# Signoff Request - September 7th, 2022 - Navigation (Ultrasonic Sensors)

Saturday, June 11, 2022 1:48 PM

## *Navigation Subsystem - Ultrasonic Sensors :*

### *Abstract: Ultrasonic Sensor Signoff Takeaways:*


This signoff request is for the four ultrasonic sensors which will be used in the design for the Autonomous Crawl Space Inspection Robot. The Ultrasonic sensors reside in the "Navigation Subsystem" on our block diagram. First, for this signoff request, the expectations or specifications of using the Ultrasonic sensors in the design of the inspection robot are explained in verbal terms. Then, analysis is performed so that the specifications of how the Ultrasonic sensors are used can be stated quantitatively as constraints and so that the quantitatively stated specifications can be justified. Finally, an Ultrasonic sensor is chosen, examined, and analyzed to whether or not it can meet the specifications and constraints of the atomic subsystem.

*Specifications:*

1. *Two Ultrasonic Sensors will be used as "cliff" sensors and will measure the depth of the crawlspace floor in relation to the reference floor so that the robot can safely navigate throughout the crawlspace*
2. *Two Ultrasonic Sensors will be used as "wall" sensors and will measure the robot's distance from objects and obstructions within the crawlspace that are out of sight of the 360 Degree Lidar sensor (which is mounted on top of the inspection robot)*
3. *The Ultrasonic sensors must sample at a frequency that will allow enough datapoints for navigation throughout the crawlspace without "lagging" (the robot waiting for movement instructions)*
4. *The Ultrasonic sensors must be able to be powered from the Raspberry Pi 4B and report sampled data through the 3.3 Volt GPIO pins on the Raspberry Pi 4B*

*Constraints:*

1. *The two Ultrasonic Sensors used as "cliff" sensors must be able to "see" or accurately measure a depth of 8.99 inches from the sensor (reasoning explained through analysis later in the signoff)*
2. *The two Ultrasonic Sensors used as "wall" sensors must be able to "see" or accurately measure a distance of **at least twice t**he length of the longest attachment on the chassis, in the given example would be **at** least 8.6 inches*
3. *The four Ultrasonic Sensors used must have a sampling frequency that is sufficient for navigating throughout the crawlspace without the robot "lagging". Since the robot velocity is roughly 1 foot per second, the Ultrasonic sensors chosen must have a sampling frequency of at least more than 1 samples per second, with the preferred sampling frequency at least 12 samples per second or 1 sample per inch (most commercially available Ultrasonic sensors, including the one chosen, have a sampling frequency of **at least** 26 samples per second or 2 samples per inch).*
4. *The four Ultrasonic Sensors used must be able to be powered by the voltage available from the Raspberry Pi 4B (5 Volts or 3.3 Volts). Since the Raspberry Pi 4B GPIO pins are rated for 3.3 Volt inputs, the voltage output from the Ultrasonic sensors to the Raspberry Pi 4B must be already 3.3 Volts or stepped down to 3.3 Volts*

*Analysis:*

*Analysis was done for calculating the maximum vertical depth as well as what the minimum horizontal distance from the robot to obstructions in the crawlspace could be for the robot to traverse on safely in the crawlspace. In this analysis, size estimates of the robot were used (12 inches by 12 inches by 12 inches) as well as a maximum slope constraint of common robot chassis, such as the one in the "Robotics Chassis Kit" signoff. The sampling frequency needed for the sensors was determined by analyzing the sampling frequency of Ultrasonic sensors used for similar projects and comparing that sampling frequency to the velocity of the inspection robot and thus determining an appropriate sampling frequency for this application (26 samples per foot will provide plenty of information).*

*Chosen Component:*

*Grove - Ultrasonic Ranger 2.0 - $4.30/Unit - 4 Units Needed - $17.20 BOM*


## *Expectations (Specifications) and Constraints of Ultrasonic Sensors:*

An Ultrasonic sensor is a module which determines distance from objects by emitting a sound wave and recording the time that it takes for the soundwave to be received. Two Ultrasonic sensors will be mounted on the front-bottom and back-bottom of the robot and will be responsible for obtaining vertical (more so diagonal) distance measurements of the robot from the floors of the crawlspace environment so that the robot will not be damaged by sudden drops or become stuck in various depths of the crawlspace. In order to not be damaged by drops or become stuck due to a change in depth, the team members believe it is best that at least one end of the tracks as well as the center of the tracks of the robot remain on the ground at all times, which will allow for constant contact and grip as the robot moves. Commonly stated as a constraint for hobbyist robot track chassis, such as the one the team plans to use in this project, the max slope which the robot can traverse on will be constraint to 30 degrees [1]. Two more Ultrasonic sensors will be working in conjunction with the Lidar sensor. These third and fourth Ultrasonic sensors will be mounted on the front and back of the robot and will serve as a failsafe/error check for horizontally detecting objects which are close to the robot chassis but out of sight of the Lidar sensor as the robot moves forwards and backwards. All Ultrasonic sensors will need to provide accurate and timely measurements so that the robot can quickly navigate throughout the crawlspace at an acceptable speed of roughly 1 foot per second (based on the average speed of an autonomous house vacuum) without colliding with objects or becoming stuck due to depth changes [2]. The Ultrasonic sensors must be able to be powered by a Raspberry Pi 4B and measurements must be able to be recorded on the GPIO pins of a Raspberry Pi 4B.

