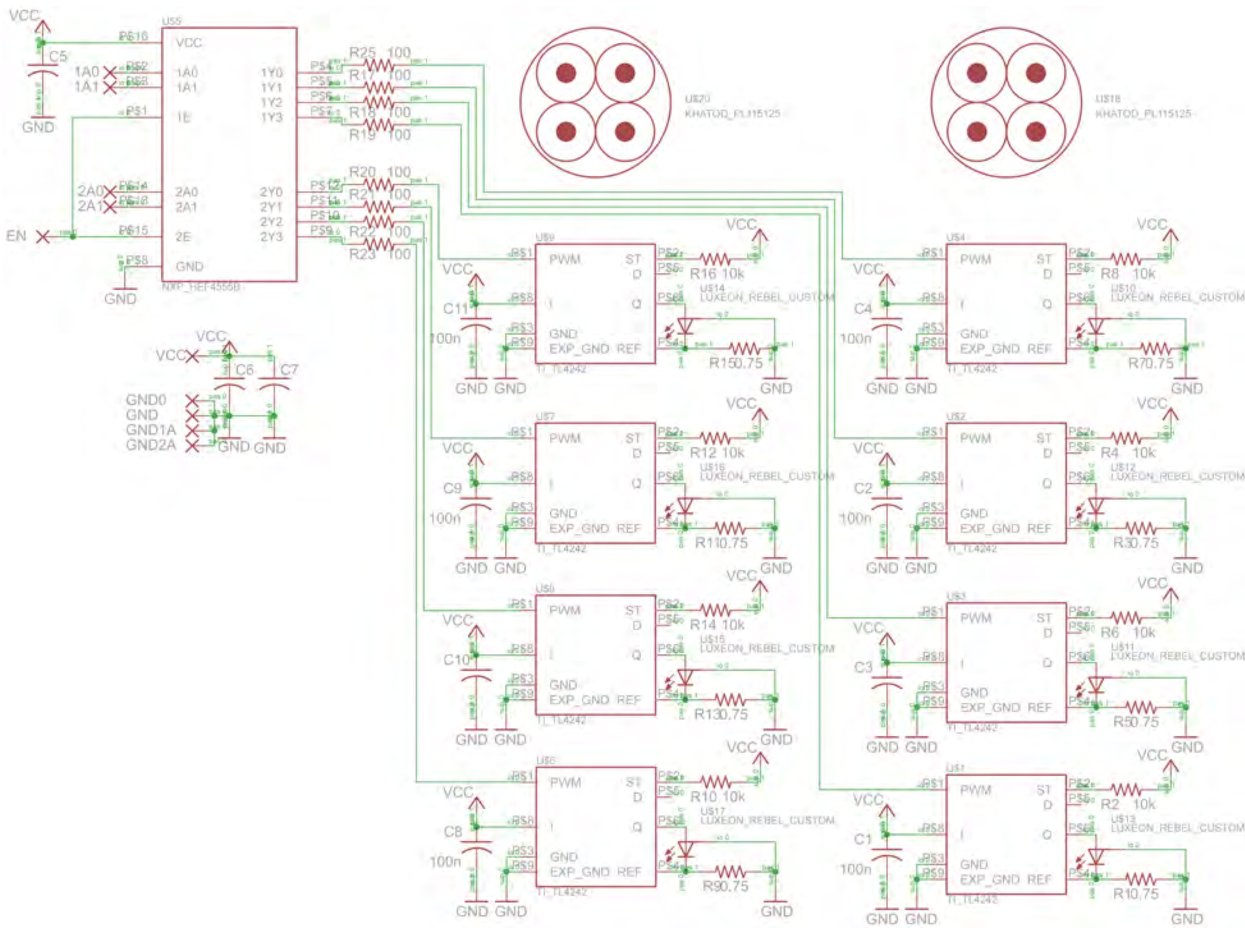

Figure 2: Light Indicator Printed Circuit Board Schematic designed in CadSoft Eagle

Figure 3 shows a single light indicator printed circuit board during a simulated scour event. The simulated scour event was created using custom test code on a microcontroller to simulate the reception of a float-out device at each depth for a given scour location after a button on the microcontroller has been pressed. This test was created to ensure that the two light indicators on one light indicator printed circuit board could be distinguished from each other at 200 feet. A vias is used as an electrical connection between physical layers of a printed circuit board. Thermal vias are used to dissipate heat from one location on the printed circuit board to another. These thermal vias are important inclusions on the light indicator printed circuit board as each Luxeon LEDs will dissipate 1W of power, creating significant heat. The design recommendation from the datasheet was implemented and no thermal problems were seen during operation.

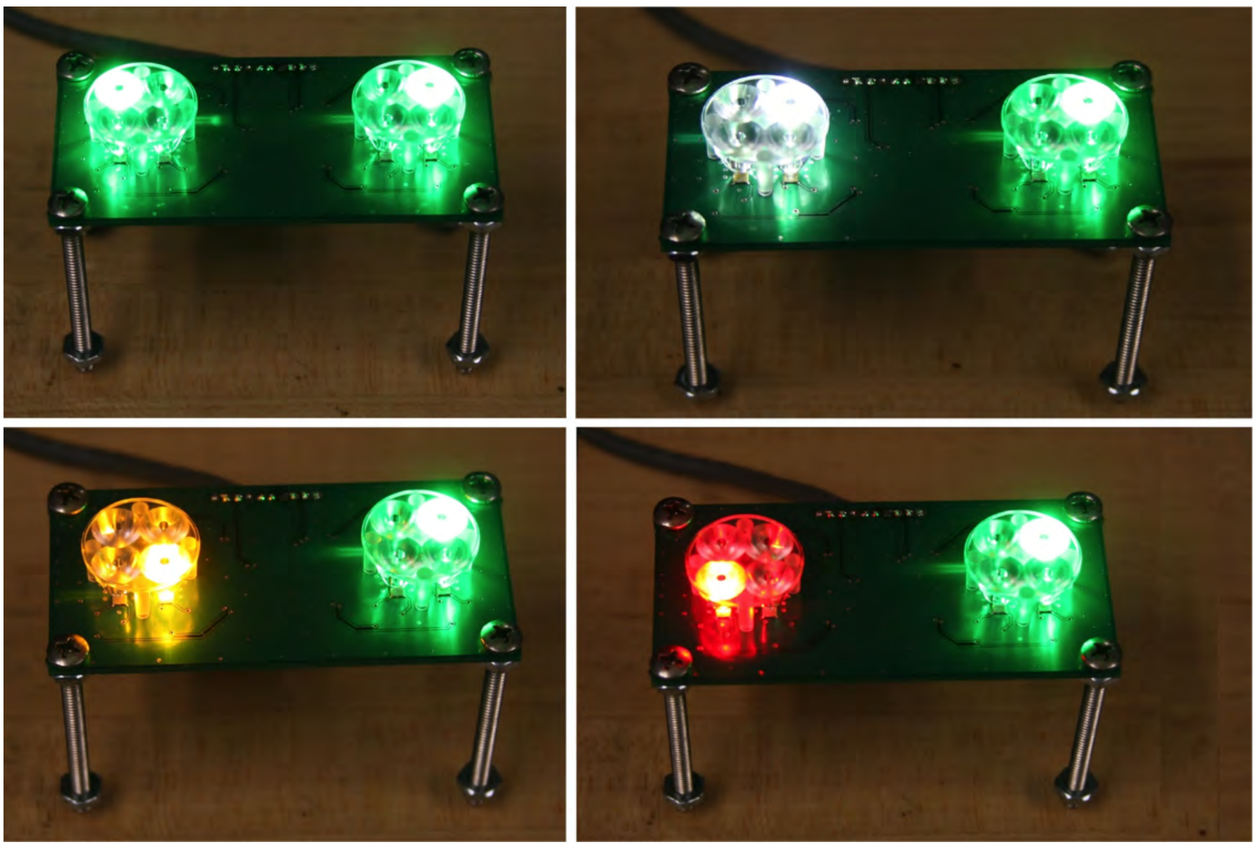

Figure 3: Light Indicator Simulating a Scour Event at Various Depths

3.1.3 Receiver Unit Housing

The Phase 2 light indicator unit and the receiver unit have been combined into a single enclosure that will be pole mounted near the bridge. The requirements of Phase 2 state that the light indicators must to be viewable from outside of the enclosure and the enclosure must provide sufficient protection from rain, snow, debris and tampering. Ideally, a stainless steel enclosure would be used as it would provide the greatest degree of durability and tamper proofing. Multiple holes would need to be drilled into the stainless steel cover for the LEDs to be viewable. If holes are drilled in the stainless steel, additional weather sealing must be implemented to ensure that the electronics inside are operational in extreme weather conditions. Due to the wide range of harsh weather conditions in Pennsylvania, it would be difficult to guarantee the weather seal over the lifetime of the receiver unit. A polycarbonate enclosure with a clear cover was found to be the optimal balance between weatherproofing, durability and externally viewable LEDs. A NEMA 6P rated enclosure was chosen, which is capable of withstanding submersion in water, protects against corrosion and will remain undamaged after the formation of ice around the enclosure. Figure 4 shows an image of

Figure 4: Receiver Enclosure with Receiver Unit, Two Light Indicators and Patch Antenna

the 12.5x11.5x5.2 polycarbonate NEMA 6P enclosure purchased from McMaster-Carr. The receiver unit enclosure contains a radio frequency receiver interfaced with two light indicator printed circuit boards. Each of the components inside the enclosure is mounted to the stainless steel back plate using #10-24 2.5 machine screws. Stand-offs were used between the printed circuit board and the stainless steel back plate to provide support for each of the boards. The dimensions of the receiver unit enclosure allow four light indicator printed circuit boards, or eight light indicators, to be mounted to the back plate. The receiver unit enclosure has been mounted to a 4” PVC pipe to provide a mobile platform that allows for consistency during testing in the laboratory and in the field. A patch antenna has been mounted to the PVC pipe above the receiver unit enclosure with cable routed through the PVC pipe to a hole in the bottom of the receiver unit enclosure. The patch antenna connects to the radio frequency receiver board with an SMA connector. The holes in the bottom of the receiver unit enclosure for the antenna and power are sealed using an Ancor marine wire seal for wire OD 0.08” to 0.24”. The enclosure is sealed with four captive screws, a neoprene gasket and two additional quick release latches that have been mounted onto the enclosure for a locking mechanism. Figure 5 and Figure 6 show images of the captive screw and quick release latches.

Figure 5: Captive Screws to Ensure the Neoprene Seal is Watertight

Figure 6: Quick Release Latch with Locking Mechanisms

3.1.4 Solar Power and Battery Backup

Although the use of AC power at the bridge would be ideal, it is not recommended as the sole power source for the receiver unit due to the variability in weather conditions. If the power source for the receiver unit is unreliable, the radio frequency receiver may not register the release of a float-out device. In addition, many bridges that require a form of scour monitoring are in locations that do not have access to AC power at or near the bridge. A solar power system with multiple solar panels and a battery backup controller is suggested. The number of solar panels and the power output can be determined by the continuous current draw of the receiver unit and capacity of the battery bank. A Photovoltaic (PV) Maximum Power Point Tracking (MPPT) controller is a device that interfaces the receiver unit to the solar panels and battery bank, providing a regulated DC voltage from the solar panels or the battery.

The location of the receiver unit depends on the location of maximum available sunlight. Since the individual solar cells inside of the solar panel are often wired in series, shade cast onto a small portion of the solar panel can have significant effects on the output power of the solar panel. For example, if 50% of a single solar cell inside of the solar panel is in the shade, the output power of the entire solar panel will be reduced by 50%. Because of this, it is recommended that multiple solar panels are placed in parallel. When there is sufficient light cast onto the solar panel array, the MPPT controller will provide power to the receiver unit and simultaneously charge the sealed AGM batteries. When there is insufficient light supplied to each panel, the sealed Absorbed Glass Mat (AGM) lead-acid battery bank will provide power to the PV MPPT controller. The quantity and capacity of each battery will determine the lifetime of the receiver unit without a sufficient light source. Table 1 shows the calculations for the required battery capacity.

In order to determine the minimum required battery capacity and solar panel configuration, the current draw and days of system autonomy must be known. The depth of discharge is a divider that provides a safety factor to prevent over-discharging the battery bank. As the depth of discharge for the battery bank increases, the number of charge cycles decreases due to the chemical stresses of a complete discharge and charge cycle. Although lower ambient temperatures allow for increased battery lifetimes, the capacity of the battery bank is reduced proportionally. This effect is designed for using the battery temperature multiplier. The adjusted sun hours accounts for the misalignment between the sun and the solar panel throughout the day. Because of this misalignment, the solar panel will only output the maximum power during a short period during the day. The sun hours is a constant factor

Table 1: Battery Calculations for Off-Grid Power

Days of Autonomy	45 Days
Continuous Current	0.2A
Capacity per Day	4.8 AHr
Battery - Depth of Discharge	0.5
Battery - Temperature Multiplier	1.5
Battery - Capacity Required	648 AHr
Sun Hours	4.2 Hr
Solar Temperature Multiplier	1.55
Adjusted Sun Hours	2.7097 Hr
Solar Panel - Power	100 W
Solar Panel - Current	5.814 A
Solar Panel - Daily Capacity	15.7542 AHr

ranging from 3.5 to 6 hours, depending on the location. Although calculations performed indicate that a single solar panel will provide enough energy to charge the battery bank, it is recommended that additional solar panels are implemented into the system as a safety factor within the allowances of the budget. The solar panel capacity output per day must be greater than the receiver capacity consumed per day. The solar panel and battery bank can be adjusted depending on the requirements of the receiver unit.

3.2 Float-out Device

Due to changes in the design from Phase 1 to Phase 2, the sensor unit is now referred to as a float-out device. Each float-out device is buried at a specific depth and location around a bridge abutment. This section details the modifications to the Phase 1 float-out design.

3.2.1 Float-out Device Hardware States

Each float-out device has been designed to operate and transition between one of three hardware states: Off-State, Arm-State and On-State. The Off-State occurs when the reset switch is open, caused by the placement of a magnetic actuator in the proximity of the magnetic reed switch, forcing the switch open. In this state, the ball bearing tilt switches will not activate the relay and the float-out device will remain in a dormant state regardless of the orientation. The Off-State is used during transportation and storage of the float-out devices to reduce the probability of false triggers. The Arm-State is entered when the magnetic actuator is physically removed from the proximity of the magnetic reed switch causing the switch to close, creating a short between the battery and the power circuitry. In the Arm-State, the ball bearing tilt switches have the ability to latch the relay closed. The float-out device should be transitioned from the Off-State to the Arm-State immediately prior to the installation. The On-State is transitioned to from the Arm-State after the float-out device is rotated at least 45^o from perpendicular orientation at which point the relay latches closed. Power is then delivered to the microcontroller and power amplifier and the embedded software begins to run. The float-out device will transmit for 20 seconds, at which point a reset signal is activated by the microcontroller and the float-out device is transitioned back into the Arm-State.

