Autonomous Underwater Vehicle: A Surveillance Protocol

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Preface

This project is an attempt at combining all of my major skills into creating a simulation, imaging, perception and control pipeline for Autonomous Underwater Vehicles (AUV). As such, creating this project involves creating a number of pipelines.

The first pipeline is the signal simulation pipeline. The signal simulation pipeline involves sea-floor point-cloud creation and simulating the signals received by the sensor arrays of the AUV. The signals recorded by the sensor-arrays on the AUV contains information from the surrounding environment. The imaging pipeline performs certain operations on the recorded signals to obtain acoustic images of the surrounding environment. To that end, this pipeline involves the topics of signal processing, linear algebra, signals and systems.

As such, the second pipeline is the imaging pipeline. The inputs to the imaging pipeline is the signals recorded by the different sensor-arrays of the AUV, in addition to the parameters of the AUV and its components. This pipeline involves match-filtering, focussing and beamforming operations to create acoustic images of the surrounding environment. Depending on the number of ULAs present, the imaging pipeline is responsible for creating multiple acoustic images in real-time. Thus, this pipeline involves the topics of Digital Signal Processing, Match-Filtering, Estimation and Detection Theory and so on.

The images created by the imaging pipeline are fed to the perception-to-control pipeline. This pipeline takes in the image formed created from the ULA signals, parameters of AUV and its components, and some historical data, it provides instructions regarding the movement of the AUV. The mapping from the inputs to the controls is called policy. Learning policies is a core part of reinforcement learning. Thus, this pipeline mainly involves the topics of reinforcement learning. And since we'll be using convolutional neural nets and transformers for learning the policies, this pipeline involves a significant amount of machine and deep learning.

The final result is an AUV that is primarily trained to map an area of the sea-floor in a constant surveillance mode. The RL-trained policy will also be trained to deal with different kinds of sea-floor terrains: those containing hills, valleys, and path-obstructing features. Due to the resource constrained nature of the marine vessel, we also prioritize efficient policies in the policy-training pipeline.

The project is currently written in C++. And since there is non-trivial amount of training and adaptive features in the pipelines, we'll be using LibTorch (the C++ API of PyTorch) to enable computation graphs, backpropagation and thereby, learning in our AUV pipeline.

Introduction

Contents

Chapter 1

Setup

1.1 Overview

- Clone the AUV repository: `https://github.com/vrsreeganesh/AUV.git`.
- This can be performed by entering the terminal, "cd"-ing to the directory you wish and then typing: `git clone https://github.com/vrsreeganesh/AUV.git` and press enter.
- Note that in case it has not been setup, ensure github setup in the terminal. If not familiar with the whole git work-routine, I suggest sticking to Github Desktop. Its a lot easier and the best to get started right away.
- Or if you do not wish to follow a source-control approach, just download the repository as a zip file after clicking the blue code button.

Chapter 2

Underwater Environment Setup

Overview

All matter in this framework is represented using point-clouds. Thus, the sea-floor also is represented using a number of 3-dimensional points. In addition to the coordinates, these points also contain another attribute, we term, ”reflectivity”. It is the impulse response of a single-scatterer to a probing signal.

Sea-floors in real-life are rarely flat. They contain valleys, mountains, hills and much much more rich features. Thus, training an agent to be able to perform in the sheer different number of sea-floors involve being able to create a number of different sea-floors. Even though there are countably infinite number of variations, we shall take a structured approach to creating these variations. To that end, we start with an additive approach. The full-script for creating the sea-floor is given in section 8.2.1.

2.1 Sea “Floor”

The first addition is the sea-bottom. This is the lowest set of points that are in the point-cloud representing the total sea-floor. The most basic approach to creating these are to create a large grid of 3D points with the same height: the perfectly flat sea-floor. While this is a good place to start, we'd prefer something that looks a little bit more, “natural”. This is where we bring in the concept of rolling hills. Each hill is created as per Algorithm 1. So this becomes the lowest set of points in the overall cloud representing the matter, underwater.

Algorithm 1 Hill Creation

num_hills $\leftarrow$ Number of Hills

2.2 Simple Structures

2.2.1 Boxes

2.2.2 Sphere

Algorithm 2 Box Creation

num_hills ← Number of Hills

Algorithm 3 Sphere Creation

num_hills ← Number of Hills

Chapter 3

Hardware Setup

Overview

The AUV contains a number of hardware that enables its functioning. A real AUV contains enough components to make a victorian child faint. And simulating the whole thing and building pipelines to model their working is not the kind of project to be handled by a single engineer. So we'll only model and simulate those components that are absolutely required for the running of these pipelines.

3.1 Transmitter

Probing systems are those systems that send out a signal, listen to the reflection and infer qualitative and quantitative qualities of the environment, matter or object, it was trying to infer information about. The transmitter is one of the most fundamental components of probing systems. As the name suggests, the transmitter is the equipment responsible for sending out the probing signal into the medium.

Transmitters are of many kinds. But the ones that we will be considering will be directed transmitters, which means that these transmitters have an associated beampattern. To the uninitiated, this means that the power of the transmitted signal is not transmitted in all directions equally. A beampattern is a graphical representation of the power received by an ideal receiver when placed at different angles.

Transmitters made out of a linear-array of individual transmitters use beamforming to "direct" the major power of the transmitter. These kind of systems have well studied beampatterns which can be utilized in our simulations. These kind of studies and inculcating that in our pipelines produce accurate signal simulation pipelines.

For now, we stick to a very simple model of a transmitter. We assume that the transmitter sends out the power equally into a particular cone from the AUV position.

The full-script for the setup of the transmitter is given in section 8.2.2 and the class definition for the transmitter is given in section 8.1.2.

3.2 Uniform Linear Array

Perhaps the most important component of probing systems are the “listening” systems. After “illuminating” the medium with the signal, we need to listen to the reflections in order to infer properties. In fact, there are some probing systems that do not use transmitter. Thus, this easily makes the case for the simple fact that the “listening” components of probing systems are the most important components of the whole system.

Uniform arrays are of many kinds but the most popular ones are uniform linear arrays and uniform planar arrays. The arrays in this case contain a number of sensors arranged in a uniform manner across a line or a plane.

Linear arrays have the property that the information obtained from elevation, ϕ is no longer available due to the dimensionality of the array-structure. Thus, the images obtained from processing the signals recorded by a uniform linear array will only have two-dimensions: the azimuth, θ and the range, r.

Thus, for 3D imaging, we shall be working with planar arrays. However, due to the higher dimensionality of the output signal, the class of algorithms required to create 3D images are a lot more computationally efficient. In addition, due to the simpler nature of the protocols involved with our AUV, uniform linear arrays will work just fine.

3.3 Marine Vessel

Chapter 4

Signal Simulation

Overview

- Define LFM.
- Define shadowing.
- Simulate Signals (basic)
- Simulate Signals with additional effects (doppler)

4.1 Transmitted Signal

- In probing systems, which are systems which transmit a signal and infer qualitative and quantiative characterisitics of the environment from the signal return, the ideal signal is the dirac delta signal. However, dirac-deltas are nearly impossible to create because of their infinite bandwidth structure. Thus, we need to use something else that is more practical but at the same time, gets us quite close the diract-delta. So we use something of a watered-down delta-function, which is a bandlimited delta function, or the linear frequency-modulated signal. The LFM is a asignal whose frequency increases linearly in its duration. This means that the signal has a flat magnitude spectrum but quadratic phase.
- The LFM is characterised by the bandwidth and the center-frequency. The higher the resolution required, the higher the transmitted bandwidth is. So bandwidth is a characterizing factor. The higher the bandwidth, the better the resolution obtained.
- The transmitted signals used in these cases depend highly on the kind of SONAR we're using it for. The systems we're using currently contain one FLS and two side-scan or 3 FLS (I'm yet to make up mind here).
- The signal is defined in setup-script of the transmitter. Please refer to section: 8.1.2;

4.2 Signal Simulation

1. The signals simulation is performed using simple ray-tracing. The distance travelled from the transmitted to scatterer and then the sensor is calculated for each scatter-sensor pair. And the transmitted signal is placed at the recording of each sensor corresponding to each scatterer.
2. First we obtain the set of scatterers that reflect the transmitted signal.
3. The distance between all the sensors and the scatterer distances are calculated.
4. The time of flight from the transmitter to each scatterer and each sensor is calculated.
5. This time is then calculated into sample number by multiplying with the sampling-frequency of the uniform linear arrays.
6. We then build a signal matrix that has the dimensions corresponding to the number of samples that are recorded and the number of sensors that are present in the sensor-array.
7. We place impulses in the points corresponding to when the signals arrives from the scatterers. The result is a matrix that has x-dimension as the number of samples and the y-dimension as the number of sensors.
8. Each column is then convolved (linearly convolved) with the transmitted signal. The resulting matrix gives us the signal received by each sensor. Note that this method doesn't consider doppler effects. This will be added later.

Algorithm 4 Signal Simulation

ScatterCoordinates $\leftarrow$
ScatterReflectivity $\leftarrow$
AngleDensity $\leftarrow$ Quantization of angles per degree.
AzimuthalBeamwidth $\leftarrow$ Azimuthal Beamwidth
RangeCellWidth $\leftarrow$ The range-cell width

4.3 Ray Tracing

- There are multiple ways for ray-tracing.
- The method implemented during the FBLS and SS SONARs weren't super efficient as it involved pair-wise dot-products. Which becomes an issue when the number of points are increased, which is the case when the range is super high or the beamwidth is super high.

4.3.1 Pairwise Dot-Product

- In this method, given the coordinates of all points that are currently in the illumination cone, we find the cosines between every possible pairs of points.
- This is where the computational complexity arises as the number of dot products increase exponentially with increasing number of points.

- This method is a liability when it comes to situations where the range is super high or when the angle-beamwidth is non-narrow.

4.3.2 Range Histogram Method

- Given the angular beamwidths: azimuthal beamwidth and elevation beamwidth, we quantize square cone into a number of different values (note that the square cone is not an issue as the step before ensures conical subsetting).
- We split the points into different ”range-cells”.
- For each range-cell, we make a 2D histogram of azimuths and elevations. Then within each range-cell and for each azimuth-elevation pair, we find the closest point and add it to the check-box.
- In the next range-cell, we only work with those azimuth-elevation pairs whose check-box has not been filled. Since, for the filled ones, the filled scatter will shadow the othersin the following range cells.

Algorithm 5 Range Histogram Method

ScatterCoordinates $\leftarrow$
ScatterReflectivity $\leftarrow$
AngleDensity $\leftarrow$ Quantization of angles per degree.
AzimuthalBeamwidth $\leftarrow$ Azimuthal Beamwidth
RangeCellWidth $\leftarrow$ The range-cell width

Chapter 5

Imaging

Overview

- Present basebanding, low-pass filtering and decimation.
- Present beamforming.
- Present different synthetic-aperture concepts.

5.1 Decimation

1. Due to the large sampling-frequencies employed in imaging SONAR, it is quite often the case that the amount of samples received for just a couple of milliseconds make for non-trivial data-size.
2. In such cases, we use some smart signal processing to reduce the data-size without loss of information. This is done using the fact that the transmitted signal is non-baseband. THis means that using a method known as quadrature modulation, we can maintain the information content without the humongous amount data.
3. After basebanding the signal, this process involves decimation of the signal respecting the bandwidth of the transmitted signal.

5.1.1 Basebanding

1. Basebanding is performed utilizing the frequency-shifting property of the fourier transform

$$x(t)e^{j2\pi\omega_0 t} \leftrightarrow X(\omega - \omega_0)$$

2. Since we're working with digital signals, this is implemented in the following manner

$$x[n]e^{j\frac{2\pi k_0 n}{N}} \leftrightarrow X(k - k_0)$$

Algorithm 6 Basebanding

ScatterCoordinates $\leftarrow$
ScatterReflectivity $\leftarrow$
AngleDensity $\leftarrow$ Quantization of angles per degree.
AzimuthalBeamwidth $\leftarrow$ Azimuthal Beamwidth
RangeCellWidth $\leftarrow$ The range-cell width

5.1.2 Lowpass filtering

1. Now that we have the signal in the baseband, we lowpass filter the signal based on the bandwidth of the signal. Since we're perfectly centering the signal using f_c, we can have the cutoff-frequency of the lowpass filter to be just above half the bandwidth of the transmitted signal. Note that the signals should not be brought down back into the real-domain using abs() or real() functions since the negative frequencies are no longer symmetrical.

2. After low-pass filtering, we have a band-restricted signal that contains all of the data in the baseband. This allows for decimation, which is what we'll do in the next step.

5.1.3 Decimation

1. Now that we have the bandlimited signal, what we shall do is decimation. Decimation essentially involves just taking every n-th sample where n in this case is the decimation factor.

2. The resulting signal contains the same information as that of the real-sampled signal but with much less number of samples.

5.2 Match-Filtering

1. To understand why match-filtering is going on, it is important to understand pulse compression.

2. In "probing" systems, which are basically systems where we send out some signal, listen to the reflection and infer quantitative and qualitative aspects of the environment, the best signal is the impulse signal (see Dirac Delta). However. this signal is not practical to use. Primarily due to the very simple fact that this particular signal has a flat and infinite bandwidth. However, this signal is the idea.

3. So instead, we're left with using signals that have a finite length, $T_{\text{Transmitted Signal}}$. However, the issue with that is that a scatter of initesimal dimension produce a response that has a length of $T_{\text{Transmitted Signal}}$. Thus, it is important to ensure that the response of each object, scatter or what not has comparable dimensions. This is where pulse compression comes in. Using this technique, we transform the received signal to produce a signal that is as close as possible to the signal we'd receive if we were to send out a diract delta pulse.

4. Thus, this process involves something of a detection. The closest method is something of a correlation filter where we run a copy of the transmitted signal through the received recording and take inner-products at each time step (known as the cor-

relation operation). This method works great if we're in the real domain. However, thanks to the quadrature demodulation we performed, this process is now no longer valid. But the idea remainds the same. The point of doing a correlation analysis is so that where there is a signal, a spike appears. The sample principle is used to develop the match-filter.

5. We want to produce a filter, which when convolved with the received signal produces a spike. Since we're trying to produce something similar to the response of an ideal transmission system, we want the output to be that of an ideal spike, which is the delta function. So we're essentially trying to find a filter, which when multiplied with the transmitted signal, produces the diract delta.

6. The answer can be found by analyzing the frequency domain. The frequency domain basis representation of the delta-function is a flat magnitude and linear phase. Thus, this means that the filter that we use on the transmitted signal must produce a flat magnitude and linear phase. The transmitted signal that we're working with, being an LFM, means that the magnitude is already flat. The phase, however, is quadratic. So we need the matched filter to have a flat magnitude and a quadratic phase that cancels away that of the transmitted signa's quadratic component. All this leads to the best candidate: the complex conjugate of the transmitted signal. However, since we're now working with the quadrature demodulated signal, the matched filter is the complex conjugate of the quadrature demodulated transmitted signal.

7. So once the filter is made, convolving that with the received signal produces a number of spikes in the processed signal. Note that due to working in the digital domain and some other factors, the spikes will not be perfect. Thus it is not safe to take the abs() or real() just yet. We'll do that after beamforming.

8. But so far, this marks the first step of the perception pipeline.

Algorithm 7 Match-Filtering

ScatterCoordinates ←
ScatterReflectivity ←
AngleDensity ← Quantization of angles per degree.
AzimuthalBeamwidth ← Azimuthal Beamwidth
RangeCellWidth ← The range-cell width

Beamforming

- Prior to imaging, we precompute the range-cell characteristics.
- In addition, we also calculate the delays given to each sensor for each of those range-azimuth combinations.
- Those are then stored as a look-up table member of the class.
- At each-time step, what we do is we buffer split the simulated/received signal into a 3D matrix, where each signal frame corresponds to the signals for a particular range-cell.
- Then for each range-cell, we beamform using the delays we precalculated. We perform this without loops in order to utilize CPU and reduce latency.

Algorithm 8 Beamforming

ScatterCoordinates $\leftarrow$
ScatterReflectivity $\leftarrow$
AngleDensity $\leftarrow$ Quantization of angles per degree.
AzimuthalBeamwidth $\leftarrow$ Azimuthal Beamwidth
RangeCellWidth $\leftarrow$ The range-cell width

Chapter 6

Control Pipeline

Overview

1. The inputs to the control-pipeline is the images obtained from previous pipeline.
2. Currently the plan is to use DQN.

DQN

1. Here we're essentially trying to create a control pipeline that performs the protocol that we need.
2. The aim of the AUV is to continuously map a particular area of the sea-floor and perform it despite the presence of sea-floor structures.
3.