## *Understanding Quantitative Constraints of the Ultrasonic Sensors Through Analysis of the Expectations/Specifications :*

1. *Vertical "Cliff" Sensor Maximum Allowed Depth:*

The first specification examined for analysis is the max depth measurement that can present for the robot to still be allowed to move either forward or backwards. Two Ultrasonic sensors, one on the front-bottom and one of the back-bottom, must measure the distance from the robot to the crawlspace floor. These Ultrasonic sensors will act as cliff sensors, which alert the robot if some maximum depth is surpassed, prohibit the robot from moving forward in the direction of the max depth, and thus allowing the robot to avoid becoming stuck or damaged due to "falling" **[2].** The maximum depth is a function of the total length of the robot, the maximum slope of 30 degrees (or a grade of 57.8 %), as well as the height position of the Ultrasonic sensor when mounted onto the robot.

As previously mentioned, the robot can move on a maximum slope of 30 degrees (or a grade of 57.8 %). In order to calculate the slope of a plane that an object is moving on, the change in height is divided by the change in length (rise/run). For a 30 degree slope, the ratio of the change in height to the change in length (rise/run) must be 0.578 which comes from the ratio of rise/run for the 30 degrees (or pi/6) segment of the unit circle, which when multiplied by 100 will result in a "grade" of 57.8 % [3]. Therefore, the ratio of the change in height to the change in length of the robot's movement must be a max of 0.578 at all times in order to adhere to the maximum allowed slope of 30 degrees. While crawlspaces differ in the makeup and slope of the ground, a maximum scenario is considered in which the quickest change in height and length takes place, or, the steepest and most rapid 30 degree slope.

In order to determine the maximum depth allowed for the robot to still move, a reference depth is considered which can be thought of as an x-axis the robot is moving on and the base (reference) depth of the crawlspace, as shown in figure 1. Next, the lowest depth or bottom depth is considered and is identified as the lowest point which the robot can present on while allowing the center and one end of the track to be present on the ground, as shown in figure 2 and figure 3. As seen in figure 2 and figure 3, a triangle can be visualized, which will allow for the analysis of the maximum depth through the use of trig equations.

***Figure 1:***

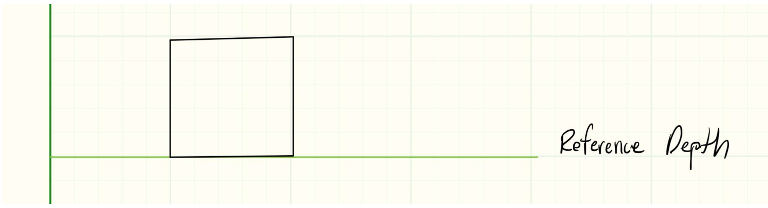



***Figure 2:***

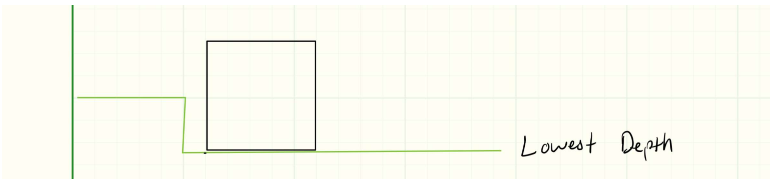
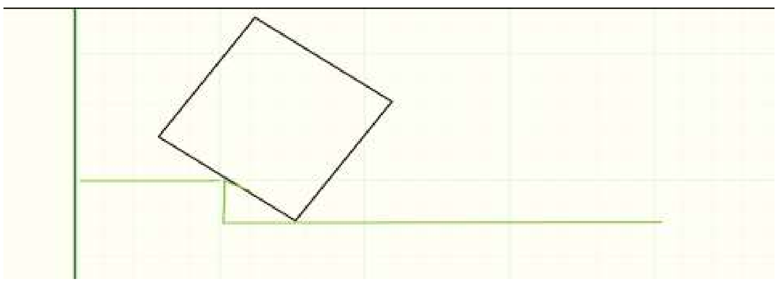



***Figure 3:***



As shown in figure 4, each side of this triangle can be assigned an element (a, b, and c) which will allow for an initial equation, as shown in equation 1, to be constructed for solving for the maximum depth. Since the maximum slope allowed is 30 degrees, this triangle shown in figure 4 will be modeled after a 30, 60, 90 triangle and will have the following measurements of each side*:* *a* is equivalent to 0.5 times the length of the hypotenuse; *b* is equivalent to 0.865 times the length of the hypotenuse; and *c* is equivalent to 1 times the hypotenuse. As stated in equation 1, when adding the square of side *a* and the square of side *b*, the square of the hypotenuse (or *c*) is obtained. As shown in figure 5, when at the steepest slope possible while adhering to the 30 degree slope constraint, the hypotenuse of this *triangle c* will have a length of one half the length of the robot. Additionally, side a will be one half of *c* (or 0.25 times *c*) and side *b* will be 0.865 times *c*.

