Application Note

Liquid Level Sensing with Hall Sensors

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ABSTRACT

There are several approaches for liquid level sensing including capacitive, ultrasonic, magnetic, and mechanical solutions. Modern linear 3D Hall sensors allow us to measure the level of a liquid using a single sensor. This document covers a single-sensor implementation of liquid level sensing using a float arm and 3D linear hall sensor. The document discusses the design principles behind a Hall-based liquid level demo using the TMAG5273 linear 3D Hall-effect sensor, a float, and a magnet.

Table of Contents

List of Figures

List of Tables

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1 Introduction

Determining the level of liquid inside a container is a common challenge across many industries and applications.

- Around the house, liquid level sensing is used in mopping robots to let the user know when the robot has run out of cleaning solution.
- Single cup coffee makers will detect when they are low on water and notify the user to add more water to brew a cup of a certain size.
- Vehicles use liquid level sensing to detect when more windshield wiper fluid needs to be added to the reservoir. Every car has a fuel gauge displaying how full or empty the gas tank is.
- Airplanes similarly measure the amount of fuel left.
- Level sensors can shut down a unit if the liquid runs out, such as a humidifier turning off when the water tank is empty or an AC unit disabling itself if the drip pan isn't draining.

There are many applications for liquid level sensing around us every day, and there are many different measuring implementations.

2 Liquid Level Sensing Implementations

2.1 Capacitive

Conventional *FDC1004: Basics of Capacitive Sensing and Applications* typically measure the change in capacitance between sensors attached to the exterior walls of a tank made of non-conductive material, like plastic. In Figure 2-1, the level-detecting sensors are represented by LEVEL and GND, while additional pairs of capacitive sensors provide a reference for the liquid (RL, GND below) and for the outside environment (RE, GND). These sensors enable environmental tracking, such as temperature-related shifts, in the liquid and the surrounding environment.

This conventional level-sensing method imposes a non-zero potential on the liquid being measured, which makes it susceptible to grounded interference or parasitic capacitance on the system, such as a hand close to or touching the tank. Note that, in general, capacitive sensing can have difficulty sensing the level of thicker solutions like clothes washing detergent, or conductive solutions such as salt water. A downside to the capacitive approach is liquid sticking to the walls of the container. This can severely impact the accuracy of the system if the liquid is a solvent or cleaning solution with a higher viscosity.

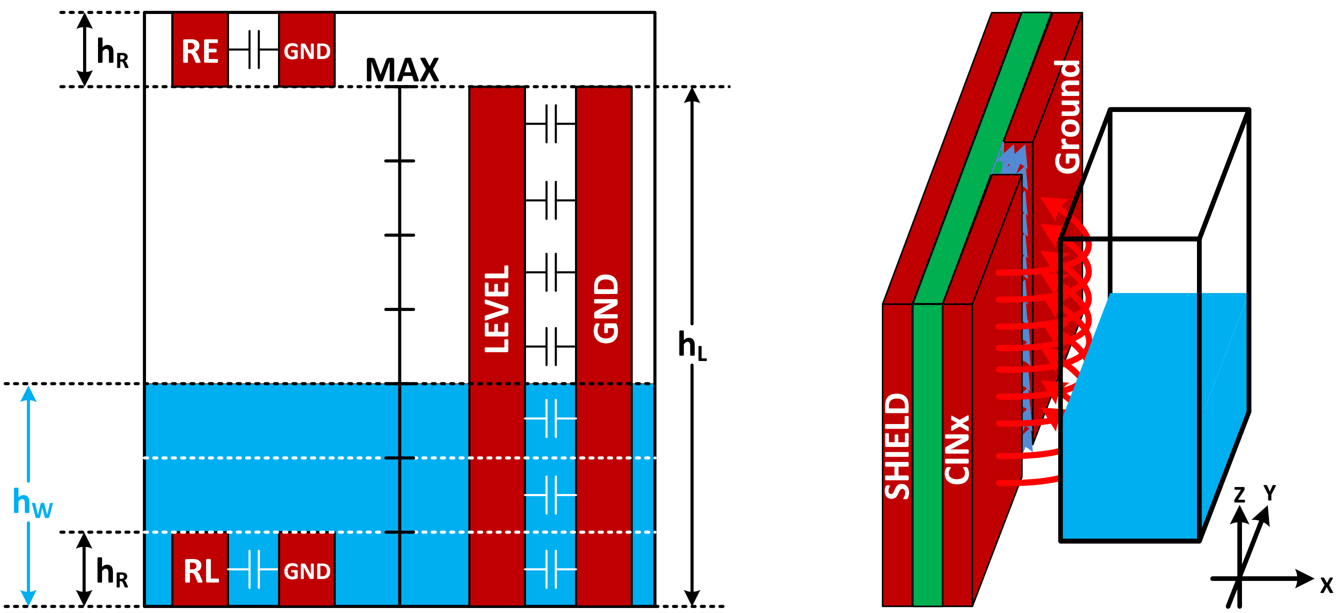

Figure 2-1. Capacitive Liquid Level Sensing

Another implementation for capacitive liquid level sensing is the *Capacitive Sensing: Out-of-Phase Liquid Level Technique* which uses a symmetrical sensor layout as well as equal-and-opposite waveforms for the level sensors (LEVEL, GND above). The result is that the liquid under measurement is at or near zero potential, which reduces the system's sensitivity to interference or parasitic capacitance, such as a hand or other grounded object near the tank. The OoP technique could be implemented in Figure 2-1by replacing the GND sensor in the LEVEL/GND sensor pair with a sensor driven by a signal equal-and-opposite to the LEVEL sensor's waveform.

An OoP sensor array implemented as a flex PCB is available as the Capacitive-Based Liquid Level Sensing Sensor Reference Design. It is compatible with the *FDC1004 4-Channel Capacitance-to-Digital Converter for Capacitive Sensing Solutions*, a 4-channel, 16-bit, capacitance-to-digital converter with active shield driver. For more information on capacitive liquid-level sensing please see the *E2E FDC1004 Frequently Asked Questions* page.

2.2 Ultrasonic

Ultrasonic level sensing relies on a series of pulses being sent from a transducer on one side of the tank and then listening for the return pulses that reflect off the top of the liquid. The time-of-flight (TOF) indicates the fluid level as shown in Figure 2-1.

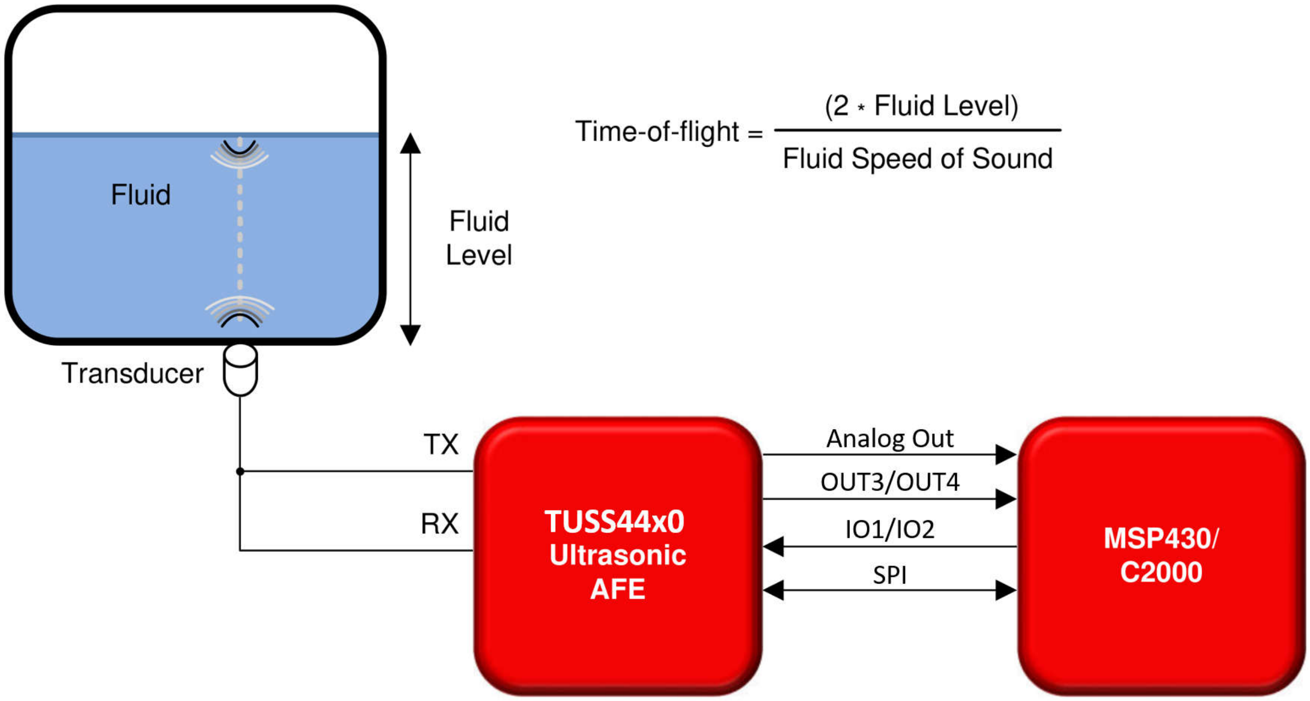

Figure 2-2. Ultrasonic Liquid Level Sensing

Ultrasonic sensing can produce accurate level readings, even down to the micrometer in certain conditions. Ultrasonic designs tend to be a more expensive sensing design compared to capacitive or Hall. The electrical properties of the liquid does not affect ultrasonic measurements compared to capacitive sensing designs. Air coupled vs water coupled ultrasonic sensing give similar performance but give flexibility in the transducer mounting location - above, below, or inside of the tank.