Algorithm 9 DQN

ScatterCoordinates $\leftarrow$
ScatterReflectivity $\leftarrow$
AngleDensity $\leftarrow$ Quantization of angles per degree.
AzimuthalBeamwidth $\leftarrow$ Azimuthal Beamwidth
RangeCellWidth $\leftarrow$ The range-cell width

Artificial Acoustic Imaging

1. In order to ensure faster development, we shall start off with training the DQN algorithm with artificial acoustic images. This is rather important due to the fact that the imaging pipelines (currently) has some non-trivial latency. This means that using those pipelines to create the inputs to the DQN algorithm will skyrocket the training time.
2. So the approach that we shall be taking will be write functions to create artifical acoustic images directly from the scatterer-coordinates and scatterer-reflectivity values. The latency for these functions are negligible compared to that of beamforming-

based imaging algorithms. The function for this has been added and is available in section 8.1.3 under the function name, *nfdc_createAcousticImage*. Please note that these functions are not to be directly called from the main function. Instead, it is expected that the main function calls the AUV classes's method, *create_ArtificialAcousticImage*. This function calls the class ULA's method appropriately.

3. After the ULA's create their respective acoustic images, they are put together, either by dimension-wise concatenation or depth-wise concatenation and feed to the neural net to produce control sequences.

4. We need to work on the dimensions of these images though. The best thing to do right now is to finalize the transmitter and receiver parameters and then overestimate the dimensions of the final beamforming-produced image. We shall then use these dimensions to create the artificial acoustic image and start training the policy.

Algorithm 10 Artifical Acoustic Imaging

ScatterCoordinates $\leftarrow$ Coordinates of points in the point-cloud.
auvCoordinates $\leftarrow$ Coordinates of AUV/ULA.

Chapter 7

Results

Chapter 8

Software

Overview

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8.1 Class Definitions

8.1.1 Class: Scatter

The following is the class definition used to encapsulate attributes and methods of the scatterers.

```
// header-files
#include <iostream>
#include <ostream>
#include <torch/torch.h>

#pragma once

// hash defines
#ifndef PRINTSPACE
#define PRINTSPACE   std::cout<<"\n\n\n\n\n\n\n\n"<<std::endl;
#endif
#ifndef PRINTSMALLLINE
#define PRINTSMALLLINE std::cout<<"------------------------------------------------"<<std::endl;
#endif
#ifndef PRINTLINE
#define PRINTLINE    std::cout<<"================================================"<<std::endl;
#endif
#ifndef DEVICE
    #define DEVICE       torch::kMPS
    // #define DEVICE       torch::kCPU
#endif


#define PI            3.14159265


// function to print tensor size
void print_tensor_size(const torch::Tensor& inputTensor) {
    // Printing size
    std::cout << "[";
    for (const auto& size : inputTensor.sizes()) {
        std::cout << size << ",";
    }
```

```
    std::cout << "\b]" <<std::endl;
}

// Scatterer Class = Scatterer Class
// Scatterer Class = Scatterer Class
// Scatterer Class = Scatterer Class
// Scatterer Class = Scatterer Class
// Scatterer Class = Scatterer Class
class ScattererClass{
public:

    // public variables
    torch::Tensor coordinates; // tensor holding coordinates [3, x]
    torch::Tensor reflectivity; // tensor holding reflectivity [1, x]

    // constructor = constructor
    ScattererClass(torch::Tensor arg_coordinates = torch::zeros({3,1}),
                   torch::Tensor arg_reflectivity = torch::zeros({3,1})):
                   coordinates(arg_coordinates),
                   reflectivity(arg_reflectivity) {}

    // overloading output
    friend std::ostream& operator<<(std::ostream& os, ScattererClass& scatterer){

        // printing coordinate shape
        os<<"\t> scatterer.coordinates.shape = ";
        print_tensor_size(scatterer.coordinates);

        // printing reflectivity shape
        os<<"\t> scatterer.reflectivity.shape = ";
        print_tensor_size(scatterer.reflectivity);

        // returning os
        return os;
    }

    // copy constructor from a pointer
    ScattererClass(ScattererClass* scatterers){

        // copying the values
        this->coordinates = scatterers->coordinates;
        this->reflectivity = scatterers->reflectivity;
    }

};
```

8.1.2 Class: Transmitter

The following is the class definition used to encapsulate attributes and methods of the projectors used.

```cpp
// header-files
#include <iostream>
#include <ostream>
#include <cmath>

// Including classes
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"

// Including functions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fCart2Sph.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fSph2Cart.cpp"

#pragma once

// hash defines
#ifndef PRINTSPACE
#   define PRINTSPACE    std::cout<<"\n\n\n\n\n\n\n\n"<<std::endl;
#endif
#ifndef PRINTSMALLLINE
#   define PRINTSMALLLINE std::cout<<"------------------------------------------------"<<std::endl;
#endif
#ifndef PRINTLINE
#   define PRINTLINE     std::cout<<"================================================"<<std::endl;
#endif

#define PI           3.14159265
#define DEBUGMODE_TRANSMITTER    false

#ifndef DEVICE
    #define DEVICE        torch::kMPS
    // #define DEVICE        torch::kCPU
#endif



// control panel
#define ENABLE_RAYTRACING            false








class TransmitterClass{
public:

    // physical/intrinsic properties
    torch::Tensor location;          // location tensor
    torch::Tensor pointing_direction; // pointing direction

    // basic parameters
    torch::Tensor Signal;     // transmitted signal (LFM)
    float azimuthal_angle;    // transmitter's azimuthal pointing direction
    float elevation_angle;    // transmitter's elevation pointing direction
    float azimuthal_beamwidth; // azimuthal beamwidth of transmitter
    float elevation_beamwidth; // elevation beamwidth of transmitter
    float range;              // a parameter used for spotlight mode.

    // transmitted signal attributes
    float f_low;              // lowest frequency of LFM
    float f_high;             // highest frequency of LFM
    float fc;                 // center frequency of LFM
    float bandwidth;          // bandwidth of LFM
```

```

    // shadowing properties
    int azimuthQuantDensity;        // quantization of angles along the azimuth
    int elevationQuantDensity;      // quantization of angles along the elevation
    float rangeQuantSize;           // range-cell size when shadowing
    float azimuthShadowThreshold;   // azimuth thresholding
    float elevationShadowThreshold; // elevation thresholding

    // // shadowing related
    // torch::Tensor checkbox;         // box indicating whether a scatter for a range-angle pair has been
        found
    // torch::Tensor finalScatterBox;  // a 3D tensor where the third dimension represnets the vector length
    // torch::Tensor finalReflectivityBox; // to store the reflectivity



    // Constructor
    TransmitterClass(torch::Tensor location = torch::zeros({3,1}),
                     torch::Tensor Signal    = torch::zeros({10,1}),
                     float azimuthal_angle   = 0,
                     float elevation_angle   = -30,
                     float azimuthal_beamwidth = 30,
                     float elevation_beamwidth = 30):
                     location(location),
                     Signal(Signal),
                     azimuthal_angle(azimuthal_angle),
                     elevation_angle(elevation_angle),
                     azimuthal_beamwidth(azimuthal_beamwidth),
                     elevation_beamwidth(elevation_beamwidth) {}

    // overloading output
    friend std::ostream& operator<<(std::ostream& os, TransmitterClass& transmitter){
        os<<"\t> azimuth          : "<<transmitter.azimuthal_angle <<std::endl;
        os<<"\t> elevation        : "<<transmitter.elevation_angle <<std::endl;
        os<<"\t> azimuthal beamwidth: "<<transmitter.azimuthal_beamwidth<<std::endl;
        os<<"\t> elevation beamwidth: "<<transmitter.elevation_beamwidth<<std::endl;
        PRINTSMALLLINE
        return os;
    }

    // overloading copyign operator
    TransmitterClass& operator=(const TransmitterClass& other){

        // checking self-assignment
        if(this==&other){
            return *this;
        }

        // allocating memory
        this->location            = other.location;
        this->Signal              = other.Signal;
        this->azimuthal_angle     = other.azimuthal_angle;
        this->elevation_angle     = other.elevation_angle;
        this->azimuthal_beamwidth = other.azimuthal_beamwidth;
        this->elevation_beamwidth = other.elevation_beamwidth;
        this->range               = other.range;

        // transmitted signal attributes
        this->f_low               = other.f_low;
        this->f_high              = other.f_high;
        this->fc                  = other.fc;
        this->bandwidth           = other.bandwidth;

        // shadowing properties
        this->azimuthQuantDensity    = other.azimuthQuantDensity;
        this->elevationQuantDensity  = other.elevationQuantDensity;
        this->rangeQuantSize         = other.rangeQuantSize;
        this->azimuthShadowThreshold = other.azimuthShadowThreshold;
        this->elevationShadowThreshold = other.elevationShadowThreshold;

        // this->checkbox               = other.checkbox;
        // this->finalScatterBox        = other.finalScatterBox;
        // this->finalReflectivityBox   = other.finalReflectivityBox;
```

```cpp

        // returning
        return *this;

    };

    /*==========================================================================
    Aim: Update pointing angle
    ----------------------------------------------------------------------------
    Note:
        > This function updates pointing angle based on AUV's pointing angle
        > for now, we're assuming no roll;
    --------------------------------------------------------------------------*/
    void updatePointingAngle(torch::Tensor AUV_pointing_vector){

        // calculate yaw and pitch
        if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 140 \n";
        torch::Tensor AUV_pointing_vector_spherical = fCart2Sph(AUV_pointing_vector);
        torch::Tensor yaw                           = AUV_pointing_vector_spherical[0];
        torch::Tensor pitch                         = AUV_pointing_vector_spherical[1];
        if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 144 \n";

        // std::cout<<"\t TransmitterClass: AUV_pointing_vector = "<<torch::transpose(AUV_pointing_vector, 0, 1)<<std::endl;
        // std::cout<<"\t TransmitterClass: AUV_pointing_vector_spherical = "<<torch::transpose(AUV_pointing_vector_spherical, 0, 1)<<std::endl;

        // calculating azimuth and elevation of transmitter object
        torch::Tensor absolute_azimuth_of_transmitter = yaw + torch::tensor({this->azimuthal_angle}).to(torch::kFloat).to(DEVICE);
        torch::Tensor absolute_elevation_of_transmitter = pitch + torch::tensor({this->elevation_angle}).to(torch::kFloat).to(DEVICE);
        if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 149 \n";

        // std::cout<<"\t TransmitterClass: this->azimuthal_angle = "<<this->azimuthal_angle<<std::endl;
        // std::cout<<"\t TransmitterClass: this->elevation_angle = "<<this->elevation_angle<<std::endl;
        // std::cout<<"\t TransmitterClass: absolute_azimuth_of_transmitter = "<<absolute_azimuth_of_transmitter<<std::endl;
        // std::cout<<"\t TransmitterClass: absolute_elevation_of_transmitter = "<<absolute_elevation_of_transmitter<<std::endl;

        // converting back to Cartesian
        torch::Tensor pointing_direction_spherical = torch::zeros({3,1}).to(torch::kFloat).to(DEVICE);
        pointing_direction_spherical[0]         = absolute_azimuth_of_transmitter;
        pointing_direction_spherical[1]         = absolute_elevation_of_transmitter;
        pointing_direction_spherical[2]         = torch::tensor({1}).to(torch::kFloat).to(DEVICE);
        if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 60 \n";

        this->pointing_direction = fSph2Cart(pointing_direction_spherical);
        if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 169 \n";

    }

    /*==========================================================================
    Aim: Subsetting Scatterers inside the cone
    ............................................................................
    steps:
        1. Find azimuth and range of all points.
        2. Fint azimuth and range of current pointing vector.
        3. Subtract azimuth and range of points from that of azimuth and range of current pointing vector
        4. Use tilted ellipse equation to find points in the ellipse
    --------------------------------------------------------------------------*/
    void subsetScatterers(ScattererClass* scatterers,
                          float tilt_angle){

        // translationally change origin
        scatterers->coordinates = scatterers->coordinates - this->location; if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 188 "<<std::endl;

        /*
        Note: I think something we can do is see if we can subset the matrices by checking coordinate values right away. If one of the coordinate values is x (relative coordiantes), we know for sure that the distance is greater than x, for sure. So, maybe that's something that we can work with
```

```
        */

        // Finding spherical coordinates of scatterers and pointing direction
        torch::Tensor scatterers_spherical      = fCart2Sph(scatterers->coordinates); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 191 "<<std::endl;
        torch::Tensor pointing_direction_spherical = fCart2Sph(this->pointing_direction); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 192 "<<std::endl;

        // Calculating relative azimuths and radians
        torch::Tensor relative_spherical = scatterers_spherical - pointing_direction_spherical; if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 199 "<<std::endl;

        // clearing some stuff up
        scatterers_spherical.reset();       if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 202 "<<std::endl;
        pointing_direction_spherical.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 203 "<<std::endl;

        // tensor corresponding to switch.
        torch::Tensor tilt_angle_Tensor = torch::tensor({tilt_angle}).to(torch::kFloat).to(DEVICE); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 206 "<<std::endl;

        // calculating length of axes
        torch::Tensor axis_a  = torch::tensor({this->azimuthal_beamwidth / 2}).to(torch::kFloat).to(DEVICE); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 208 "<<std::endl;
        torch::Tensor axis_b  = torch::tensor({this->elevation_beamwidth / 2}).to(torch::kFloat).to(DEVICE); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 209 "<<std::endl;

        // part of calculating the tilted ellipse
        torch::Tensor xcosa   = relative_spherical[0] * torch::cos(tilt_angle_Tensor * PI/180);
        torch::Tensor ysina   = relative_spherical[1] * torch::sin(tilt_angle_Tensor * PI/180);
        torch::Tensor xsina   = relative_spherical[0] * torch::sin(tilt_angle_Tensor * PI/180);
        torch::Tensor ycosa   = relative_spherical[1] * torch::cos(tilt_angle_Tensor * PI/180);
        relative_spherical.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 215 "<<std::endl;

        // finding points inside the tilted ellipse
        torch::Tensor scatter_boolean = torch::div(torch::square(xcosa + ysina), torch::square(axis_a)) + \
                                        torch::div(torch::square(xsina - ycosa), torch::square(axis_b)) <= 1; if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 221 "<<std::endl;

        // clearing
        xcosa.reset(); ysina.reset(); xsina.reset(); ycosa.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 224 "<<std::endl;

        // subsetting points within the elliptical beam
        auto mask                   = (scatter_boolean == 1); // creating a mask
        scatterers->coordinates   = scatterers->coordinates.index({torch::indexing::Slice(), mask});
        scatterers->reflectivity = scatterers->reflectivity.index({torch::indexing::Slice(), mask}); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 229 "<<std::endl;

        // this is where histogram shadowing comes in (later)
        if (ENABLE_RAYTRACING) {rangeHistogramShadowing(scatterers); std::cout<<"\t\t TransmitterClass: line 232 "<<std::endl;}

        // translating back to the points
        scatterers->coordinates = scatterers->coordinates + this->location;

    }

    /*==========================================================================
    Aim: Shadowing method (range-histogram shadowing)
    ............................................................................
    Note:
        > cut down the number of threads into range-cells
        > for each range cell, calculate histogram
        >
        std::cout<<"\t TransmitterClass: "
    --------------------------------------------------------------------------*/
    void rangeHistogramShadowing(ScattererClass* scatterers){

        // converting points to spherical coordinates
```

```
    torch::Tensor spherical_coordinates = fCart2Sph(scatterers->coordinates); std::cout<<"\t\t TransmitterClass: line 252 "<<std::endl;

    // finding maximum range
    torch::Tensor maxdistanceofpoints = torch::max(spherical_coordinates[2]); std::cout<<"\t\t TransmitterClass: line 256 "<<std::endl;

    // calculating number of range-cells (verified)
    int numrangecells = std::ceil(maxdistanceofpoints.item<int>()/this->rangeQuantSize);

    // finding range-cell boundaries (verified)
    torch::Tensor rangeBoundaries = \
        torch::linspace(this->rangeQuantSize, \
                        numrangecells * this->rangeQuantSize,\
                        numrangecells); std::cout<<"\t\t TransmitterClass: line 263 "<<std::endl;

    // creating the checkbox (verified)
    int numazimuthcells   = std::ceil(this->azimuthal_beamwidth * this->azimuthQuantDensity);
    int numelevationcells = std::ceil(this->elevation_beamwidth * this->elevationQuantDensity); std::cout<<"\t\t TransmitterClass: line 267 "<<std::endl;

    // finding the deltas
    float delta_azimuth   = this->azimuthal_beamwidth / numazimuthcells;
    float delta_elevation = this->elevation_beamwidth / numelevationcells; std::cout<<"\t\t TransmitterClass: line 271"<<std::endl;

    // creating the centers (verified)
    torch::Tensor azimuth_centers = torch::linspace(delta_azimuth/2, \
                                                    numazimuthcells * delta_azimuth - delta_azimuth/2, \
                                                    numazimuthcells);
    torch::Tensor elevation_centers = torch::linspace(delta_elevation/2, \
                                                    numelevationcells * delta_elevation - delta_elevation/2, \
                                                    numelevationcells); std::cout<<"\t\t TransmitterClass: line 279"<<std::endl;

    // centering (verified)
    azimuth_centers   = azimuth_centers + torch::tensor({this->azimuthal_angle - \
                                                    (this->azimuthal_beamwidth/2)}).to(torch::kFloat);
    elevation_centers = elevation_centers + torch::tensor({this->elevation_angle - \
                                                    (this->elevation_beamwidth/2)}).to(torch::kFloat); std::cout<<"\t\t TransmitterClass: line 285"<<std::endl;

    // building checkboxes
    torch::Tensor checkbox          = torch::zeros({numelevationcells, numazimuthcells}, torch::kBool);
    torch::Tensor finalScatterBox   = torch::zeros({numelevationcells, numazimuthcells, 3}).to(torch::kFloat);
    torch::Tensor finalReflectivityBox = torch::zeros({numelevationcells, numazimuthcells}).to(torch::kFloat); std::cout<<"\t\t TransmitterClass: line 290"<<std::endl;

    // going through each-range-cell
    for(int i = 0; i<(int)rangeBoundaries.numel(); ++i){
        this->internal_subsetCurrentRangeCell(rangeBoundaries[i], \
                                              scatterers,            \
                                              checkbox,              \
                                              finalScatterBox,       \
                                              finalReflectivityBox,  \
                                              azimuth_centers,       \
                                              elevation_centers,     \
                                              spherical_coordinates); std::cout<<"\t\t TransmitterClass: line 301"<<std::endl;

        // after each-range-cell
        torch::Tensor checkboxfilled = torch::sum(checkbox);
        std::cout<<"\t\t\t\t checkbox-filled = "<<checkboxfilled.item<int>()<<"/"<<checkbox.numel()<<" | percent = "<<100 * checkboxfilled.item<float>()/(float)checkbox.numel()<<std::endl;

    }

    // converting from box structure to [3, num-points] structure
    torch::Tensor final_coords_spherical = \
        torch::permute(finalScatterBox, {2, 0, 1}).reshape({3, (int)(finalScatterBox.numel()/3)});
    torch::Tensor final_coords_cart = fSph2Cart(final_coords_spherical); std::cout<<"\t\t
```

```
TransmitterClass: line 308"<<std::endl;
        std::cout<<"\t\t finalReflectivityBox.shape = "; fPrintTensorSize(finalReflectivityBox);
        torch::Tensor final_reflectivity = finalReflectivityBox.reshape({finalReflectivityBox.numel()}); std::cout<<"\t\t TransmitterClass: line 310"<<std::endl;
        torch::Tensor test_checkbox = checkbox.reshape({checkbox.numel()}); std::cout<<"\t\t TransmitterClass: line 311"<<std::endl;

        // just taking the points corresponding to the filled. Else, there's gonna be a lot of zero zero zero tensors
        auto mask = (test_checkbox == 1); std::cout<<"\t\t TransmitterClass: line 319"<<std::endl;
        final_coords_cart = final_coords_cart.index({torch::indexing::Slice(), mask}); std::cout<<"\t\t TransmitterClass: line 320"<<std::endl;
        final_reflectivity = final_reflectivity.index({mask}); std::cout<<"\t\t TransmitterClass: line 321"<<std::endl;

        // overwriting the scatterers
        scatterers->coordinates  = final_coords_cart;
        scatterers->reflectivity = final_reflectivity; std::cout<<"\t\t TransmitterClass: line 324"<<std::endl;

    }


    void internal_subsetCurrentRangeCell(torch::Tensor rangeupperlimit, \
                                         ScattererClass* scatterers,        \
                                         torch::Tensor& checkbox,           \
                                         torch::Tensor& finalScatterBox,    \
                                         torch::Tensor& finalReflectivityBox, \
                                         torch::Tensor& azimuth_centers,    \
                                         torch::Tensor& elevation_centers,  \
                                         torch::Tensor& spherical_coordinates){

        // finding indices for points in the current range-cell
        torch::Tensor pointsincurrentrangecell = \
           torch::mul((spherical_coordinates[2] <= rangeupperlimit) , \
                      (spherical_coordinates[2] > rangeupperlimit - this->rangeQuantSize));

        // checking out if there are no points in this range-cell
        int num311 = torch::sum(pointsincurrentrangecell).item<int>();
        if(num311 == 0) return;

        // calculating delta values
        float delta_azimuth  = azimuth_centers[1].item<float>() - azimuth_centers[0].item<float>();
        float delta_elevation = elevation_centers[1].item<float>() - elevation_centers[0].item<float>();

        // subsetting points in the current range-cell
        auto mask                                  = (pointsincurrentrangecell == 1); // creating a mask
        torch::Tensor reflectivityincurrentrangecell = scatterers->reflectivity.index({torch::indexing::Slice(), mask});
        pointsincurrentrangecell                   = spherical_coordinates.index({torch::indexing::Slice(), mask});

        // finding number of azimuth sizes and what not
        int numazimuthcells   = azimuth_centers.numel();
        int numelevationcells = elevation_centers.numel();

        // go through all the combinations
        for(int azi_index = 0; azi_index < numazimuthcells; ++azi_index){
           for(int ele_index = 0; ele_index < numelevationcells; ++ele_index){

              // check if this particular azimuth-elevation direction has been taken-care of.
              if (checkbox[ele_index][azi_index].item<bool>()) break;

              // init (verified)
              torch::Tensor current_azimuth = azimuth_centers.index({azi_index});
              torch::Tensor current_elevation = elevation_centers.index({ele_index});

              // // finding azimuth boolean
              // torch::Tensor azi_neighbours = torch::abs(pointsincurrentrangecell[0] - current_azimuth);
              // azi_neighbours              = azi_neighbours <= delta_azimuth; // tinker with this.

              // // finding elevation boolean
              // torch::Tensor ele_neighbours = torch::abs(pointsincurrentrangecell[1] - current_elevation);
              // ele_neighbours              = ele_neighbours <= delta_elevation;
```

```

                // finding azimuth boolean
                torch::Tensor azi_neighbours = torch::abs(pointsincurrentrangecell[0] - current_azimuth);
                azi_neighbours               = azi_neighbours <= this->azimuthShadowThreshold; // tinker with this.

                // finding elevation boolean
                torch::Tensor ele_neighbours = torch::abs(pointsincurrentrangecell[1] - current_elevation);
                ele_neighbours               = ele_neighbours <= this->elevationShadowThreshold;


                // combining booleans: means find all points that are within the limits of both the azimuth and boolean.
                torch::Tensor neighbours_boolean = torch::mul(azi_neighbours, ele_neighbours);

                // checking if there are any points along this direction
                int num347 = torch::sum(neighbours_boolean).item<int>();
                if (num347 == 0) continue;

                // findings point along this direction
                mask                                    = (neighbours_boolean == 1);
                torch::Tensor coords_along_aziele_spherical = pointsincurrentrangecell.index({torch::indexing::Slice(), mask});
                torch::Tensor reflectivity_along_aziele = reflectivityincurrentrangecell.index({torch::indexing::Slice(), mask});

                // finding the index where the points are at the maximum distance
                int index_where_min_range_is = torch::argmin(coords_along_aziele_spherical[2]).item<int>();
                torch::Tensor closest_coord = coords_along_aziele_spherical.index({torch::indexing::Slice(), \
                                                                            index_where_min_range_is});
                torch::Tensor closest_reflectivity = reflectivity_along_aziele.index({torch::indexing::Slice(), \
                                                                               index_where_min_range_is});

                // filling the matrices up
                finalScatterBox.index_put_({ele_index, azi_index, torch::indexing::Slice()}, \
                                           closest_coord.reshape({1,1,3}));
                finalReflectivityBox.index_put_({ele_index, azi_index}, \
                                               closest_reflectivity);
                checkbox.index_put_({ele_index, azi_index}, \
                                    true);

            }
        }
    }




};
```