***Equation 1***: $\boldsymbol{a^2 + b^2 = c^2}$

***Figure 4:***

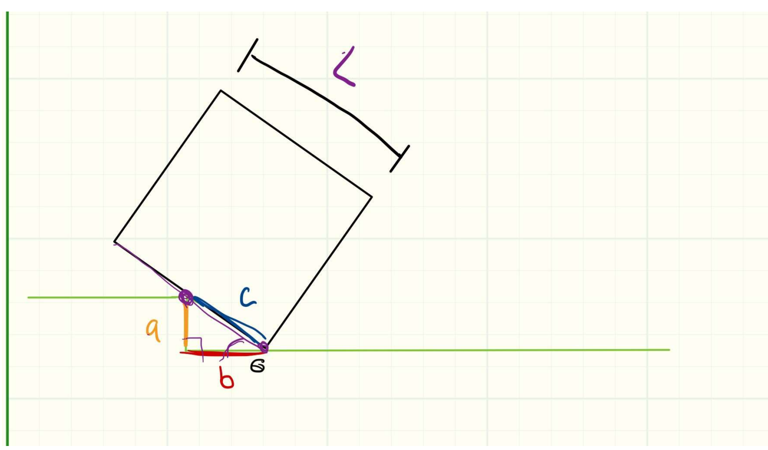
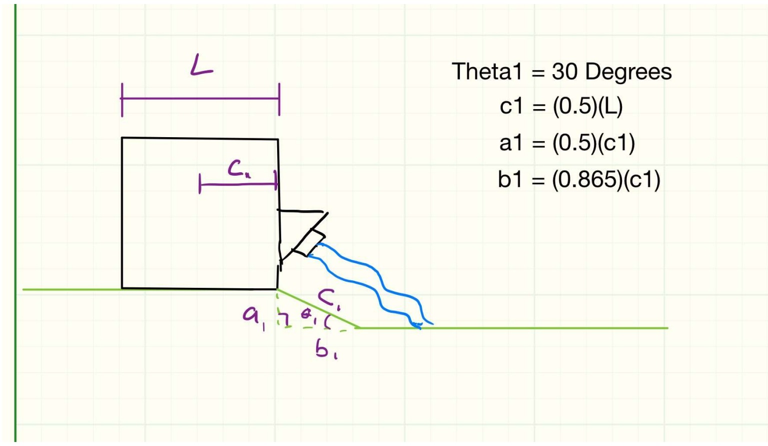


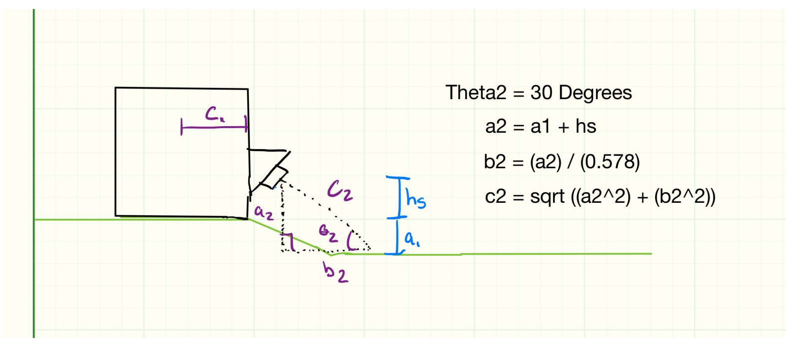

***Figure 5:***




While the triangle in figure 4 does model the robot's interaction with the crawlspace surface, it does not take into account the height at which the ultrasonic sensor is mounted at or the angle of the mounted sensor. In order to measure the depth of the crawlspace floor in front of the robot while the robot is in motion, the ultrasonic will be mounted on an angle to the side of the robot. As shown in figure 6, the distance ($c_2$) is the distance from the ultrasonic sensor to the floor of the crawlspace when a maximum slope of 30 degrees is achieved. In order to calculate ($c_2$), the height ($h_s$) is declared as the height from the reference floor of the crawlspace to the height where the ultrasonic sensor is mounted. The height ($a_1$) is also considered from the previous triangle shown in figure 5 and the total height of the new triangle ($a_2$) is found to be the summation of ($a_1$) and ($h_s$). Additionally, by taking the ratio of rise/run from the first triangle and setting it equal to the ratio of rise/run from the second triangle, a system of equations can be created and ($b_2$) can be solved for as shown in equation 2 and equation 3. Finally, the maximum depth the cliff sensor can measure without needed to alert the robot of possible danger ($c_2$) can be calculated as shown in equation 4. By setting the length of the robot to 12 inches, as suggested by the capstone team until the design of the chassis is finalized, and estimating the height of the ultrasonic sensor from the reference floor of the crawlspace ($h_s$) to be 1.5 inches, the maximum depth can be calculated to be roughly 9 inches (8.99 inches), as shown in figure 7.