3.2.2 Microcontroller, Power Amplifier and Printed Circuit Board

In Phase 1, the float-out device prototype was developed around the Texas Instruments MSP430 microcontroller and the Linx Technologies TXM-433-LR radio frequency transmitter. The combination of these two integrated circuits is obsolete in processing efficiency, power management and size when compared with current commercial-off-the-shelf parts. The Phase 2 design of the radio frequency receiver is based on the Texas Instruments CC1110F32. This is a low-power System-on-Chip (SoC) combining an 8051 microcontroller, 32kB flash memory and sub-1GHz RF transceiver in a 6mm by 6mm quad flat no-leads (QFN) package. During Phase 1 research, there was no consideration given to FCC regulation with regards to the maximum allowable transmit power in the ISM bands, and the 433MHz band was implemented because the longer wavelength is less susceptible to interference from debris. Because the Texas Instruments CC1110F32 is capable of transmitting at $+10dBm$ from 300MHz to 928MHz, the System-on-Chip was used for Phase 2 experimentation at different RF ISM bands of interest. The Texas Instruments CC1190 RF front end was implemented to amplify the 915MHz $+10dBm$ signal from the Texas Instruments CC1110F32 to $+26dBm$ driving a 50Ω antenna load. The Texas Instruments CC1110F32 has a 25-year flash memory lifetime. Figure 7 shows an image of the populated printed circuit board with radio frequency shield, antenna and tilt switch circuitry.

Figure 7: Float-out Device Populated Printed Circuit Board

3.2.3 Bridge Variables and Transmission length

In order to maximize the probability of a successful RF transmission, the length of the message transmitting from the float-out device needs to be minimized. With longer transmissions, there is a higher probability that noise will be coupled into the message causing errors in the data received. In Phase 1, a 22-byte packet that includes the Bridge Identification number, the float-out device serial number, the scour location and depth and the 16-bit cyclic redundancy check follows a 1-byte preamble. In Phase 2, the microcontroller transmits a 7-byte preamble, a 1-byte sync and a 13-byte data packet that includes the Bridge Identification Number, serial number, scour location and scour depth. The Bridge Identification Number is a 14-digit decimal number that can be represented as a 7-byte hex value that is a PennDOT value corresponding to the bridge. The float-out device serial number is stored as a 2-byte hex value. The serial number is used as a seed value for the random number generator in the collision avoidance system. By using a unique serial number/seed value for each float-out device, the sequence of random numbers generated will be different. The scour location and depth are combined into a 2-byte hex value. The upper 12-bits are the scour location and allow for 4096 different installation locations at each bridge. The lower 4-bits are the scour depth and allow for 16 different installation depths. A 2-byte cyclic redundancy check is automatically generated by the microcontroller and appended to the end of the packet before transmission. While the 23-byte packet in Phase 2 is the same length as the Phase 1 packet, the longer preamble allows the radio frequency receiver to synchronize the transition timing before the data packet is received. If noise is present in the system, a longer preamble will help the radio frequency receiver to correctly interpret the packet.

3.2.4 Position Sensitive Power Trigger and Reset Switch

In Phase 1, the ball bearing tilt switches and reset circuitry created design flaws that make the float-out device unusable. The float-out device can only be transitioned from the Arm-State to the On-State once. Only with physical access to the capsule could the float-out device be transitioned from the On-State to the Arm-State. Because of the sensitive nature of the tilt switches, a false trigger is likely to occur during installation in which the float-out device inadvertently transitions into the On-State. In the Phase 1 design, once the float-out device enters the On-State, it will continue to transmit until the battery is depleted. Since the lifetime of the float-out device is dependent on the ability of the relay to isolate the battery from the electronics, the ball bearing tilt switches and power circuitry were redesigned in Phase 2. Figure 8 is the schematic of the redesigned tilt sensitive power enable with microcontroller reset.

The ability to reset the relay, transitioning the float-out device from the On-State to the Arm-State has been implemented using a bipolar junction transistor and a dual-coil latching relay, the Panasonic Electric Works DSP1A-L2-DC3V. Because the microcontroller will transition the float-out device from the On-State to the Arm-State after 20 seconds, the external reset of the float-out device is no longer required and the external reset switch has been replaced with an arm switch. The arm switch is a normally closed magnetic reed switch, the Hamlin 59065-040. The reed switch is rated for 200V DC and 1.5A that provides sufficient overhead for the 4.2V at 850mA of the float-out device. When a magnetic actuator is placed within 4mm of the magnetic reed switch, the switch will open. When a magnetic actuator is removed from the proximity of the magnetic reed switch, the switch will close. During transportation, the magnetic actuator is secured to the float-out device with a silicone adhesive, forcing the float-out device into the Off-State.

The Phase 1 ball bearing tilt switch has been replaced with the E-Switch TM-1000. The

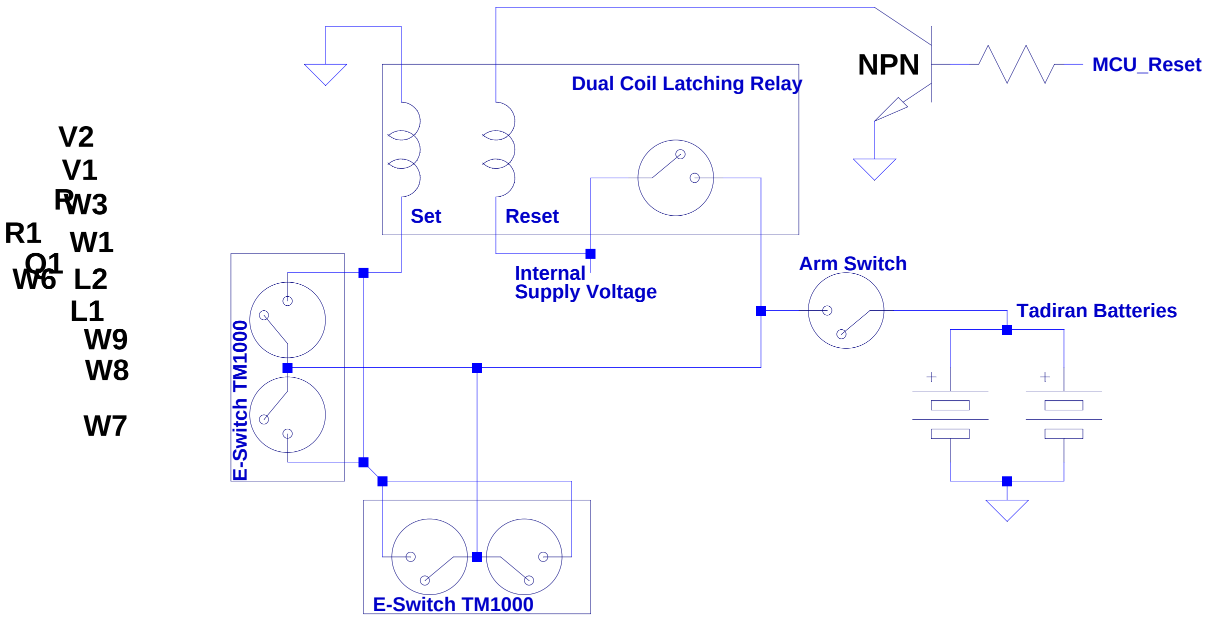

Figure 8: Position Sensitive Power and Reset Circuitry

TM-1000 is a 3-pin passive component that can independently detect rotation to the left or right by shorting pin 2, the middle pin, to either pin 1 or pin 3. The TM-1000 does not require orientation adjustments after the component has been soldered to the float-out device printed circuit board. By implementing two TM-1000 switches on the float-out device perpendicular to each other, an approximate 45^o rotation resolution in the X-Y plane has been achieved. Pin 1 and Pin 3 are connected on both tilt switches because the direction of rotation is not important. Pin 2 on both tilt switches is connected to the magnetic reed switch. The E-Switch TM-1000 orientation sensitivities are shown in Figure 9.

Because the dual-coil relay is latching, once the float-out device enters the On-State, only the microcontroller can force a transition to the Arm-State. Since the arm switch has no control of the relay, a hardware transition can occur that would be unexpected. If the float-out device is in the On-State and the magnetic actuator is replaced, the float-out device will enter the Off-State. If the magnetic actuator is removed again, the float-out device will enter the On-State instead of the Arm-State and the 20-second timer on the microcontroller will restart. This transition of states does not affect the operation of the float-out device.

During the startup of the Texas Instruments CC1110F32, all of the general purpose input output pins are configured as output and set to high. Although the general purpose input output reset pin is set low in the beginning of the embedded program, the voltage pulse is

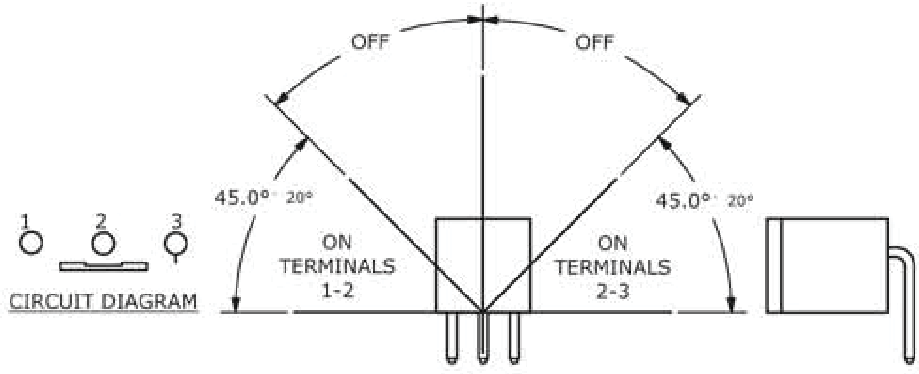

Figure 9: E-Switch TM-1000 Orientation Sensitivities

long enough to drive the base of the bipolar junction transistor, transitioning the float-out device back into the Arm-State. This can cause a continuous cycling between the Arm-State and On-State. This problem was solved through the addition of a 1000Ω ferrite bead in series with the bipolar junction transistor's base resistance. The ferrite bead acts as a low-pass filter, effectively blocking the voltage pulse during startup.

3.2.5 Tadiran Battery and Voltage Regulators

The battery used in the Phase 1 float-out device prototype was for testing purposes only and is not rated for the appropriate lifetimes or capacity that is required in the Phase 2 hardware. During research for a high energy density battery with a 25-year lifetime, the Tadiran TLM series was the only one to provide an expected lifetime near 25-years. The Tadiran TLM-1550/HP battery provides 2Whr of energy with an 18% capacity loss after 20 years at a storage temperature of 22^oC. While the battery is only rated for a 20-year lifetime, the battery will likely remain operational with an expected capacity loss of 22% after 25 years. While this calculation was performed based on a linear extrapolation of the capacity loss from the data sheet, the manufacturer does not guarantee it and a 20-year lifetime is documented.

When the float-out device is in the Arm-State, a low storage temperature will correspond to less accumulated capacity loss [5]. When the float-out device is in the On-State, a higher operating temperature will provide a larger battery capacity [5]. In order to determine the estimated lifetime of the float-out device after 20 years, the temperature of soil underground must be estimated. Because of the heat capacity of the soil, seasonal changes in soil temperature tend to vary less and lag behind air temperature. The estimated soil temperature at 3 feet depends on the depth of the soil type, air temperature and geographic location and is assumed to be $11^oC \pm 10^oC$ [3, 4, 1]. If the float-out device is released after 20 years in a -20^oC environment with 18% capacity loss, a single Tadiran battery will have a capacity of 164mAh. To ensure the float-out device can transmit for a sufficient period after release, it is recommended that two Tadiran batteries are placed in parallel corresponding to 1 hour and 17 minutes of float-out device battery life after 20 years.

Because of the change in microcontroller and the addition of a power amplifier, three voltage regulators are required for the float-out device. The Texas Instruments CC1110F32 requires a separate analog and digital voltage regulator to reduce noise coupling between the supply voltages. Two Texas Instruments TPS78230D were used for the analog and digital voltage regulators on the float-out device. The TPS79530D provides a 3.0V output at 150mA from up to a 6.0V input with a 130mV dropout. The 130mV dropout allows the regulator to continue to operate and supply a constant 3.0V voltage to the microcontroller as the battery voltage decreases down to 3.13V. The Texas Instruments CC1190 power amplifier requires a separate voltage regulator that can output higher currents than the regulators for the Texas Instruments CC1110F32. A single Texas Instrument TPS79530D provides a regulated 3.0V output at 500mA from up to a 6.0V input with 110mV dropout. Although the Texas Instruments CC1110F32 and CC1190 can operate down to 2.5V, the Tadiran TLM-1550HP voltage output decreases exponentially after 3.0V at -20^oC and the cut-out from the voltage regulator will have negligible effect on the float-out device lifetime.

3.2.6 PVC Pipe and Custom Caps

Because of the excessive weight of the commercial-off-the-shelf PVC caps, a custom cap was designed in SolidWorks and milled from a solid rod of PVC by the machine shop in the Swanson School of Engineering at the University of Pittsburgh. The custom PVC cap weighs 81.7 grams (2.88 oz.) while the commercial-off-the-shelf cap weighs 196.8 grams (6.945 oz.). The custom cap reduces the weight of each float-out device by 44.5%. The custom PVC cap has a constant wall thickness of 0.250 inch and the hole for the magnetic reed switch has a wall thickness of 0.100 inch. The cap is sealed onto the PVC pipe using PVC primer and cement to create an impermeable seal. A hole has been milled into the center of the cap to allow for a simplified mounting procedure for the magnetic reed switch in a known location. The magnetic reed switch mounting hole has no effect on the watertight nature of the PVC capsule. The printed circuit board will be mounted to the PVC cap with silicone sealant that ensures the printed circuit board will remain in the same location inside of the capsule.

A NPS 2.5 PVC pipe of 8-inch length was used to encapsulate the float-out device.

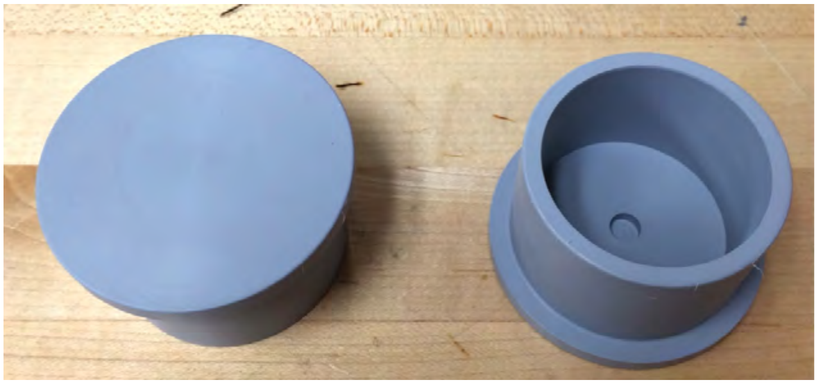

Figure 10: Top and Bottom of Custom PVC Cap

3.3 Wireless Communication

The design of wireless communication systems is a complicated procedure that involves a variety of trade-offs between carrier frequency, data rate, transmitting power, and operating distance. In order to determine the optimal carrier frequency, the Friis transmission equation, the link budget and the receiver sensitivity must be examined and evaluated with the system requirements. The Friis transmission equation relates the ratio of the power received and power transmitted to the distance between the antennas, the gain and directivity of the antennas. The Friis equation can account for antenna orientation mismatches, inefficiencies between the antenna and the electronics and absorption. When the Friis equation is converted to the decibel scale, the equation becomes an simple algebraic equation referred to as the link budget. Equation 1 assumes that the transmitter and receiver are perfectly aligned in a lossless media with negligible reflections between the antenna and electronics.

$$P_{r|dBm} = G_{r|dB} + G_{t|dB} + P_{t|dBm} - FSPL \tag{1}$$

$$FSPL = 20 \cdot log_{10}(\frac{4\pi}{c} \cdot f \cdot R) \tag{2}$$

where P_r is the power received, G_r is the gain of the receiving antenna, G_t is the gain of the transmitting antenna, P_t is the power transmitted and $FSPL$ is the free-space path loss. The link budget can be used to provide an initial indication of the expected operating distance in ideal conditions for a given system. Equation 2 is referred to as the free-space path loss equation that corresponds to the reduction in RF signal power due to propagation through air over a given distance (R) at a specific carrier frequency (f) where c is the speed of light in air. The gain of the transmitting antenna and receiving antenna are $0dB$ throughout the calculations. The free-space path loss is a constant value at 1000 feet for a specific carrier frequency. At 915MHz, the free-space path loss is 81.219dB. At 433MHz, the free-space path loss is 74.738dB. The transmit power can be adjusted within FCC regulation but should be as high as legally possible.