8.1.3 Class: Uniform Linear Array

The following is the class definition used to encapsulate attributes and methods for the uniform linear array.

```
// bringing in the header files
#include <cstdint>
#include <iostream>
#include <stdexcept>
#include <torch/torch.h>


// class definitions
#include "ScattererClass.h"
#include "TransmitterClass.h"

// bringing in the functions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fConvolveColumns.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fBuffer2D.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fConvolve1D.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fCart2Sph.cpp"

#pragma once

// hash defines
#ifndef PRINTSPACE
    #define PRINTSPACE   std::cout<<"\n\n\n\n\n\n\n\n"<<std::endl;
#endif
#ifndef PRINTSMALLLINE
    #define PRINTSMALLLINE std::cout<<"------------------------------------------------"<<std::endl;
#endif
#ifndef PRINTLINE
    #define PRINTLINE    std::cout<<"================================================"<<std::endl;
#endif

#ifndef DEVICE
    // #define DEVICE       torch::kMPS
    #define DEVICE       torch::kCPU
#endif

#define PI           3.14159265
#define COMPLEX_1j          torch::complex(torch::zeros({1}), torch::ones({1}))

// #define DEBUG_ULA true
#define DEBUG_ULA false



class ULAClass{
public:
    // intrinsic parameters
    int num_sensors;                // number of sensors
    float inter_element_spacing;    // space between sensors
    torch::Tensor coordinates;      // coordinates of each sensor
    float sampling_frequency;       // sampling frequency of the sensors
    float recording_period;         // recording period of the ULA
    torch::Tensor location;         // location of first coordinate

    // derived stuff
    torch::Tensor sensorDirection;
    torch::Tensor signalMatrix;

    // decimation-related
    int decimation_factor;
    torch::Tensor lowpassFilterCoefficientsForDecimation; //

    // imaging related
    float range_resolution;         // theoretical range-resolution = $\frac{c}{2B}$
    float azimuthal_resolution;     // theoretical azimuth-resolution =
        $\frac{\lambda}{(N-1)*inter-element-distance}$
```

```
    float range_cell_size;          // the range-cell quanta we're choosing for efficiency trade-off
    float azimuth_cell_size;        // the azimuth quanta we're choosing
    torch::Tensor mulFFTMatrix;     // the matrix containing the delays for each-element as a slot
    torch::Tensor azimuth_centers;  // tensor containing the azimuth centeres
    torch::Tensor range_centers;    // tensor containing the range-centers
    int frame_size;                 // the frame-size corresponding to a range cell in a decimated signal matrix
    torch::Tensor matchFilter;      // torch tensor containing the match-filter
    int num_buffer_zeros_per_frame; // number of zeros we're adding per frame to ensure no-rotation

    // artificial acoustic-image related
    torch::Tensor currentArtificalAcousticImage; // the acoustic image directly produced

    // constructor
    ULAClass(int numsensors             = 32,
            float inter_element_spacing = 1e-3,
            torch::Tensor coordinates   = torch::zeros({3, 2}),
            float sampling_frequency    = 48e3,
            float recording_period      = 1,
            torch::Tensor location      = torch::zeros({3,1}),
            torch::Tensor signalMatrix  = torch::zeros({1, 32}),
            torch::Tensor lowpassFilterCoefficientsForDecimation = torch::zeros({1,10})):
            num_sensors(numsensors),
            inter_element_spacing(inter_element_spacing),
            coordinates(coordinates),
            sampling_frequency(sampling_frequency),
            recording_period(recording_period),
            location(location),
            signalMatrix(signalMatrix),
            lowpassFilterCoefficientsForDecimation(lowpassFilterCoefficientsForDecimation){
                // calculating ULA direction
                torch::Tensor sensorDirection = coordinates.slice(1, 0, 1) - coordinates.slice(1, 1, 2);

                // normalizing
                float normvalue = torch::linalg_norm(sensorDirection, 2, 0, true, torch::kFloat).item<float>();
                if (normvalue != 0){
                    sensorDirection = sensorDirection / normvalue;
                }

                // copying direction
                this->sensorDirection = sensorDirection;
        }

    // overrinding printing
    friend std::ostream& operator<<(std::ostream& os, ULAClass& ula){
        os<<"\t number of sensors : "<<ula.num_sensors        <<std::endl;
        os<<"\t inter-element spacing: "<<ula.inter_element_spacing <<std::endl;
        os<<"\t sensor-direction "   <<torch::transpose(ula.sensorDirection, 0, 1)<<std::endl;
        PRINTSMALLLINE
        return os;
    }

    /* ==========================================================================
    Aim: Init
    ------------------------------------------------------------------------ */
    void init(TransmitterClass* transmitterObj){

        // calculating range-related parameters
        this->range_resolution    = 1500/(2 * transmitterObj->fc);
        this->range_cell_size     = 40 * this->range_resolution;

        // status printing
        if(DEBUG_ULA) std::cout<<"\t\t ULAClass::init():: this->range_resolution = " << this->range_resolution << std::endl;
        if(DEBUG_ULA) std::cout<<"\t\t ULAClass::init():: this->range_cell_size = " << this->range_cell_size << std::endl;

        // calculating azimuth-related parameters
        this->azimuthal_resolution   = (1500/transmitterObj->fc)/((this->num_sensors-1)*this->inter_element_spacing);
        this->azimuth_cell_size      = 2 * this->azimuthal_resolution;

        // creating and storing the match-filter
```

```
        this->nfdc_CreateMatchFilter(transmitterObj);
    }

    // Create match-filter
    void nfdc_CreateMatchFilter(TransmitterClass* transmitterObj){

        // creating matrix for basebanding the signal
        torch::Tensor basebanding_vector = \
            torch::linspace(0, \
                          transmitterObj->Signal.numel() - 1, \
                          transmitterObj->Signal.numel()).reshape(transmitterObj->Signal.sizes());
        basebanding_vector = \
            torch::exp(COMPLEX_1j * 2 * PI * transmitterObj->fc * basebanding_vector);

        // multiplying the signal with the basebanding vector
        torch::Tensor match_filter = \
            torch::mul(transmitterObj->Signal, basebanding_vector);

        // low-pass filtering
        fConvolve1D(match_filter, this->lowpassFilterCoefficientsForDecimation);

        // creating sampling-indices
        int decimation_factor = std::floor((static_cast<float>(this->sampling_frequency)/2) / \
                                        (static_cast<float>(transmitterObj->bandwidth)/2));
        int final_num_samples =
             std::ceil(static_cast<float>(match_filter.numel())/static_cast<float>(decimation_factor));
        torch::Tensor sampling_indices = \
            torch::linspace(1, \
                          (final_num_samples-1) * decimation_factor,
                          final_num_samples).to(torch::kInt) - torch::tensor({1}).to(torch::kInt);

        // sampling the signal
        match_filter = match_filter.index({sampling_indices});

        // taking conjugate and flipping the signal
        match_filter = torch::flipud( match_filter);
        match_filter = torch::conj(  match_filter);

        // storing the match-filter to the class member
        this->matchFilter = match_filter;
    }

    // overloading the "=" operator
    ULAClass& operator=(const ULAClass& other){
        // checking if copying to the same object
        if(this == &other){
            return *this;
        }

        // copying everything
        this->num_sensors        = other.num_sensors;
        this->inter_element_spacing = other.inter_element_spacing;
        this->coordinates        = other.coordinates.clone();
        this->sampling_frequency = other.sampling_frequency;
        this->recording_period   = other.recording_period;
        this->sensorDirection    = other.sensorDirection.clone();

        // new additions
        // this->location           = other.location;
        this->lowpassFilterCoefficientsForDecimation = other.lowpassFilterCoefficientsForDecimation;
        // this->sensorDirection    = other.sensorDirection.clone();
        // this->signalMatrix       = other.signalMatrix.clone();


        // returning
        return *this;
    }

    // build sensor-coordinates based on location
    void buildCoordinatesBasedOnLocation(){

        // length-normalize the sensor-direction
        this->sensorDirection = torch::div(this->sensorDirection, torch::linalg_norm(this->sensorDirection, \
```

```
                                                                    2, 0, true, \
                                                                    torch::kFloat));
        if(DEBUG_ULA) std::cout<<"\t ULAClass: line 105 \n";

        // multiply with inter-element distance
        this->sensorDirection = this->sensorDirection * this->inter_element_spacing;
        this->sensorDirection = this->sensorDirection.reshape({this->sensorDirection.numel(), 1});
        if(DEBUG_ULA) std::cout<<"\t ULAClass: line 110 \n";

        // create integer-array
        // torch::Tensor integer_array = torch::linspace(0, \
        //                                         this->num_sensors-1, \
        //                                         this->num_sensors).reshape({1,
            this->num_sensors}).to(torch::kFloat);
        torch::Tensor integer_array = torch::linspace(0,                                 \
                                              this->num_sensors-1,                       \
                                              this->num_sensors).reshape({1,             \
                                                                       this->num_sensors});
        std::cout<<"integer_array = "; fPrintTensorSize(integer_array);
        if(DEBUG_ULA) std::cout<<"\t ULAClass: line 116 \n";

        //
        torch::Tensor test = torch::mul(torch::tile(integer_array, {3, 1}).to(torch::kFloat), \
                                    torch::tile(this->sensorDirection, {1,
                                        this->num_sensors}).to(torch::kFloat));
        this->coordinates = this->location + test;
        if(DEBUG_ULA) std::cout<<"\t ULAClass: line 120 \n";

    }

    // signal simulation for the current sensor-array
    void nfdc_simulateSignal(ScattererClass* scatterers,
                             TransmitterClass* transmitterObj){

        // creating signal matrix
        int numsamples    = std::ceil((this->sampling_frequency * this->recording_period));
        this->signalMatrix = torch::zeros({numsamples, this->num_sensors}).to(torch::kFloat);

        // getting shape of coordinates
        std::vector<int64_t> scatterers_coordinates_shape = scatterers->coordinates.sizes().vec();

        // making a slot out of the coordinates
        torch::Tensor slottedCoordinates = \
            torch::permute(scatterers->coordinates.reshape({scatterers_coordinates_shape[0], \
                                                    scatterers_coordinates_shape[1], \
                                                    1                                }), \
                        {2, 1, 0}).reshape({1, (int)(scatterers->coordinates.numel()/3), 3});

        // repeating along the y-direction number of sensor times.
        slottedCoordinates = torch::tile(slottedCoordinates, {this->num_sensors, 1, 1});
        std::vector<int64_t> slottedCoordinates_shape = slottedCoordinates.sizes().vec();

        // finding the shape of the sensor-coordinates
        std::vector<int64_t> sensor_coordinates_shape = this->coordinates.sizes().vec();

        // creating a slot tensor out of the sensor-coordinates
        torch::Tensor slottedSensors = \
            torch::permute(this->coordinates.reshape({sensor_coordinates_shape[0], \
                                              sensor_coordinates_shape[1], \
                                              1}), {2, 1, 0}).reshape({(int)(this->coordinates.numel()/3),
                                                  \
                                                                    1, \
                                                                    3});

        // repeating slices along the y-coordinates
        slottedSensors = torch::tile(slottedSensors, {1, slottedCoordinates_shape[1], 1});

        // slotting the coordinate of the transmitter
        torch::Tensor slotted_location = torch::permute(this->location.reshape({3, 1, 1}), \
                                                {2, 1, 0}).reshape({1,1,3});
        slotted_location = torch::tile(slotted_location, \
                                    {slottedCoordinates_shape[0], slottedCoordinates_shape[1], 1});
```

```
    // subtracting to find the relative distances
    torch::Tensor distBetweenScatterersAndSensors = \
        torch::linalg_norm(slottedCoordinates - slottedSensors, 2, 2, true, torch::kFloat);

    // substracting distance between relative fields
    torch::Tensor distBetweenScatterersAndTransmitter = \
        torch::linalg_norm(slottedCoordinates - slotted_location, 2, 2, true, torch::kFloat);

    // adding up the distances
    torch::Tensor distOfFlight   = distBetweenScatterersAndSensors + distBetweenScatterersAndTransmitter;
    torch::Tensor timeOfFlight   = distOfFlight/1500;
    torch::Tensor samplesOfFlight = torch::floor(timeOfFlight.squeeze() * this->sampling_frequency);

    // Adding pulses
    for(int sensor_index = 0; sensor_index < this->num_sensors; ++sensor_index){
        for(int scatter_index = 0; scatter_index < samplesOfFlight[0].numel(); ++scatter_index){

            // getting the sample where the current scatter's contribution must be placed.
            int where_to_place = samplesOfFlight.index({sensor_index, scatter_index}).item<int>();

            // checking whether that point is out of bounds
            if(where_to_place >= numsamples) continue;

            // placing a point in there
            this->signalMatrix.index_put_({where_to_place, sensor_index}, \
                                          this->signalMatrix.index({where_to_place, sensor_index}) + \
                                          torch::tensor({1}).to(torch::kFloat));

            this->signalMatrix.index_put_({where_to_place, sensor_index}, \
                                          this->signalMatrix.index({where_to_place, sensor_index}) + \
                                            scatterers->reflectivity.index({0, scatter_index}) );
        }
    }

    // Convolving signals with transmitted signal
    torch::Tensor signalTensorAsArgument = \
        transmitterObj->Signal.reshape({transmitterObj->Signal.numel(),1});
    signalTensorAsArgument = torch::tile(signalTensorAsArgument, \
                                         {1, this->signalMatrix.size(1)});