Ultrasonic Sensing Basics for Liquid Level Sensing, Flow Sensing, and Fluid Identification Applications application note provides more details on the ultrasonic implementation.

2.3 Magnetic Hall-Effect Implementations

There are multiple options to do liquid-level sensing with Hall-effect sensors and magnets. The following sections describe the different options.

2.3.1 Different Types of Hall-Effect Sensors

The basis of measuring a liquid with a Hall sensor is that a magnet moves along with the water level and a Hall-effect sensor measures the magnetic field from the moving magnet. Based on the measured magnetic field from the magnet, the system can determine what is the position of the magnet.

TI offers several different types of Hall-effect sensors: latches, switches, 1-axis linear, and linear 3D sensors. Linear sensors can provide detailed magnetic data since they represent the magnetic flux density using an analog voltage or a digital numeric representation that changes as the field experienced by the device changes.

The magnetic field from two directions can be obtained using two 1D sensors orthogonal with each other. Alternatively, one 2D or 3D sensor that sense magnetic fields in orthogonal axes can be used instead. Figure 2-3 shows an example mapping of the three axes of sensitivity of a linear 3D Hall-effect sensor, the TMAG5170. The mapping of the X, Y, and Z directions as well as how a positive field is defined can vary among different parts.

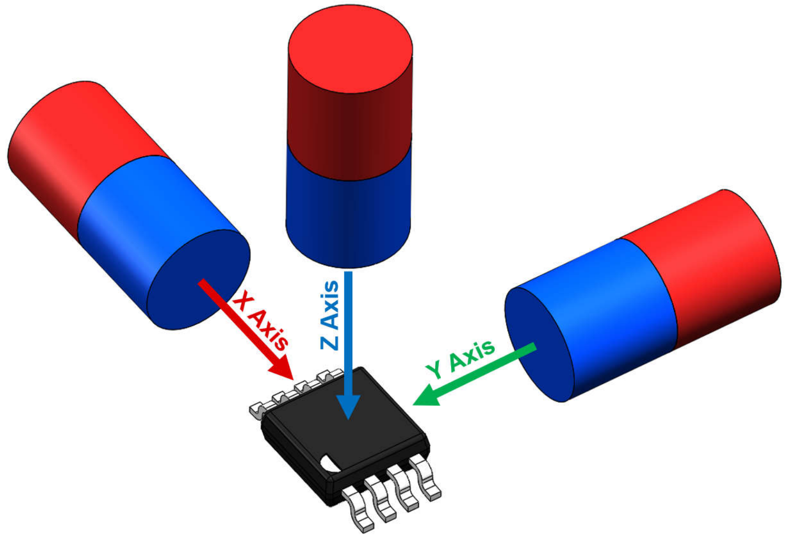

Figure 2-3. 3D Hall Sensor Axis

TI offers linear 3D Hall-effect sensors with different interface options, such as SPI and I2C. These sensors are listed in Table 2-1. Dual-Die sensors such as the TMA5170D-Q1 provide integrated redundancy within a single device package. This is especially important for many automotive applications.

Table 2-1. TI Linear Magnetic Position Sensors

Device	Type	Characteristics	Design Considerations
TMAG5170and TMAG5170-Q1	3D Hall-Effect	Commercial & Automotive grade linear 3D Hall-effect position sensors with SPI available in 8 pin DGK package	Complete magnetic vector sensitivity. This device is able to track a wide range of magnet positions, though careful planning is still required to make sure all input conditions map to a unique position.
TMAG5170D-Q1	3D Hall-Effect	Dual-die Automotive high-precision 3D linear Hall-effect sensor with SPI available in 16-pin TSSOP package	Identical to the TMAG5170, but with stacked sensor dies for integrated redundancy. Developed for functional safety applications, with resources supporting design up to ASIL D.
TMAG5273	3D Hall-Effect	Commercial grade Linear 3D Hall-effect position sensor with I2C interface available in 6 pin SOT-23 package	Similar to the TMAG5170, but operates over I2C with wider sensitivity tolerance specifications.
TMAG5173-Q1	3D Hall-Effect	Automotive grade Linear 3D Hall-effect position sensor with I2C interface available in 6 pin SOT-23 package	Operates over I2C with improved performance over the TMAG5273.
TMAG6180-Q1 and TMAG6181-Q1	2D AMR	These devices are high-precision angle sensors based on Anisotropic Magneto Resistive (AMR) technology. The TMAG6180-Q1 has a 360° angle range, while the TMAG6181-Q1 has an integrated turns counter.	Supports both differential & single-ended Sin/Cos outputs for angular speeds up to 60,000 RPM providing an angular error <0.6 degree across temperature with no system-level calibration needed.

Compared with a resistor-wiper implementation, Hall-effect sensors are more reliable, and they are minimally affected by environment changes like humidity, dust, or water. Hall-effect liquid level sensing implementations are not prone to the wear and tear issues of mechanical solutions, which extends the lifetime of these solutions.

2.3.2 Implementation Option 1: Floating Magnet with Linear Hall

One implementation involves placing the magnet in the float so that the magnet floats up and down vertically as the liquid level changes.

In the head-on orientation shown in Figure 2-4, the sensor is placed directly below the magnet so that the magnet moves towards and away from the sensor as the magnet floats up and down. More details on the head-on implementation can be found in the *Head-on Linear Displacement Sensing Using Hall-Effect Sensors* application brief.

In the slide-by orientation shown in Figure 2-5, the sensor is placed next to the magnet so that the magnet moves next to the sensor. Details on the slide-by displacement implementation can be found in the *Tracking Slide-By Displacement with Linear Hall-Effect Sensors*, application brief.

The fluid measurement range and resolution is restricted based on the size and strength of the magnet and the sensor sensitivity. This setup sometimes requires large magnets and thus a large floating piece. If the tank geometry results in a large distance, there can also be issues since the magnetic field reduces greatly the further it is away from the magnet. Both head-on and slide-by setups can work well if the system only needs to know when the tank is nearing empty, or if there is a tank that is shallow.