Through examination of Equations 1 and 2, approximations can be made about the free-space path loss with respect to the carrier frequency and the transmission distance with all other factors held constant in a given system. If the carrier frequency is doubled, an increase of $20 * log_{10}(2) = 6.0206dB \cong 6dB$, will be added to the free-space path loss coefficient, corresponding to a halving of the operating distance. To overcome this increase in free-space path loss and achieve the same operating distance, the transmit power must be increased by approximately $6dB$.

In the United States, the Federal Communication Commission (FCC) regulates the maximum emissions in Code of Federal Regulations Title 47 Part 15. The FCC regulations for emissions at 433MHz are detailed in Title 47 Part 15.231 with the limitations for emissions at 3 meters being no greater than $10,958.3\mu V/m$. When the emissions value at 433MHz is converted into an effective isotropic radiated power, the maximum continuous allowable transmit power is $-14.44dBm$. Since the FCC averages the emissions over a 100ms period, a gain of $20dB$ can be implemented if the transmission time is $1ms$ long. The 20dB gain means a maximum transmit power of $+5.56dBm$ at 433MHz is possible. The FCC regulations for emissions at 915MHz are detailed in Title 47 Part 15.247. A digital modulation allows a maximum transmit power of $+30dBm$ assuming a $+6dB$ bandwidth of at least 500kHz and a power spectral density no greater than $+8dBm$ in any $3kHz$ band during continuous transmission.

In order to determine the optimal ISM band to use for communication, the link budget must be calculated for the Texas Instruments CC1110F32 at a specific data rate and operating frequency. The link budget for 433MHz and 915MHz are shown in Table 2. At 433MHz, the Texas Instruments CC1110F32 has been configured to output $-14.440dBm$ at $1.680kbps$ and $+5.560dBm$ at $168kbps$ to achieve a 100ms and 1ms transmission time. At 915MHz, the Texas Instruments CC1110F32 and CC1190 have been configured to output $+26dBm$ for both $2.435kbps$ and $4.8kbps$ to ensure the emissions from the Texas Instruments CC1110F32 meet FCC regulation. The values for the receiver sensitivity were calculated using a linear approximation from values in the data sheet for data rates of 1.2kbaud, 38.4kbaud and

Table 2: Link Budget Calculations according to FCC Regulations

Frequency	433.920MHz		915.000MHz	
Data Rate	1.680 kbaud	168.000 kbaud	2.435 kbaud	4.800 kbaud
Transmit Time	100.00 ms	1.00 ms	68.99 ms	35.00 ms
Receiver Sensitivity	-109.897 dBm	-97.713 dBm	-107.734 dBm	-107.226 dBm
FSPL at 300m	74.738 dB		81.219 dB	
Transmit Power	-14.44 dBm	5.56 dBm	26.00 dBm	26.00 dBm
Fade Margin	20.719 dB	28.535 dB	52.515 dB	52.007 dB

250kbaud.

The fade margin is a design allowance that accounts for unexpected attenuation changes, i.e. humidity or interference and allows for the direct comparison between different communication systems. The fade margin is calculated by subtracting the free-space path loss and receiver sensitivity from the transmission power. When designing a wireless communication system, the largest fade margin possible is advantageous to ensure wireless communication is possible. When comparing the calculated fade margins in Table 2, 915MHz is approximately $+24dB$ greater than 433MHz. In a perfect environment, this increase in fade margin corresponds to an $8x$ increase in the operating distance at 915MHz from 433MHz.

4 Float-out Device

This section details the float-out device software architecture and hardware architecture designed for the Texas Instruments CC1110 System-on-Chip and the Texas Instruments CC1190 RF front end. The embedded software was designed around a simple finite state machine. The microcontroller transitions between four states, in a specific order, and only after a timer or radio event has occurred. The embedded hardware was designed in ExpressPCB, a free commercial software package that provides quick-turn printed circuit boards. In this section, the software states of the finite state machine will be displayed in all capital letters. The hardware states, discussed in Section 3.2.1, are shown with the first letter capitalized and a hyphen separating the labels.

4.1 Software Architecture

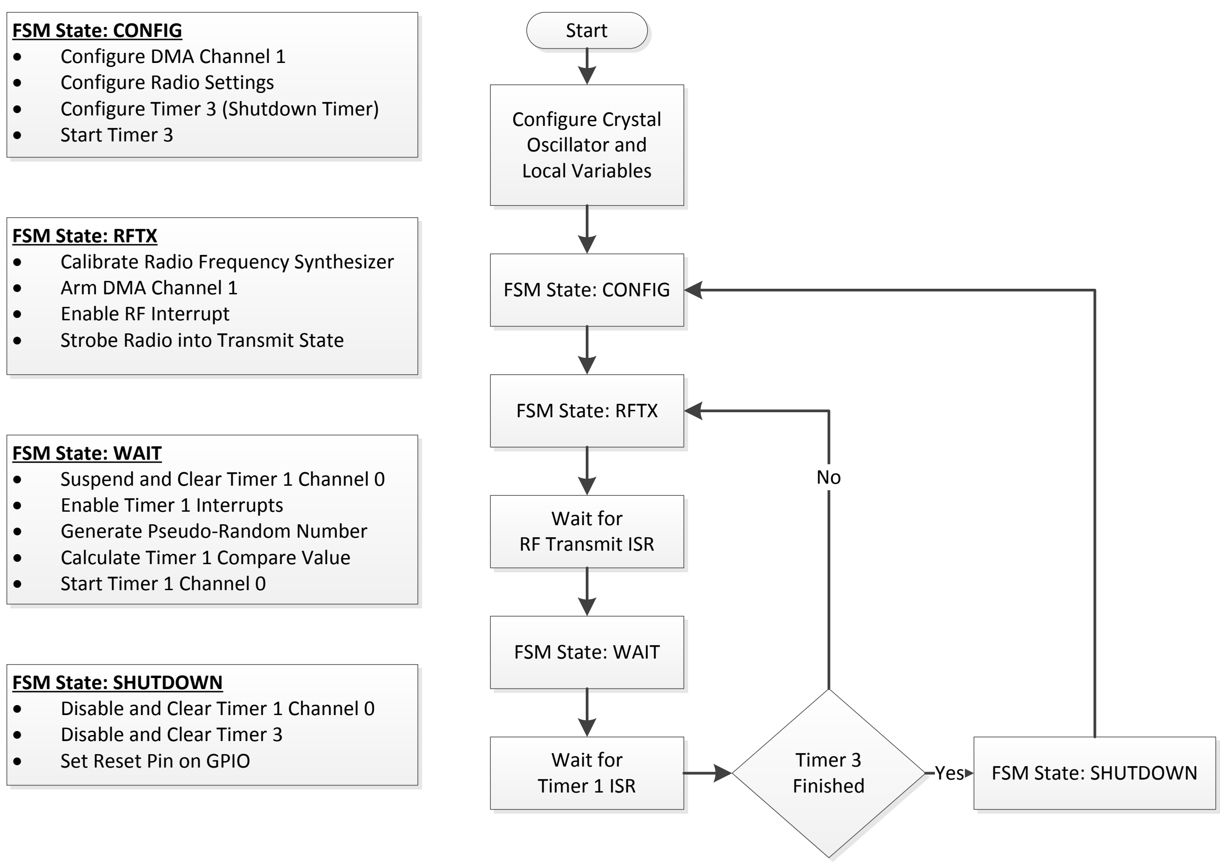

Figure 11: Float-out Device Software Architecture

Figure 11 shows the software architecture for the float-out devices. The states of the finite state machine are shown on the left side of the figure. The embedded software for the float-out devices is designed around a finite state machine with four states: CONFIG, RFTX, WAIT, and RESET. The code transitions through the states continuously and only after a hardware interrupt of timer 1, timer 3 or a radio transmission. Timer 1 is used to delay additional transmissions after a set period of time. Because timer 1 is a 16-bit timer and a wide range of delays are needed, it is configured for a clock tick of $157.5\mu sec$ and will interrupt after $200msec$, $400msec$, $800msec$ or $1,600msec$ depending on the pseudo-random number generated.

Timer 3 is used as the shutdown timer to allow the software to enter the RESET that forces the float-out device into the Arm-State. The finite state machine enters RESET only after the embedded interrupt for timer 3 occurs a specified number of times. Since timer 3 is an 8-bit timer configured with a clock tick of $157.5\mu sec$ or an interrupt period of $40.2msec$, a counter is incremented until 498 interrupts or $20.086sec$ occur. The finite state machine then transitions into the RESET state. When the float-out device has been released, the finite state machine will attempt to enter the shutdown state but will be forced back into the On-State because of the orientation of the device.

4.2 Hardware Architecture

Figure 12 shows the hardware architecture of the float-out device. The Texas Instruments CC1110F32 is configured to output of $+7dBm$ at 915MHz. The balun converts the balanced signal to an unbalanced signal and impedance matches the Texas Instruments CC1110F32 to 50Ω. There is a $+2dB$ loss between the balun and the saw filter that arises from impedance mismatches. The optimal input power into the Texas Instruments CC1190 is $+5dBm$ that is amplified to $+26dBm$ and delivered into the 50Ω antenna. The Texas Instruments CC1190 is configured for a high-gain mode with the power amplifier enabled and the low noise amplifier disabled. The 4-layer printed circuit board was designed with a radius of $1.125in$ and is shown in Figure 13. While only the top and bottom layers are visible, electronic copies of the file have been included as images of the design will not be helpful in recreating the printed circuit board due to the complexity of the design.

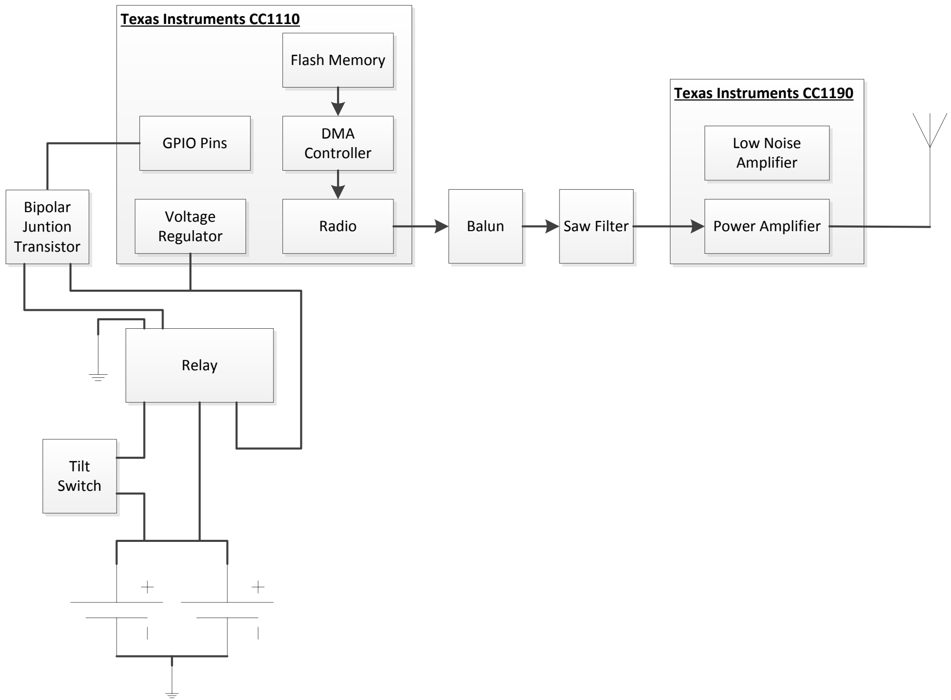

Figure 12: Float-out Device Hardware Architecture

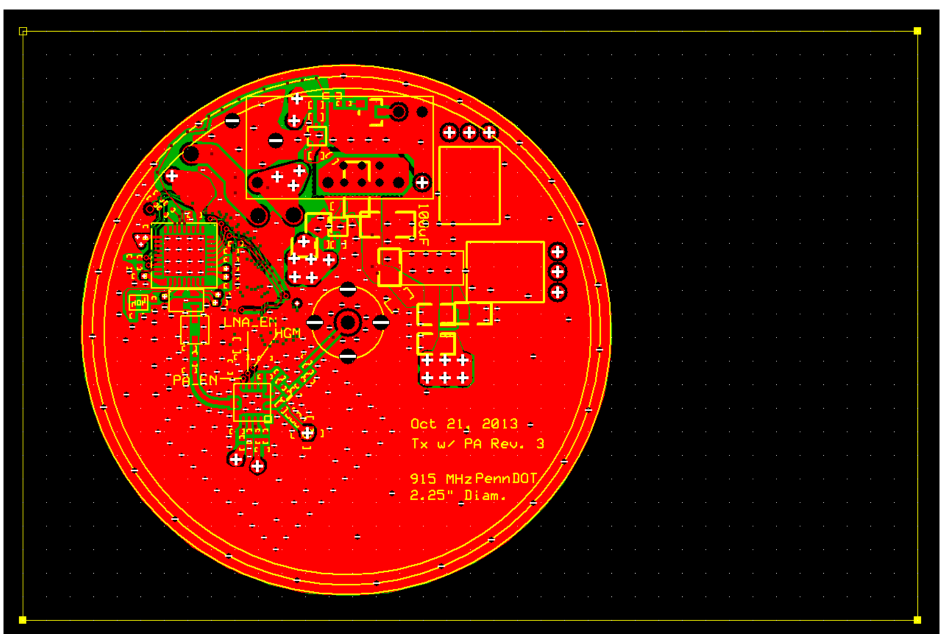

Figure 13: Float-out Device Printed Circuit Board in ExpressPCB Software Package

5 Radio Frequency Receiver and Light Indicators

This section details the software architecture and hardware architecture of the radio frequency receiver and the light indicators. The embedded software for the Texas Instruments CC1111 on the radio frequency receiver was designed around a simple finite state machine. The microcontroller transitions between four states, in a specific order, and only after a timer or radio event has occurred. The embedded hardware for the radio frequency receiver and light indicator printed circuit board was designed in ExpressPCB and CadSoft Eagle, respectively. Both of these software packages are free and allow for quick turn-around orders. In this section, the software states of the finite state machine will be displayed in all capital letters.