While all analysis up until this point has been targeted towards a drop in depth (a.k.a descending), the slope or grade is positively and negatively interchangeable, meaning that even when climbing at a slop of 30 degrees the robot should have a maximum depth measurement of 9 inches on the front or back cliff sensors, depending on the direction the robot is facing. If figure 4 is examined with the aspect of an upward climb of 30 degrees, at the point where the middle and end of the track are still on the ground the ultrasonic cliff sensor on the front of the robot will have a depth measurement of 9 inches from the sensor to the crawlspace floor, as ($a_1$) and ($h_s$) are constant in both ascending and descending circumstances. Therefore, when ascending or descending, a maximum allowed depth measurement of 9 inches will allow the robot to stay within the constraint of not climbing a slope steeper than 30 degrees (or a 57.8 % grade) [3]**.**

***Figure 6:***




$$\boldsymbol{Equation\ 2}:\ \left(\frac{\boldsymbol{a_1}}{\boldsymbol{b_1}}\right) = \mathbf{0.578} = \left(\frac{\boldsymbol{a_2}}{\boldsymbol{b_2}}\right)$$

$$\boldsymbol{Equation\ 3}:\ (\boldsymbol{b_2}) = \left(\frac{\boldsymbol{a_1} + \boldsymbol{h_s}}{\mathbf{0.578}}\right)$$

***Figure 7:***

## Triangle 1 :

$a_1 = 0.5(0.5L)$

$b_1 = 0.865(0.5L)$

$c_1 \approx 0.5L$

**If $L = 12$ :**

$c_1 = 6$ inches

$a_1 = 1.5$ inches

$b_1 = 5.19$ inches

## Triangle 2 :

$a_2 = a_1 + hs$

$b_2 = \frac{a_1 + hs}{0.578}$

$c_2 = \sqrt{(a_2^2) + (b_2^2)}$

**If $h_s \approx 1.5$ :**

$a_2 = 4.5$ inches

$b_2 = 7.79$ inches

$c_2 = 8.99$ inches

### 2. *Vertical "Cliff" Sensor Sampling Frequency Using Estimated Chassis Specs:*

The needed sampling frequency for the vertical "cliff" sensor that will allow the robot to move forwards or backwards without lagging (waiting on instructions) and with sufficient navigation processing time can also be calculated. As previously mentioned, the inspection robot movement speed has been estimated to roughly 1 foot per second by team members. For the vertical "cliff" sensors, as shown in figure 5, if on an even (or reference) ground without slope, the distance from the edge of the robot chassis (not including the cliff sensor bracket) to spot on the crawlspace floor that is being measured can be seen as ($b_1$). This distance would be the shorter than distance ($b_2$), which is the length component used to calculate the maximum vertical depth ($c_2$). Since the ($b_1$) distance is shorter than the ($b_2$) distance, less time would be available for measurements to be taken while the robot moves forwards or backwards and therefore the minimum sampling frequency of the vertical "cliff" sensor can be calculated as a function of the ($b_1$) distance. Most commonly used ultrasonic sensors have a total sampling frequency of roughly 26 Hz (samples per second) [**4**]. If the inspection robot is moving at roughly 1 foot per second, then 26 samples can be taken per foot moved in the forward and backwards directions. As shown in figure 7, ($b_1$) can be determined by multiplying half of the length of the robot chassis (not including the sensor bracket) by 0.8650 (or $\sqrt{3}/2$). Therefore, as mentioned in the example case given, if the robot chassis has a length (L) of 12 inches, then ($b_1$) is determined to be roughly 5.19 inches. Thus, in this absolute case where the robot is on "perfectly" parallel ground, then vertical "cliff" sensors are constantly measuring the depth of the crawlspace at a distance of 5.19 inches **ahead** of the robot's current position. If the ultrasonic sensors have an estimated total sampling frequency of 26 Hz (samples per second, the inspection robot is moving at an estimated velocity of 1 foot per second, and the "cliff" sensors are measuring a distance of 0.4325 feet (5.19 inches) infront of the robot, then by the time the tracks of the robot reach the spot the "cliff" sensors have measured, 11 samples of the depth of the crawlspace will have been taken. Since the Raspberry Pi 4B GPIO pins have a sampling frequnecy of roughly 10 MHz, the 11 samples taken can be quickly analyzed and will offer more than enough information for the inspection robot to traverse without "lagging" **[5].**

### 3. *Horizontal "Wall" Sensor Minimum Distance:*

The second specification examined for analysis is the minimum horizontal distance measurement to an object that can present for the robot to still be allowed to move either forward or backwards. The final two Ultrasonic sensors, one on the front face and one of the back face, must measure the distance from the robot to obstructions within the crawlspace and will act as a safety measurement for objects outside the view of the Lidar sensor as well as an error check for the Lidar sensor. These Ultrasonic sensors will act as "wall" sensors, which alert the robot if some object is present at the minimum horizontal distance, and will prohibit the robot from moving forward in the direction of the object present, and thus allow the robot to avoid colliding with objects or "walls" [**2**]**.** Unlike the maximum vertical depth, the minimum horizontal distance is easier to calculate and is only a function of the total length of attachments on the robot. Currently, the "longest" attachment on the front and rear of the robot will be the USB HD Camera being considered with a length of roughly 4.3 inches. In order to determine a quantitative minimum horizontal distance, the length of the longest attachments on the front and rear faces of the robot are considered and the minimum horizontal distance is determined by equation 4, where $D_{min}$ represents the minimum horizontal distnace and $l_{max}$ represents the largest attachment length. The inequality shown in equation 4 allows for the robot to set an imaginary boundary so objects can only be within a distance of $D_{min}$ from the robot, ensuring that no physical contact or collision happens between the robot and the crawlspace envrionment. Currently, the attachment with the greatest horizontal length being considered in the design is the HD USB Camera with a length of 4.3 inches. Therefore, if considering 4.3 inches as the largest attachement length ($l_{max}$), the minimum horizontal distance ($D_{min}$) would be 4.3 inches and the robot would only be able to move forwards or backwards if obstructions in front of the robot are at a distance greater than 4.3 inches.