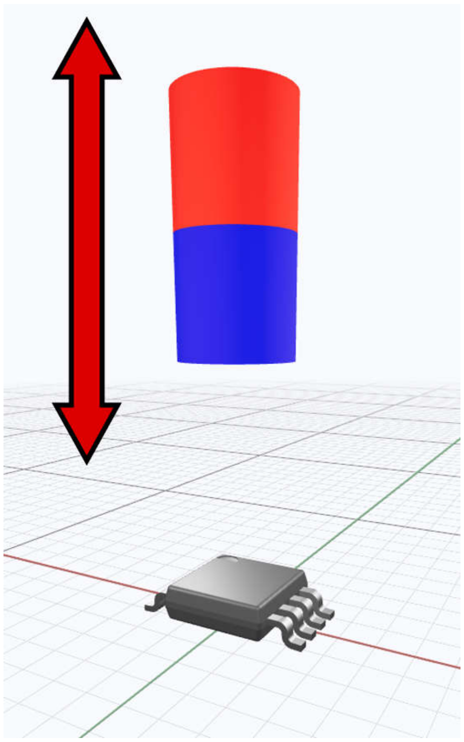

Figure 2-4. Head-On

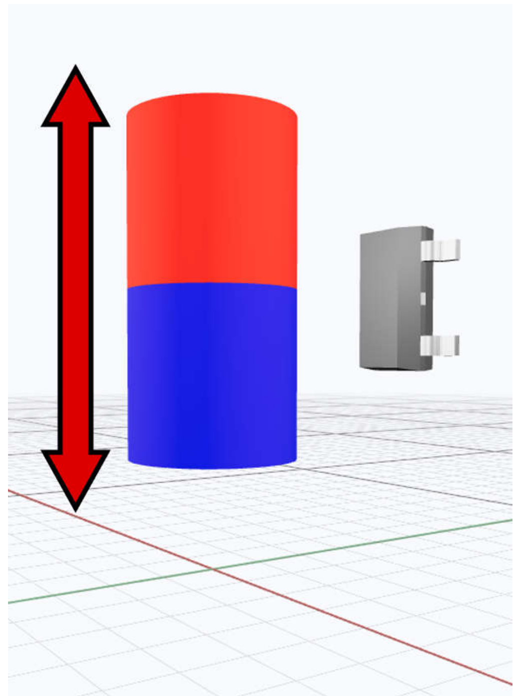

Figure 2-5. Slide-By

2.3.3 Implementation Option 2: Floating Magnet with Array of Latches or Switches

An array of sensors can be used to detect specific liquid positions as a magnet passes each sensor. Hall-effect *latches* can be used with a sideways magnet as shown in Figure 2-6 if it is desired for the sensors to stay active when the liquid is above that sensor. It can be useful to know the liquid level region when the magnet is between the sensors without needing to keep track of the most recently detected level.

Hall-effect *switches* can be used with a magnet facing the sensors as shown in Figure 2-7. This is useful if the system only needs to know when the liquid has reached a specific level and doesn't need to know the liquid level region when the magnet is between sensors.

Either setup needs a sensor for each liquid level position to detect, and thus a PCB running the length of the detection region. However, this design can allow for a smaller magnet than the vertically floating magnet setup.

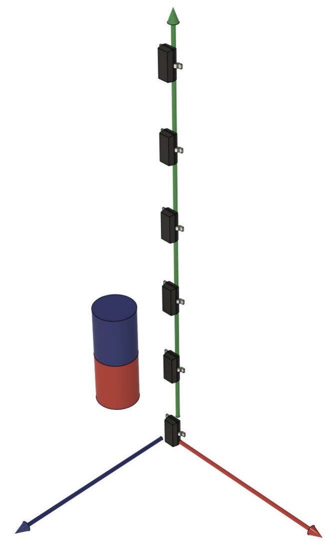

Figure 2-6. Hall Latch Array

Figure 2-7. Hall Switch Array

2.3.4 Flotation Device on Axial Arm

The magnet can be attached to a flotation device so that the angle of the magnet changes with the height of the float arm. This setup, shown in Figure 2-8, works with a very small magnet compared to the other designs and can be used to measure any size of liquid tank simply by changing the dimensions of the float arm. This implementation only requires one sensor. The sensor can be placed on-axis with the magnet or off to the side.

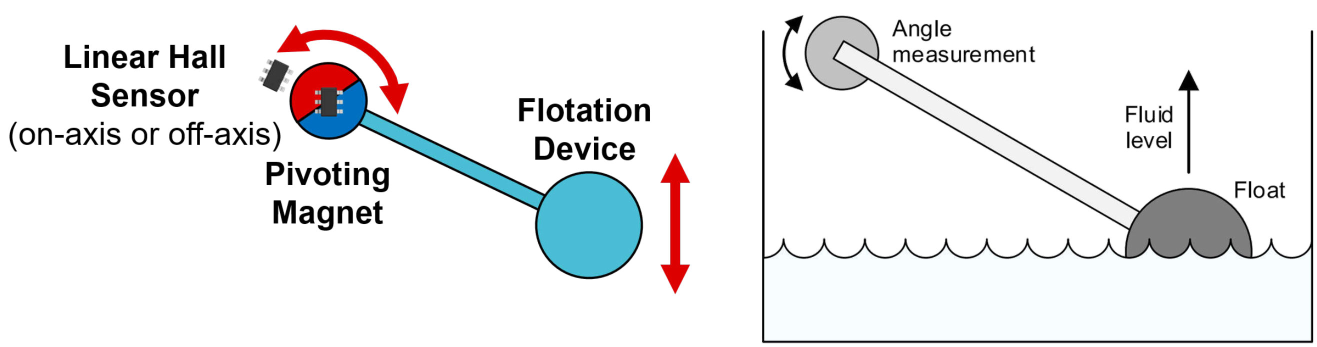

Figure 2-8. Pivoting Magnet Float Arm Implementation

Common measurement topology include angular position measurements in on-axis or off-axis angular measurements shown in Figure 2-9. Select the on-axis measurement topology whenever possible as this offers the best optimization of magnetic field and the device measurement ranges. The TMAG5273 offers on-chip gain adjustment option to account for mechanical position misalignment.

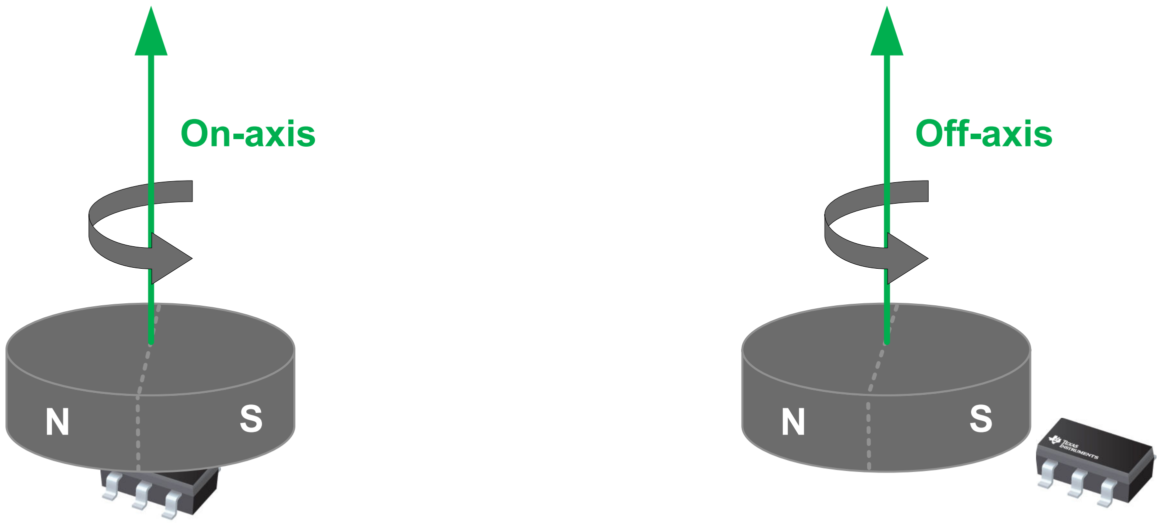

Figure 2-9. On-Axis vs. Off-Axis Angle Measurements

Figure 2-10 shows example X and Y sensor data for on-axis measurement, where the strength of the two axes are equal. Figure 2-11 shows example sensor data for off-axis measurement, where the Y-axis is half the strength of the X-axis.

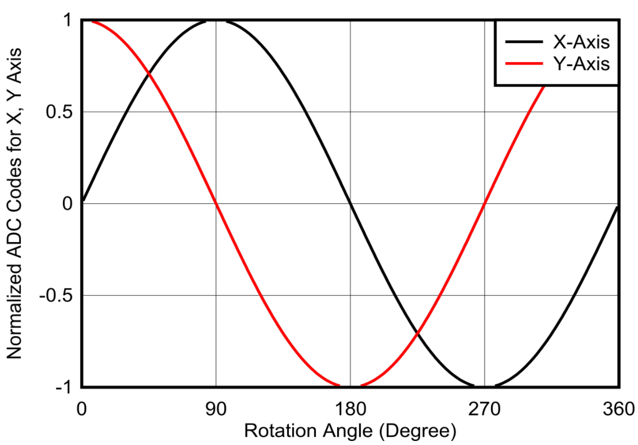

Figure 2-10. X and Y Sensor Data for Full 360 Degree Rotation for On-Axis Measurement

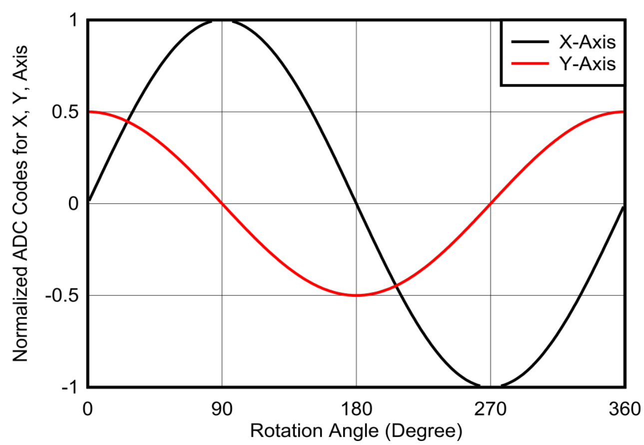

Figure 2-11. X and Y Sensor Data for Full 360 Degree Rotation for Off-Axis Measurement

Traditional vehicle fuel sensor systems use a rotational float sensor implementation. These conventionally use a foam piece on an arm attached to a resistor wiper. As the float drops or rises in height, the resistance of the wiper changes. Current is passed through the wiper resistance and into a heating coil around a bimetallic strip. As the bimetallic strip heats up it bends one direction, and moves the fuel gauge needle. This system can't compensate for the shape of the fuel tank, and is suscpetible to wear and tear of the resistor wiper and bimetallic strip. It also creates a non-linear behavior in the fuel gauge, where the tank looks full for a while before the fuel level starts to indicate it is decreasing and then the fuel level drops faster as the tank empties. Modern vehicles may use a microcontroller to read a voltage from the wiper resistance and display the fuel level digitally.