5.1 Software Architecture

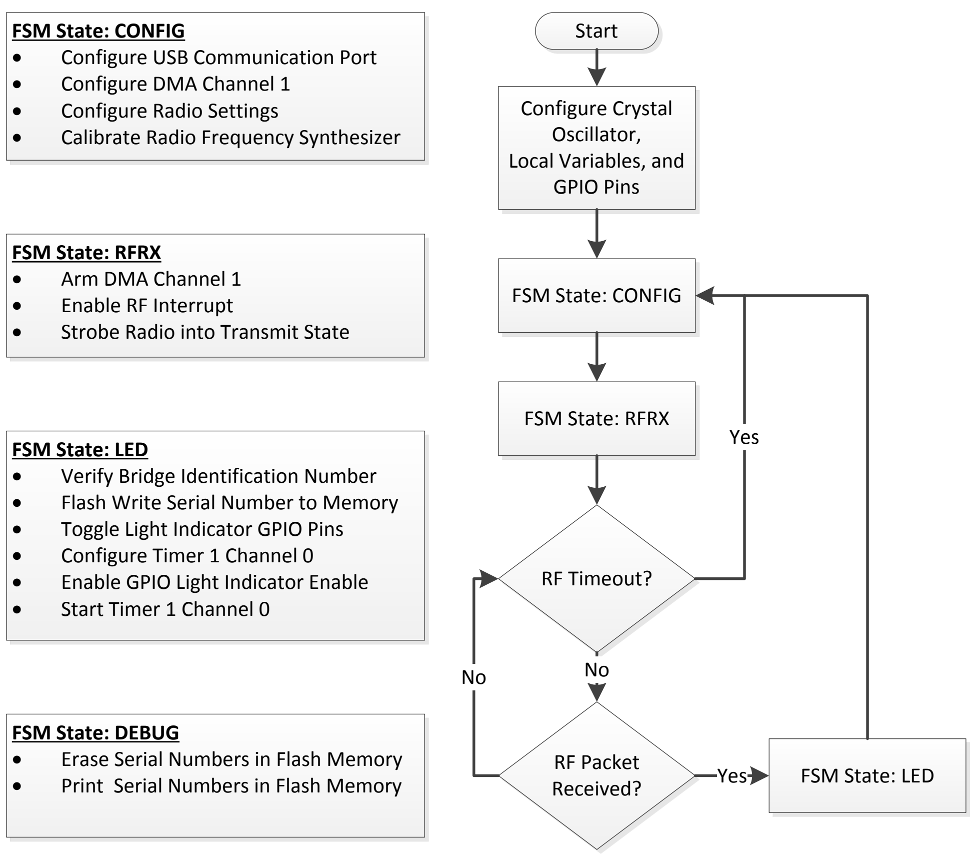

Figure 14: Receiver Unit Software Architecture

Figure 14 shows the software architecture of the Texas Instruments CC1111 on radio frequency receiver. The states of the finite state machine are shown on the left side of the figure. The embedded software for the radio frequency receiver is designed around a finite state machine with four states: CONFIG, RFRX, LED, and DEBUG. The code transitions through the states continuously and only after a hardware interrupt of timer 1, sleep timer, radio or USB. The radio frequency receiver embedded software waits for a packet from the float-out device. A radio timeout is configured for $30sec$ that will re-calibrate the radio to ensure that the phase locked loop generating the 915MHz carrier wave does not drift significantly.

Timer 1 is configured with a timer tick of $78.76\mu sec$ and an interrupt period of $2.5sec$ and is used to continuously turn-on and turn-off the light indicators to conserve power. An interrupt counter is used to determine a 24-hour period after a float-out device has been received. After 34,560 timer 1 interrupts, the light indicators will no longer turn-on and turn-off. While the addition of the USB port allows for communication with the Texas Instruments CC1111 through a computer program and the software architecture has been designed with this addition, the use of USB in the embedded program has not been developed completely and should be completed in the next work order. Since this was not a specified by the requirements of the work order listed in Section 2, it does not affect the operation of the float-out device monitoring system as designed.

5.2 Hardware Architecture

Figure 15 shows the hardware architecture of radio frequency receiver and the light indicator printed circuit board. The Texas Instruments CC1111F32 radio frequency receiver transmits control signals to the light indicator printed circuit board through 5 general purpose input output pins. Two sets of 2-pins indicate the LED to be turned on from the corresponding data received from the float-out device. A single enable pin connects to all of the light indicator printed circuit boards. Power is supplied from the radio frequency receiver printed circuit board to the light indicator. The solar panel, battery bank and maximum power point controller are included in the hardware architecture but were not investigated in this work order.

Figure 16 and Figure 17 show the radio frequency receiver and light indicator printed circuit boards. A push button switch has been implemented on the radio frequency receiver that activates the light indicators with their current status level for the duration of the button press. A hardware switch on the radio frequency receiver allows the receiver unit

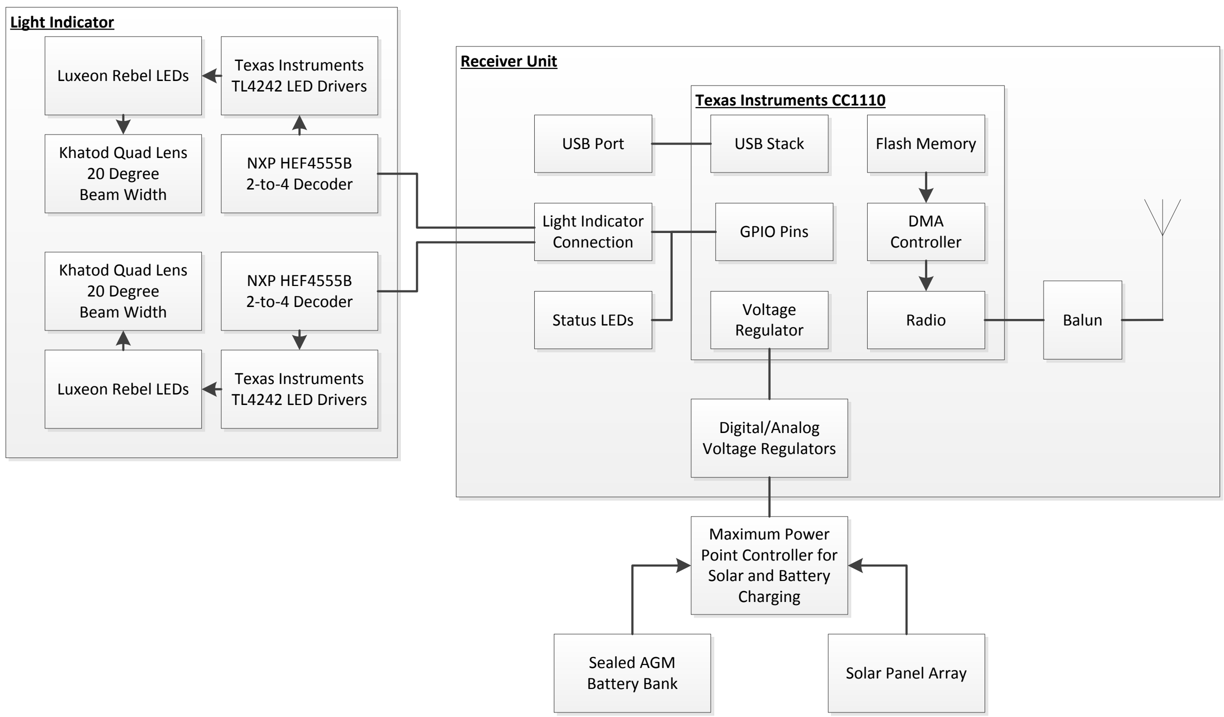

Figure 15: Radio Frequency Receiver and Light Indicator Hardware Architecture

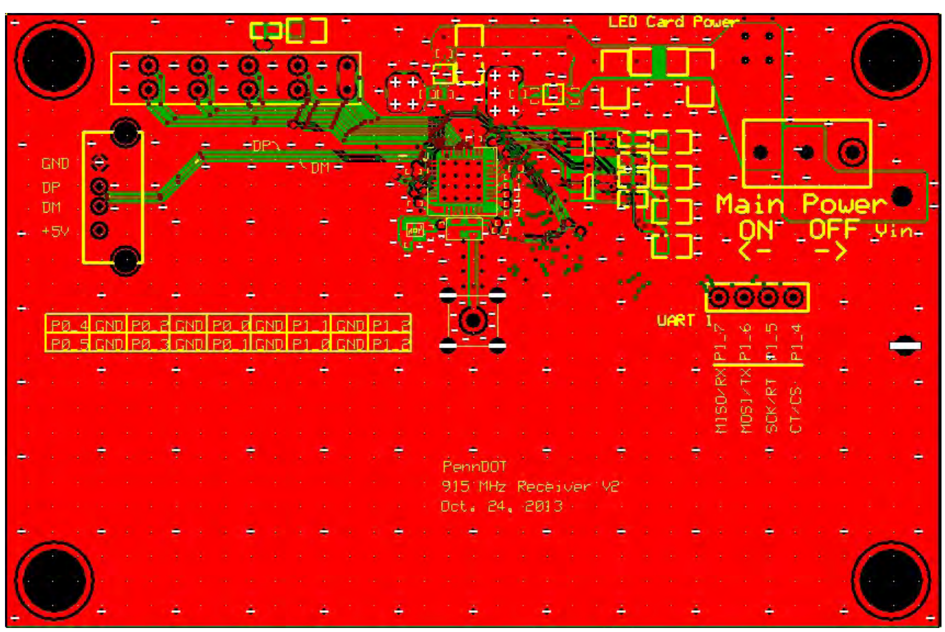

Figure 16: Radio Frequency Receiver Printed Circuit Board Designed in ExpressPCB

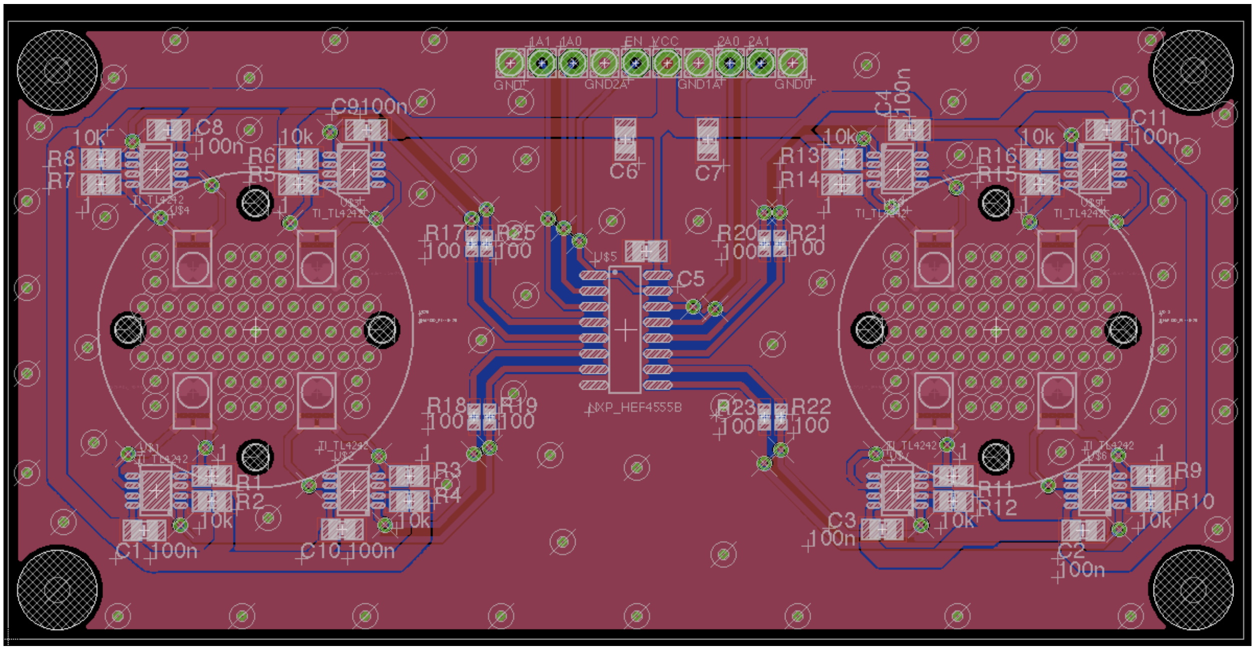

Figure 17: Light Indicator Printed Circuit Board Designed in CadSoft Eagle

to be turned-on or turned-off. It was used for testing purposes in the laboratory and can be removed if PennDOT does not want the ability for the receiver unit to be shut down. The radio frequency receiver printed circuit boards are the 4-layer MiniBoard Pro manufactured by ExpressPCB. The radio frequency receiver printed circuit board is 3.8in by 2.5in with 0.251in diameter mounting holes at each of the four corners, recessed by 0.2in. The light indicator printed circuit boards are the 2-layer PCBexpress Quickturn manufactured by Sunstone Circuits. The light indicator printed circuit board is 100mm by 50mm with 6.35mm diameter mounting holes at each of the four corners, recessed 4mm from each side.

6 Validation Testing

This section details the validation testing that was performed in the laboratory environment and during River Test 1 and River Test 2. The laboratory testing was to ensure the float-out device will conform to the specifications in Section 2.

6.1 Collision Avoidance

Because multiple float-out devices can be simultaneously released during a scour event, radio frequency packet collisions will occur if each float-out device continuously transmits. If a collision occurs, the radio frequency receiver will be unable to decipher the data transmitted from either float-out device and the scour event will not be registered. Because there is insufficient time to set up a time-division multiple access (TDMA) system between the float-out device and the radio frequency receiver, a multiple access system was developed for the bridge scour application. For a given transmission between multiple float-out devices to be successful, a period of at least twice the packet length is required. The packet transmission time is 36ms in order to achieve the high transmit power but a wait period (T) of 100ms is used for the collision avoidance to comply with FCC regulations. In order to minimize the number of collisions, a delay is introduced between successive packet transmissions. Since there is no control over the release time of each float-out device, four different delay lengths have been implemented into the transmission algorithm. Each delay is a multiple of two times the transmission length of the message: 200ms, 400ms, 800ms and 1600ms. The delay length after a packet transmission is chosen based on a pseudo-random number generated by the microcontroller that is seeded by the unique float-out device serial number. Additionally, the color code assigned to each float-out device depth will control the probability of the delay interval. This was designed to ensure that a scour depth of red would transmit more frequently than a scour depth of amber and white.

Table 3: Probability for a Specified Delay at a given Scour Depth

Delay	**White**	**Amber**	**Red**
200ms	25.00%	37.50%	50.00%
400ms	25.00%	37.50%	25.00%
800ms	25.00%	12.50%	25.00%
1600ms	25.00%	12.50%	0.00%

Because the float-out device will be placed into the Arm-State for a brief period of time, there is a probability the float-out device will remain in the Arm-State for a long enough period that the microcontroller shuts down completely before the tilt switches trigger the float-out device back into the On-State. If a complete shutdown occurs, the same sequence of delays over the 20 second period will occur. For this design, three float-out devices will be buried at various depths to monitor scour at a single location. Scour depth of red indicates the deepest possible scour while a scour depth of white indicates the shallowest possible scour level monitored at the bridge abutment. Table 3 shows the probability that a scour depth will transmit with a specified delay. The czollision avoidance system was successfully tested with four float-out devices transmitting simultaneously. Four float-out devices were used to simulate three scour depths, White/Amber/Red, being released from scour location 1 and a single float-out device, Amber, being released from scour location 2. A general purpose input output pin on the float-out device was set high at the beginning of a packet transmission and set low immediately after. A Saleae Logic16 logic analyzer was used to sample the general purpose input output pins on the float-out devices at a rate of 50MHz. All four float-out devices were started within 170ms of each other. Figure 18 shows the setup for the float-out collision avoidance protocol.

