Study on sonars : scanning the seafloors

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Introduction

We use sonars for multiple purposes. One is analyzing the compositions of sediments under large oceans. Another is to scan the surface of sediments to obtain an image of seabeds. In the course of one my subjects at Sorbonne Université, I had the opportunity to understand how sonars work in a nutshell. Part of the "Romarin" project, the goal of this project is to make a functional sonar in order to obtain a seafloor mapping of the Seine in Paris. In order to do so, colleagues and I decided to first understand the sonar that the personnel at Saint-Cyr had, get a better understanding of the electronics, and most importantly, try and obtain images of the floor of the pool.

Sonar technology

A sonar is made of multiple transducers, an instrument that transforms one physical quantity into another. In our case, the transducers converts acoustic vibrations into an electrical voltage. Regarding its composition, the transducers are surrounded by an absorbing material called backing and impedance matching layers. The backing prevents wave reflections from the rear, while the impedance matching layers provide better transmission in the intended medium. Similarly, our transducers are made of composite ceramics because they offer piezoelectric characteristics (the material becomes electrically polarized when subjected to mechanical stress). We had the idea of verifying the proper functioning of the sonar by evaluating each slice of it: we placed a receiver probe in front of the sonar and measured the amplitude sent by the sonar. We observed that every transducer functions correctly, except those located in the center.

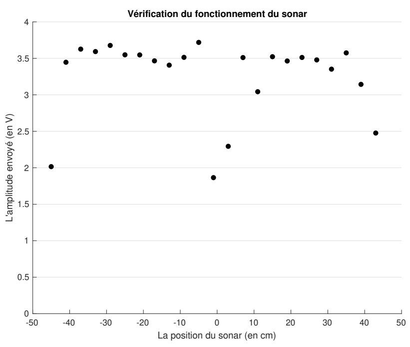
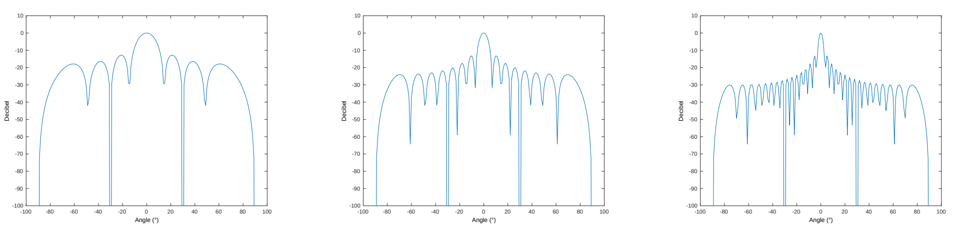


Figure 1: Verifying the functionality of the sonar

Because the transducers are placed in the same axis, the emission of the same acoustic wave allows for the creation of a stronger intensity beam located at the center of the sonar. It is the phase difference of each transducer that creates this phenomenon. Examples can be represented using radiation pattern diagrams.

It is observed that the more transducers the sonar is composed of, the more precise its opening beam becomes. It is assumed that the sonar emits energy forward at an angle in the vertical plane, even though this phenomenon does not actually occur exactly. However, let us not forget that the sonar also emits waves in the horizontal plane. Therefore, the opening beam is defined in both planes. Also, it is noticed that the curves observed in figures (2 to 4) are similar to that defined by the cardinal sine function:

$$sinc(x) = \frac{\sin(x)}{x} \tag{1}$$



(a) 8 transducers (b) 16 transducers (c) 32 transducers

As previously seen, the sonar's opening beam is defined by two angles in the two planes. If we position the sonar as shown in the figure below, our sonar emits waves to its left (along the y-axis) at an angle α, and similarly along a small width defined by β (along the x-axis).