A float arm paired with a magnet and hall sensor can provide a low-cost, single-sensor design to liquid level sensing.

3 Functional Demo Design

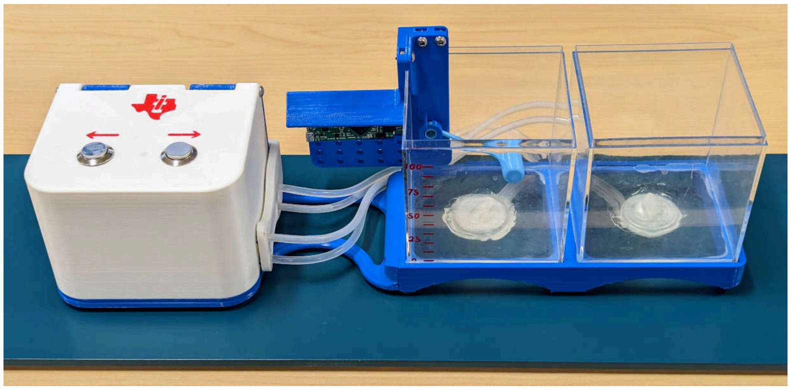

Figure 3-1. Full Demo Overview

This functional prototype shown in Figure 3-1 was built for demonstrating liquid level sensing using a TMAG5273. The white box on the left houses a DRV8704 motor driver EVM and a pair of pumps that transfer water from one tank to the other. The center water tank has the TI-SCB and TMAG5273EVM along with the float arm and magnet.

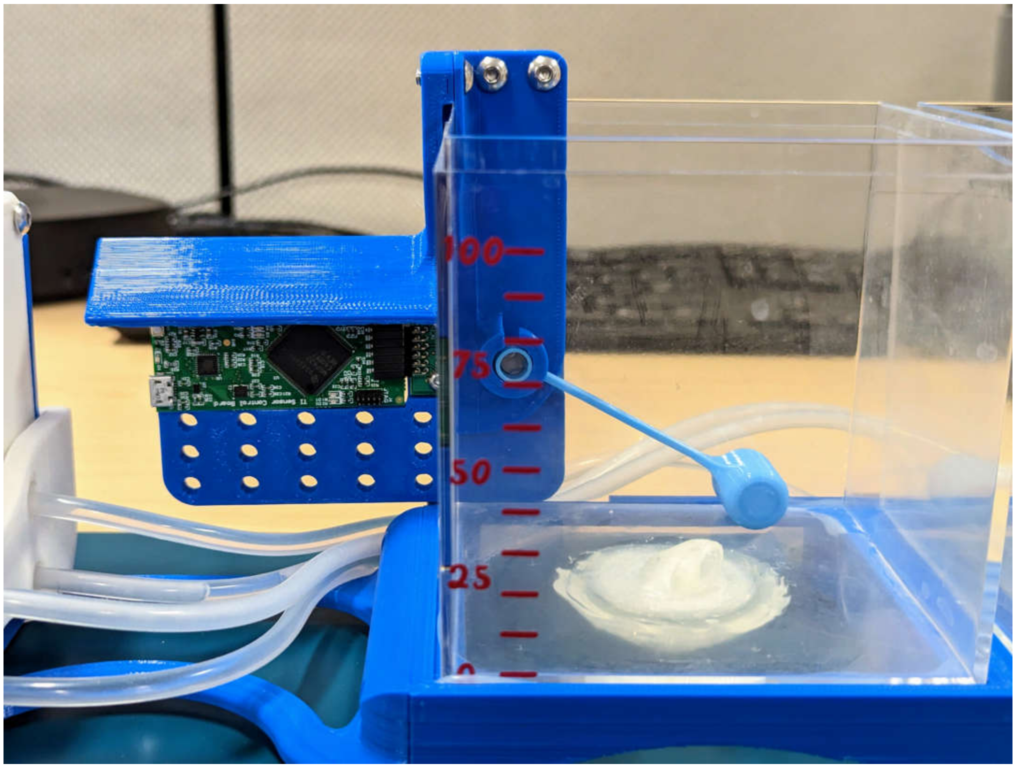

Figure 3-2. Sensing-Focused Demo Closeup

A closer view of the sensing part of the demo is shown in Figure 3-2. There is a scale from 0 to 100 taped to front of the tank. The white attachment in the center of the bottom of the tank redirects the water into the corner of the tank instead of shooting vertically out of the container like a fountain.

The TMAG5273EVM and TI-SCB are mounted on some 3D printed pieces outside of the water tank as shown in Figure 3-3. Since they are outside of the tank, the electronics do not get wet.

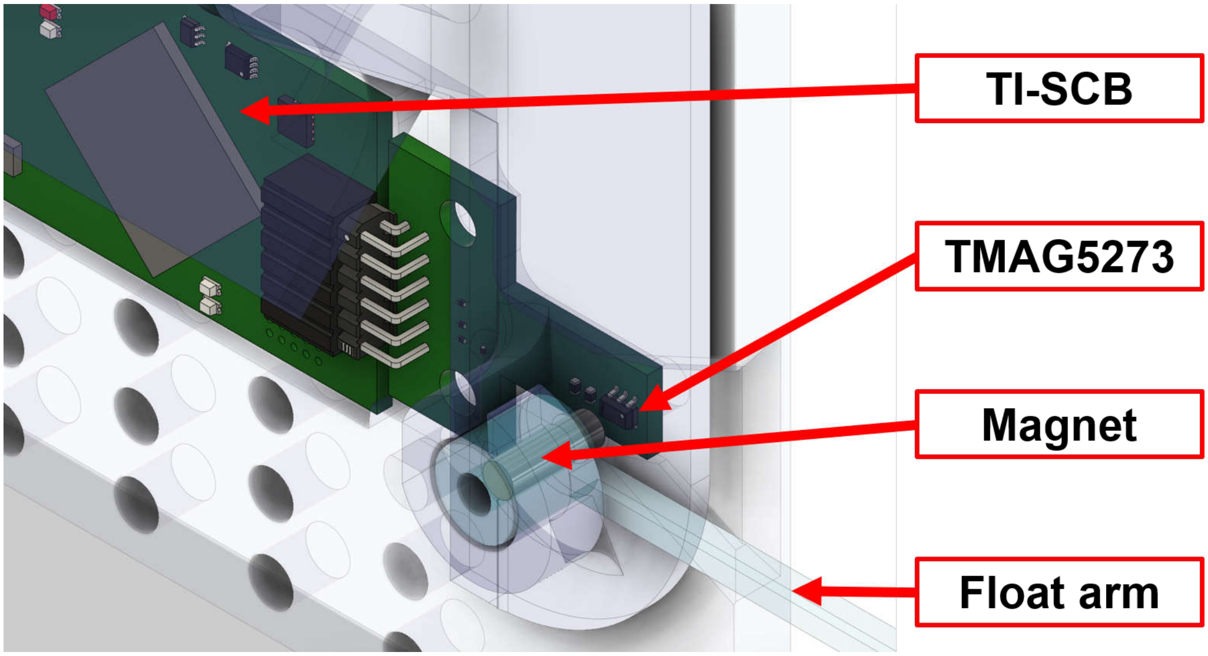

Figure 3-3. Main Component Locations

For demonstration purposes, a pair of self-priming pumps was used to transfer water from one tank to the other. One pump moved water from the left tank to the right tank, the other pump moved water from the right tank to the left tank. These pumps were driven by a DRV8704EVM. Though the DRV8704 can run a motor bidirectionally, the pumps can only pump water one direction so the demo uses two pumps instead of one. This pump setup enables the user to add and remove water in the liquid level sensing tank at the press of a button.