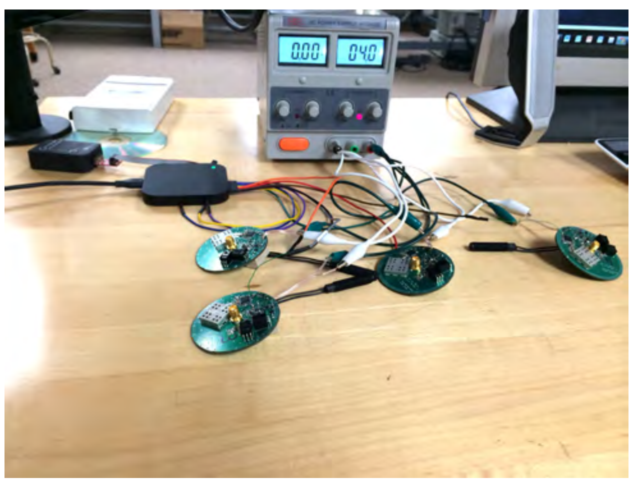

Figure 18: Collision Avoidance Testing Configuration

Table 4 shows the results of the collision avoidance test. The red scour depth transmitted most frequently while the white transmitted least frequently. Since this is a relatively small population, deviations from the transmission delays are expected. The collision avoidance protocol developed for the bridge scour float-out device monitoring system was tested successfully.

Table 4: Delay Percentages for Scour Levels

Color Code	Float-out Serial	Packets Transmitted	Packet Collisions
White	0x1234	24	12
Amber	0x4123	38	18
Amber	0x3412	33	11
Red	0x2341	46	16

6.2 Position Sensitive Power Trigger and Reset Switch

The position sensitive power trigger and reset switch is an imperative feature to achieve a 20-year battery life for each float-out device. In order to guarantee that no power is consumed in the Off-State and the Arm-State, the float-out device was mounted onto a gimbal and connected to a voltage supply and a precision multi-meter. The precision multi-meter is connected in series and the current output of the voltage supply was measured in the Off-State, Arm-State and On-State. This test verified the power requirements of the float-out device and the orientation sensitivity of the tilt switches. Figures 19, 20 and 21 show the orientation of the float-out device printed circuit board on the gimbal and the corresponding current that is being supplied to the electronics. The Rigol DM3058 has 5.5 digits of resolution that can accurately measure down to $200\mu A$. There was no measurable current in the Off-State or Arm-State. The current consumed by the float-out device in the On-State is a combination of relay drive current (100mA), the Texas Instruments CC1110F32 (36.2mA) and the Texas Instruments CC1190 (302mA). The tests performed on the position sensitive power trigger and reset switch proved a working prototype that allows for a 20-year lifetime of the float-out device.

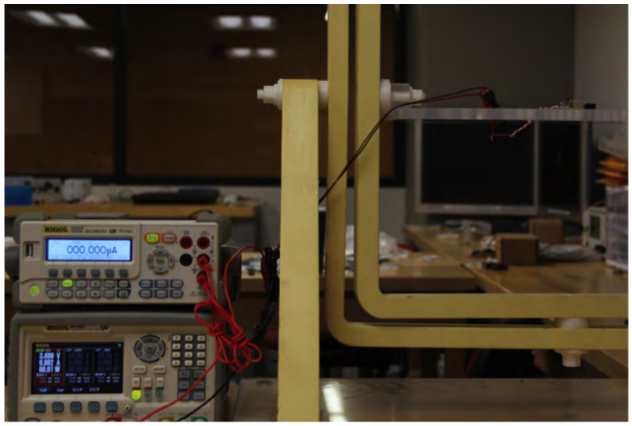

Figure 19: Position Sensitive Circuitry: Off-State

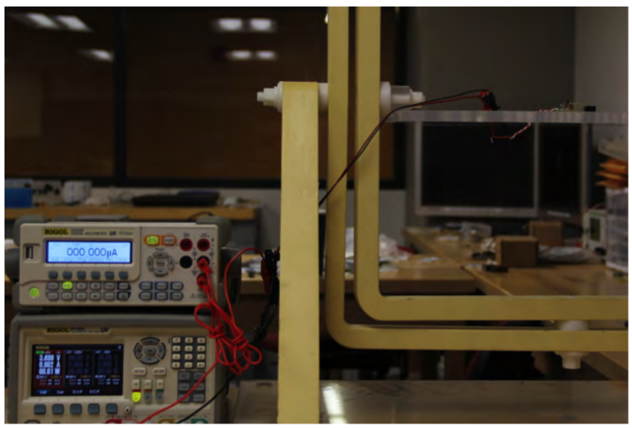

Figure 20: Position Sensitive Circuitry: Arm-State

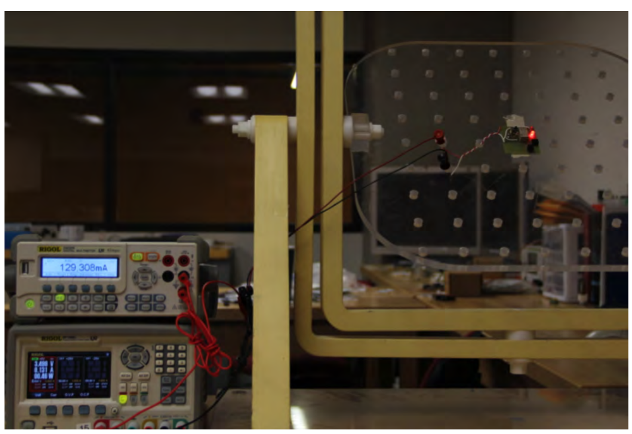

Figure 21: Position Sensitive Circuitry: On-State

6.3 Pressure Testing

As specified by Section 2, the float-out device must be able to maintain watertight integrity up to 50 PSI for a period of 48 hours. A pressure of 50 PSI corresponds to a fresh water depth of approximately 80 feet and an installation at that depth would not be practical or cost effective. The compressive and tensile forces on the chemical seal (PVC Cement) between the PVC pipe and cap can be approximated as the same value for submerging the capsule underwater and pressurizing the inside of the capsule. An air compressor was used to generate 80 PSI that was regulated to 50 PSI. All of the tubing and interconnects used were 0.25 inch NPT connections. A 0.25 inch brass bulkhead was secured to the top of the PVC cap using silicone to ensure an airtight seal. The float-out device was pressurized to 50 PSI and submerged for a period for 48 hours in shallow water to provide a visual indication of air leakage between the PVC pipe and cap. The float-out device was successfully able to withstand the 50 PSI pressure. Figure 22 shows the PVC capsule with a 0.25 inch brass bulkhead connector with the silicone sealing the outside of the bulkhead.

Figure 22: Float-out Device with 0.25” Bulkhead Sealed to custom PVC Cap

6.4 Drop Testing

The float-out device must be capable of withstanding the mechanical stress of installation while maintaining electronic operation. This mechanical stress was simulated by dropping the float-out device from 10 feet onto concrete. During each drop, the float-out device will be falsely triggered from the Arm-State into the On-State. The float-out device will transmit for 20 seconds before the microcontroller forces a transition from the On-State to the Arm-State. After this transition, the float-out device will be tested to ensure the electronics are operating. This test is performed by rotating the capsule to trigger the tilt switches and transition the float-out device into the On-State. After verification that the float-out device electronics are operational, the float-out device is reset and the test is performed again. A 10 foot segment of 4" PVC pipe was used to ensure that each drop occurred under the same controlled conditions. The tested float-out device was able to successfully withstand each impact and continued to operate electronically after four free falls. Figure 23 shows the drop test setup with a 10 foot 4 inch PVC pipe and a float-out device.

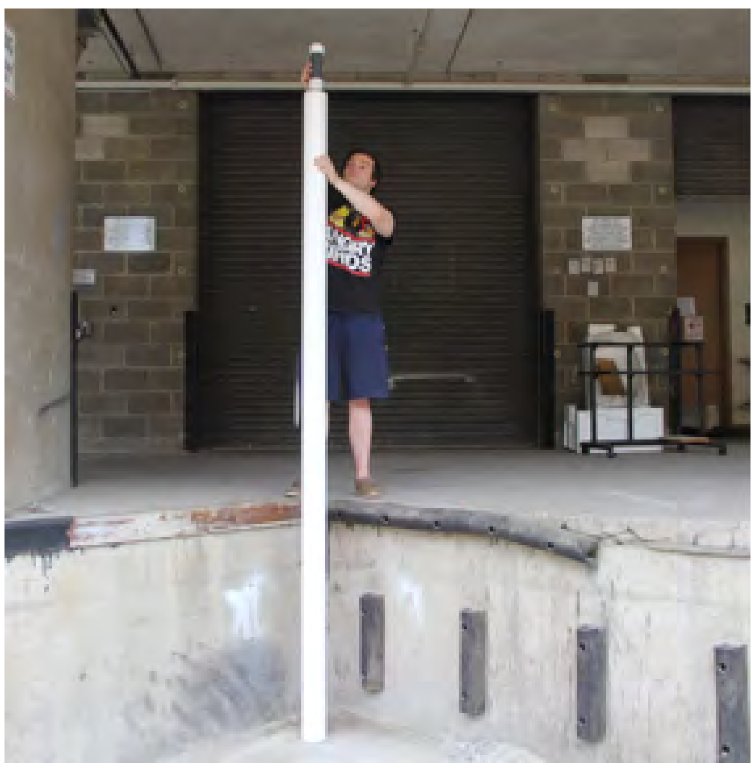

Figure 23: Test Configuration for the Drop Test

6.5 River Test 1

The Phase 2 River Test 1 was performed on Friday August 30th, 2013 at Founders Field in Cheswick, PA. Deer Creek runs through Founders Field under Cove Run Road. The stream provides optimal conditions for testing the bridge scour float-out device monitoring system. There is sufficient water flow and the stream depth varies between four (4) to twelve (12) inches. The float-out device was submerged vertically under water and was released three (3) separate times. The radio frequency receiver, located on the riverbank, successfully received the radio frequency signal and triggered the light indicators. The light indicators began flashing every 10 seconds. Since adjustments to the printed circuit board were still being made at the time of testing and internal access was required at Founder's Field, the float-out device was sealed at one end using Gorilla Tape.

Figure 24: PVC Capsule used during River Test 1

During River Test 1, it was found that the NPS 2.5 PVC floated low in the water due to the increase in weight from the caps. Since the float-out device printed circuit board was designed for the NPS 2.5 diameter PVC pipe, major changes would be required to the printed circuit board and operation could not be guaranteed with the smaller diameter NPS 2 sized pipe. Custom PVC caps were designed to fit inside of the NPS 2.5 pipe and a 44.5% reduction in weight was achieved.

6.6 River Test 2

The Phase 2 River Test 2 was performed on October 31st, 2013 at Deer Creek in Cheswick, PA. The objective was to verify the final operation of the bridge scour float-out device system with multiple float-out devices being released into a river simultaneously that would simulate a scour event occurring at multiple locations. The radio frequency receiver was configured to wait for communication from the float-out devices and toggle the appropriate light indicator. Figure 25 shows the sealed capsules of the float-out devices used for River Test 2. Each numbered float-out device corresponds to the float-out value in Table 5.

Table 5: River Test 2 Float-out Device Stored and Transmitted Information

Float-Out	Bridge ID	Serial Number	Location & Depth	
1	0xF0E1D2C3B4A59687	0x1234	0xA0	0x02
2	0xF0E1D2C3B4A59687	0x4123	0xA0	0x04
3	0xF0E1D2C3B4A59687	0x3412	0xC0	0x03

Figure 25: River Test 2 Float-out Devices Sealed for Deployment

The radio frequency receiver's populated printed circuit board is shown in Figure 26. There are four (4) status LEDs on the receiver unit: red, green, blue and white. The red

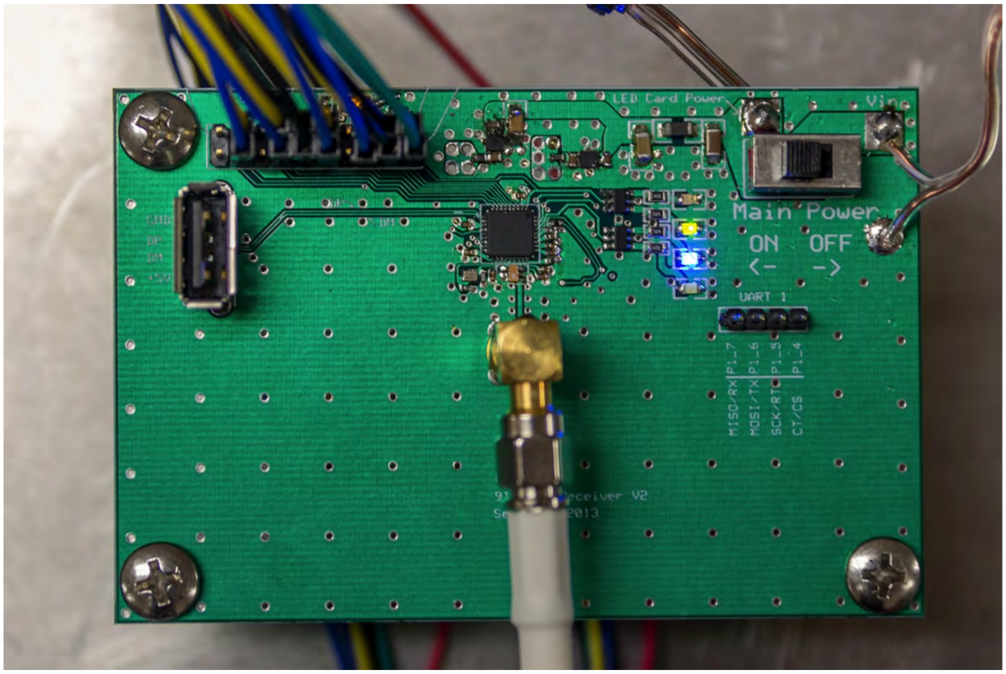

Figure 26: Receiver Unit Printed Circuit Board with CC1111 and USB Access

LED is an indicator that an error has occurred during the toggling of the light indicators. The green LED indicates the light indicator status. The blue status LED indicates that the microcontroller is currently waiting for an RF signal from a float-out device. The blue LED will toggle when the microcontroller has received a packet of data from the float-out device. The white LED indicates a float-out device has been successfully received. The white LED is only toggled when a float-out device is initially and successfully received and not for successive packet receptions. The USB port allows for a possible connection to the Texas Instruments CC1111F32 and can transmit a list of float-out devices that have been received. The serial communication port allows for a cellular modem to be attached to the printed circuit board. The blue, yellow, black, green and red wires that are connected to the receiver unit connect power, ground and enable to each of the light indicators. The receiver unit and float-out devices were tested in the lab prior to the river test. Each float-out device was triggered individually to ensure that the radio frequency receiver could properly communicate. After each successful trigger, the receiver unit was reset and all three float-out devices were triggered simultaneously. The radio frequency receiver properly toggled each light indicator unit corresponding to the correct float-out device location and depth. The laboratory test was documented in Figures 27, 28 and 29.