    // convolving the pulse-matrix with the signal matrix
    fConvolveColumns(this->signalMatrix,    \
                     signalTensorAsArgument);

    // trimming the convolved signal since the signal matrix length remains the same
    this->signalMatrix = this->signalMatrix.index({torch::indexing::Slice(0, numsamples), \
                                                   torch::indexing::Slice()});

    // printing the shape
    if(DEBUG_ULA) {
        std::cout<<"\t\t\t> this->signalMatrix.shape (after signal sim) = ";
        fPrintTensorSize(this->signalMatrix);
    }

    return;
}

// decimating the obtained signal
void nfdc_decimateSignal(TransmitterClass* transmitterObj){

    // creating the matrix for frequency-shifting
    torch::Tensor integerArray = torch::linspace(0, \
                                                 this->signalMatrix.size(0)-1, \
                                                 this->signalMatrix.size(0)).reshape({this->signalMatrix.size(0),
                                                     1});
    integerArray              = torch::tile(integerArray, {1, this->num_sensors});
    integerArray              = torch::exp(COMPLEX_1j * transmitterObj->fc * integerArray);

    // storing original number of samples
    int original_signalMatrix_numsamples = this->signalMatrix.size(0);

    // // printing
    // std::cout << "this->signalMatrix.shape = "<< this->signalMatrix.sizes().vec() << std::endl;
```

```
    // std::cout << "integerArray.shape     = "<< integerArray.sizes().vec()     << std::endl;

    // producing frequency-shifting
    this->signalMatrix       = torch::mul(this->signalMatrix, integerArray);

    // low-pass filter
    torch::Tensor lowpassfilter_impulseresponse = \
       this->lowpassFilterCoefficientsForDecimation.reshape(\
          {this->lowpassFilterCoefficientsForDecimation.numel(), 1});
    lowpassfilter_impulseresponse = torch::tile(lowpassfilter_impulseresponse, \
                              {1, this->signalMatrix.size(1)});

    // Convolving
    fConvolveColumns(this->signalMatrix, lowpassfilter_impulseresponse);

    // Cutting down the extra-samples from convolution
    this->signalMatrix = \
       this->signalMatrix.index({torch::indexing::Slice(0, original_signalMatrix_numsamples), \
                              torch::indexing::Slice()});

    // building parameters for downsampling
    int decimation_factor        = std::floor(this->sampling_frequency/transmitterObj->bandwidth);
    this->decimation_factor      = decimation_factor;
    int numsamples_after_decimation = std::floor(this->signalMatrix.size(0)/decimation_factor);

    // building the samples which will be subsetted
    torch::Tensor samplingIndices = \
       torch::linspace(0, \
                   numsamples_after_decimation * decimation_factor - 1, \
                   numsamples_after_decimation).to(torch::kInt);

    // downsampling the low-pass filtered signal
    this->signalMatrix = \
       this->signalMatrix.index({samplingIndices, \
                              torch::indexing::Slice()});


}

/* ========================================================================
Aim: Match-filtering
------------------------------------------------------------------------ */
void nfdc_matchFilterDecimatedSignal(){
    // Creating a 2D marix out of the signal
    torch::Tensor matchFilter2DMatrix = \
       this->matchFilter.reshape({this->matchFilter.numel(), 1});
    matchFilter2DMatrix = torch::tile(matchFilter2DMatrix, \
                                 {1, this->num_sensors});

    // 2D convolving to produce the match-filtering
    fConvolveColumns(this->signalMatrix, \
                 matchFilter2DMatrix);

}

/* ==========================================================================
Aim: precompute delay-matrices
------------------------------------------------------------------------ */
void nfdc_precomputeDelayMatrices(TransmitterClass* transmitterObj){

    // calculating range-related parameters
    int number_of_range_cells    = \
       std::ceil(((this->recording_period * 1500)/2)/this->range_cell_size);
    int number_of_azimuths_to_image = \
       std::ceil(transmitterObj->azimuthal_beamwidth / this->azimuth_cell_size);

    // creating centers of range-cell centers
    torch::Tensor range_centers = \
       this->range_cell_size *                          \
       torch::linspace(0,                               \
                   number_of_range_cells-1,             \
                   number_of_range_cells).to(torch::kFloat) + \
       this->range_cell_size/2;
```

```
        this->range_centers = range_centers;

        // creating discretized azimuth-centers
        torch::Tensor azimuth_centers = \
            this->azimuth_cell_size *                       \
            torch::linspace(0,                              \
                            number_of_azimuths_to_image - 1, \
                            number_of_azimuths_to_image) +  \
            this->azimuth_cell_size/2;
        this->azimuth_centers = azimuth_centers;

        // finding the mesh values
        auto range_azimuth_meshgrid = \
            torch::meshgrid({range_centers, azimuth_centers}, "ij");
        torch::Tensor range_grid = range_azimuth_meshgrid[0]; // the columns are range_centers
        torch::Tensor azimuth_grid = range_azimuth_meshgrid[1]; // the rows are azimuth-centers

        // going from 2D to 3D
        range_grid = torch::tile(range_grid.reshape({range_grid.size(0), \
                                                    range_grid.size(1), \
                                                    1}), \
                                  {1,1,this->num_sensors});
        azimuth_grid = torch::tile(azimuth_grid.reshape({azimuth_grid.size(0), \
                                                        azimuth_grid.size(1), \
                                                        1}), \
                                    {1, 1, this->num_sensors});

        // creating x_m tensor
        torch::Tensor sensorCoordinatesSlot = \
            this->inter_element_spacing * \
            torch::linspace(0, \
                            this->num_sensors - 1,\
                            this->num_sensors).reshape({1,1,this->num_sensors}).to(torch::kFloat);
        sensorCoordinatesSlot = \
            torch::tile(sensorCoordinatesSlot, \
                        {range_grid.size(0),\
                         range_grid.size(1),
                         1});
        if(DEBUG_ULA)
            std::cout << "\t sensorCoordinatesSlot.sizes().vec() = " \
                      <<  sensorCoordinatesSlot.sizes().vec()       \
                      <<  std::endl;

        // calculating distances
        torch::Tensor distanceMatrix =                              \
            torch::square(range_grid - sensorCoordinatesSlot) +     \
            torch::mul((2 * sensorCoordinatesSlot),                 \
                       torch::mul(range_grid,                       \
                                  1 - torch::cos(azimuth_grid * PI/180)));
        distanceMatrix = torch::sqrt(distanceMatrix);

        // finding the time taken
        torch::Tensor timeMatrix = distanceMatrix/1500;
        torch::Tensor sampleMatrix = timeMatrix * this->sampling_frequency;

        // finding the delay to be given
        auto bruh390             = torch::max(sampleMatrix, 2, true);
        torch::Tensor max_delay  = std::get<0>(bruh390);
        torch::Tensor delayMatrix = max_delay - sampleMatrix;

        // now that we have the delay entries, we need to create the matrix that does it
        int decimation_factor = \
            std::floor(static_cast<float>(this->sampling_frequency)/transmitterObj->bandwidth);
        this->decimation_factor = decimation_factor;


        // calculating frame-size
        int frame_size = \
            std::ceil(static_cast<float>((2 * this->range_cell_size / 1500) * \
                      static_cast<float>(this->sampling_frequency)/decimation_factor));
        this->frame_size = frame_size;

        // calculating the buffer-zeros to add
```

```
        int num_buffer_zeros_per_frame = \
            static_cast<float>(this->num_sensors - 1) * \
            static_cast<float>(this->inter_element_spacing) * \
            this->sampling_frequency /1500;

        // storing to class member
        this->num_buffer_zeros_per_frame = \
            num_buffer_zeros_per_frame;

        // calculating the total frame-size
        int total_frame_size = \
            this->frame_size + this->num_buffer_zeros_per_frame;

        // creating the multiplication matrix
        torch::Tensor mulFFTMatrix = \
            torch::linspace(0, \
                            total_frame_size-1, \
                            total_frame_size).reshape({1, \
                                                       total_frame_size, \
                                                       1}).to(torch::kFloat); // creating an array
                                                            1,...,frame_size of shape [1,frame_size, 1];
        mulFFTMatrix = \
            torch::div(mulFFTMatrix, \
                       torch::tensor(total_frame_size).to(torch::kFloat)); // dividing by N
        mulFFTMatrix = mulFFTMatrix * 2 * PI * -1 * COMPLEX_1j; // creating tenosr values for -1j * 2pi * k/N
        mulFFTMatrix = \
            torch::tile(mulFFTMatrix, \
                        {number_of_range_cells * number_of_azimuths_to_image, \
                         1, \
                         this->num_sensors}); // creating the larger tensor for it


        // populating the matrix
        for(int azimuth_index = 0; \
            azimuth_index<number_of_azimuths_to_image; \
            ++azimuth_index){
            for(int range_index = 0; \
                range_index < number_of_range_cells; \
                ++range_index){
                // finding the delays for sensors
                torch::Tensor currentSensorDelays = \
                    delayMatrix.index({range_index, \
                                       azimuth_index, \
                                       torch::indexing::Slice()});
                // reshaping it to the target size
                currentSensorDelays = \
                    currentSensorDelays.reshape({1, \
                                                 1, \
                                                 this->num_sensors});
                // tiling across the plane
                currentSensorDelays = \
                    torch::tile(currentSensorDelays, \
                                {1, total_frame_size, 1});
                // multiplying across the appropriate plane
                int index_to_place_at = \
                    azimuth_index * number_of_range_cells + \
                    range_index;
                mulFFTMatrix.index_put_({index_to_place_at, \
                                         torch::indexing::Slice(),
                                         torch::indexing::Slice()}, \
                                         currentSensorDelays);
            }
        }

        // storing the mulFFTMatrix
        this->mulFFTMatrix = mulFFTMatrix;
    }

    // beamforming the signal
    void nfdc_beamforming(TransmitterClass* transmitterObj){

        // ensuring the signal matrix is in the shape we want
        if(this->signalMatrix.size(1) != this->num_sensors)
```

```
        throw std::runtime_error("The second dimension doesn't correspond to the number of sensors \n");

    // adding the batch-dimension
    /* This is to accomodate a particular property of torch library.
    In torch, the first dimension is always the batch-related dimension.
    So in order to use the function torch::bmm(), we need to ensure that the first dimension is that of
        shape. */
    this->signalMatrix = \
        this->signalMatrix.reshape({1, \
                                    this->signalMatrix.size(0), \
                                    this->signalMatrix.size(1)});

    // zero-padding to ensure correctness
    int ideal_length                              = std::ceil(this->range_centers.numel() * this->frame_size);
    int num_zeros_to_pad_signal_along_dimension_0 = ideal_length - this->signalMatrix.size(1);

    // printing
    PRINTSMALLLINE
    std::cout<<"\t\t ULAClass::nfdc_beamforming | this->range_centers.numel()      =
        "<<this->range_centers.numel() <<std::endl;
    std::cout<<"\t\t ULAClass::nfdc_beamforming | this->frame_size                 = "<<this->frame_size
                <<std::endl;
    std::cout<<"\t\t ULAClass::nfdc_beamforming | ideal_length                     = "<<ideal_length
                <<std::endl;
    std::cout<<"\t\t ULAClass::nfdc_beamforming | this->signalMatrix.size(1)       =
        "<<this->signalMatrix.size(1)   <<std::endl;
    std::cout<<"\t\t ULAClass::nfdc_beamforming | num_zeros_to_pad_signal_along_dimension_0 =
        "<<num_zeros_to_pad_signal_along_dimension_0 <<std::endl;

    // appending or slicing based on the requirements
    if (num_zeros_to_pad_signal_along_dimension_0 <= 0) {

        // sending out a warning that slicing is going on
        std::cerr <<"\t\t ULAClass::nfdc_beamforming | Please note that the signal matrix has been sliced.
            This could lead to loss of information"<<std::endl;

        // slicing the signal matrix
        PRINTSPACE
        std::cout<<"\t\t ULAClass::nfdc_beamforming | this->signalMatrix.shape (before slicing) = "<<
            this->signalMatrix.sizes().vec() <<std::endl;
        this->signalMatrix = \
            this->signalMatrix.index({torch::indexing::Slice(), \
                                      torch::indexing::Slice(0, ideal_length), \
                                      torch::indexing::Slice()});
        std::cout<<"\t\t ULAClass::nfdc_beamforming | this->signalMatrix.shape (after slicing) = "<<
            this->signalMatrix.sizes().vec() <<std::endl;
        PRINTSPACE

    }
    else {
        // creating a zero-filled tensor to append to signal matrix
        torch::Tensor zero_tensor = torch::zeros({this->signalMatrix.size(0),           \
                                                  num_zeros_to_pad_signal_along_dimension_0, \
                                                  this->num_sensors}).to(torch::kFloat);

        // appending to signal matrix
        this->signalMatrix       = torch::cat({this->signalMatrix,                      \
                                               zero_tensor}, 1);
    }

    // breaking the signal into frames
    fBuffer2D(this->signalMatrix, frame_size);

    // add some zeros to the end of frames to accomodate delaying of signals.
    torch::Tensor zero_filled_tensor =                   \
        torch::zeros({this->signalMatrix.size(0),        \
                      this->num_buffer_zeros_per_frame, \
                      this->num_sensors}).to(torch::kFloat);
    this->signalMatrix =                                 \
        torch::cat({this->signalMatrix,                  \
                    zero_filled_tensor}, 1);