$\boldsymbol{Equation\ 4}$: $\boldsymbol{D_{min} > l_{max}}$

Since the previous case is the **absolute** minimum horizontal distance, it makes sense to allow an error for the minimum horizontal distance, so that there is always space between the longest attachment and obstructions within the crawlspace. An error of 100 percent has been chosen which is twice the length of ($D_{min}$) and will be plenty of compensation for error to allow the robot to maintain a safe space between obstructions and the front and rear faces of the robot. Therefore, in the previouse case, if ($D_{min}$) is determined to be 4.3 inches, then the minimum horiztonal distacne

$min$

would be twice ($D_{min}$), or 8.6 inches. In case of additional attachments on the rear of the robot and to maintain dimension symmetry, this minimum horiztonal distance will be issued as a constraint to both the front and rear face ultrasonic sensors.

4. *Horizontal "Wall" Sensor Sampling Frequency Using Estimated Chassis Specs:*

The needed sampling frequency for the vertical "cliff" sensor that will allow the robot to move forwards or backwards without lagging (waiting on instructions) and with sufficient navigation processing time can also be calculated. As previously mentioned, the inspection robot movement speed has been estimated to roughly 1 foot per second by team members. For the horizontal "wall" sensors, as shown in figure (), when a largest attachment length ($l_{max}$) of 4.3 inches and an error equivalent to that distance is allowed (an additional 4.3 inches) then the minimum horizontal distance ($D_{min}$) is computed to be 8.6 inches, as with the previously stated example. This minimum horizontal distance ($D_{min}$) is also the distance which the ultrasonic sensor will be measuring in front of the inspection robot. If the ultrasonic sensors have an estimated total sampling frequnecy of 26 Hz (samples per second), the robot is moving at an estimated velocity of 1 foot per second, and the horizontal "wall" sensors are constantly measuring at a distance of 0.7167 feet (8.6 inches) in front of the robot chassis, then by the time the tracks of the robot each the spot the "wall" sensors have measured, 18 samples will have been taken. Since the Raspberry Pi 4B GPIO pins have a samplig frequnecy of rouhgly 10MHz, the 18 samples taken can be quickly analysed and will off more than enough information for the inspection robot to traverse without "lagging" [5].

## *HC-SR04-3942 Ultrasonic Sonar Distance Sensors:*

The chosen Ultrasonic sensor is the Grove - Ultrasonic Ranger 2.0 Sonar Distance Sensor, manufactured by Seeed Studio LLC **[4],** as shown in figure 8. The Ultrasonic Ranger 2.0 has four connections, one for the supplied voltage (VCC), one for the ground (GND), one for the emitted sound signal and received sound signal (SIG), and one pin that is to not be connected to anything or serve as a neutral (NC). While other Ultrasonic Sensors such as the HC-SR04 have separate ECHO and TRIG pins for the sent and received sound signals, the Ultrasonic Ranger 2.0 has one pin (SIG) which is responsible for emitting and receiving the sound signal for distance determination, thus reducing the GPIO pins needed for operation to one instead of two [4]. Since there will be four ultrasonic sensors used on the robot, one positioned towards the bottom front, one positioned to the bottom back, one positioned in the forwards movement direction and one positioned in the backwards movement direction, in total there will be four VCC connections, four GND connections, four SIG connections to the Raspberry Pi. The chosen ultrasonic sensors output digital data with the digital data being observed as low (0 Volts) or as high (3.3/5 Volts). The specific range of the ultrasonic sensor can vary from 2 to 350 cm, however, any measurements above 250 cm start to become slightly less accurate [4]. A band pass filter is included in the design of the sensor and the schematic with detailed information of the ultrasonic sensor is shown in figure 9 **[4].** In total, four ultrasonic sensors will be needed and are priced at $4.30 per unit, resulting in a total price of $17.20.