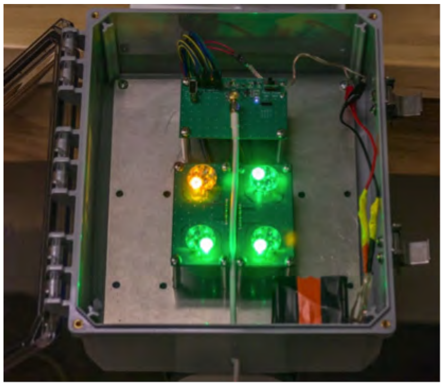

Figure 27: Light Indicator Status: Float-out Device 1 - Location: Yellow - Depth: Amber

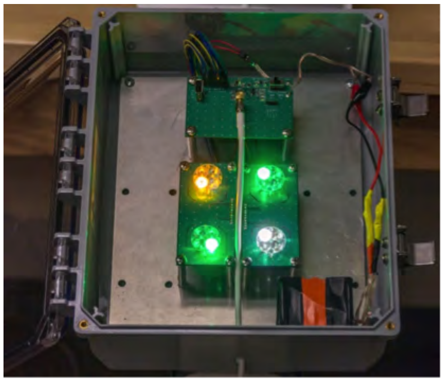

Figure 28: Light Indicator Status: Float-out Device 2 - Location: Orange - Depth: White

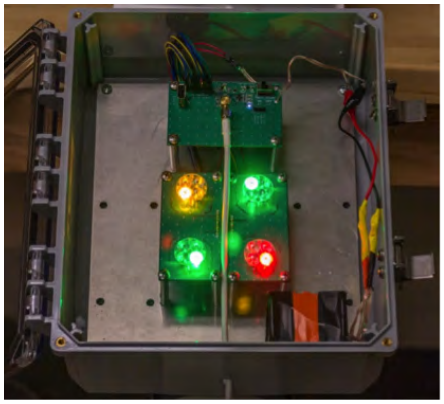

Figure 29: Light Indicator Status: Float-out Device 3 - Location: Orange - Depth: Red

During River Test 2, each float-out device was submerged underwater and individually released. Each float-out device rose to the surface and transmitted the information in Table 5 to the radio frequency receiver. The radio frequency receiver properly interpreted the data received from the float-out device and toggled the appropriate light indicator. It was noted that the radio frequency receiver consistently received a packet from the float-out device before the float-out device had entered the major lobe of the patch antenna. The ability to communicate with the receiver unit when the float-out device is outside of the major lobe is advantageous to the float-out system. The patch antenna will be mounted above the receiver unit enclosure on the same pole and oriented with the patch facing downstream. This will increase the probability that in fast moving waters, the radio frequency receiver will properly communicate with each float-out device released both downstream and at the release location. Multiple patch antennas could be implemented to increase the effective area of communication for the radio frequency receiver.

7 Draft Installation and Operation Instructions

This section contains detailed installation and operation instructions for the float-out device bridge scour monitoring system that was developed at the University of Pittsburgh. Multiple float-out devices are buried at various locations around a bridge structure. These devices are released after a scour event occurs, due to removal of sediment around each device. A radio frequency receiver located near the bridge continuously waits for communication from the float-out devices. Once successful communication has occurred, the radio frequency receiver indicates the location and depth of scour through light indicators. The system is comprised of two components:

1. Float-out device is a radio frequency transmitter and microcontroller that is encased in a watertight capsule. The capsules are buried in various locations and depths surrounding bridge abutments or piers.
2. Receiver unit is a radio frequency receiver and microcontroller that is installed near the bridge overpass. The receiver unit also includes an antenna and light indicators.

Before the bridge scour monitoring system can be installed, the location and number of float-out devices required must be determined. This will allow the University of Pittsburgh to provide the float-out devices to PennDOT with a watertight seal, as well as with the bridge identification number, scour location and color code programmed onto the microcontroller. The receiver unit will be provided to PennDOT fully assembled with light indicators corresponding to the locations and color codes of the float-out devices. The receiver unit is installed at a predetermined location near the bridge. The float-out devices are installed in their specified scour locations. The receiver unit contains light indicators that display the severity of scour for each float-out device and a microcontroller with flash memory to store the float-out device's serial number.

7.1 Receiver Unit Installation Instructions

The receiver unit is provided to PennDOT for the installation with the radio frequency (RF) receiver, microcontroller and appropriate number of light indicators mounted to the enclosure. The receiver unit will be pre-programmed for the corresponding Bridge ID. At least one receiver unit will be installed at a fixed location near the bridge to receive transmissions from a released float-out device. The installation location depends on the unique environment around each bridge, specifically: direct exposure to sunlight for a solar panel, downstream line-of-sight (LOS) to receive communication from float-out devices, accessibility for PennDOT and the space required for the installation. A balance between these factors listed above must be taken into account with priority given to sunlight exposure and line-of-sight for the antenna. The receiver unit location must be accessible to a PennDOT operator to facilitate proper monitoring and data retrieval. An operator must be able to access and open the enclosure to view the current scour status and retrieve float-out device data via the USB port. Additionally, the ground at the installation location must be capable of supporting the receiver unit post in severe weather conditions. Based on these criteria, the location of the receiver unit will be decided before the installation and PennDOT will install the support pole for the receiver unit at the predetermined location. Once the support pole has been installed, the receiver unit enclosure will be attached to the support pole. Holes in the bottom of the enclosure allow for an antenna feed and power connection. The antenna is mounted above the enclosure and is oriented downstream without objects obstructing the line-of-sight (LOS) of the antenna. This ensures that the radio frequency receiver will properly communicate with each float-out device as it is released and travels downstream.

A backup battery and maximum power point (MPPT) controller should be installed below the receiver unit in a separate enclosure. The solar panel should be mounted above the antenna to ensure that no blockage of sunlight will occur. The solar panel and battery backup system will connect to a maximum power point controller (MPPT) controller. This optimally converts the solar power and battery power to the receiver unit and simultaneously charges the batteries. The power supply output from the MPPT connects to the receiver unit enclosure using the power entry port on the bottom of the enclosure. After the receiver unit is properly installed, it is powered ON using the ON/OFF switch. In order to test the operation of each float-out device before installation, each float-out device will be activated and individually triggered to ensure the receiver unit will change the appropriate light indicator. After all of the float-out devices have been tested, the serial numbers from each float-out device that are stored in memory on the receiver unit need to be deleted. They are deleted by sending a RESET command from a computer through USB to the receiver unit. After the testing and installation of the float-out devices and a reset has been performed on the receiver unit, the receiver enclosure is sealed with four (4) captive screws and a neoprene gasket to protect against weather. Two (2) quick release latches have been mounted onto the enclosure that allow a lock to secure the receiver unit. Multiple receiver units can be installed on the opposite sides of the bridge for redundancy in receiving transmissions from released float-out devices. This allows access to current scour status from either side of the bridge. Multiple receiver units enable the ability for scour status information to be obtained without needing to cross the bridge, as the bridge may be unsafe after a scour event.

7.2 Float-out Device Installation Instructions

The float-out device electronics will be housed in cylindrical polyvinyl chloride (PVC) pipe segments with custom PVC caps. The float-out devices are pre-programmed with the bridge identification, a unique serial number, the scour location and the scour depth. The PVC pipes will be color coded and numbered according to the installation location and depth. A PennDOT Bridge ID number will be printed on the outside of the pipe for public safety reasons, i.e. identification of a float-out device by the public after the release. The physical nature of the tilt switches that activate the float-out device can cause false triggers during transportation. Because of this, a magnetic reed switch has been implemented between the battery and the electronics. When in the presence of an external magnet, the battery is completely disconnected from the electronics and the tilt switches are unable to activate the float-out device. This is known as the Off-State. The external magnet, in the form of a black plastic magnetic bolt, is mounted to the outside of the PVC cap with a small amount of RTV silicone. In order to activate the float-out device for installation, simply remove the black plastic bolt from the proximity of the PVC cap, causing the float-out device to enter the Arm-State. In order to test the float-out device, tilt it from a vertical orientation to horizontal and check the receiver unit for the corresponding LED indication. As soon as the float-out device enters the On-State, a 20 second timer begins running that will return the float-out device to the Arm-State after completion.

In order to install the float-out devices, the location and depth for each sensor must be determined. The hole is to be drilled in the sediment with a standard NX3-3/16 inch inner diameter hollow stem auger. Each hole must be kept as vertical as possible in order to ensure the float-out devices are not inadvertently triggered due to the tilt of the scour hole instead of a scour event. Initially, drill 6 inches deeper than the desired depth at which the float-out device should be buried. Once the hole is drilled, remove the drill head and slowly add material to the hollow stem while slowly retracting the auger 6 inches. During the fill process it may be necessary to tamp down the fill, with a push rod, in order to provide a sturdy base for the float-out device and to expel any water that may have entered the hole. This is done to ensure the vertical orientation of the float-out device during installation. If the float-out device is installed improperly, it will remain in the On-State until the batteries have drained. Once the float-out device has been armed and tested, place it in the hollow stem auger and push it down to the bottom using the push rod. Finally, continue to slowly fill the auger with fill material and compact it with the push rod while slowly retracting the auger until the hole is filled. Repeat this process for any additional float-out device that may need to be installed in the scour location. After the installation of the float-out devices is complete, the receiver unit can be reset after a period of 5 minutes has passed. This time period guarantees that no float-out devices are still transmitting from the false triggers during installation.

7.3 Operation Instructions

The receiver unit is configured to continually wait for communication from a released float-out device. Each LED indicates the current status of an installed float-out device at a pre-determined scour location. When a radio frequency (RF) transmission is received, the receiver unit verifies the bridge ID of the float-out device. If the bridge ID matches the receiver unit's stored value, the microcontroller stores the float-out device serial number in flash memory and toggles the appropriate light indicator corresponding to the scour location and depth. If the bridge ID does not match the radio frequency receiver's stored value, the bridge ID, float-out device serial number, location and depth are stored in flash memory and no light indicator is enabled. An LED on the radio frequency receiver will indicate if a float-out device has been received from another bridge installation upstream. Once the light indicators are enabled, the corresponding LED is toggled ON for a period of 2.5 seconds and then OFF for 2.5 seconds. After the 24-hour period, the light indicators are turned off and the released float-out device's serial numbers remain stored in flash memory on the microcontroller of the receiver unit. There is a push button on the radio frequency receiver that will enable the light indicators and display the current scour status.

The radio frequency receiver communicates with multiple light indicators depending on the number of scour locations installed at the bridge. Each light indicator printed circuit board (PCB) contains two (2) light indicators that show the current depths of scour at two (2) scour locations. Each light indicator has four (4) LEDs corresponding to each float-out device installed at a given scour location: green, white, amber, and red. The LEDs correspond to the depth of each float-out device installed. In a typical application, the green LED indicates the shallowest scour depth at a given location, the white LED indicates the second deepest float-out device, the amber LED indicates the third deepest float-out device, and the red LED indicates the fourth deepest float-out device. Therefore, the colors in order of scour severity are: green, white, amber and red. The color code is programmable and can be adjusted depending on the number of float-out devices. The receiver unit is equipped with a USB connection that allows PennDOT personnel to communicate RESET and STATUS commands to the receiver unit. The RESET command deletes all received float-out device serial numbers from the flash memory on the microcontroller. This brings the receiver unit back to the pre-testing state. The reset command should only be used after the installation process has been completed or in the event that a receiver unit will be re-purposed for another bridge installation. The STATUS command will have the receiver unit transmit a list of successfully received float-out devices serial numbers, bridge ID, scour location and depths to the PennDOT personnel's computer. These commands will be provided by the University of Pittsburgh and be packaged in an executable program that will run on the PC of PennDOT personnel.

The receiver unit has an ON/OFF switch that connects or disconnects the receiver unit to the power source. The receiver unit is mounted inside of a locked enclosure to ensure that the ON/OFF switch is physically protected from the weather and only accessible by PennDOT personnel. The receiver unit is turned to the ON position during initial installation and should not be turned off for any other reason. If the receiver unit is turned OFF, the list of float-out device serial numbers that is stored in the flash memory on the microcontroller are preserved. The list of stored float-out device serial numbers can be deleted if a RESET command is sent from a PennDOT personnel's PC through the USB port to the receiver unit.

A Appendix: Receiver Unit Bill of Materials

Part	Qty	Description	DigiKey Part Number
J1	1	SMA Female Through-hole	A97594-ND
J2	1	Vertical Type A USB Receptacle	UE27AE54100-ND
J3	1	1x4 Male Header 0.1" pitch	609-3255-ND
J4	1	2x5 Male Header 0.1" pitch 0.1" row spacing	609-3458-ND
J5	1	2x5 Male Header 0.05" pitch, 0.05" row spacing	S9012E-05-ND
R1	1	68 Ohm current limiting resistor	P68JCT-ND
R2,R3,R4,R5	4	470 Ohm current limiting resistor	P470JCT-ND
R6	1	56K 0402 0.1% Precision Resistor	P56KDCCT-ND
R7	1	2.7k 0402 1%	P2.7KDCCT-ND
D1	1	Yellow LED 0805	754-1135-1-ND
D2	1	White LED 0805	754-1651-1-ND
D3	1	Blue LED 0805	350-2046-1-ND
D4	1	Green LED 0805	754-1651-1-ND
D5	1	Red LED 0805	754-1135-1-ND
C1,C2,C5	3	100uF 20% X5R 1206	445-6007-1-ND
C3,C4,C6,C8	4	4.7uF 0603 X7R	445-7478-1-ND
C7,C11,C12, C13,C14,C15, C18,C19	8	100nF 0402 NP0	445-6902-1-ND
C9,C10	2	9pF 0402 NP0	445-4894-1-ND
C16	1	1000pF 0402 NP0	399-8940-1-ND
C17	1	1uF 0402	445-9073-1-ND
S1	1	Miniature SPDT Slide Switch	CKN5001-ND

Y1	1	48 MHz Crystal	887-1853-1-ND
FL1	1	Chip Balun	712-1540-1-ND
FB1	1	Ferrite Bead Power 160 Ohm 1206	240-2411-1-ND
FB2	1	Ferrite Bead @ 915 MHz for AVDD on CC1111	445-8678-1-ND
FB3	1	Ferrite Bead for DVDD on CC1111	445-8672-1-ND
U1,U5	2	Voltage Regulator LDO 3Vout 0.15A	296-24636-1-ND
U2,U3	2	1 pair P-Channel MOSFET	DMP2240UDMDICT-ND
U4	1	TI CC1111 SoC	296-22740-1-ND