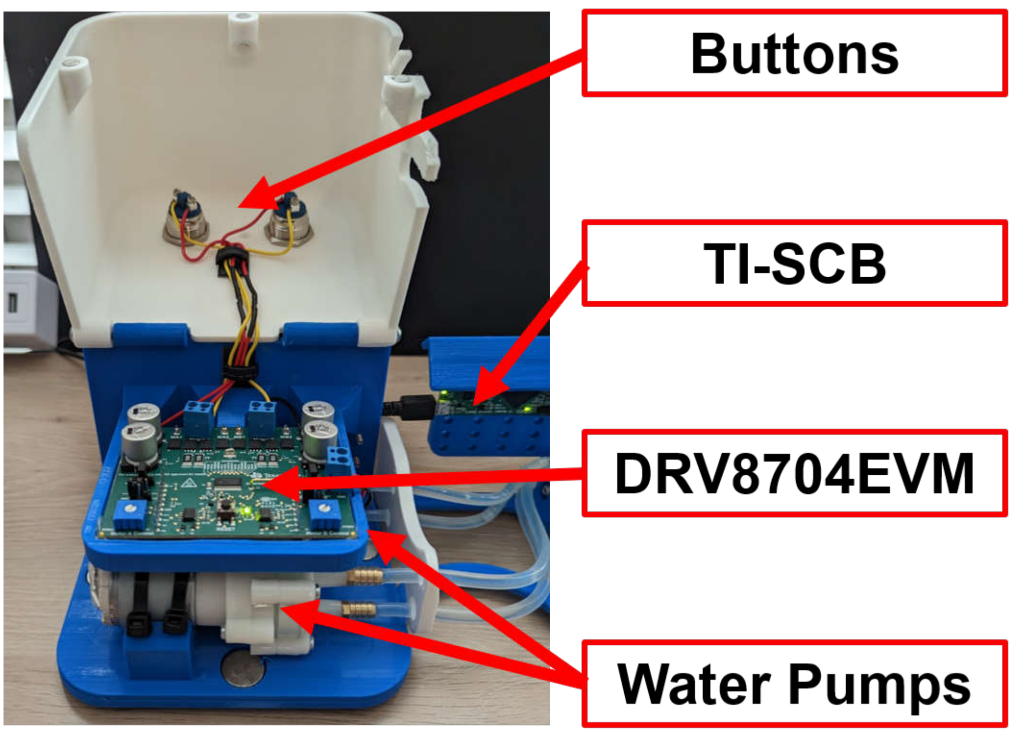

Figure 3-4. Pump Box

3.1 Float Arm

For this application, a diametric magnet must be installed on the float sensor so that it rotates with the float arm movement. As the float rises, the magnet will rotate in one direction, and as the float sinks the magnet will rotate in the other direction. This movement is shown in Figure 3-5.

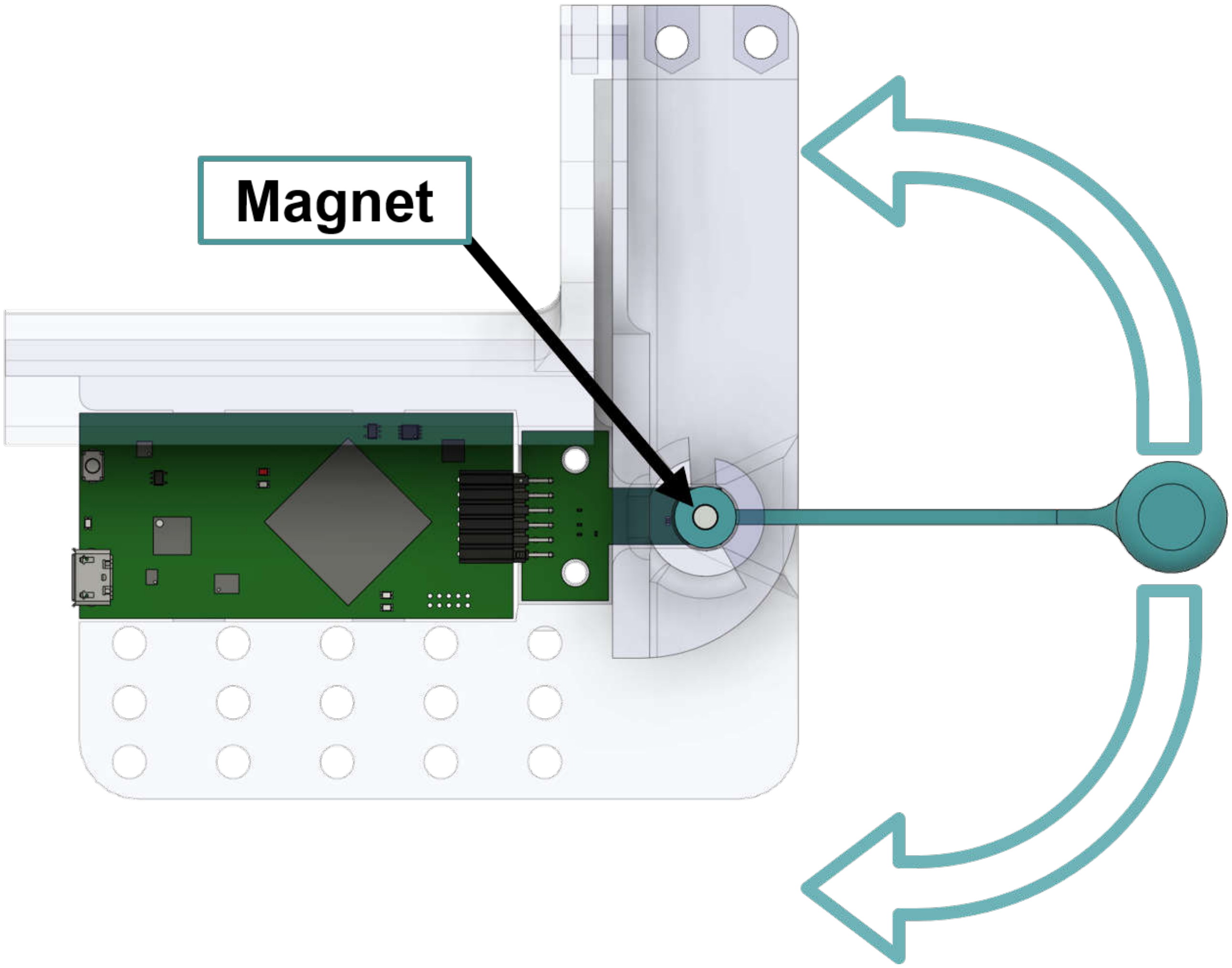

Figure 3-5. Float Rotation and Magnet Placement

The hall sensor is mounted on the outside of the water container, sensing the magnetic field through the side of the container wall. The size of the magnet will determine the strength of the magnetic field and thus the maximum distance between the magnet and the sensor.

This demo was tested with 3 different float arm models to test 3 different sized diametric cylinder magnets from 1/8", 3/16", and 1/4" diameter as seen in Figure 3-6. All three magnets work with this solution, the field strength is sufficient to accurately track the angle through the water tank wall.