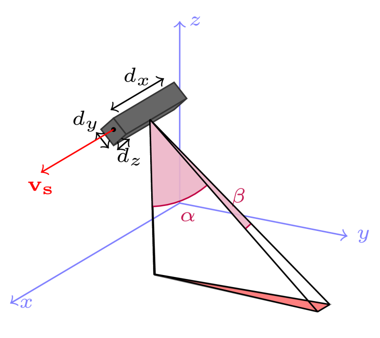


Figure 3: Schematic of the sonar

As suggested by the diagram, the angle β is very small compared to α. These values can be calculated theoretically, by assuming λ as the wavelength, c as the speed of sound in water, and f as the sonar emission frequency:

$$\beta_{-3dB} = \frac{\lambda}{d_x} = \frac{c}{f d_x} \tag{2}$$

$$\alpha_{-3dB} = \frac{\lambda}{d_y} = \frac{c}{f d_y} \tag{3}$$

In other words, the angle β is defined as the opening angle in the vertical plane, and α as the opening angle in the horizontal plane.
It is important to know the values of these angles in order to better map the seafloor. The angle β will allow us to determine the spacing between each measurement, and the angle α will tell us how far we can look. We conducted two experiments to determine these angles, but with the formulas stated above, we can already calculate the theoretical values. With our sonar functioning between $80kHz$ and $120kHz$, supposing $c = 1500m \cdot s^{-1}$, $d_x = 100cm$ and $d_y = 2cm$, we get:

$$\beta_{-3dB} = \frac{1.5 \cdot 10^3}{100 \cdot 10^{-2} \cdot 10^5} = 0.015rad = 1^\circ \tag{4}$$

$$\alpha_{-3dB} = \frac{1.5 \cdot 10^3}{2 \cdot 10^{-2} \cdot 10^5} = 0.75rad = 43^\circ \tag{5}$$

Experimentally, we obtain the following graphs, with $\alpha = 40^\circ$ and $\beta = 10^\circ$:

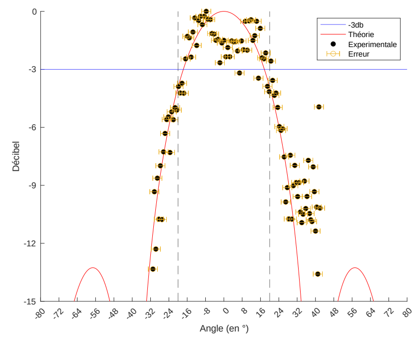


Figure 4: Determination of the α angle

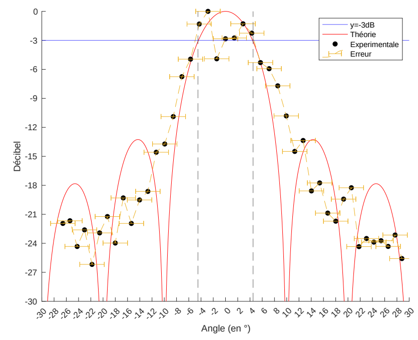


Figure 5: Determination of the β angle

Electronics

Signal processing places a key role when it comes to mapping the seabeds. Let's take interest in the theory.
A chirp is a pseudo-periodic signal that is frequency-modulated between two instants. It is used in the field of sonar to increase the resolution of the measurement (in distance) and especially to increase the signal-to-noise ratio. However, there are several methods for generating a chirp: linear, quadratic, and logarithmic. In our study, we are interested in the case of the linear mode to perform pulse compression. By setting T as the duration of the signal and f as the frequency band centered on f_0, the signal sent by the sonar can be written as:

$$s(t) = A\exp\left[i2\pi\left(f_0 + \frac{\Delta f}{2T}(t-T)\right)\right]t \tag{6}$$

By definition, the achievable distance resolution with this method is:

$$\frac{c}{2\Delta f} \tag{7}$$

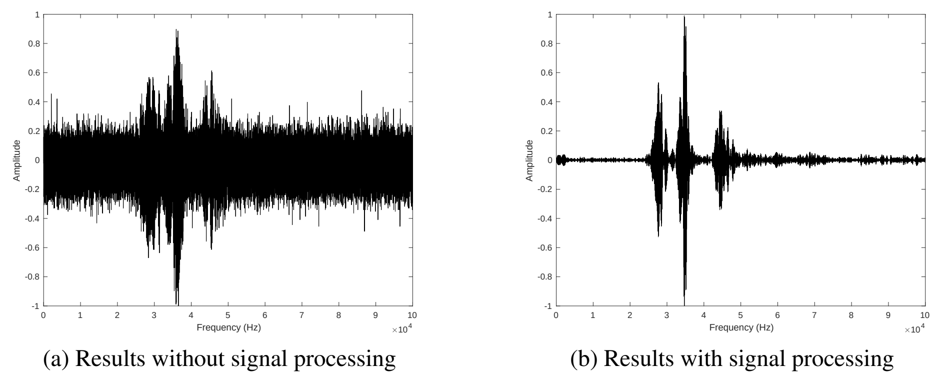
Therefore, we notice that to increase the resolution, the frequency bandwidth should be decreased. However, too high a resolution can lead to a reduction in range. In our case, the sonar operates at 100kHz. Therefore, it is interesting to vary the sonar's emitting frequency between $80kHz$ and $120kHz$ (i.e., $\Delta f = 40kHz$). Thus, our resolution is:

$$\frac{1.5 \cdot 10^3}{2 \cdot 40 \cdot 10^3} = 1.875cm \tag{8}$$

By definition, the fast Fourier transform is useful for transforming the received signal from the time domain to the frequency domain. The inverse Fourier transform allows us to perform the reverse. The complex conjugate of the Fourier transform allows us to invert the phase of the Fourier transform in order to correct phase delays.
Convolution is a mathematical operation that measures the interaction between two functions. It can be understood as the overlap of two functions where they are shifted in time:

$$(f*g)(x) = \int_{-\infty}^{+\infty} f(x-t)g(t)\,dt \tag{9}$$

Here, we use this operation with the Fourier transform of the chirp and that of the signal received by the sonar. As the sonar receives all frequencies, we only want to retrieve those sent, defined by the chirp function. Thus, by comparing the frequency domains, we can remove all other frequencies from the signal spectrum (including noise).
Now that we have explained the functions used in our signal processing, here is a comparison between the raw signal received by the sonar and the signal obtained by signal processing.



(a) Results without signal processing (b) Results with signal processing

The electronic circuit is an integral part of the sonar system, along with the transducer. It transmits the desired signal and ensures its reception once the waves have propagated through the pool. The circuit currently in use is quite complex and bulky, but it may be simplified in the years to come. But here is a simplified schematic of how we get our sonar to work : with amplifiers, we get the pulse generator to send a chirp to the transducer, and the returning signal is sent to a TiePie box, which is connected to our computer.

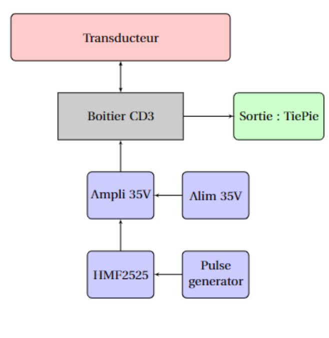


Figure 7: Schematic of the sonar

Experiments

For our first experiment, we placed the sonar at the bottom of the pool. We only immersed it 50cm in the water to better photograph the other side, and also to play with the echoes from the surface. Since the pool has borders along the sides, it is difficult to space out the objects properly. However, to occupy the entire side of the pool, we placed the ladder diagonally to observe, as suggested by the diagram in the TOP VIEW section, a rectangle occupying a large part of the side. We also have a ball and a PVC pipe. These objects are interesting because they are echogenic, making it easy to observe them on the image even though they occupy a small space in the pool. For this experiment, we decided to place all our objects as far away from the sonar as possible and close to the width of the pool. We wanted to simulate a "real" situation as if we were in the Seine river and mapping the bottom: objects are very often on the bottom and very rarely close to the sonar.