```

```
        // tiling it to ensure that it works for all range-angle combinations
        int number_of_azimuths_to_image = this->azimuth_centers.numel();
        this->signalMatrix = \
            torch::tile(this->signalMatrix, \
                        {number_of_azimuths_to_image, 1, 1});

        // element-wise multiplying the signals to delay each of the frame accordingly
        this->signalMatrix = torch::mul(this->signalMatrix, \
                                        this->mulFFTMatrix);

        // summing up the signals
        this->signalMatrix = torch::sum(this->signalMatrix, \
                                        2,                  \
                                        true);
        // this->signalMatrix = torch::sum(this->signalMatrix, 2, false);

        // printing some stuff
        std::cout<<"\t\t ULAClass::nfdc_beamforming: this->azimuth_centers.numel() =
             "<<this->azimuth_centers.numel() <<std::endl;
        std::cout<<"\t\t ULAClass::nfdc_beamforming: this->range_centers.numel() =
             "<<this->range_centers.numel() <<std::endl;
        std::cout<<"\t\t ULAClass::nfdc_beamforming: total number = "<<this->range_centers.numel() *
             this->azimuth_centers.numel() <<std::endl;
        std::cout<<"\t\t ULAClass::nfdc_beamforming: this->signalMatrix.sizes().vec() =
             "<<this->signalMatrix.sizes().vec() <<std::endl;
    }

    /* ===================================================================
    Aim: create acoustic image directly
    ------------------------------------------------------------------- */
    void nfdc_createAcousticImage(ScattererClass* scatterers, \
                                  TransmitterClass* transmitterObj){

        // first we ensure that the scattersers are in our frame of reference
        scatterers->coordinates = scatterers->coordinates - this->location;

        // finding the spherical coordinates of the scatterers
        torch::Tensor scatterers_spherical = fCart2Sph(scatterers->coordinates);

        // note that its not precisely projection. its rotation. So the original lengths must be maintained.
             but thats easy since the operation of putting th eelevation to be zero works just fine.
        scatterers_spherical.index_put_({1, torch::indexing::Slice()}, 0);

        // converting the points back to cartesian
        torch::Tensor scatterers_acoustic_cartesian = fSph2Cart(scatterers_spherical);

        // removing the z-dimension
        scatterers_acoustic_cartesian = \
            scatterers_acoustic_cartesian.index({torch::indexing::Slice(0, 2, 1), \
                                                torch::indexing::Slice()});

        // deciding image dimensions
        int num_pixels_x = 512;
        int num_pixels_y = 512;
        torch::Tensor acousticImage =                   \
            torch::zeros({num_pixels_x,                 \
                          num_pixels_y}).to(torch::kFloat);

        // finding the max and min values
        torch::Tensor min_x   = torch::min(scatterers_acoustic_cartesian[0]);
        torch::Tensor max_x   = torch::max(scatterers_acoustic_cartesian[0]);
        torch::Tensor min_y   = torch::min(scatterers_acoustic_cartesian[1]);
        torch::Tensor max_y   = torch::max(scatterers_acoustic_cartesian[1]);

        // creating query grids
        torch::Tensor query_x = torch::linspace(0, 1, num_pixels_x);
        torch::Tensor query_y = torch::linspace(0, 1, num_pixels_y);

        // scaling it up to image max-point spread
        query_x           = min_x + (max_x - min_x) * query_x;
        query_y           = min_y + (max_y - min_y) * query_y;
```

```
        float delta_queryx = (query_x[1] - query_x[0]).item<float>();
        float delta_queryy = (query_y[1] - query_y[0]).item<float>();

        // creating a mesh-grid
        auto queryMeshGrid = torch::meshgrid({query_x, query_y}, "ij");
        query_x = queryMeshGrid[0].reshape({1, queryMeshGrid[0].numel()});
        query_y = queryMeshGrid[1].reshape({1, queryMeshGrid[1].numel()});;
        torch::Tensor queryMatrix = torch::cat({query_x, query_y}, 0);

        // printing shapes
        if(DEBUG_ULA) PRINTSMALLLINE
        if(DEBUG_ULA) std::cout<<"\t\t ULAClass::nfdc_createAcousticImage: query_x.shape = "<<query_x.sizes().vec()<<std::endl;
        if(DEBUG_ULA) std::cout<<"\t\t ULAClass::nfdc_createAcousticImage: query_y.shape = "<<query_y.sizes().vec()<<std::endl;
        if(DEBUG_ULA) std::cout<<"\t\t ULAClass::nfdc_createAcousticImage: queryMatrix.shape = "<<queryMatrix.sizes().vec()<<std::endl;

        // setting up threshold values
        float threshold_value =      \
            std::min(delta_queryx,   \
                     delta_queryy); if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 711"<<std::endl;

        // putting a loop through the whole thing
        for(int i = 0; i<queryMatrix[0].numel(); ++i){
            // for each element in the query matrix
            if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 716"<<std::endl;

            // calculating relative position of all the points
            torch::Tensor relativeCoordinates = \
                scatterers_acoustic_cartesian - \
                queryMatrix.index({torch::indexing::Slice(), i}).reshape({2, 1}); if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 720"<<std::endl;

            // calculating distances between all the points and the query point
            torch::Tensor relativeDistances = \
                torch::linalg_norm(relativeCoordinates, \
                                   1, 0, true, \
                                   torch::kFloat);if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 727"<<std::endl;
            // finding points that are within the threshold
            torch::Tensor conditionMeetingPoints = \
                relativeDistances.squeeze() <= threshold_value;if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 729"<<std::endl;

            // subsetting the points in the neighbourhood
            if(torch::sum(conditionMeetingPoints).item<float>() == 0){

                // continuing implementation if there are no points in the neighbourhood
                continue; if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 735"<<std::endl;
            }
            else{
                // creating mask for points in the neighbourhood
                auto mask = (conditionMeetingPoints == 1);if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 739"<<std::endl;

                // subsetting relative distances in the neighbourhood
                torch::Tensor distanceInTheNeighbourhood = \
                    relativeDistances.index({torch::indexing::Slice(), mask});if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 743"<<std::endl;

                // subsetting reflectivity of points in the neighbourhood
                torch::Tensor reflectivityInTheNeighbourhood = \
                    scatterers->reflectivity.index({torch::indexing::Slice(), mask});if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 747"<<std::endl;

                // assigning intensity as a function of distance and reflectivity
                torch::Tensor reflectivityAssignment =                    \
                    torch::mul(torch::exp(-distanceInTheNeighbourhood),   \
                               reflectivityInTheNeighbourhood);if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_createAcousticImage: line 752"<<std::endl;
```

```
                reflectivityAssignment = \
                    torch::sum(reflectivityAssignment);if(DEBUG_ULA) std::cout<<"\t\t\t
                        ULAClass::nfdc_createAcousticImage: line 754"<<std::endl;

                // assigning this value to the image pixel intensity
                int pixel_position_x = i%num_pixels_x;
                int pixel_position_y = std::floor(i/num_pixels_x);
                acousticImage.index_put_({pixel_position_x, \
                                          pixel_position_y}, \
                                         reflectivityAssignment.item<float>());if(DEBUG_ULA) std::cout<<"\t\t\t
                                             ULAClass::nfdc_createAcousticImage: line 761"<<std::endl;
            }

        }

        // storing the acoustic-image to the member
        this->currentArtificalAcousticImage = acousticImage;

        // // saving the torch::tensor
        // torch::save(acousticImage, \
        //            "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/Assets/acoustic_image.pt");
















        // // bringing it back to the original coordinates
        // scatterers->coordinates = scatterers->coordinates + this->location;
    }





















};
```