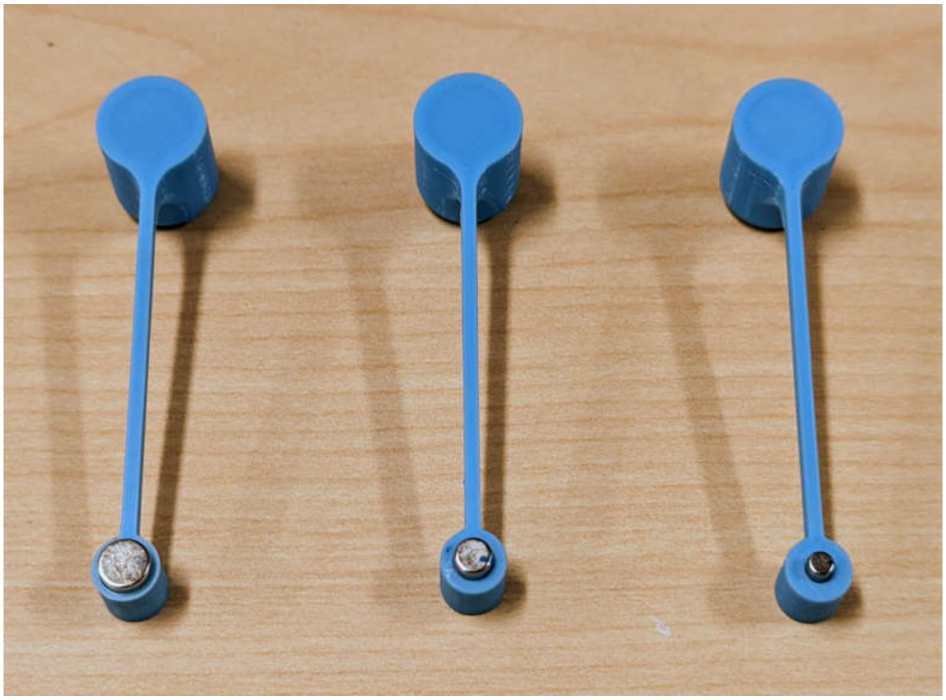

Figure 3-6. Three Magnet Sizes in Float Arms

The magnets are approximately 4 mm from the surface of the TMAG5273 when the setup is assembled. This results in a max field strength of 19.3 mT with the 1/8 inch magnet (Figure 3-7), and a max of 42.9 mT with the 1/4" magnet. Depending on the accuracy of your 3D prints and assembly, you might need to increase the maximum input setting of the TMAG5273 from 40.0 mT to 80.0 mT. Figure 3-8 shows the result from TI Magnetic Sense Simulator (TIMSS) for the 1/8" diameter magnet at 4.00 mm separation from the sensor. TIMSS can be found at TI-MAGNETIC-SENSE-SIMULATOR.

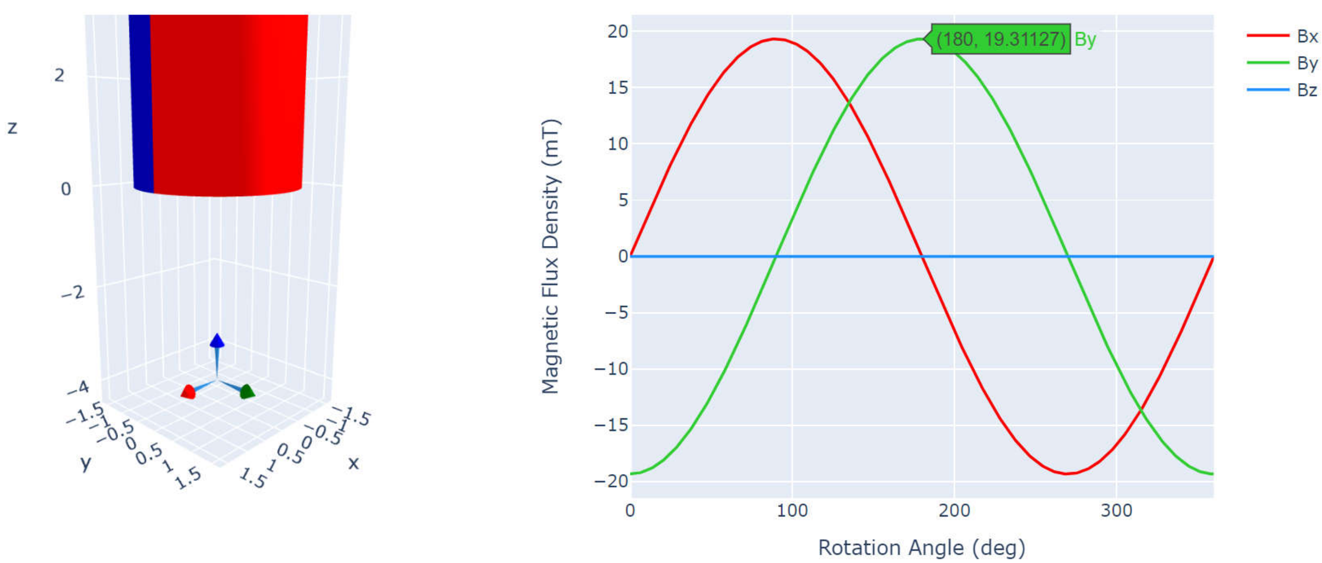

Figure 3-7. Magnetic Field Strength Results at 4.0 mm with 1/8 Inch Magnet

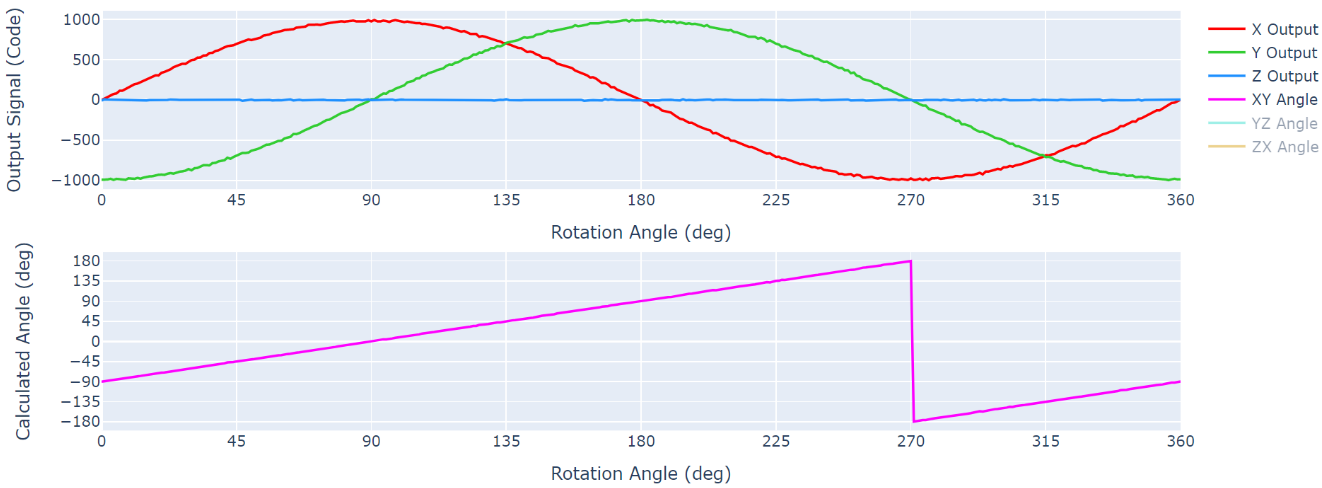

Figure 3-8. TMAG5273 Output Across 360°

This design can easily be modified to work with many size water tanks. Simply change the length of the float arm and the height of the magnet and sensor. Figure 3-9 shows the demo adapted for a larger water container by using a larger arm and adjusted sensor location. The maximum measurable range will be achieved with the sensor at the middle height of the tank and the float arm just long enough to reach the bottom and top of the tank. With a longer arm, the angle measurement range decreases. For a short arm the range of measurement approaches 180°, but for a long arm if the angle at *Empty* can be 0° then the angle at *Full* can only be 45°. Thus, an appropriately shaped flotation arm needs to be designed for the end equipment system.