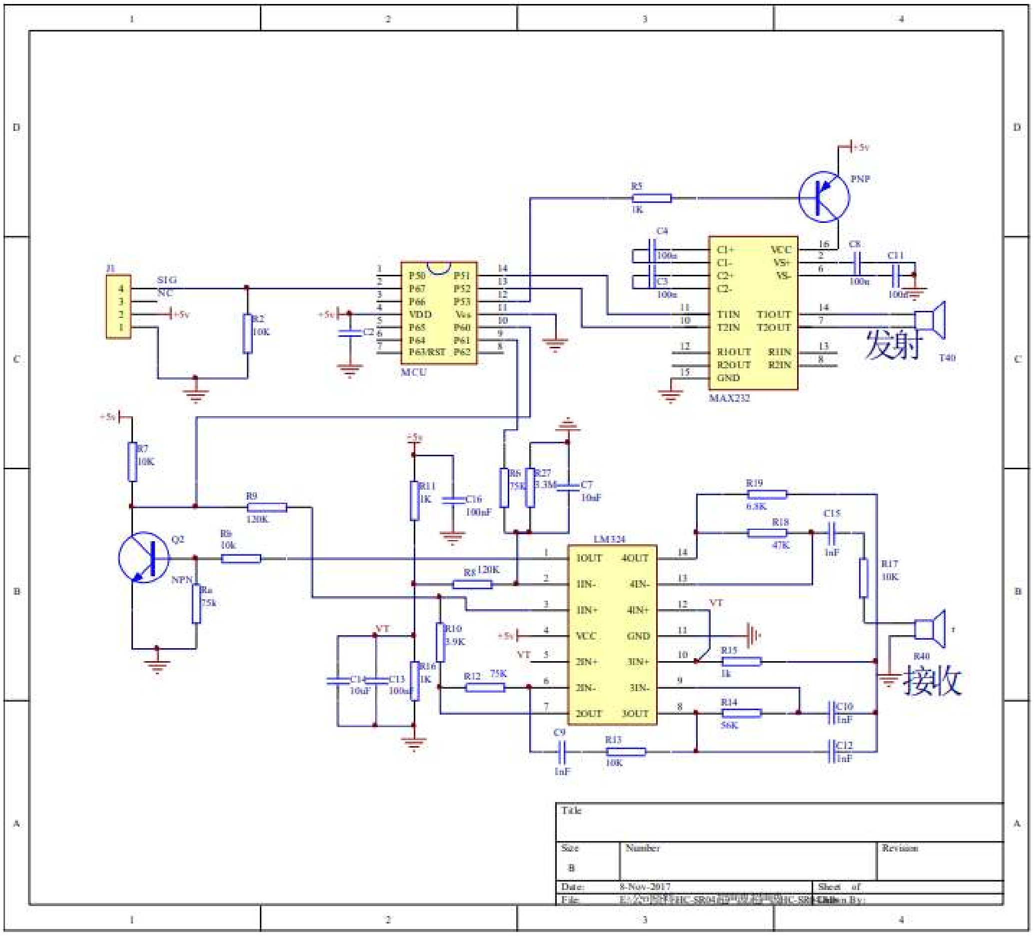
The Ultrasonic Ranger 2.0 sensors each have an operating current of 8 mA **[4].** Since four sensors will be connected to the same Raspberry Pi 4B 5 V power rail, the total max current draw if all sensors are measuring at once is 32 mA. Since the Raspberry Pi 4B's 5 V power pins are connected directly to the main power bus of the device, the max current that can be output on the 5 V pins is equivalent to the difference of 3 Amps minus the total current being used by the device **[5].** The Raspberry Pi 4B uses roughly 1.5 Amps of current under a normal load of operation of the CPU and peripherals such as a monitor, a mouse, and a keyboard **[5].** Thus, roughly 1.5 Amps are left over for additional sensors connected to the 5 V rails of the Raspberry Pi 4B, meaning that the roughly 32 mA needed for the ultrasonic sensors is well within the operating limits of the overall system.

The ultrasonic sensors must be able to connect to and communicate with the Raspberry Pi 4B, the main MCU of the Navigation Subsystem, which will be achieved via wired connections between the sensors and the GPIO pins of the Raspberry Pi 4B. The selected ultrasonic sensors must be able to receive distance measurements of the robot from close surfaces within the crawlspace environment. The Ultrasonic Ranger 2.0 sensors chosen for this project have a distance measuring range of 2 cm to 350 cm (0.787 inches to 158.48 inches)**.** The Ultrasonic Ranger 2.0 sensors have the highest accuracy of measurements up until 250 cm, at which point the accuracy of the sensors begins to slightly decrease [4]**.** Thus, the ultrasonic sensors on the side of the robot will have a maximum accurate detection range of up to 250 cm away from the inspection robot. The ultrasonic sensors initiate measurements when a 10 microsecond pulse is initiated onto the SIG pin [4]. Once the 10 micro second pulse is observed, eight 40 kHz sound waves are transmitted from the ultrasonic sensors and the SIG pin is set high. If no objects are detected, the SIG pin will remain high and once the SIG pin has been high for 38 milliseconds, the distance determination will time out and the SIG pin will return to low, indicating that no objects have been detected. When an object is detected, the SIG pin will be high for some time ranging from 150 microseconds to 25 milliseconds, corresponding to a distance measured [4]. This pulse time will then be used to calculate the distance of the robot from the surrounding objects. Equation 5 shows the relationship between the speed of sound *(Speed = 343 meters per second)* and the time taken for a sound signal to be emitted and received by the device *(Time*) [4]**.** This resulting calculation is then divided by two in order to determine the one-way distance from the sensor to the object detected. In order to confirm that measurements with the ultrasonic sensors can be taken fast enough for live navigation, the total time for a pulse to be measured and the movement speed of the robot can be considered. The assumption of a movement speed of roughly 1 foot per second as been selected for the crawlspace inspection robot by comparing different velocities of cleaning Roomba's **[5].** The maximum time taken for one measurement with the ultrasonic sensors would be 38 milliseconds, since this is the time of the pulse on the echo pin that is the largest possible and represents no objects obstructing the robot's path. If 38 milliseconds are needed for the sensors to properly consider all distances of objects from the robot, including the possibility of no obstructions, then the total period of needed sampling time is 38 milliseconds, or roughly 26 Hz, Therefore, roughly 26 measurements are taken each second, and each foot, that the robot moves in the crawlspace environment.