8.1.4 Class: Autonomous Underwater Vehicle

The following is the class definition used to encapsulate attributes and methods of the marine vessel.

```
#include "ScattererClass.h"
#include "TransmitterClass.h"
#include "ULAClass.h"
#include <iostream>
#include <ostream>
#include <torch/torch.h>
#include <cmath>


// including functions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fGetCurrentTimeFormatted.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fCart2Sph.cpp"

#pragma once

// function to plot the thing
void fPlotTensors(){
    system("python /Users/vrsreeganesh/Documents/GitHub/AUV/Code/Python/TestingSaved_tensors.py");
}


void fSaveSeafloorScatteres(ScattererClass scatterer, \
                            ScattererClass scatterer_fls, \
                            ScattererClass scatterer_port, \
                            ScattererClass scatterer_starboard){

    // saving the ground-truth
    ScattererClass SeafloorScatter_gt = scatterer;
    torch::save(SeafloorScatter_gt.coordinates,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt.pt");
    torch::save(SeafloorScatter_gt.reflectivity,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt_reflectivity.pt");

    // saving coordinates
    torch::save(scatterer_fls.coordinates,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates.pt");
    torch::save(scatterer_port.coordinates,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates.pt");
    torch::save(scatterer_starboard.coordinates,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates.pt");

    // saving reflectivities
    torch::save(scatterer_fls.reflectivity,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates_reflectivity.pt");
    torch::save(scatterer_port.reflectivity,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates_reflectivity.pt");
    torch::save(scatterer_starboard.reflectivity,
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates_reflectivity.pt");

    // plotting tensors
    fPlotTensors();

    // // saving the tensors
    // if (true) {

    //     // getting time ID
    //     auto timeID = fGetCurrentTimeFormatted();

    //     std::cout<<"\t\t\t\t\t\t\t Saving Tensors (timeID: "<<timeID<<")"<<std::endl;

    //     // saving the ground-truth
    //     ScattererClass SeafloorScatter_gt = scatterer;
    //     torch::save(SeafloorScatter_gt.coordinates, \
    //                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt.pt");
    //     torch::save(SeafloorScatter_gt.reflectivity, \
    //
         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt_reflectivity.pt");
```

```
    //    // saving coordinates
    //    torch::save(scatterer_fls.coordinates, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates.pt");
    //    torch::save(scatterer_port.coordinates, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates.pt");
    //    torch::save(scatterer_starboard.coordinates, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates.pt");

    //    // saving reflectivities
    //    torch::save(scatterer_fls.reflectivity, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates_reflectivity.pt");
    //    torch::save(scatterer_port.reflectivity, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates_reflectivity.pt");
    //    torch::save(scatterer_starboard.reflectivity, \
    //
        "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates_reflectivity.pt");

    //    // plotting tensors
    //    fPlotTensors();

    //    // indicating end of thread
    //    std::cout<<"\t\t\t\t\t\t\t Ended (timeID: "<<timeID<<")"<<std::endl;
    // }
}

// including class-definitions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"

// hash defines
#ifndef PRINTSPACE
#define PRINTSPACE   std::cout<<"\n\n\n\n\n\n\n\n"<<std::endl;
#endif
#ifndef PRINTSMALLLINE
#define PRINTSMALLLINE std::cout<<"------------------------------------------------"<<std::endl;
#endif
#ifndef PRINTLINE
#define PRINTLINE    std::cout<<"================================================"<<std::endl;
#endif

#ifndef DEVICE
#define DEVICE       torch::kMPS
// #define DEVICE       torch::kCPU
#endif

#define PI           3.14159265
// #define DEBUGMODE_AUV true
#define DEBUGMODE_AUV false


class AUVClass{
public:
    // Intrinsic attributes
    torch::Tensor location;          // location of vessel
    torch::Tensor velocity;          // current speed of the vessel [a vector]
    torch::Tensor acceleration;      // current acceleration of vessel [a vector]
    torch::Tensor pointing_direction; // direction to which the AUV is pointed

    // uniform linear-arrays
    ULAClass ULA_fls;                // front-looking SONAR ULA
    ULAClass ULA_port;               // mounted ULA [object of class, ULAClass]
    ULAClass ULA_starboard;          // mounted ULA [object of class, ULAClass]

    // transmitters
    TransmitterClass transmitter_fls;   // transmitter for front-looking SONAR
    TransmitterClass transmitter_port;  // mounted transmitter [obj of class, TransmitterClass]
    TransmitterClass transmitter_starboard; // mounted transmitter [obj of class, TransmitterClass]
```

```cpp

    // derived or dependent attributes
    torch::Tensor signalMatrix_1;         // matrix containing the signals obtained from ULA_1
    torch::Tensor largeSignalMatrix_1;    // matrix holding signal of synthetic aperture
    torch::Tensor beamformedLargeSignalMatrix;// each column is the beamformed signal at each stop-hop

    // plotting mode
    bool plottingmode;  // to suppress plotting associated with classes

    // spotlight mode related
    torch::Tensor absolute_coords_patch_cart; // cartesian coordinates of patch

    // Synthetic Aperture Related
    torch::Tensor ApertureSensorLocations; // sensor locations of aperture


    /*===========================================================================
    Aim: stepping motion
    ---------------------------------------------------------------------------*/
    void step(float timestep){

        // updating location
        this->location = this->location + this->velocity * timestep;
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 81 \n";

        // updating attributes of members
        this->syncComponentAttributes();
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 85 \n";
    }



    /*===========================================================================
    Aim: updateAttributes
    ---------------------------------------------------------------------------*/
    void syncComponentAttributes(){

        // updating ULA attributes
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 97 \n";

        // updating locations
        this->ULA_fls.location       = this->location;
        this->ULA_port.location      = this->location;
        this->ULA_starboard.location = this->location;

        // updating the pointing direction of the ULAs
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 99 \n";
        torch::Tensor ula_fls_sensor_direction_spherical = fCart2Sph(this->pointing_direction);      // spherical coords
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 101 \n";
        ula_fls_sensor_direction_spherical[0]          = ula_fls_sensor_direction_spherical[0] - 90;
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 98 \n";
        torch::Tensor ula_fls_sensor_direction_cart    = fSph2Cart(ula_fls_sensor_direction_spherical);
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 100 \n";

        this->ULA_fls.sensorDirection       = ula_fls_sensor_direction_cart; // assigning sensor directionf or ULA-FLS
        this->ULA_port.sensorDirection      = -this->pointing_direction;    // assigning sensor direction for ULA-Port
        this->ULA_starboard.sensorDirection = -this->pointing_direction;    // assigning sensor direction for ULA-Starboard
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 105 \n";

        // // calling the function to update the arguments
        // this->ULA_fls.buildCoordinatesBasedOnLocation();  if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 109 \n";
        // this->ULA_port.buildCoordinatesBasedOnLocation(); if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 111 \n";
        // this->ULA_starboard.buildCoordinatesBasedOnLocation(); if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 113 \n";

        // updating transmitter locations
        this->transmitter_fls.location    = this->location;
```

```cpp
        this->transmitter_port.location   = this->location;
        this->transmitter_starboard.location = this->location;
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 102 \n";

        // updating transmitter pointing directions
        this->transmitter_fls.updatePointingAngle(     this->pointing_direction);
        this->transmitter_port.updatePointingAngle(    this->pointing_direction);
        this->transmitter_starboard.updatePointingAngle( this->pointing_direction);
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 108 \n";
    }



    /*=========================================================================
    Aim: operator overriding for printing
    -------------------------------------------------------------------------*/
    friend std::ostream& operator<<(std::ostream& os, AUVClass &auv){
        os<<"\t location = "<<torch::transpose(auv.location, 0, 1)<<std::endl;
        os<<"\t velocity = "<<torch::transpose(auv.velocity, 0, 1)<<std::endl;
        return os;
    }


    /*=========================================================================
    Aim: Subsetting Scatterers
    -------------------------------------------------------------------------*/
    void subsetScatterers(ScattererClass* scatterers,\
                          TransmitterClass* transmitterObj,\
                          float tilt_angle){

        // ensuring components are synced
        this->syncComponentAttributes();
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 120 \n";

        // calling the method associated with the transmitter
        if(DEBUGMODE_AUV) {std::cout<<"\t\t scatterers.shape = "; fPrintTensorSize(scatterers->coordinates);}
        if(DEBUGMODE_AUV) std::cout<<"\t\t tilt_angle = "<<tilt_angle<<std::endl;
        transmitterObj->subsetScatterers(scatterers, tilt_angle);
        if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 124 \n";
    }

    // yaw-correction matrix
    torch::Tensor createYawCorrectionMatrix(torch::Tensor pointing_direction_spherical, \
                                            float target_azimuth_deg){

        // building parameters
        torch::Tensor azimuth_correction        =
             torch::tensor({target_azimuth_deg}).to(torch::kFloat).to(DEVICE) - \
                                                      pointing_direction_spherical[0];
        torch::Tensor azimuth_correction_radians = azimuth_correction * PI / 180;

        torch::Tensor yawCorrectionMatrix = \
            torch::tensor({torch::cos(azimuth_correction_radians).item<float>(), \
                           torch::cos(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
                                azimuth_correction_radians).item<float>(), \
                           (float)0,                                              \
                           torch::sin(azimuth_correction_radians).item<float>(), \
                           torch::sin(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
                                azimuth_correction_radians).item<float>(), \
                           (float)0,                                              \
                           (float)0,                                              \
                           (float)0,                                              \
                           (float)1}).reshape({3,3}).to(torch::kFloat).to(DEVICE);

        // returning the matrix
        return yawCorrectionMatrix;
    }

    // pitch-correction matrix
    torch::Tensor createPitchCorrectionMatrix(torch::Tensor pointing_direction_spherical, \
                                              float target_elevation_deg){

        // building parameters
```

```
    torch::Tensor elevation_correction      =
        torch::tensor({target_elevation_deg}).to(torch::kFloat).to(DEVICE) - \
                                                pointing_direction_spherical[1];
    torch::Tensor elevation_correction_radians = elevation_correction * PI / 180;

    // creating the matrix
    torch::Tensor pitchCorrectionMatrix = \
        torch::tensor({(float)1,                                              \
                       (float)0,                                              \
                       (float)0,                                              \
                       (float)0,                                              \
                       torch::cos(elevation_correction_radians).item<float>(), \
                       torch::cos(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
                           elevation_correction_radians).item<float>(),\
                       (float)0,                                              \
                       torch::sin(elevation_correction_radians).item<float>(), \
                       torch::sin(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
                           elevation_correction_radians).item<float>()}).reshape({3,3}).to(torch::kFloat);

    // returning the matrix
    return pitchCorrectionMatrix;
}

// Signal Simulation
void simulateSignal(ScattererClass& scatterer){

    // making three copies
    ScattererClass scatterer_fls     = scatterer;
    ScattererClass scatterer_port    = scatterer;
    ScattererClass scatterer_starboard = scatterer;

    // printing size of scatterers before subsetting
    std::cout<< "> AUVClass: Beginning Scatterer Subsetting"<<std::endl;
    std::cout<<"\t AUVClass: scatterer_fls.coordinates.shape (before) = ";
        fPrintTensorSize(scatterer_fls.coordinates);
    std::cout<<"\t AUVClass: scatterer_port.coordinates.shape (before) = ";
        fPrintTensorSize(scatterer_port.coordinates);
    std::cout<<"\t AUVClass: scatterer_starboard.coordinates.shape (before) = ";
        fPrintTensorSize(scatterer_starboard.coordinates);

    // finding the pointing direction in spherical
    torch::Tensor auv_pointing_direction_spherical = fCart2Sph(this->pointing_direction);

    // asking the transmitters to subset the scatterers by multithreading
    std::thread transmitterFLSSubset_t(&AUVClass::subsetScatterers, this, \
                                       &scatterer_fls,\
                                       &this->transmitter_fls, \
                                       (float)0);
    std::thread transmitterPortSubset_t(&AUVClass::subsetScatterers, this, \
                                        &scatterer_port,\
                                        &this->transmitter_port, \
                                        auv_pointing_direction_spherical[1].item<float>());
    std::thread transmitterStarboardSubset_t(&AUVClass::subsetScatterers, this, \
                                             &scatterer_starboard, \
                                             &this->transmitter_starboard, \
                                             - auv_pointing_direction_spherical[1].item<float>());

    // joining the subset threads back
    transmitterFLSSubset_t.join(); transmitterPortSubset_t.join(); transmitterStarboardSubset_t.join();

    // printing the size of these points before subsetting
    PRINTDOTS
    std::cout<<"\t AUVClass: scatterer_fls.coordinates.shape (after) = ";
        fPrintTensorSize(scatterer_fls.coordinates);
    std::cout<<"\t AUVClass: scatterer_port.coordinates.shape (after) = ";
        fPrintTensorSize(scatterer_port.coordinates);
    std::cout<<"\t AUVClass: scatterer_starboard.coordinates.shape (after) = ";
        fPrintTensorSize(scatterer_starboard.coordinates);

    // multithreading the saving tensors part.
    std::thread savetensor_t(fSaveSeafloorScatteres, \
                             scatterer,            \
                             scatterer_fls,        \
```

```
                                 scatterer_port,          \
                                 scatterer_starboard);

        // asking ULAs to simulate signal through multithreading
        std::thread ulafls_signalsim_t(&ULAClass::nfdc_simulateSignal,   \
                                       &this->ULA_fls,                   \
                                       &scatterer_fls,                   \
                                       &this->transmitter_fls);
        std::thread ulaport_signalsim_t(&ULAClass::nfdc_simulateSignal,  \
                                        &this->ULA_port,                 \
                                        &scatterer_port,                 \
                                        &this->transmitter_port);
        std::thread ulastarboard_signalsim_t(&ULAClass::nfdc_simulateSignal, \
                                             &this->ULA_starboard,       \
                                             &scatterer_starboard,       \
                                             &this->transmitter_starboard);

        // joining them back
        ulafls_signalsim_t.join();       // joining back the thread for ULA-FLS
        ulaport_signalsim_t.join();      // joining back the signals-sim thread for ULA-Port
        ulastarboard_signalsim_t.join(); // joining back the signal-sim thread for ULA-Starboard
        savetensor_t.join();             // joining back the signal-sim thread for tensor-saving

        // saving the tensors
        if (true) {
            // saving the ground-truth
            torch::save(this->ULA_fls.signalMatrix,
                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_fls.pt");
            torch::save(this->ULA_port.signalMatrix,
                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_port.pt");
            torch::save(this->ULA_starboard.signalMatrix,
                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_starboard.pt");
        }


    }

    // Imaging Function
    void image(){

        // asking ULAs to decimate the signals obtained at each time step
        std::thread ULA_fls_image_t(&ULAClass::nfdc_decimateSignal,      \
                                    &this->ULA_fls,                      \
                                    &this->transmitter_fls);
        std::thread ULA_port_image_t(&ULAClass::nfdc_decimateSignal,     \
                                     &this->ULA_port,                    \
                                     &this->transmitter_port);
        std::thread ULA_starboard_image_t(&ULAClass::nfdc_decimateSignal, \
                                          &this->ULA_starboard,          \
                                          &this->transmitter_starboard);

        // joining the threads back
        ULA_fls_image_t.join();
        ULA_port_image_t.join();
        ULA_starboard_image_t.join();

        // asking ULAs to match-filter the signals
        std::thread ULA_fls_matchfilter_t(&ULAClass::nfdc_matchFilterDecimatedSignal, &this->ULA_fls);
        std::thread ULA_port_matchfilter_t(&ULAClass::nfdc_matchFilterDecimatedSignal, &this->ULA_port);
        std::thread ULA_starboard_matchfilter_t(&ULAClass::nfdc_matchFilterDecimatedSignal,
             &this->ULA_starboard);

        // joining the threads back
        ULA_fls_matchfilter_t.join();
        ULA_port_matchfilter_t.join();
        ULA_starboard_matchfilter_t.join();


        // performing the beamforming
        // std::thread ULA_fls_beamforming_t(&ULAClass::nfdc_beamforming,   \
        //                                   &this->ULA_fls,                \
        //                                   &this->transmitter_fls);
        // std::thread ULA_port_beamforming_t(&ULAClass::nfdc_beamforming,  \
```

```
        //                                &this->ULA_port,                  \
        //                                &this->transmitter_port);
        // std::thread ULA_starboard_beamforming_t(&ULAClass::nfdc_beamforming, \
        //                                     &this->ULA_starboard,        \
        //                                     &this->transmitter_starboard);

        // joining the filters back
        // ULA_fls_beamforming_t.join();
        // ULA_port_beamforming_t.join();
        // ULA_starboard_beamforming_t.join();

    }


    /* =========================================================================
    Aim: Init
    -------------------------------------------------------------------------*/
    void init(){

        // call sync-component attributes
        this->syncComponentAttributes();

        // initializing all the ULAs
        this->ULA_fls.init(      &this->transmitter_fls);
        this->ULA_port.init(     &this->transmitter_port);
        this->ULA_starboard.init( &this->transmitter_starboard);

        // precomputing delay-matrices for the ULA-class
        std::thread ULA_fls_precompute_weights_t(&ULAClass::nfdc_precomputeDelayMatrices, \
                                          &this->ULA_fls,                           \
                                          &this->transmitter_fls);
        std::thread ULA_port_precompute_weights_t(&ULAClass::nfdc_precomputeDelayMatrices, \
                                           &this->ULA_port,                         \
                                           &this->transmitter_port);
        std::thread ULA_starboard_precompute_weights_t(&ULAClass::nfdc_precomputeDelayMatrices, \
                                                &this->ULA_starboard,               \
                                                &this->transmitter_starboard);

        // joining the threads back
        ULA_fls_precompute_weights_t.join();
        ULA_port_precompute_weights_t.join();
        ULA_starboard_precompute_weights_t.join();

    }

    /* =========================================================================
    Aim: directly create acoustic image
    ------------------------------------------------------------------------ */
    void createAcousticImage(ScattererClass* scatterers){

        // making three copies
        ScattererClass scatterer_fls     = scatterers;
        ScattererClass scatterer_port    = scatterers;
        ScattererClass scatterer_starboard = scatterers;

        // printing size of scatterers before subsetting
        PRINTSMALLLINE
        std::cout<< "\t > AUVClass::createAcousticImage: Beginning Scatterer Subsetting"<<std::endl;
        std::cout<<"\t AUVClass::createAcousticImage: scatterer_fls.coordinates.shape (before) = "; fPrintTensorSize(scatterer_fls.coordinates);
        std::cout<<"\t AUVClass::createAcousticImage: scatterer_port.coordinates.shape (before) = "; fPrintTensorSize(scatterer_port.coordinates);
        std::cout<<"\t AUVClass::createAcousticImage: scatterer_starboard.coordinates.shape (before) = "; fPrintTensorSize(scatterer_starboard.coordinates);

        // finding the pointing direction in spherical
        torch::Tensor auv_pointing_direction_spherical = fCart2Sph(this->pointing_direction);

        // asking the transmitters to subset the scatterers by multithreading
        std::thread transmitterFLSSubset_t(&AUVClass::subsetScatterers, this, \
                                    &scatterer_fls,\
                                    &this->transmitter_fls, \
                                    (float)0);
```

```
        std::thread transmitterPortSubset_t(&AUVClass::subsetScatterers, this, \
                                    &scatterer_port,\
                                    &this->transmitter_port, \
                                    auv_pointing_direction_spherical[1].item<float>());
        std::thread transmitterStarboardSubset_t(&AUVClass::subsetScatterers, this, \
                                         &scatterer_starboard, \
                                         &this->transmitter_starboard, \
                                         - auv_pointing_direction_spherical[1].item<float>());

        // joining the subset threads back
        transmitterFLSSubset_t.join(    );
        transmitterPortSubset_t.join(   );
        transmitterStarboardSubset_t.join( );


        // asking the ULAs to directly create acoustic images
        std::thread ULA_fls_acoustic_image_t(&ULAClass::nfdc_createAcousticImage, this->ULA_fls, \
                                     &scatterer_fls, &this->transmitter_fls);
        std::thread ULA_port_acoustic_image_t(&ULAClass::nfdc_createAcousticImage, &this->ULA_port, \
                                     &scatterer_port, &this->transmitter_port);
        std::thread ULA_starboard_acoustic_image_t(&ULAClass::nfdc_createAcousticImage, &this->ULA_starboard, \
                                          &scatterer_starboard, &this->transmitter_starboard);

        // joining the threads back
        ULA_fls_acoustic_image_t.join(  );
        ULA_port_acoustic_image_t.join( );
        ULA_starboard_acoustic_image_t.join();

    }


};
```