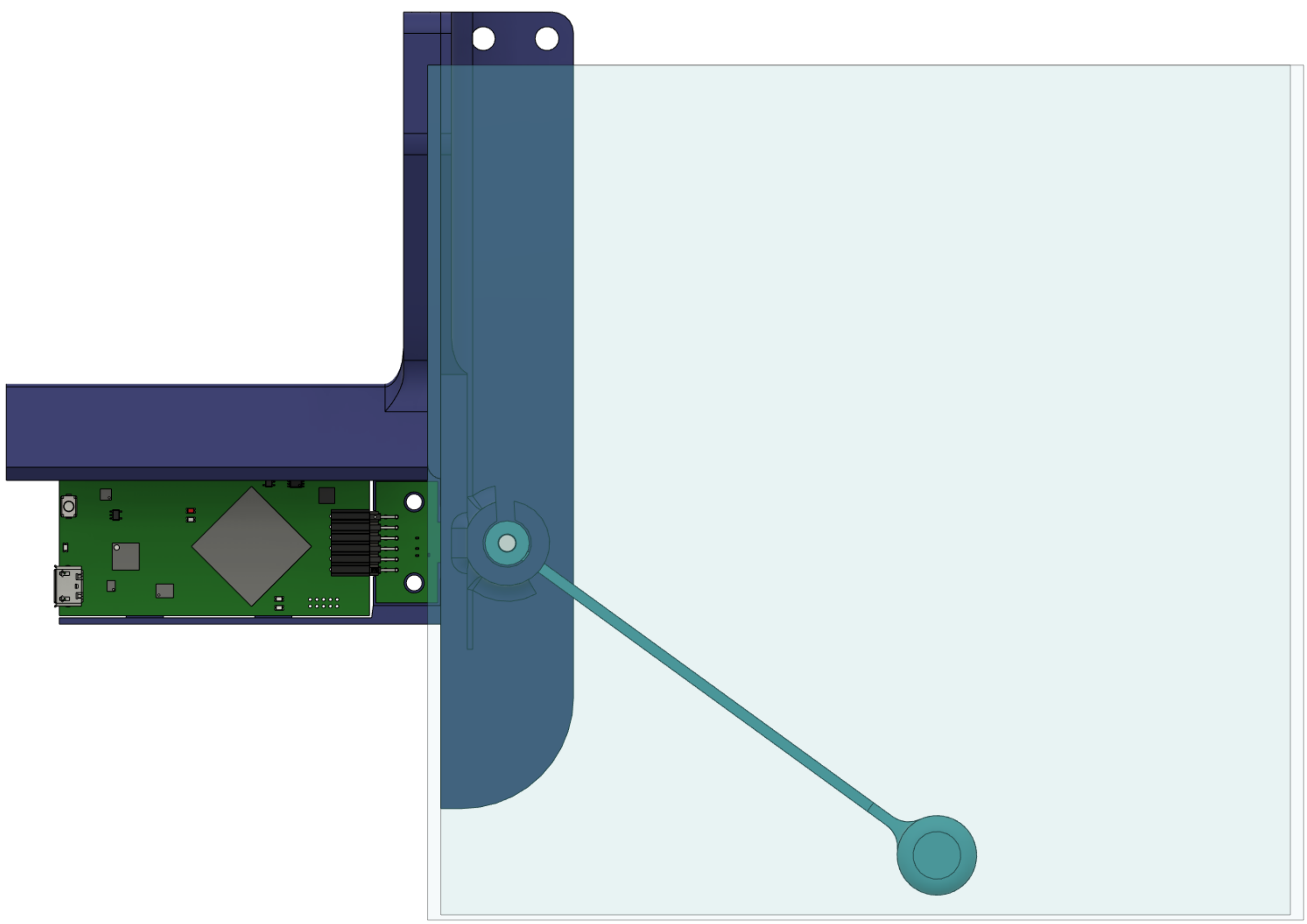

Figure 3-9. Adapt Design for Larger Water Container

3.2 GUI Operation

The web GUI for this demo can be found at https://dev.ti.com/gallery/info/PositionSensing/TMAG5x73_LiquidLevelDemo/. You must be logged into your account on *dev.ti.com* to access the GUI. Click white space anywhere to launch the GUI. The demo can be downloaded for offline use by clicking the download button and selecting the appropriate downloads.

Open the GUI and connect the TI-SCB with the TMAG5273 A1. Navigate to the Registers page and set the following items:

- (Optional) Set DEVICE_CONFIG_1→CONV_AVG to "101b= 32x Average ..."
- Set SENSOR_CONFIG_1 → MAG_CH_EN to "0011b = X, Y Channel Enabled"
- Set SENSOR_CONFIG_2 → ANGLE_EN to "01b = X 1st - Y 2nd" angle calculation
- Confirm that SENSOR_CONFIG_2 → X_Y_RANGE to ±40mT for A1 EVM/device version.

Then set *Auto Read* to *As fast as possible* at the top of the register map page.

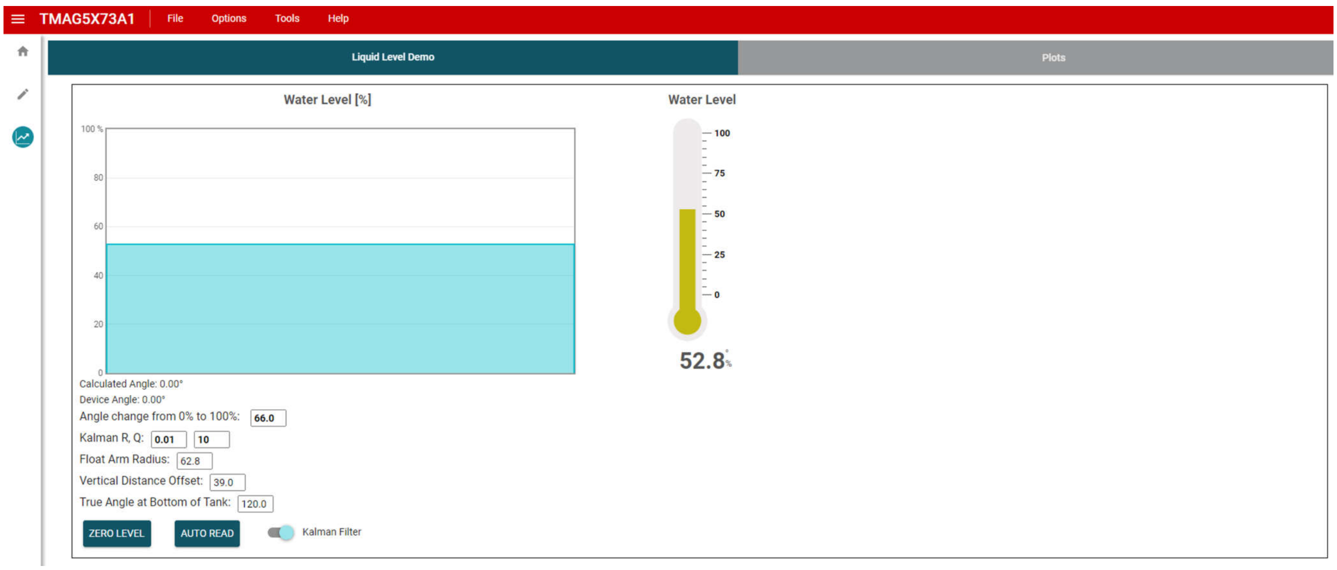

Figure 3-10. GUI Overview

Next, navigate to the Plots page. The "Liquid Level Demo" tab opens as shown in Figure 3-10.

Below the first plot the window displays the *Calculated Angle* and *Device Angle*. The *Device Angle* is the angle reported by the TMAG5273 device itself which is in increments of 0.25°. The *Calculated Angle* is the angle calculated from the magnetic field strength of the selected two axis, which for the magnet orientation in the demo is X and Y.

The GUI values are initially configured for our demo setup which used a 4" × 4" × 4" acrylic cube. The 3D printed parts sit over the edge of the water tank so that the magnet and sensor are 39.0 mm from the bottom of the tank. The radius of our float arms are 62.8 mm. For the magnet glued into our float arm, the true angle read by the TMAG5273 is 120°, and it changes by 66 degrees (to 54°) from 0% full to 100% full. All of these parameters can be adjusted to match the end system to account for any size of tank or arm radius. These parameters are illustrated in Figure 3-11. These parameters are used to calculate the tank full percentage as the float rises. It calculates the vertical distance change of the arc the float arm follows as the liquid level rises.