$$\boldsymbol{Equation\ 4: Distance = \frac{Speed * Time}{2}}$$

***Figure 8 [4]:***

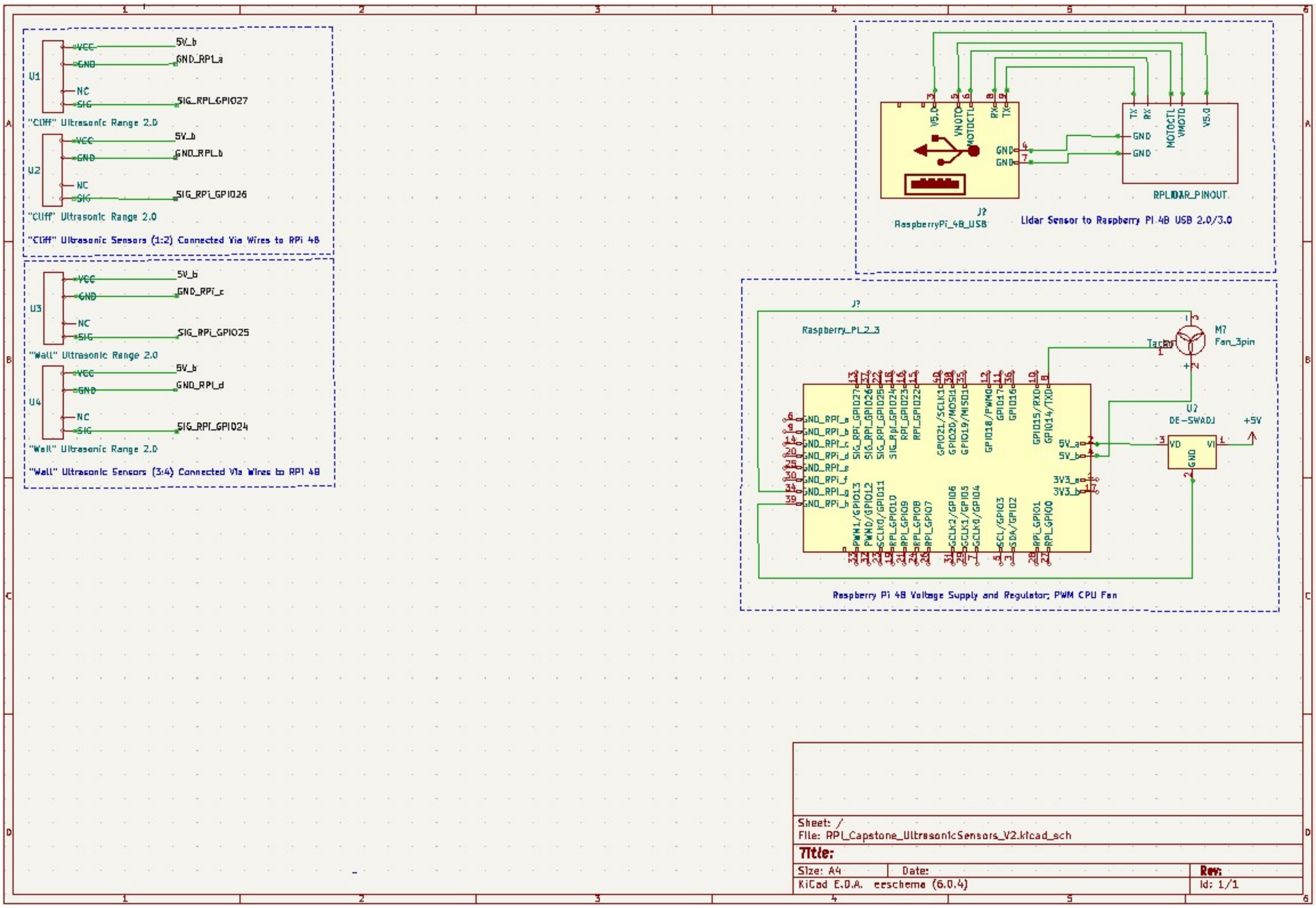

***Figure 9 [4]:***




## 1. *Ultrasonic Sensors With Raspberry Pi Schematic:*

As previously mentioned, each of the six ultrasonic sensors will be connected to the Raspberry Pi 4B onboard 5 V power rail, ground pins, and GPIO pins. Other Ultrasonic sensors such as the HC-SR04 output a voltage of 5 Volts on the output ECHO and TRIG pins and require a voltage divider in order to not damage the Raspberry Pi 4B GPIO Pins which are rated for 3.3 Volts. The Ultrasonic Ranger 2.0 sensors, however, include a built-in voltage divider on the sensor printed circuit board and can be connected directly to the Raspberry Pi 4B GPIO pin **[4].** The ultrasonic sensors connected to the Raspberry Pi 4B are shown In figure 3.