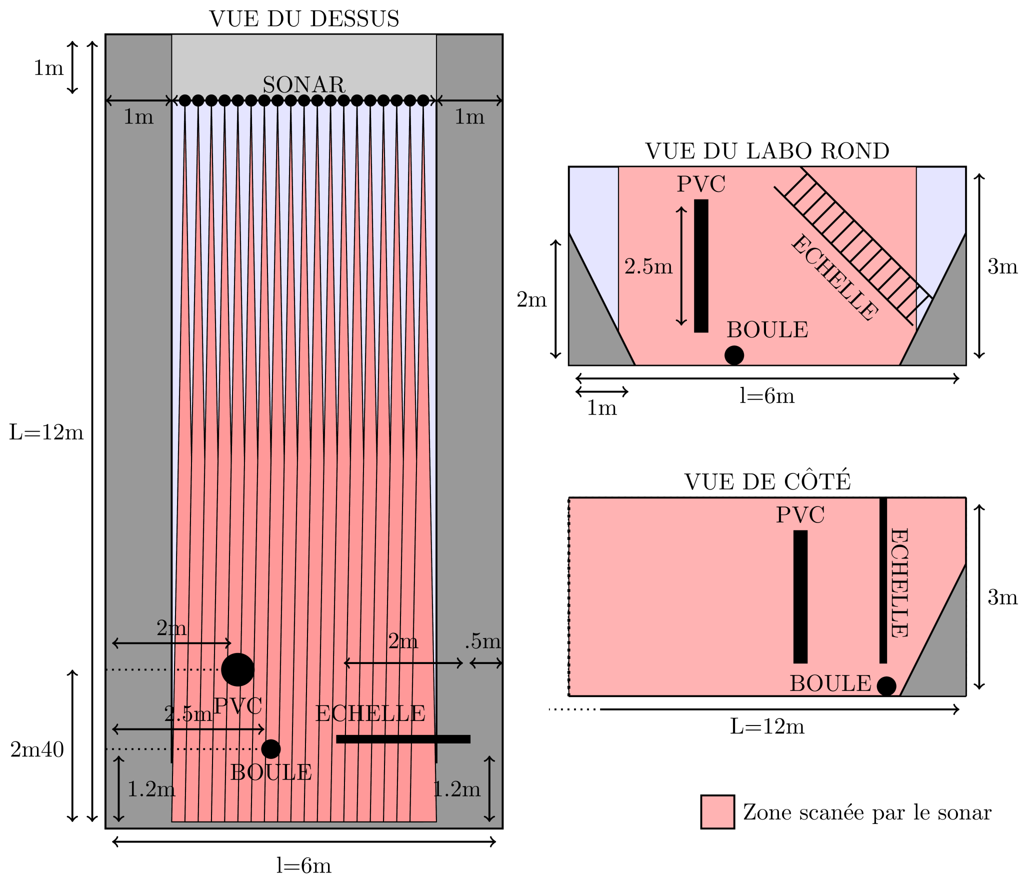


Figure 8: Image of the first experiment

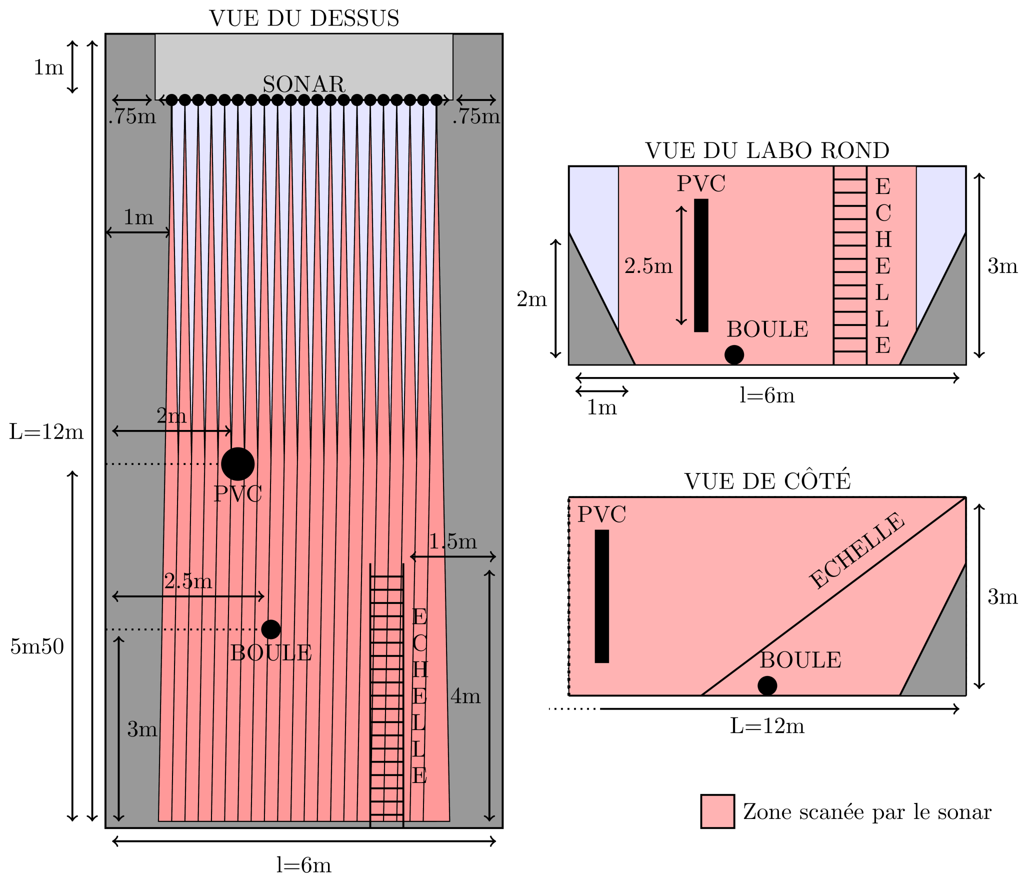


Figure 9: Image of the first experiment

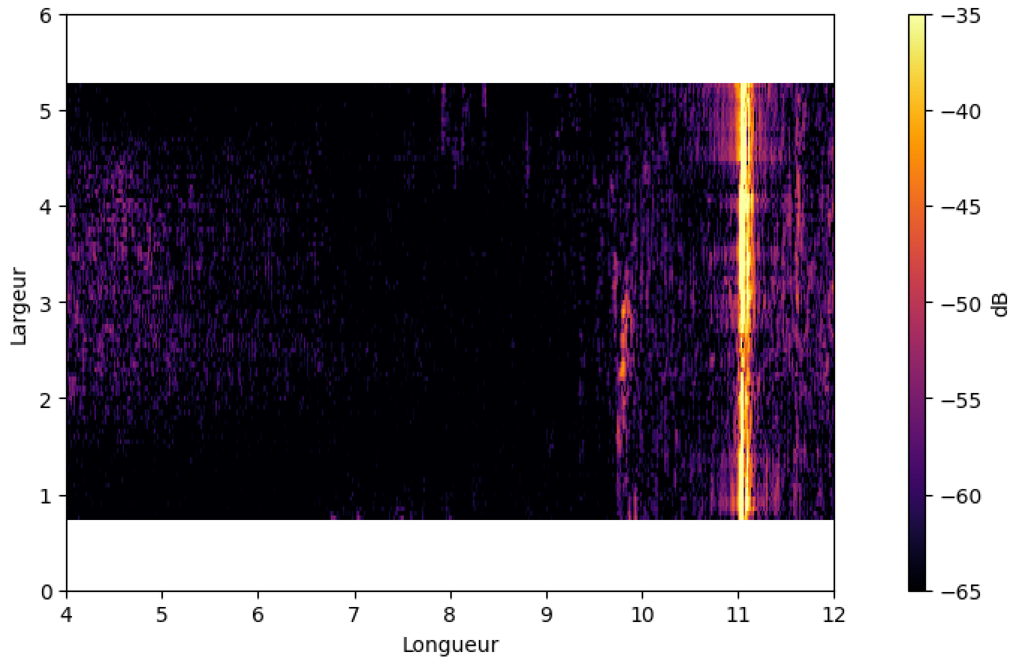


Figure 10: Image of the first experiment

For our second experiment, we decided to space out our objects. The PVC tube was moved forward significantly, with the ball placed 2.5m behind it. In turn, the ladder was turned 90° and its legs were oriented towards the sonar. This way, we could observe the different levels of the ladder in the image. As for the movement of the sonar, we tried to scan the entire pool as much as possible. However, it is surrounded by a metal part at the back that measures 1.2m, which prevented us from scanning the entire width of the pool. Otherwise, we took measurements every 5cm to ensure the same precision and a better quality image.