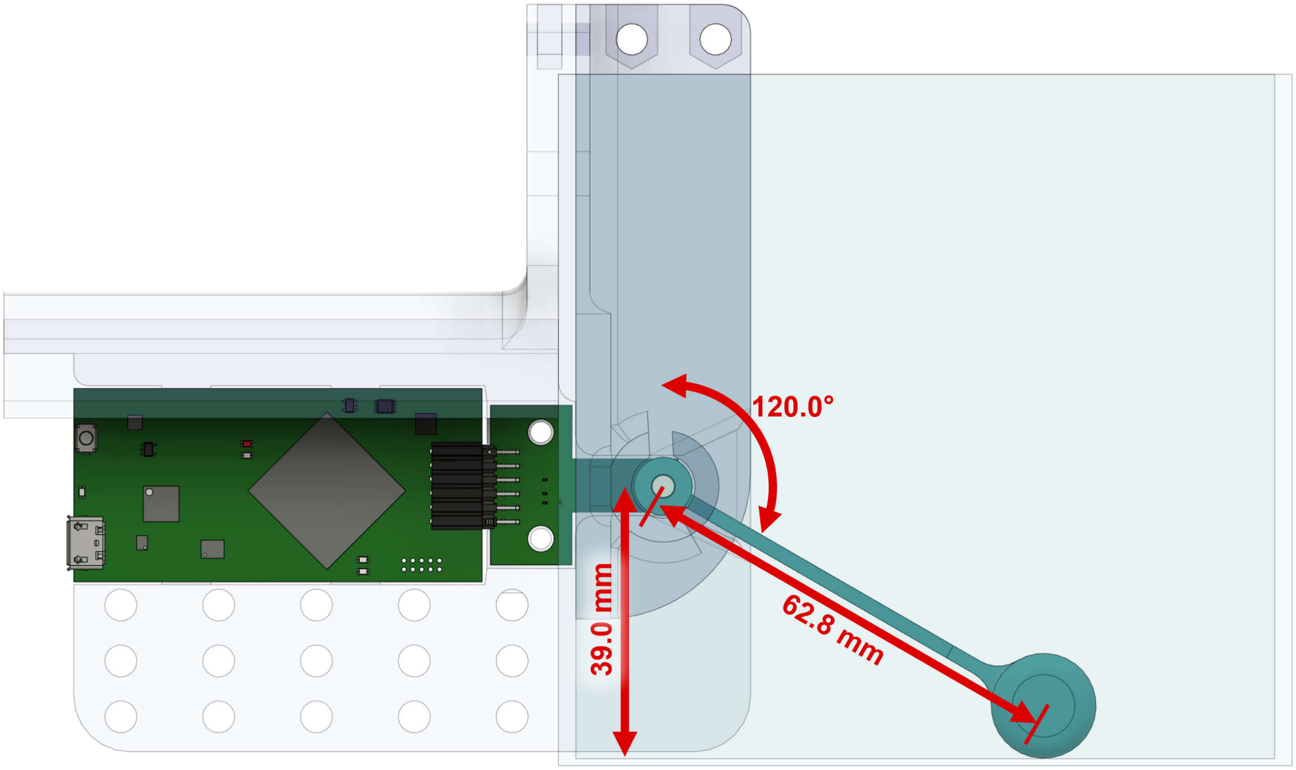

Figure 3-11. GUI Preset Configurable Parameters

There are configuration controls for the R and Q values of a Kalman filter that is being applied to the data. This is effectively a moving average, and helps account for liquid sloshing in the tank. By default these values are 0.01 for R and 10 for Q, but these can be tweaked as designed for each application. There is a toggle at the bottom to disable the Kalman Filter completely.

Click the *ZERO LEVEL* button when there is no water in the tank to set the zero location of the float arm. The zero level from one float arm to another can be different depending on how the magnet was installed - the position of the magnet when the system is at the empty liquid level.

Both plots display the liquid level as you add or remove liquid from the tank. Both charts display the same data, but the thermometer-based chart on the right updates slightly quicker and has a large readout of the fill percentage. The GUI can also work as the standard TMAG5273 EVM GUI if you navigate to the Plots tab.

3.3 3D Printing Part Orientations and Settings

The TMAG5273 was designed with 3D printing in mind for rapid prototyping, so the parts all can easily be printed on a common hobby-grade 3D printer using PLA plastic. All of the demo parts were printed with PLA filament on a Prusa MK3S with a 0.4 mm nozzle.

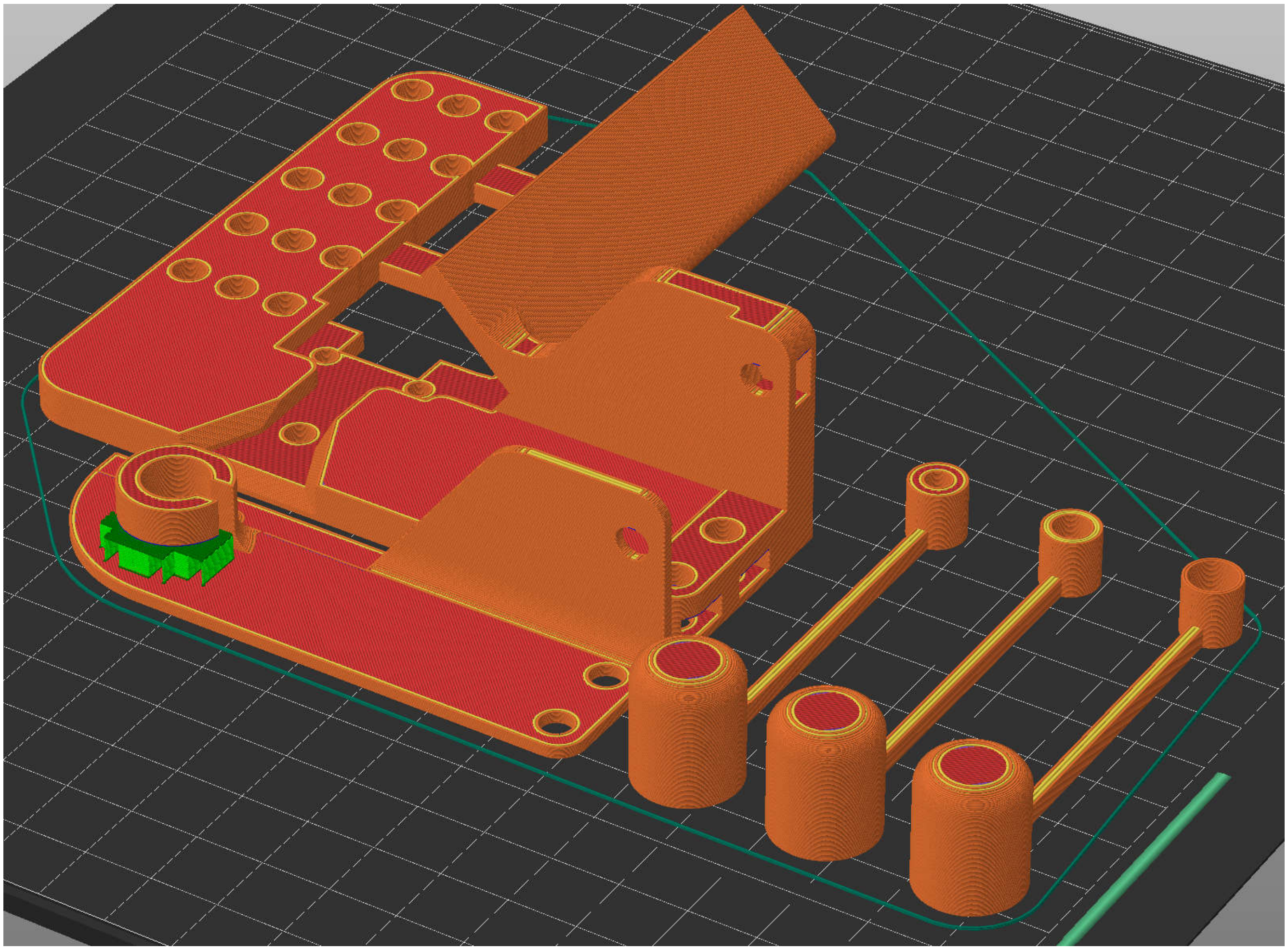

Figure 3-12. Part Orientation in Slicer

Orient the 3D printed parts in your slicer as shown in Figure 3-12. Supports are recommended for the *Liquid Level Inside Piece.stl* under the float arm ring section as shown in green in Figure 3-12. The floats are printed as hollow as possible to achieve maximum float. The floats for the demo were printed with 3 perimeters and 10% infill. The hollow end part of the float can also be replaced with a foam piece or another buoyant material.

4 Summary

Using Hall-effect sensors to measure the level of a liquid in a container can be done in a variety of ways. An array of Hall-effect latches or switches can measure the magnetic field of a floating magnet. A Hall-effect switch can measure the field of a magnet head-on as the magnet floats up and down. A 3D linear Hall-effect sensor can measure the rotation of a magnet attached to a floating arm. The 3D linear Hall-effect implementation with a floating arm provides a stable and accurate reading with a small required magnet size. The measuring capability of the design can be varied as needed by designing a different shaped float arm or using a different magnet or sensor.

5 References

5.1 Device Support

- TI Magnetic Sense Simulator (TIMSS)
- TMAG5273 Product Page
- TI Sensor Control Board (TI-SCB) Product Page
- TMAG5273EVM Product Page
- TMAG5x73 Code Example

5.2 Related Documentation

1. Texas Instruments, *[FAQ] What solutions do you recommend for measuring liquid via level sensing and other delivery methods in Medical applications?*.
2. Texas Instruments, *Capacitive-Based Liquid Level Sensing Sensor Reference Design*.
3. Texas Instruments, *High Resolution Ultrasonic Liquid Level Sensing*, application note.
4. Texas Instruments, *Overview Using Linear Hall Effect Sensors to Measure Angle*, application brief.
5. Texas Instruments, *TI Magnetic Sense Simulator (TIMSS)*
6. Texas Instruments, *Linear Hall-Effect Sensor Array Design*, application note.
7. Texas Instruments, *Angle Measurement With Multi-Axis Linear Hall-Effect Sensors*, application note.
8. Texas Instruments, *Sensor Array Fan-out Techniques and Implementation*, application brief.
9. Texas Instruments, *Absolute Angle Measurements for Rotational Motion Using Hall-Effect Sensors*, application brief.

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