B Appendix: Float-Out Device Bill of Materials

Part	Qty	Description	Supplier Part Number
J1	1	SMA Female Through-Hole	A97594-ND
J2	1	2 x 5 Male Header 0.05” pitch, 0.05” row spacing	S9012E-05-ND
R6	1	56K 0402 0.1% Precision Resistor	P56KDCCT-ND
R7	1	2.7k 0402 1%	P2.7KDCCT-ND
R5,R9	2	10K 5% 0402	311-10KJRCT-ND
R8	1	100 Ohm	
C12,C13,C14, C15	4	4.7uF 0603 X7R	445-7478-1-ND
C3,C4,C5,C6, C7,C8,C9,C23	8	100nF 0402 NP0	445-6902-1-ND
C9,C10	2	8pF 0402 NP0	445-4890-1-ND
C11	1	1000pF 0402 NP0	399-8940-1-ND
C10	1	1uF 0402	445-9073-1-ND
Y1	1	26 MHz Crystal	SER3679CT-ND
FL2	1	SAW Filter 915MHz	495-1674-1-ND
P1	1	Board Shield 0.65” x 0.65” Frame	903-1051-1-ND
P1 addition	1	Board Shield 0.65” x 0.65” Cover (no pads on PCB)	903-1014-1-ND
FL1	1	Chip Balun	712-1540-1-ND
FB4	1	Ferrite Bead Power 160 Ohm 1206	240-2411-1-ND
FB2,FB3	2	Ferrite Bead @ 915 MHz for AVDD on CC1111	445-8678-1-ND
FB1,FB5	2	Ferrite Bead for DVDD on CC1111	445-8672-1-ND
U2,U3	2	Voltage Regulator LDO 3Vout 0.15A	296-24636-1-ND

U1	1	TI CC1110 Sub 1GHz SoC Radio + MCU + USB	595-CC1110F32RSPR
U4	1	IC Regulator LDO 3Vout 0.5A	296-13809-1-ND
U5	1	IC RF Front-End	296-25826-1-ND
Q1	1	Ferrite Bead for DVDD on CC1111	
L1	1	11nH 500mA 0402	490-6766-1-ND
C17,C18,C19, C20	4	22uF 20% X5R 0805	490-1719-1 -ND
C16	1	100uF 20% X5R 1206	445-6007-1-ND
C32	1	15pF 5% NP0 0402	490-5888-1-ND
L6	1	1.5nH 0402	490-2612-1-ND
R13	1	3k3 0.1% Precision 0402	A102835CT-ND
Part	Qty	Description	Supplier Part Number
R12	1	47 1% 0402	408-1419-1-ND
R11	1	10 1% 0402	408-1413-1-ND
C31	1	27pF 5% 0402 NP0	490-5869-1-ND
C30	1	1u 0402 X5R	490-1320-1-ND
C21,C26	2	47pF 5% NP0 0402	720-1291-ND
C27	1	1nF 0402 NP0	490-3244-1-ND
L3	1	22nH 5% 0603	490-6876-1-ND
C24	1	3.3pF NP0 0402	399-1007-1-ND
L4	1	2.9nH 0402	490-6801-1-ND
C25	1	7.5pF NP0 0402	490-6075-1-ND
L5	1	9.1nH 0402	490-6854-1-ND
L2	1	7.5nH 0402	490-6846-1-ND
C22,C29	2	12p 5% NP0 0402	490-6154-1-ND
ANT1	1	Linx Antenna 916 MHz 1/2 Wave Dipole	ANT-916-CW-HW-ND

C Appendix: Receiver Unit Embedded Code

```c
/***************************************************************************
**********************      RECEIVER UNIT INCLUDES      **********************
***************************************************************************/
#include <scour_Receiver.h>


/***************************************************************************
* LOCAL VARIABLES
***************************************************************************/
static __xdata DMA_DESC DMA_Channel[NUM_CHANNEL];

static __xdata uint8 FSMstate;
static __xdata uint8 gotoNextState;

static __xdata uint8 SENSOR_RxAgain = FALSE;

static __xdata uint8    SENSOR_Count    = 0x00;
static __xdata uint16   SENSOR_Ser      = 0x0000;
static __xdata uint8    SENSOR_Col      = 0x00;
static __xdata uint8    SENSOR_Loc      = 0x00;

static __xdata uint8 counter = 0x00;

static __xdata uint16 shutdownCount = 0x0000;

/**************************************************************************
* LOCAL FUNCTIONS
**************************************************************************/
void Radio__config(void);


int main(void)
{
    SLEEP &= ~SLEEP_OSC_PD;
    while( !(SLEEP & SLEEP_XOSC_S) );
    CLKCON = (CLKCON & ~CLKCON_OSC) | CLKCON_OSC32 | TICKSPD_DIV_64 |
   CLKSPD_DIV_1;
    while (CLKCON & CLKCON_OSC);
    SLEEP |= SLEEP_OSC_PD;
```

```
    // GPIO OUTPUT - PCB LED ENABLE - ACTIVE LOW
    P2SEL &= ~BIT3;
    P2DIR |=  BIT3;
    P2_3   = 0;

    // GPIO OUTPUT - PCB LEDs - ACTIVE HIGH
    P1SEL &= ~(BIT2 | BIT4 | BIT5 | BIT6);
    P1DIR |=  (BIT2 | BIT4 | BIT5 | BIT6);
    P1_4 = 0;    // 1ST PCB LED - TOP    - RED
    P1_2 = 1;    // 2ND PCB LED -        - GREEN - LIGHT INDICATOR UNIT ENABLE
    P1_5 = 0;    // 3RD PCB LED -        - BLUE
    P1_6 = 0;    // 4TH PCB LED - BOTTOM - WHITE


    // GPIO OUTPUT - LIGHT INDICATOR - ACTIVE HIGH
    P0SEL &= ~(BIT0 | BIT1 | BIT2 | BIT3 | BIT4 | BIT5);
    P0DIR |=  (BIT0 | BIT1 | BIT2 | BIT3 | BIT4 | BIT5);
    P1SEL &= ~(BIT0 | BIT1);
    P1DIR |=  (BIT0 | BIT1);
    P0_5 = 0; P0_4 = 0; // Light Indicator - 2_1
    P0_3 = 0; P0_2 = 0; // Light Indicator - 2_0
    P0_1 = 0; P0_0 = 0; // Light Indicator - 1_0
    P1_0 = 0; P1_1 = 0; // Light Indicator - 1_1

    FSMstate = STATE_CONFIG;

    while (1)
    {
        switch(FSMstate)
        {
            case STATE_CONFIG:
            {
                DMA_Channel[0].SRCADDRH  = (uint16)(&X_RFD) >> 8;
                DMA_Channel[0].SRCADDRL  = (uint16)(&X_RFD);
                DMA_Channel[0].DESTADDRH = ((uint16)&Rx_Buff) >> 8;
                DMA_Channel[0].DESTADDRL = ((uint16)&Rx_Buff);
                DMA_Channel[0].VLEN      = DMA_VLEN_FIXED;
                DMA_Channel[0].LENH      = 0;
                DMA_Channel[0].LENL      = SENSOR_LEN+2;
                DMA_Channel[0].TRIG      = DMA_TRIG_RADIO;
```

```
            DMA_Channel[0].WORDSIZE   = DMA_WORDSIZE_BYTE;
            DMA_Channel[0].TMODE      = DMA_TMODE_SINGLE;
            DMA_Channel[0].SRCINC     = DMA_SRCINC_0;
            DMA_Channel[0].DESTINC    = DMA_DESTINC_1;
            DMA_Channel[0].IRQMASK    = DMA_IRQMASK_DISABLE;
            DMA_Channel[0].M8         = DMA_M8_USE_8_BITS;
            DMA_Channel[0].PRIORITY   = DMA_PRI_HIGH;

            DMA0CFGL = (uint16)(&(DMA_Channel[0]));
            DMA0CFGH = (uint16)(&(DMA_Channel[0])) >> 8;

            IP1 |=  IP1_IPG0; IP0 |=  IP0_IPG0;  // set IPG3 to highest priority
            IP1 |=  IP1_IPG1; IP0 &= ~IP0_IPG1;  // set IPG0 to second lowest priority

            Radio__config();

            RFST = RFST_SCAL;          // Strobe radio to calibrate frequency synthesizer
            while(MARCSTATE != MARC_STATE_IDLE);         // wait until Radio enters idle state

            FSMstate = STATE_RFRX;
            gotoNextState = TRUE;
        }break;

        case STATE_RFRX:
        {
            P1_5 ^= 1;

            PKTLEN = SENSOR_LEN;       // Set RF Packet Lengths

            RFIF = 0x00;              // Clear RF IRQ flags
            IEN2 |= IEN2_RFIE;        // RF Interrupts Enabled
            RFIM = RFIF_IRQ_DONE;     // Interrupt on Tx/Rx Completed
            EA = 1;                   // Enable General Interrupts

            DMAARM |= DMA_CHANNEL_0;
            NOP();NOP();NOP();NOP();NOP();NOP();NOP();NOP();NOP();
```

```
                RFST = RFST_SRX;    // Strobe radio into Rx
                while((MARCSTATE != MARC_STATE_RX));    // Wait for Radio to enter RX
            }break;

            case STATE_LED:
            {
                if(Rx_Buff[0]==BrID_0 && Rx_Buff[1]==BrID_1 && Rx_Buff[2]==BrID_2 && Rx_Buff[3]==BrID_3 && Rx_Buff[4]==BrID_4 && Rx_Buff[5]==BrID_5 && Rx_Buff[6]==BrID_6 && Rx_Buff[7]==BrID_7)
                {
                    SENSOR_Ser = (0xFF00 & (Rx_Buff[8]<<8)) | (0x00FF & (Rx_Buff[9]<<0));
                    SENSOR_Loc  = (Rx_Buff[10] & 0xF0);
                    SENSOR_Col  = (Rx_Buff[10] & 0x0F);

                    // Loop and Check if Sensor Serial Number has already been Received
                    for(int i=0;i<SENSOR_NUM; i++)
                    {
                        if(SENSOR_Ser == Rx_Sensor[i])
                        {
                            SENSOR_RxAgain = TRUE;
                        }
                    }

                    NOP();

                    // If Sensor Serial has been received, reset semaphore
                    // otherwise, toggle the Light Inidicator Units accordingly
                    if (SENSOR_RxAgain == TRUE)
                    {
                        SENSOR_RxAgain  = FALSE;
                    }
                    else
                    {
                        Rx_Sensor[SENSOR_Count++] = SENSOR_Ser;

                        if(SENSOR_Loc == SCOUR_LOC1)
                        {
```

```
                    if(SENSOR_Col == SCOUR_RED)
                      {P0_5 = 1; P0_4 = 1;}
                    else if(SENSOR_Col == SCOUR_ORANGE)
                      {P0_5 = 1; P0_4 = 0;}
                    else if(SENSOR_Col == SCOUR_WHITE)
                      {P0_5 = 0; P0_4 = 1;}
                    else if(SENSOR_Col == SCOUR_GREEN)
                      {P0_5 = 0; P0_4 = 0;}
                    else
                      {P1_4 = 1;}
                }
                else if(SENSOR_Loc == SCOUR_LOC2)
                {
                    if(SENSOR_Col == SCOUR_RED)
                      {P0_3 = 1; P0_2 = 1;}
                    else if(SENSOR_Col == SCOUR_ORANGE)
                      {P0_3 = 1; P0_2 = 0;}
                    else if(SENSOR_Col == SCOUR_WHITE)
                      {P0_3 = 0; P0_2 = 1;}
                    else if(SENSOR_Col == SCOUR_GREEN)
                      {P0_3 = 0; P0_2 = 0;}
                    else
                      {P1_4 = 1;}
                }
                else if(SENSOR_Loc == SCOUR_LOC3)
                {
                    if(SENSOR_Col == SCOUR_RED)
                      {P0_1 = 1; P0_0 = 1;}
                    else if(SENSOR_Col == SCOUR_ORANGE)
                      {P0_1 = 1; P0_0 = 0;}
                    else if(SENSOR_Col == SCOUR_WHITE)
                      {P0_1 = 0; P0_0 = 1;}
                    else if(SENSOR_Col == SCOUR_GREEN)
                      {P0_1 = 0; P0_0 = 0;}
                    else
                      {P1_4 = 1;}
                }
                else if(SENSOR_Loc == SCOUR_LOC4)
                {
                    if(SENSOR_Col == SCOUR_RED)
                      {P1_0 = 1; P1_1 = 1;}
```

```
                        else if(SENSOR_Col == SCOUR_ORANGE)
                          {P1_0 = 0; P1_1 = 1;}
                        else if(SENSOR_Col == SCOUR_WHITE)
                          {P1_0 = 1; P1_1 = 0;}
                        else if(SENSOR_Col == SCOUR_GREEN)
                          {P1_0 = 0; P1_1 = 0;}
                        else
                          {P1_4 = 1;}
                    }

                    P1_6 ^= 1;
                    P1_2  = 0;                     // ENABLE LIGHT INDICATOR LEDS

                    shutdownCount = 0x0000;        // Reset LED Flash Time Count

                    // Clear Timer 1 Interrupt Channels 0, 1 and 2
                    T1CTL = (T1CTL & ~(T1CTL_CH0IF | T1CTL_CH1IF | T1CTL_CH2IF));

                    T1CCTL0 |=  T1CCTL0_IM | T1CCTL0_MODE;   // Enable Interrupt  on Channel 0 & Compare Mode
                    T1CCTL1 &= ~T1CCTL1_IM;                  // Disable Interrupt on Channel 1
                    T1CCTL2 &= ~T1CCTL2_IM;                  // Disable Interrupt on Channel 2

                    EA = 1; T1IE = 1; OVFIM = 0;                 // Enable Timer 1 and Global CPU Interrupts & Disable Overflow Interrupt Mask

                    T1CC0H = TIMER1_H; T1CC0L = TIMER1_L;        // Configure Timer 1 Interrupt for 5 Second Intervals

                    // Start Timer 1 in Modulo and Tick/32
                    T1CTL |= T1CTL_MODE_MODULO | T1CTL_DIV_32;
                }
            }
            else
            {
```

```
                    // STORE BRIDGE ID & SENSOR SERIAL/LOC/COLOR TO FLASH
    MEMORY
                    // TRANSMIT BRIDGE ID & SENSOR SERIAL/LOC/COLOR TO SERVER
                }

                FSMstate = STATE_CONFIG;
                gotoNextState = TRUE;

            }break;

            case STATE_DEBUG:
            {

            }break;

            default:
            {
                FSMstate = STATE_CONFIG;
                gotoNextState = TRUE;
            }break;
        }
        while(gotoNextState != TRUE);
        gotoNextState = FALSE;
    }
    return 0;
}



void Radio__config(void)
{
    /* RF settings SoC: CC1111 */
    SYNC1       = 0xD3; // sync word, high byte
    SYNC0       = 0x91; // sync word, low byte
    PKTLEN      = 0x0B; // packet length
    PKTCTRL1    = 0x04; // packet automation control
    PKTCTRL0    = 0x44; // packet automation control
    ADDR        = 0x00; // device address
    CHANNR      = 0x00; // channel number
    FSCTRL1     = 0x06; // frequency synthesizer control
    FSCTRL0     = 0x00; // frequency synthesizer control
```

```
    FREQ2      = 0x26; // frequency control word, high byte
    FREQ1      = 0x1F; // frequency control word, middle byte
    FREQ0      = 0xFF; // frequency control word, low byte
    MDMCFG4    = 0xE5; // modem configuration
    MDMCFG3    = 0xA3; // modem configuration
    MDMCFG2    = 0x03; // modem configuration
    MDMCFG1    = 0x23; // modem configuration
    MDMCFG0    = 0x11; // modem configuration
    DEVIATN    = 0x16; // modem deviation setting
    MCSM2      = 0x07; // main radio control state machine configuration
    MCSM1      = 0x30; // main radio control state machine configuration
    MCSM0      = 0x18; // main radio control state machine configuration
    FOCCFG     = 0x17; // frequency offset compensation configuration
    BSCFG      = 0x6C; // bit synchronization configuration
    AGCCTRL2   = 0x03; // agc control
    AGCCTRL1   = 0x40; // agc control
    AGCCTRL0   = 0x91; // agc control
    FREND1     = 0x56; // front end rx configuration
    FREND0     = 0x10; // front end tx configuration
    FSCAL3     = 0xE9; // frequency synthesizer calibration
    FSCAL2     = 0x2A; // frequency synthesizer calibration
    FSCAL1     = 0x00; // frequency synthesizer calibration
    FSCAL0     = 0x1F; // frequency synthesizer calibration
    TEST2      = 0x81; // various test settings
    TEST1      = 0x35; // various test settings
    TEST0      = 0x09; // various test settings
    PA_TABLE0  = 0x8E; // pa power setting 0
}



#pragma vector=RF_VECTOR
__interrupt void RF_IRQ(void)
{
    S1CON &= ~0x03;                    // Clear the cpu RF interrupt flag

    if (RFIF & RFIF_IRQ_DONE)
    {
        RFIF &= ~RFIF_IRQ_DONE;        // Clear RF Timeout Interrupt Flag
        DMAIRQ &= ~DMAIRQ_DMAIF0;      // Clear DMA Channel 0 Interrupt Flag