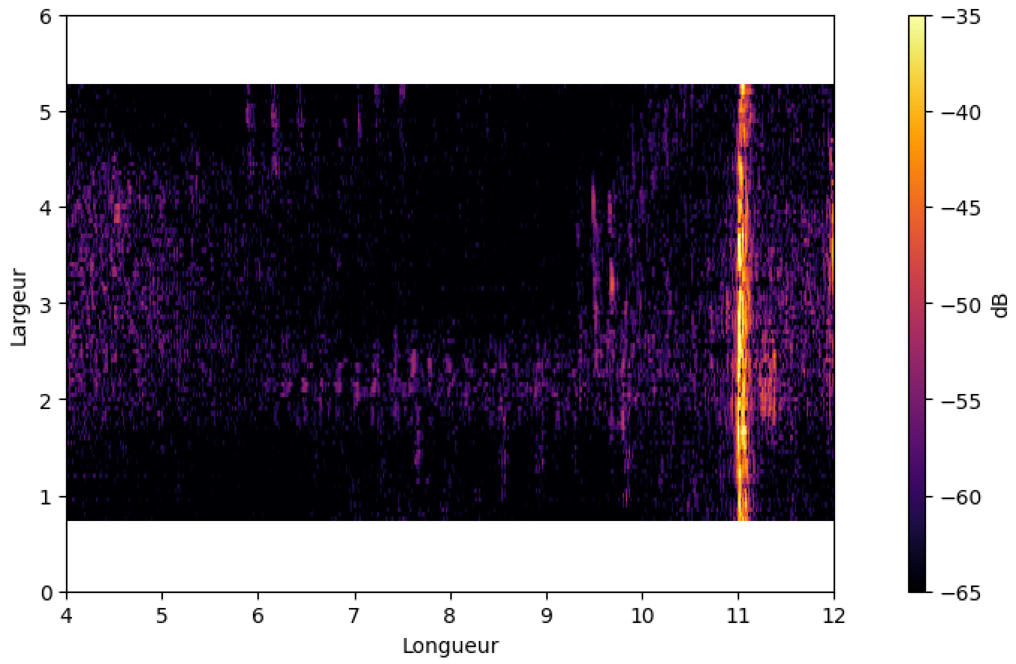


Figure 11: Image of the second experiment

For the last experiment, we tilted the transducer at a 45° angle towards the bottom of the water. This modification prevents the capture of echoes caused by the water surface. This configuration will be used for future acquisitions in the Seine River.

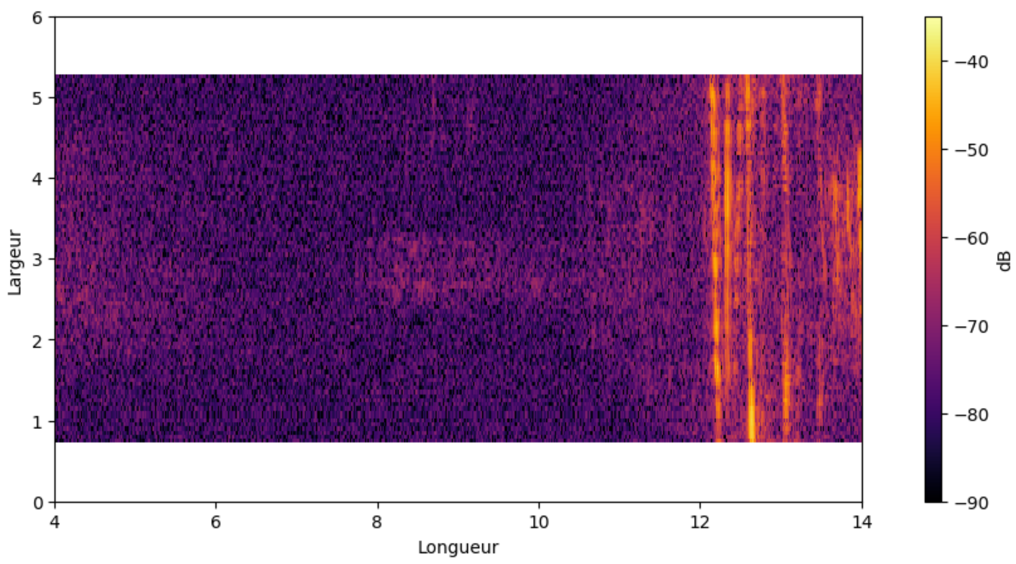


Figure 12: Image of the third experiment

We can notice that the first experiment is not really conclusive, as no objects are distinguishable. However, we can clearly see the ladder in the last two experiments. Unfortunately, the metal ball and the PVC tube remain invisible for now.

Conclusion

We have successfully obtained the initial images, which was our primary goal. However, we spent some time comprehensively understanding the operation principles of the sonar and its codes. Therefore, we have tried to provide as many explanations and instructions as possible so that in the future, understanding the device won't be a hindrance.
By focused solely on the transducer and electronics aspects, we didn't have the opportunity to explore a way to attach the sonar to a floater. But this would have been quite challenging, considering that the entire electronic circuit takes a lot of space and needs to be waterproof.
Overall, I really enjoyed this project. It had our team occupied for months.