8.2 Setup Scripts

8.2.1 Seafloor Setup

Following is the script to be run to setup the seafloor.

```cpp
/* =====================================
Aim: Setup sea floor
=====================================*/
#include <torch/torch.h>
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"

#ifndef DEVICE
    // #define DEVICE       torch::kMPS
    #define DEVICE      torch::kCPU
#endif


// adding terrrain features
#define BOXES        false
#define TERRAIN      false
#define DEBUG_SEAFLOOR false



// Adding boxes
void fCreateBoxes(float across_track_length, \
                float along_track_length, \
                torch::Tensor& box_coordinates,\
                torch::Tensor& box_reflectivity){

    // converting arguments to torch tensos

    // setting up parameters
    float min_width        = 2;     // minimum across-track dimension of the boxes in the sea-floor
    float max_width        = 5;    // maximum across-track dimension of the boxes in the sea-floor

    float min_length       = 2;     // minimum along-track dimension of the boxes in the sea-floor
    float max_length       = 5;    // maximum along-track dimension of the boxes in the sea-floor

    float min_height       = 3;    // minimum height of the boxes in the sea-floor
    float max_height       = 20;    // maximum height of the boxes in the sea-floor

    int meshdensity        = 10;     // number of points per meter.
    float meshreflectivity = 2;     // average reflectivity of the mesh

    int num_boxes          = 10;    // number of boxes in the sea-floor
    if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 41\n";

    // finding center point
    torch::Tensor midxypoints = torch::rand({3, num_boxes}).to(torch::kFloat).to(DEVICE);
    midxypoints[0]           = midxypoints[0] * across_track_length;
    midxypoints[1]           = midxypoints[1] * along_track_length;
    midxypoints[2]           = 0;
    if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 48\n";

    // assigning dimensions to boxes
    torch::Tensor boxwidths = torch::rand({num_boxes})*(max_width - min_width) + min_width; // assigning widths to each boxes
    torch::Tensor boxlengths = torch::rand({num_boxes})*(max_length - min_length) + min_length; // assigning lengths to each boxes
    torch::Tensor boxheights = torch::rand({num_boxes})*(max_height - min_height) + min_height; // assigning heights to each boxes
    if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 54\n";

    // creating mesh for each box
    for(int i = 0; i<num_boxes; ++i){

        // finding x-points
        torch::Tensor xpoints = torch::linspace(-boxwidths[i].item<float>()/2, \
                                              boxwidths[i].item<float>()/2, \
```

```
                                          (int)(boxwidths[i].item<float>() * meshdensity));
        torch::Tensor ypoints = torch::linspace(-boxlengths[i].item<float>()/2, \
                                          boxlengths[i].item<float>()/2, \
                                          (int)(boxlengths[i].item<float>() * meshdensity));
        torch::Tensor zpoints = torch::linspace(0, \
                                         boxheights[i].item<float>(),\
                                         (int)(boxheights[i].item<float>() * meshdensity));
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 69\n";

        // meshgridding
        auto mesh_grid = torch::meshgrid({xpoints, ypoints, zpoints}, "xy");
        auto X        = mesh_grid[0];
        auto Y        = mesh_grid[1];
        auto Z        = mesh_grid[2];
        X             = torch::reshape(X, {1, X.numel()});
        Y             = torch::reshape(Y, {1, Y.numel()});
        Z             = torch::reshape(Z, {1, Z.numel()});
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 79\n";

        // coordinates
        torch::Tensor boxcoordinates = torch::cat({X, Y, Z}, 0).to(DEVICE);
        boxcoordinates[0] = boxcoordinates[0] + midxypoints[0][i];
        boxcoordinates[1] = boxcoordinates[1] + midxypoints[1][i];
        boxcoordinates[2] = boxcoordinates[2] + midxypoints[2][i];
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 86\n";

        // creating some reflectivity points too.
        torch::Tensor boxreflectivity = meshreflectivity + torch::rand({1, boxcoordinates[0].numel()}) - 0.5;
        boxreflectivity = boxreflectivity.to(DEVICE);
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 90\n";

        // adding to larger matrices
        if(DEBUG_SEAFLOOR) {std::cout<<"box_coordinates.shape = "; fPrintTensorSize(box_coordinates);}
        if(DEBUG_SEAFLOOR) {std::cout<<"box_coordinates.shape = "; fPrintTensorSize(boxcoordinates);}

        if(DEBUG_SEAFLOOR) {std::cout<<"box_reflectivity.shape = "; fPrintTensorSize(box_reflectivity);}
        if(DEBUG_SEAFLOOR) {std::cout<<"boxreflectivity.shape = "; fPrintTensorSize(boxreflectivity);}

        box_coordinates   = torch::cat({box_coordinates.to(DEVICE), boxcoordinates}, 1);
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 95\n";
        box_reflectivity  = torch::cat({box_reflectivity.to(DEVICE), boxreflectivity}, 1);
        if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 97\n";
    }
}



// functin that setups the sea-floor
void SeafloorSetup(ScattererClass* scatterers) {

    // sea-floor bounds
    int bed_width = 100; // width of the bed (x-dimension)
    int bed_length = 100; // length of the bed (y-dimension)

    // multithreading the box creation

    // creating some tensors to pass. This is put outside to maintain scope
    bool add_boxes_flag = BOXES;
    torch::Tensor box_coordinates = torch::zeros({3,1}).to(torch::kFloat).to(DEVICE);
    torch::Tensor box_reflectivity = torch::zeros({1,1}).to(torch::kFloat).to(DEVICE);
    // std::thread boxes_t(fCreateBoxes, \
    //                     bed_width, bed_length, \
    //                     &box_coordinates, &box_reflectivity);
    fCreateBoxes(bed_width, \
                 bed_length, \
                 box_coordinates, \
                 box_reflectivity);

    // scatter-intensity
    // int bed_width_density    = 100; // density of points along x-dimension
    // int bed_length_density   = 100; // density of points along y-dimension
    int bed_width_density    = 10; // density of points along x-dimension
    int bed_length_density   = 10; // density of points along y-dimension
```

```

    // setting up coordinates
    auto xpoints = torch::linspace(0, \
                                bed_width, \
                                bed_width * bed_width_density).to(DEVICE);
    auto ypoints = torch::linspace(0, \
                                bed_length, \
                                bed_length * bed_length_density).to(DEVICE);

    // creating mesh
    auto mesh_grid = torch::meshgrid({xpoints, ypoints}, "ij");
    auto X        = mesh_grid[0];
    auto Y        = mesh_grid[1];
    X             = torch::reshape(X, {1, X.numel()});
    Y             = torch::reshape(Y, {1, Y.numel()});

    // creating heights of scattereres
    torch::Tensor Z = torch::zeros({1, Y.numel()}).to(DEVICE);

    // setting up floor coordinates
    torch::Tensor floorScatter_coordinates = torch::cat({X, Y, Z}, 0);
    torch::Tensor floorScatter_reflectivity = torch::ones({1, Y.numel()}).to(DEVICE);

    // populating the values of the incoming argument.
    scatterers->coordinates  = floorScatter_coordinates; // assigning coordinates
    scatterers->reflectivity = floorScatter_reflectivity;// assigning reflectivity

    // // rejoining if multithreading
    // boxes_t.join();// bringing thread back

    // combining the values
    if(DEBUG_SEAFLOOR) std::cout<<"\t SeafloorSetup: line 166 \n";
    if(DEBUG_SEAFLOOR) {std::cout<<"\t scatterers->coordinates.shape = ";
        fPrintTensorSize(scatterers->coordinates);}
    if(DEBUG_SEAFLOOR) {std::cout<<"\t box_coordinates.shape = "; fPrintTensorSize(box_coordinates);}
    if(DEBUG_SEAFLOOR) {std::cout<<"\t scatterers->reflectivity.shape = ";
        fPrintTensorSize(scatterers->reflectivity);}
    if(DEBUG_SEAFLOOR) {std::cout<<"\t box_reflectivity = "; fPrintTensorSize(box_reflectivity);}


    // assigning values to the coordinates
    scatterers->coordinates  = torch::cat({scatterers->coordinates, box_coordinates}, 1);
    scatterers->reflectivity = torch::cat({scatterers->reflectivity, box_reflectivity}, 1);


}
```

8.2.2 Transmitter Setup

Following is the script to be run to setup the transmitter.

```
/* ====================================
Aim: Setup sea floor
=====================================*/
#include <torch/torch.h>
#include <cmath>

#ifndef DEVICE
   // #define DEVICE       torch::kMPS
   #define DEVICE       torch::kCPU
#endif



// function to calibrate the transmitters
void TransmitterSetup(TransmitterClass* transmitter_fls,
                      TransmitterClass* transmitter_port,
                      TransmitterClass* transmitter_starboard) {

   // Setting up transmitter
   float sampling_frequency = 160e3;                // sampling frequency
   float f1                = 50e3;                  // first frequency of LFM
   float f2                = 70e3;                  // second frequency of LFM
   float fc                = (f1 + f2)/2;           // finding center-frequency
   float bandwidth         = std::abs(f2 - f1); // bandwidth
   float pulselength       = 0.2;                   // time of recording

   // building LFM
   torch::Tensor timearray = torch::linspace(0, \
                                         pulselength, \
                                         floor(pulselength * sampling_frequency)).to(DEVICE);
   float K                = (f2 - f1)/pulselength;          // calculating frequency-slope
   torch::Tensor Signal  = K * timearray;                  // frequency at each time-step, with f1 = 0
   Signal                = torch::mul(2*PI*(f1 + Signal), \
                                    timearray);            // creating
   Signal                = cos(Signal);                    // calculating signal


   // Setting up transmitter
   torch::Tensor location              = torch::zeros({3,1}).to(DEVICE); // location of transmitter
   float azimuthal_angle_fls           = 0;               // initial pointing direction
   float azimuthal_angle_port          = 90;               // initial pointing direction
   float azimuthal_angle_starboard     = -90;                // initial pointing direction

   float elevation_angle               = -60;               // initial pointing direction

   float azimuthal_beamwidth_fls       = 20;                // azimuthal beamwidth of the signal cone
   float azimuthal_beamwidth_port      = 20;                // azimuthal beamwidth of the signal cone
   float azimuthal_beamwidth_starboard = 20;                // azimuthal beamwidth of the signal cone

   float elevation_beamwidth_fls       = 20;                // elevation beamwidth of the signal cone
   float elevation_beamwidth_port      = 20;                // elevation beamwidth of the signal cone
   float elevation_beamwidth_starboard = 20;                // elevation beamwidth of the signal cone

   int azimuthQuantDensity      = 10;  // number of points, a degree is split into quantization density
        along azimuth (used for shadowing)
   int elevationQuantDensity    = 10;  // number of points, a degree is split into quantization density
        along elevation (used for shadowing)
   float rangeQuantSize         = 10;  // the length of a cell (used for shadowing)

   float azimuthShadowThreshold = 1;     // azimuth threshold   (in degrees)
   float elevationShadowThreshold = 1;   // elevation threshold  (in degrees)



   // transmitter-fls
   transmitter_fls->location               = location;           // Assigning location
   transmitter_fls->Signal                 = Signal;             // Assigning signal
   transmitter_fls->azimuthal_angle        = azimuthal_angle_fls; // assigning azimuth angle
```

```
    transmitter_fls->elevation_angle       = elevation_angle;     // assigning elevation angle
    transmitter_fls->azimuthal_beamwidth   = azimuthal_beamwidth_fls; // assigning azimuth-beamwidth
    transmitter_fls->elevation_beamwidth   = elevation_beamwidth_fls; // assigning elevation-beamwidth
    // updating quantization densities
    transmitter_fls->azimuthQuantDensity   = azimuthQuantDensity;     // assigning azimuth quant density
    transmitter_fls->elevationQuantDensity  = elevationQuantDensity;   // assigning elevation quant density
    transmitter_fls->rangeQuantSize        = rangeQuantSize;          // assigning range-quantization
    transmitter_fls->azimuthShadowThreshold = azimuthShadowThreshold;  // azimuth-threshold in shadowing
    transmitter_fls->elevationShadowThreshold = elevationShadowThreshold; // elevation-threshold in shadowing
    // signal related
    transmitter_fls->f_low                 = f1;          // assigning lower frequency
    transmitter_fls->f_high                = f2;          // assigning higher frequency
    transmitter_fls->fc                    = fc;          // assigning center frequency
    transmitter_fls->bandwidth             = bandwidth;   // assigning bandwidth



    // transmitter-portside
    transmitter_port->location             = location;                 // Assigning location
    transmitter_port->Signal               = Signal;                   // Assigning signal
    transmitter_port->azimuthal_angle      = azimuthal_angle_port;     // assigning azimuth angle
    transmitter_port->elevation_angle      = elevation_angle;          // assigning elevation angle
    transmitter_port->azimuthal_beamwidth  = azimuthal_beamwidth_port; // assigning azimuth-beamwidth
    transmitter_port->elevation_beamwidth  = elevation_beamwidth_port; // assigning elevation-beamwidth
    // updating quantization densities
    transmitter_port->azimuthQuantDensity  = azimuthQuantDensity;      // assigning azimuth quant density
    transmitter_port->elevationQuantDensity = elevationQuantDensity;    // assigning elevation quant density
    transmitter_port->rangeQuantSize       = rangeQuantSize;           // assigning range-quantization
    transmitter_port->azimuthShadowThreshold = azimuthShadowThreshold;  // azimuth-threshold in shadowing
    transmitter_port->elevationShadowThreshold = elevationShadowThreshold; // elevation-threshold in shadowing
    // signal related
    transmitter_port->f_low                = f1;                       // assigning lower frequency
    transmitter_port->f_high               = f2;                       // assigning higher frequency
    transmitter_port->fc                   = fc;                       // assigning center frequency
    transmitter_port->bandwidth            = bandwidth;                // assigning bandwidth



    // transmitter-starboard
    transmitter_starboard->location               = location;                 // assigning location
    transmitter_starboard->Signal                 = Signal;                   // assigning signal
    transmitter_starboard->azimuthal_angle        = azimuthal_angle_starboard; // assigning azimuthal signal
    transmitter_starboard->elevation_angle        = elevation_angle;
    transmitter_starboard->azimuthal_beamwidth    = azimuthal_beamwidth_starboard;
    transmitter_starboard->elevation_beamwidth    = elevation_beamwidth_starboard;
    // updating quantization densities
    transmitter_starboard->azimuthQuantDensity    = azimuthQuantDensity;
    transmitter_starboard->elevationQuantDensity  = elevationQuantDensity;
    transmitter_starboard->rangeQuantSize         = rangeQuantSize;
    transmitter_starboard->azimuthShadowThreshold  = azimuthShadowThreshold;
    transmitter_starboard->elevationShadowThreshold = elevationShadowThreshold;
    // signal related
    transmitter_starboard->f_low                  = f1;          // assigning lower frequency
    transmitter_starboard->f_high                 = f2;          // assigning higher frequency
    transmitter_starboard->fc                     = fc;          // assigning center frequency
    transmitter_starboard->bandwidth              = bandwidth;   // assigning bandwidth

}
```

8.2.3 Uniform Linear Array

Following is the script to be run to setup the uniform linear array.

```
/* ====================================
Aim: Setup sea floor
NOAA: 50 to 100 KHz is the transmission frequency
we'll create our LFM with 50 to 70KHz
=====================================*/


// Choosing device
#ifndef DEVICE
   // #define DEVICE       torch::kMPS
   #define DEVICE       torch::kCPU
#endif


// the coefficients for the low-pass filter.
#define LOWPASS_DECIMATE_FILTER_COEFFICIENTS 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0001, 0.0003,
    0.0006, 0.0015, 0.0030, 0.0057, 0.0100, 0.0163, 0.0251, 0.0364, 0.0501, 0.0654, 0.0814, 0.0966, 0.1093,
    0.1180, 0.1212, 0.1179, 0.1078, 0.0914, 0.0699, 0.0451, 0.0192, -0.0053, -0.0262, -0.0416, -0.0504,
    -0.0522, -0.0475, -0.0375, -0.0239, -0.0088, 0.0057, 0.0179, 0.0263, 0.0303, 0.0298, 0.0253, 0.0177,
    0.0086, -0.0008, -0.0091, -0.0153, -0.0187, -0.0191, -0.0168, -0.0123, -0.0065, -0.0004, 0.0052, 0.0095,
    0.0119, 0.0125, 0.0112, 0.0084, 0.0046, 0.0006, -0.0031, -0.0060, -0.0078, -0.0082, -0.0075, -0.0057,
    -0.0033, -0.0006, 0.0019, 0.0039, 0.0051, 0.0055, 0.0050, 0.0039, 0.0023, 0.0005, -0.0012, -0.0025,
    -0.0034, -0.0036, -0.0034, -0.0026, -0.0016, -0.0004, 0.0007, 0.0016, 0.0022, 0.0024, 0.0023, 0.0018,
    0.0011, 0.0003, -0.0004, -0.0011, -0.0015, -0.0016, -0.0015




void ULASetup(ULAClass* ula_fls,
             ULAClass* ula_port,
             ULAClass* ula_starboard) {

   // setting up ula
   int num_sensors          = 64;                        // number of sensors
   float sampling_frequency = 160e3;                     // sampling frequency
   float inter_element_spacing = 1500/(2*sampling_frequency); // space between samples
   float recording_period    = 0.25;                        // sampling-period

   // building the direction for the sensors
   torch::Tensor ULA_direction = torch::tensor({-1,0,0}).reshape({3,1}).to(torch::kFloat).to(DEVICE);
   ULA_direction            = ULA_direction/torch::linalg_norm(ULA_direction, 2, 0, true,
       torch::kFloat).to(DEVICE);
   ULA_direction            = ULA_direction * inter_element_spacing;

   // building the coordinates for the sensors
   torch::Tensor ULA_coordinates = torch::mul(torch::linspace(0, num_sensors-1, num_sensors).to(DEVICE), \
                                       ULA_direction);

   // the coefficients for the decimation filter
   torch::Tensor lowpassfiltercoefficients =
       torch::tensor({LOWPASS_DECIMATE_FILTER_COEFFICIENTS}).to(torch::kFloat);

   // assigning values
   ula_fls->num_sensors         = num_sensors;           // assigning number of sensors
   ula_fls->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
   ula_fls->coordinates         = ULA_coordinates;       // assigning ULA coordinates
   ula_fls->sampling_frequency  = sampling_frequency;    // assigning sampling frequencys
   ula_fls->recording_period    = recording_period;      // assigning recording period
   ula_fls->sensorDirection     = ULA_direction;         // ULA direction
   ula_fls->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;

   // assigning values
   ula_port->num_sensors         = num_sensors;           // assigning number of sensors
   ula_port->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
   ula_port->coordinates         = ULA_coordinates;       // assigning ULA coordinates
   ula_port->sampling_frequency  = sampling_frequency;    // assigning sampling frequencys
   ula_port->recording_period    = recording_period;      // assigning recording period
   ula_port->sensorDirection     = ULA_direction;         // ULA direction
```

```
    ula_port->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;


    // assigning values
    ula_starboard->num_sensors        = num_sensors;           // assigning number of sensors
    ula_starboard->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
    ula_starboard->coordinates        = ULA_coordinates;       // assigning ULA coordinates
    ula_starboard->sampling_frequency = sampling_frequency;    // assigning sampling frequencys
    ula_starboard->recording_period   = recording_period;      // assigning recording period
    ula_starboard->sensorDirection    = ULA_direction;         // ULA direction
    ula_starboard->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;


}
```

8.2.4 AUV Setup

Following is the script to be run to setup the vessel.

```
/* ====================================
Aim: Setup sea floor
NOAA: 50 to 100 KHz is the transmission frequency
we'll create our LFM with 50 to 70KHz
=====================================*/

#ifndef DEVICE
    #define DEVICE        torch::kMPS
    // #define DEVICE        torch::kCPU
#endif

// ==========================================================
void AUVSetup(AUVClass* auv) {

    // building properties for the auv
    torch::Tensor location        = torch::tensor({0,50,30}).reshape({3,1}).to(torch::kFloat).to(DEVICE); // starting location of AUV
    torch::Tensor velocity        = torch::tensor({5,0, 0}).reshape({3,1}).to(torch::kFloat).to(DEVICE); // starting velocity of AUV
    torch::Tensor pointing_direction = torch::tensor({1,0, 0}).reshape({3,1}).to(torch::kFloat).to(DEVICE); // pointing direction of AUV

    // assigning
    auv->location         = location;           // assigning location of auv
    auv->velocity         = velocity;           // assigning vector representing velocity
    auv->pointing_direction = pointing_direction; // assigning pointing direction of auv
}
```