```

```
            if(PKTSTATUS & 0x80)
            {
                FSMstate = STATE_LED;
            }
            else
            {
                FSMstate = STATE_RFRX;
            }
            gotoNextState = TRUE;          // Continue onto next state
        }
}


#pragma vector = T1_VECTOR
__interrupt void TIMER1_ISR(void)
{
    if (T1CTL & T1CTL_CH0IF)
    {
        // Clear Timer 1 Channel 0 interrupt flag
        T1CTL = (~T1CTL_CH0IF & 0xF0) | (T1CTL & 0x0F);

        P1_2 ^= 1;        // TOGGLE LIGHT INDICATOR LEDS

        if(shutdownCount++ >= TIMER1_COUNT)
        {
            T1CCTL0 &= ~T1CCTL0_IM;     // Disable Interrupt Mask for Timer 1
            T1IE = 0;                    // Disable CPU Interrupts for Timer 1

            P1_6 ^= 1;
            P1_2  = 1;                   // TURN-OFF LIGHT INDICATOR LEDS
        }
    }
}
```

code/scour_Receiver.c

D Appendix: Float-out Device Embedded Code

```
/*************************************************************************
*********************** SENSOR UNIT INCLUDES **********************
*************************************************************************/
#include <scour_Sensor.h>

/*************************************************************************
* LOCAL VARIABLES
*************************************************************************/
static __xdata uint8 FSMstate;
static __xdata uint8 gotoNextState;

static __xdata DMA_DESC DMA_Channel[NUM_CHANNEL];

static __xdata uint16 T1_Val    = 0x0000;
static __xdata uint16 RandNum   = 0x0000;
static __xdata uint8  RandSeed  = TRUE;

static __xdata uint16 shutdownCount = 0x0000;

/*************************************************************************
* LOCAL FUNCTIONS
*************************************************************************/
void Radio__config(void);


int main(void)
{
    SLEEP &= ~SLEEP_OSC_PD;
    while( !(SLEEP & SLEEP_XOSC_S) );
    CLKCON = (CLKCON & ~CLKCON_OSC) | CLKCON_OSC32 | TICKSPD_DIV_32 |
   CLKSPD_DIV_1;
    while (CLKCON & CLKCON_OSC);
    SLEEP |= SLEEP_OSC_PD;

    // Configure P0_0/1/2 GPIO Outut - Shutdown
    P0SEL &= ~(BIT0 | BIT1 | BIT2);      // Configure P0_0/1/2 as GPIO
    P0DIR |=  (BIT0 | BIT1 | BIT2);      // Configure P0_0/1/2 as Output
    P0_0 = 0; P0_1 = 0; P0_2 = 0;        // Set All Outputs Low

```

```
    RandSeed = TRUE;
    FSMstate = STATE_CONFIG;

    while (1)
    {
        switch(FSMstate)
        {
            case STATE_CONFIG:
            {
                DMA_Channel[1].SRCADDRH  = (uint16)(&bridge_ID) >> 8;
                DMA_Channel[1].SRCADDRL  = (uint16)(&bridge_ID);
                DMA_Channel[1].DESTADDRH = ((uint16)&X_RFD) >> 8;
                DMA_Channel[1].DESTADDRL = ((uint16)&X_RFD);
                DMA_Channel[1].VLEN      = DMA_VLEN_FIXED;
                DMA_Channel[1].LENH      = 0;
                DMA_Channel[1].LENL      = BUFF_LEN;
                DMA_Channel[1].TRIG      = DMA_TRIG_RADIO;
                DMA_Channel[1].WORDSIZE  = DMA_WORDSIZE_BYTE;
                DMA_Channel[1].TMODE     = DMA_TMODE_SINGLE;
                DMA_Channel[1].SRCINC    = DMA_SRCINC_1;
                DMA_Channel[1].DESTINC   = DMA_DESTINC_0;
                DMA_Channel[1].IRQMASK   = DMA_IRQMASK_DISABLE;
                DMA_Channel[1].M8        = DMA_M8_USE_8_BITS;
                DMA_Channel[1].PRIORITY  = DMA_PRI_HIGH;

                DMA1CFGL = (uint16)(&(DMA_Channel[1]));
                DMA1CFGH = (uint16)(&(DMA_Channel[1])) >> 8;

                Radio__config();            // Configure Radio: 10dBm, 433MHz,
    500kbaud MSK

                shutdownCount = 0x0000;
                T3CTL = T3CTL_DIV_128 | T3CTL_START | T3CTL_OVFIM | T3CTL_CLR
    | T3CTL_MODE_FREERUN;
                T3IE = 1; EA = 1;

//                P0_1 ^= 1;        // Toggle LED for Shutdown Timer Start

                FSMstate = STATE_RFTX;
                gotoNextState = TRUE;
            }break;
```

```c

            case STATE_RFTX:
            {
                RFST = RFST_SCAL;               // Strobe radio to calibrate frequency synthesizer
                while(MARCSTATE != MARC_STATE_IDLE);          // wait until Radio enters idle state

                DMAIE = 0; DMAIF = 0;    // Disable DMA Interrupt and Clear DMA Flag

                PKTLEN = BUFF_LEN;        // Set Radio PKTLEN to size of bridge_ID buffer

                DMAARM |= DMA_CHANNEL_1;          // Arm DMA CH1 for RF Transmission
                NOP();NOP();NOP();NOP();NOP();NOP();NOP();NOP();NOP();

                RFIF = 0x00;              // Clear RF IRQ flags
                IEN2 |= IEN2_RFIE;        // RF Interrupts Enabled
                RFIM = RFIF_IRQ_DONE;     // Interrupt on Tx Completed
                EA = 1;                   // Enable General Interrupts

//                  P0_2 ^= 1;

                RFST = RFST_STX;          // Strobe radio into Tx
                while((MARCSTATE != MARC_STATE_TX));     // Wait for Radio to enter RX
            } break;

            case STATE_WAIT:
            {
                T1CTL |= T1CTL_MODE_SUSPEND;               // Suspend Operation for Timer 1
                T1CNTL = 0x0000;                           // Clear the count for Timer 1

                // Clear Timer 1 Interrupt Channels 0, 1 and 2
                T1CTL = (T1CTL & ~(T1CTL_CH0IF | T1CTL_CH1IF | T1CTL_CH2IF));

```

```c
        T1CCTL0 |=  T1CCTL0_IM | T1CCTL0_MODE;  // Enable Interrupt on Channel 0 & Compare Mode
        T1CCTL1 &= ~T1CCTL1_IM;                 // Disable Interrupt on Channel 1
        T1CCTL2 &= ~T1CCTL2_IM;                 // Disable Interrupt on Channel 2

        OVFIM = 0;              // Disable overflow interrupt
        T1IE = 1; EA = 1;       // Enable Timer 1 and Global Interrupts

        if (RandSeed == TRUE)
        {
            RNDL = SENSORSER_8;
            RNDL = SENSORSER_9;

            RandSeed = FALSE;
        }

        ADCCON1 |= ADCCON1_RCTRL_LFSR13;
        while(ADCCON1 & 0x04);

        RandNum = ((RNDH & 0x00FF)<<8) | (RNDL & 0x00FF);

        T1_Val = (T1VAL_HIGH << 8) | T1VAL_LOW;

        if (RandNum <= T1_DELAY_2T)
        {
            T1_Val = (T1_Val << 0);
        }
        else if (RandNum > T1_DELAY_2T && RandNum <= T1_DELAY_4T)
        {
            T1_Val = (T1_Val << 1);
        }
        else if (RandNum > T1_DELAY_4T && RandNum <= T1_DELAY_8T)
        {
            T1_Val = (T1_Val << 2);
        }
        else if (RandNum > T1_DELAY_8T)
        {
            T1_Val = (T1_Val << 3);
```

```
            }

            // Set Timer 1 Compare Registers based on T1_Val
            T1CC0H = ((T1_Val >> 8) & 0xFF);
            T1CC0L = (T1_Val & 0xFF);

            // Start Timer 1 in Modulo and Tick/128
            T1CTL |= T1CTL_MODE_MODULO | T1CTL_DIV_128;
        } break;

        case STATE_SHUTDOWN:
        {
            T1CCTL0 &= ~T1CCTL0_IM;          // Disable Interrupt for Timer 1 Channel 0
            OVFIM = 0; T1IE = 0; EA = 0;     // Disable Overflow, Timer 1 and Global Interrupts
            T1CTL |= T1CTL_MODE_SUSPEND;              // Suspend Operation for Timer 1
            T1CNTL = 0x0000;                          // Clear the count for Timer 1

            // Suspend Timer 3 & Clear Timer 3 Count & Diable Interrupts
            T3CTL = (T3CTL & ~(T3CTL_START | T3CTL_OVFIM)) | T3CTL_CLR; T3IE = 0;

//              P0_2  = 0;      // Toggle LED for RF TX Finished
//              P0_1 ^= 1;      // Toggle LED for Shutdown Timer End
//              P0_0  = 1;      // Drive BJT Current through Reset Coil of Relay

            FSMstate = STATE_CONFIG;
            gotoNextState = TRUE;
        } break;

        default:
        {
            FSMstate = STATE_CONFIG;
            gotoNextState = TRUE;
        } break;
    }
```

```
        while(gotoNextState != TRUE);
        gotoNextState = FALSE;
    }
}



void Radio__config(void)
{
    SYNC1       = 0xD3; // sync word, high byte
    SYNC0       = 0x91; // sync word, low byte
    PKTLEN      = 0x0B; // packet length
    PKTCTRL1    = 0x04; // packet automation control
    PKTCTRL0    = 0x44; // packet automation control
    ADDR        = 0x00; // device address
    CHANNR      = 0x00; // channel number
    FSCTRL1     = 0x06; // frequency synthesizer control
    FSCTRL0     = 0x00; // frequency synthesizer control
    FREQ2       = 0x23; // frequency control word, high byte
    FREQ1       = 0x31; // frequency control word, middle byte
    FREQ0       = 0x3B; // frequency control word, low byte
    MDMCFG4     = 0xF7; // modem configuration
    MDMCFG3     = 0x83; // modem configuration
    MDMCFG2     = 0x03; // modem configuration
    MDMCFG1     = 0x22; // modem configuration
    MDMCFG0     = 0xF8; // modem configuration
    DEVIATN     = 0x15; // modem deviation setting
    MCSM2       = 0x07; // main radio control state machine configuration
    MCSM1       = 0x30; // main radio control state machine configuration
    MCSM0       = 0x18; // main radio control state machine configuration
    FOCCFG      = 0x17; // frequency offset compensation configuration
    BSCFG       = 0x6C; // bit synchronization configuration
    AGCCTRL2    = 0x03; // agc control
    AGCCTRL1    = 0x40; // agc control
    AGCCTRL0    = 0x91; // agc control
    FREND1      = 0x56; // front end rx configuration
    FREND0      = 0x10; // front end tx configuration
    FSCAL3      = 0xE9; // frequency synthesizer calibration
    FSCAL2      = 0x2A; // frequency synthesizer calibration
    FSCAL1      = 0x00; // frequency synthesizer calibration
    FSCAL0      = 0x1F; // frequency synthesizer calibration
```

```
    TEST2      = 0x88; // various test settings
    TEST1      = 0x31; // various test settings
    TEST0      = 0x09; // various test settings
    PA_TABLE0  = 0xC7; // pa power setting 0
    IOCFG2     = 0x00; // radio test signal configuration (p1_7)
    IOCFG1     = 0x00; // radio test signal configuration (p1_6)
    IOCFG0     = 0x06; // radio test signal configuration (p1_5)
    PARTNUM    = 0x01; // chip id[15:8]
    VERSION    = 0x03; // chip id[7:0]
    FREQEST    = 0x00; // frequency offset estimate from demodulator
    LQI        = 0xFF; // demodulator estimate for link quality
    VCO_VC_DAC = 0x94; // current setting from pll calibration module
}



#pragma vector=RF_VECTOR
__interrupt void RF_IRQ(void)
{
    S1CON &= ~0x03;                    // Clear the cpu RF interrupt flag

    if (RFIF & RFIF_IRQ_DONE)
    {
        RFIF   &= ~RFIF_IRQ_DONE;    // Clear RF Timeout Interrupt Flag
        DMAIRQ &= ~DMAIRQ_DMAIF1;    // Clear DMA Channel 1 Interrupt Flag

//        P0_2 ^= 1;

        FSMstate = STATE_WAIT;
        gotoNextState = TRUE;
    }
}



#pragma vector = T1_VECTOR
__interrupt void TIMER1_ISR(void)
{
    if (T1CTL & T1CTL_CH0IF)
    {
        // Clear Timer 1 Channel 0 interrupt flag
```

```c
        T1CTL = (~T1CTL_CH0IF & 0xF0) | (T1CTL & 0x0F);

        T1CTL    |= T1CTL_MODE_SUSPEND;           // Suspend Operation for Timer 1
        T1CNTL    = 0x0000;                       // Clear the count for Timer 1
        T1CCTL0 &= ~T1CCTL0_IM; T1IE = 0;         // Disable Interrupts for Timer 1

        FSMstate = STATE_RFTX;
        gotoNextState = TRUE;
    }
}


#pragma vector = T3_VECTOR
__interrupt void TIMER3_ISR(void)
{
    T3IF = 0; T3OVFIF = 0; // Clears the CPU and Overflow interrupt flags

    if(shutdownCount++ > 500)
    {
        FSMstate = STATE_SHUTDOWN;
        gotoNextState = TRUE;
    }
}
```

code/scour_Sensor.c

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