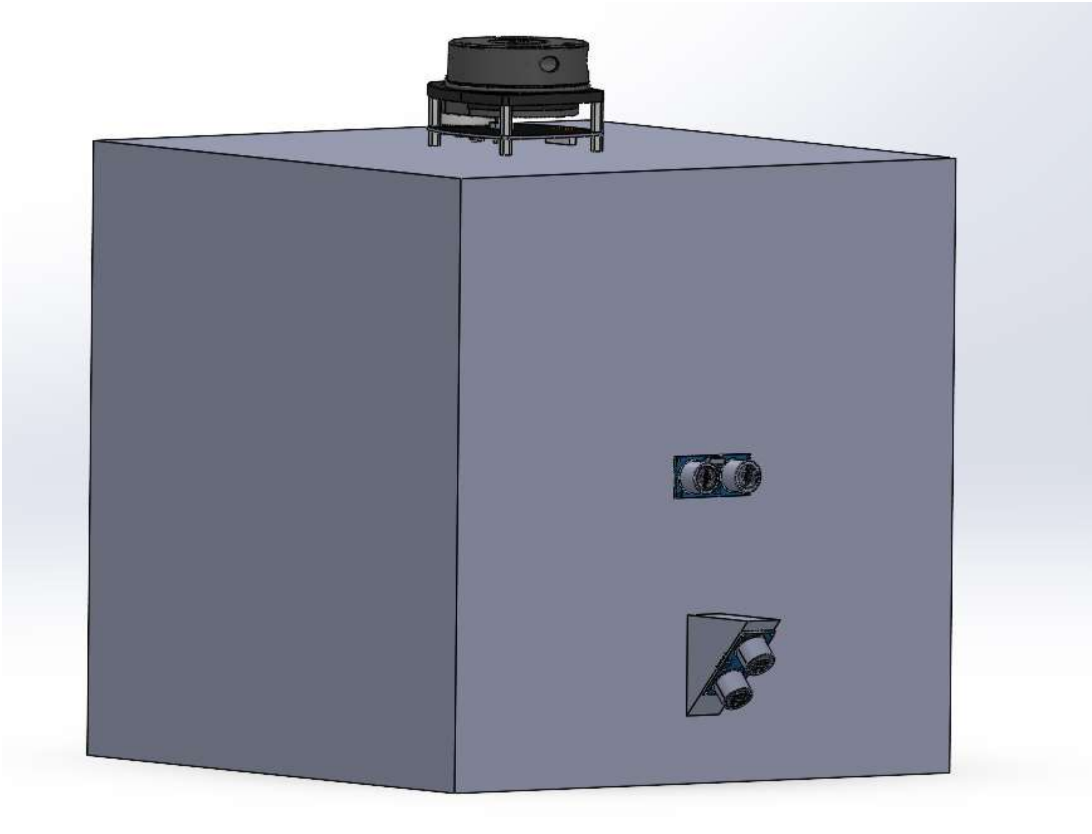
***Figure 10:***




## 2. *3D Model (Position On Robot)*

As stated by the manufacturer, the dimensions of the Ultrasonic sensor are as follows: a length of 50 mm, a width of 25 mm, and a height of 16 mm (1.969 inches x 0.984 inches x 0.630 inches) [1]. In this initial design of the robot's structure, the Ultrasonic Sensors will be mounted on the front and back of the robot, pointing perpendicular to the faces on which they are mounted. Additionally, two sensors will be mounted on the front-bottom and back-bottom of the robot. As seen in figure () and figure 5, the ultrasonic sensors on the front and back faces of the robot will sit at a height above ($h_s$) and will detect the distance from the upcoming objects to the robot. Additionally, the two ultrasonic sensors that will be used as cliff sensors will be mounted on the front-bottom and back-bottom of the robot at a height of ($h_s$), which in the previous examples was given to be roughly 1.5 inches. The ultrasonic sensors are said to have a maximum measuring angle of 15 degrees, thus, two right triangular pieces have been added so that the sensors point towards the ground and are able to utilize the extra 15 degrees viewing angle to anticipate upcoming drop-offs [4]. The overall structure of the robot has not yet been designed, so, as with the Lidar sensor, an estimated size of the robot is being used of 12 inches in length by 12 inches in width by 12 inches in height.

***Figure 11:***



## Sources:


**[1] Tank Chassis On 30 Degree Slope:**
https://www.amazon.com/XiaoR-Geek-Aluminum-Raspberry-Absorbing/dp/B077Z4GYLB/ref=asc_df_B09C7TK9Y9/?tag=hyprod-20&linkCode=df0&hvadid=533431677067&hvpos=&hvnetw=g&hvrand=1867927543083052465&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9013670&hvtargid=pla-1430389449296&th=1

**[2] iRobot Roomba Datasheet:**
https://www.irobotweb.com/~/media/MainSite/PDFs/About/STEM/Create/iRobot_Roomba_600_Open_Interface_Spec.pdf?la=en

**[3] Slope and Grade Calculations:**
https://www.engineeringtoolbox.com/slope-degrees-gradient-grade-d_1562.html

**[4] Grove - Ultrasonic Ranger 2.0 Sensor**
https://wiki.seeedstudio.com/Grove-Ultrasonic_Ranger/

**[5] Raspberry Pi 4B Specs:**
https://www.raspberrypi.com/documentation/computers/processors.html