8.3 Function Definitions

8.3.1 Cartesian Coordinates to Spherical Coordinates

```
/* =====================================
Aim: Setup sea floor
======================================*/
#include <torch/torch.h>
#include <iostream>

// hash-defines
#define PI        3.14159265
#define DEBUG_Cart2Sph false

#ifndef DEVICE
    #define DEVICE       torch::kMPS
    // #define DEVICE       torch::kCPU
#endif


// bringing in functions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"

#pragma once

torch::Tensor fCart2Sph(torch::Tensor cartesian_vector){

    // sending argument to the device
    cartesian_vector = cartesian_vector.to(DEVICE);
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 26 \n";

    // splatting the point onto xy plane
    torch::Tensor xysplat = cartesian_vector.clone().to(DEVICE);
    xysplat[2] = 0;
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 31 \n";

    // finding splat lengths
    torch::Tensor xysplat_lengths = torch::linalg_norm(xysplat, 2, 0, true, torch::kFloat).to(DEVICE);
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 35 \n";

    // finding azimuthal and elevation angles
    torch::Tensor azimuthal_angles = torch::atan2(xysplat[1],    xysplat[0]).to(DEVICE)   * 180/PI;
    azimuthal_angles             = azimuthal_angles.reshape({1, azimuthal_angles.numel()});
    torch::Tensor elevation_angles = torch::atan2(cartesian_vector[2], xysplat_lengths).to(DEVICE) * 180/PI;
    torch::Tensor rho_values     = torch::linalg_norm(cartesian_vector, 2, 0, true, torch::kFloat).to(DEVICE);
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 42 \n";


    // printing values for debugging
    if (DEBUG_Cart2Sph){
        std::cout<<"azimuthal_angles.shape = "; fPrintTensorSize(azimuthal_angles);
        std::cout<<"elevation_angles.shape = "; fPrintTensorSize(elevation_angles);
        std::cout<<"rho_values.shape     = "; fPrintTensorSize(rho_values);
    }
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 51 \n";

    // creating tensor to send back
    torch::Tensor spherical_vector = torch::cat({azimuthal_angles, \
                                                 elevation_angles, \
                                                 rho_values}, 0).to(DEVICE);
    if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 57 \n";

    // returning the value
    return spherical_vector;
}
```

8.3.2 Spherical Coordinates to Cartesian Coordinates

```
/* =====================================
Aim: Setup sea floor
=====================================*/
#include <torch/torch.h>

#pragma once

// hash-defines
#define PI        3.14159265
#define MYDEBUGFLAG false

#ifndef DEVICE
    // #define DEVICE       torch::kMPS
    #define DEVICE       torch::kCPU
#endif


torch::Tensor fSph2Cart(torch::Tensor spherical_vector){



    // sending argument to device
    spherical_vector = spherical_vector.to(DEVICE);

    // creating cartesian vector
    torch::Tensor cartesian_vector =
         torch::zeros({3,(int)(spherical_vector.numel()/3)}).to(torch::kFloat).to(DEVICE);

    // populating it
    cartesian_vector[0] = spherical_vector[2] * \
                          torch::cos(spherical_vector[1] * PI/180) * \
                          torch::cos(spherical_vector[0] * PI/180);
    cartesian_vector[1] = spherical_vector[2] * \
                          torch::cos(spherical_vector[1] * PI/180) * \
                          torch::sin(spherical_vector[0] * PI/180);
    cartesian_vector[2] = spherical_vector[2] * \
                          torch::sin(spherical_vector[1] * PI/180);

    // returning the value
    return cartesian_vector;
}
```

8.3.3 Column-Wise Convolution

```
/* =====================================
Aim: Convolving the columns of two input matrices
=====================================*/
#include <ratio>
#include <stdexcept>
#include <torch/torch.h>

#pragma once

// hash-defines
#define PI        3.14159265
#define MYDEBUGFLAG false

#ifndef DEVICE
    // #define DEVICE       torch::kMPS
    #define DEVICE       torch::kCPU
#endif


void fConvolveColumns(torch::Tensor& inputMatrix, \
                      torch::Tensor& kernelMatrix){
```

```
    // printing shape
    if(MYDEBUGFLAG) std::cout<<"inputMatrix.shape = ["<<inputMatrix.size(0)<<","<<inputMatrix.size(1)<<std::endl;
    if(MYDEBUGFLAG) std::cout<<"kernelMatrix.shape = ["<<kernelMatrix.size(0)<<","<<kernelMatrix.size(1)<<std::endl;

    // ensuring the two have the same number of columns
    if (inputMatrix.size(1) != kernelMatrix.size(1)){
        throw std::runtime_error("fConvolveColumns: arguments cannot have different number of columns");
    }


    // calculating length of final result
    int final_length = inputMatrix.size(0) + kernelMatrix.size(0) - 1; if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 27"<<std::endl;

    // calculating FFT of the two matrices
    torch::Tensor inputMatrix_FFT = torch::fft::fftn(inputMatrix, \
                                                {final_length}, \
                                                {0}); if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 32"<<std::endl;
    torch::Tensor kernelMatrix_FFT = torch::fft::fftn(kernelMatrix, \
                                                {final_length}, \
                                                {0}); if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 35"<<std::endl;

    // element-wise multiplying the two matrices
    torch::Tensor MulProduct = torch::mul(inputMatrix_FFT, kernelMatrix_FFT); if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 38"<<std::endl;

    // finding the inverse FFT
    torch::Tensor convolvedResult = torch::fft::ifftn(MulProduct, \
                                                {MulProduct.size(0)}, \
                                                {0}); if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 43"<<std::endl;

    // over-riding the result with the input so that we can save memory
    inputMatrix = convolvedResult; if(MYDEBUGFLAG) std::cout<<"\t\t\t fConvolveColumns: 46"<<std::endl;

}
```

8.3.4 Buffer 2D

```
/* =====================================
Aim: Convolving the columns of two input matrices
=====================================*/
#include <stdexcept>
#include <torch/torch.h>

#pragma once

// hash-defines
#ifndef DEVICE
    // #define DEVICE       torch::kMPS
    #define DEVICE       torch::kCPU
#endif

// #define DEBUG_Buffer2D true
#define DEBUG_Buffer2D false


void fBuffer2D(torch::Tensor& inputMatrix,
               int frame_size){

    // ensuring the first dimension is 1.
    if(inputMatrix.size(0) != 1){
        throw std::runtime_error("fBuffer2D: The first-dimension must be 1 \n");
    }
```

```

    // padding with zeros in case it is not a perfect multiple
    if(inputMatrix.size(1)%frame_size != 0){
        // padding with zeros
        int numberofzeroestoadd = frame_size - (inputMatrix.size(1) % frame_size);
        if(DEBUG_Buffer2D) {
            std::cout  << "\t\t\t fBuffer2D: frame_size = "              << frame_size             <<
                std::endl;
            std::cout  << "\t\t\t fBuffer2D: inputMatrix.sizes().vec() = " << inputMatrix.sizes().vec() <<
                std::endl;
            std::cout  << "\t\t\t fBuffer2D: numberofzeroestoadd = "    << numberofzeroestoadd    << std::endl;
        }

        // creating zero matrix
        torch::Tensor zeroMatrix = torch::zeros({inputMatrix.size(0), \
                                                 numberofzeroestoadd, \
                                                 inputMatrix.size(2)});
        if(DEBUG_Buffer2D) std::cout<<"\t\t\t fBuffer2D: zeroMatrix.sizes() =
            "<<zeroMatrix.sizes().vec()<<std::endl;

        // adding the zero matrix
        inputMatrix = torch::cat({inputMatrix, zeroMatrix}, 1);
        if(DEBUG_Buffer2D) std::cout<<"\t\t\t fBuffer2D: inputMatrix.sizes().vec() =
            "<<inputMatrix.sizes().vec()<<std::endl;
    }

    // calculating some parameters
    // int num_frames = inputMatrix.size(1)/frame_size;
    int num_frames = std::ceil(inputMatrix.size(1)/frame_size);
    if(DEBUG_Buffer2D) std::cout << "\t\t\t fBuffer2D: inputMatrix.sizes = "<< inputMatrix.sizes().vec()<<
        std::endl;
    if(DEBUG_Buffer2D) std::cout << "\t\t\t fBuffer2D: framesize = " << frame_size           << std::endl;
    if(DEBUG_Buffer2D) std::cout << "\t\t\t fBuffer2D: num_frames = " << num_frames          << std::endl;

    // defining target shape and size
    std::vector<int64_t> target_shape = {num_frames,                    \
                                         frame_size,                    \
                                         inputMatrix.size(2)};
    std::vector<int64_t> target_strides = {frame_size * inputMatrix.size(2), \
                                         inputMatrix.size(2),           \
                                         1};
    if(DEBUG_Buffer2D) std::cout << "\t\t\t fBuffer2D: STATUS: created shape and strides"<< std::endl;

    // creating the transformation
    inputMatrix = inputMatrix.as_strided(target_shape, target_strides);

}
```

8.3.5 fAnglesToTensor

```
#include <torch/torch.h>
// function: angles to vector
torch::Tensor fAnglesToTensor(float azimuthal_angle,
                              float elevation_angle)
{
  // calculating tensor
  torch::Tensor coordinateTensor = torch::tensor({cos(elevation_angle) * cos(azimuthal_angle),
                                                  cos(elevation_angle) * sin(azimuthal_angle),
                                                  sin(elevation_angle)}).view({3,1});

  // returning value
  return coordinateTensor;
}
```

8.3.6 fCalculateCosine

```cpp
// including headerfiles
#include <torch/torch.h>

// function to calculate cosine of two tensors
torch::Tensor fCalculateCosine(torch::Tensor inputTensor1,
                               torch::Tensor inputTensor2)
{
  // column normalizing the the two signals
  inputTensor1 = fColumnNormalize(inputTensor1);
  inputTensor2 = fColumnNormalize(inputTensor2);

  // finding their dot product
  torch::Tensor dotProduct = inputTensor1 * inputTensor2;
  torch::Tensor cosineBetweenVectors = torch::sum(dotProduct,
                                                  0,
                                                  true);

  // returning the value
  return cosineBetweenVectors;

}
```

8.4 Main Scripts

8.4.1 Signal Simulation

1.

```
/*=============================================================================
Aim: Signal Simulation
-------------------------------------------------------------------------------
=============================================================================*/

// including standard
#include <cstdint>
#include <ostream>
#include <torch/torch.h>
#include <iostream>
#include <thread>
#include "math.h"
#include <chrono>
#include <Python.h>
#include <cstdlib>


// hash defines
#ifndef PRINTSPACE
#define PRINTSPACE   std::cout<<"\n\n\n";
#endif
#ifndef PRINTSMALLLINE
#define PRINTSMALLLINE
    std::cout<<"-----------------------------------------------------------------------------------"<<std::endl;
#endif
#ifndef PRINTDOTS
#define PRINTDOTS
    std::cout<<"..................................................................................."<<std::endl;
#endif
#ifndef PRINTLINE
#define PRINTLINE
    std::cout<<"==================================================================================="<<std::endl;
#endif
#ifndef PI
#define PI           3.14159265
#endif

// debugging hashdefine
#ifndef DEBUGMODE
#define DEBUGMODE    false
#endif

// deciding to save tensors or not
#ifndef SAVETENSORS
   #define SAVETENSORS    true
   // #define SAVETENSORS    false
#endif

// choose device here
#ifndef DEVICE
   #define DEVICE       torch::kCPU
   // #define DEVICE       torch::kMPS
   // #define DEVICE       torch::kCUDA
#endif

// class definitions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ULAClass.h"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/TransmitterClass.h"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/AUVClass.h"

// setup-scripts
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/ULASetup/ULASetup.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/TransmitterSetup/TransmitterSetup.cpp"
```

```
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/SeafloorSetup/SeafloorSetup.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/AUVSetup/AUVSetup.cpp"

// functions
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fSph2Cart.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fCart2Sph.cpp"
#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fConvolveColumns.cpp"


// main-function
int main() {

    // Builing Sea-floor
    ScattererClass SeafloorScatter;
    std::thread scatterThread_t(SeafloorSetup, \
                                &SeafloorScatter);

    // Building ULA
    ULAClass ula_fls, ula_port, ula_starboard;
    std::thread ulaThread_t(ULASetup, \
                            &ula_fls, \
                            &ula_port, \
                            &ula_starboard);

    // Building Transmitter
    TransmitterClass transmitter_fls, transmitter_port, transmitter_starboard;
    std::thread transmitterThread_t(TransmitterSetup,
                                    &transmitter_fls,
                                    &transmitter_port,
                                    &transmitter_starboard);

    // Joining threads
    ulaThread_t.join();      // making the ULA population thread join back
    transmitterThread_t.join(); // making the transmitter population thread join back
    scatterThread_t.join();  // making the scattetr population thread join back

    // building AUV
    AUVClass auv;            // instantiating class object
    AUVSetup(&auv);      // populating

    // attaching components to the AUV
    auv.ULA_fls              = ula_fls;               // attaching ULA-FLS to AUV
    auv.ULA_port             = ula_port;              // attaching ULA-Port to AUV
    auv.ULA_starboard        = ula_starboard;         // attaching ULA-Starboard to AUV
    auv.transmitter_fls      = transmitter_fls;       // attaching Transmitter-FLS to AUV
    auv.transmitter_port     = transmitter_port;      // attaching Transmitter-Port to AUV
    auv.transmitter_starboard = transmitter_starboard; // attaching Transmitter-Starboard to AUV

    // storing
    ScattererClass SeafloorScatter_deepcopy = SeafloorScatter;

    // pre-computing the imaging matrices
    auv.init();

    // mimicking movement
    int number_of_stophops = 1;
    // if (true) return 0;
    for(int i = 0; i<number_of_stophops; ++i){

        // time measuring
        auto start_time = std::chrono::high_resolution_clock::now();

        // printing some spaces
        PRINTSPACE; PRINTSPACE; PRINTLINE; std::cout<<"i = "<<i<<std::endl; PRINTLINE

        // making the deep copy
        ScattererClass SeafloorScatter   = SeafloorScatter_deepcopy; // copy for FLS

        // simulating the signals received in this time step
        // auv.simulateSignal(SeafloorScatter);
        auv.createAcousticImage(SeafloorScatter);

```

```
        // decimating the signal received in this time step
        auv.image();

        // measuring time
        auto end_time = std::chrono::high_resolution_clock::now();
        std::chrono::duration<double> time_duration = end_time - start_time;
        PRINTDOTS; std::cout<<"Time taken (i = "<<i<<") = "<<time_duration.count()<<" seconds"<<std::endl;
            PRINTDOTS

        // moving to next position
        auv.step(0.5);

    }
```

```
  // // encapsulating coordinates and reflectivity in a dictionary
```

```
// std::unordered_map<std::string, torch::Tensor> floor_scatterers;
// torch::load(floor_scatterers["coordinates"],
//             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/floor_coordinates_3D.pt");
// torch::load(floor_scatterers["reflectivity"],
//             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/floor_scatterers_reflectivity.pt");

// // sending to GPU
// floor_scatterers["coordinates"] = floor_scatterers["coordinates"].to( torch::kMPS);
// floor_scatterers["reflectivity"] = floor_scatterers["reflectivity"].to( torch::kMPS);




// // AUV Setup
// torch::Tensor auv_initial_location       = torch::tensor({0.0, 2.0, 2.0}).view({3,1}).to(torch::kMPS); // initial location
// torch::Tensor auv_initial_velocity       = torch::tensor({1.0, 0.0, 0.0}).view({3,1}).to(torch::kMPS); // initial velocity
// torch::Tensor auv_initial_acceleration   = torch::tensor({0.0, 0.0, 0.0}).view({3,1}).to(torch::kMPS); // initial acceleration
// torch::Tensor auv_initial_pointing_direction = torch::tensor({1.0, 0.0, 0.0}).view({3,1}).to(torch::kMPS); // initial pointing direction

// // Initializing a member of class, AUV
// AUV auv(auv_initial_location,          // assigning initial location
//         auv_initial_velocity,          // assigning initial velocity
//         auv_initial_acceleration,      // assigning initial acceleration
//         auv_initial_pointing_direction); // assigning initial pointing direction



// // Setting up ULAs for the AUV: front, portside and starboard
// const int num_sensors         = 32;               // number of sensors
// const double intersensor_distance = 1e-4;         // distance between sensors

// ULA ula_portside(num_sensors, intersensor_distance); // ULA onbject for portside
// ULA ula_fbls(num_sensors,   intersensor_distance); // ULA object for front-side
// ULA ula_starboard(num_sensors, intersensor_distance); // ULA object for starboard

// auv.ula_portside             = ula_portside;      // attaching portside-ULAs to the AUV
// auv.ula_fbls                 = ula_fbls;          // attaching front-ULA to the AUV
// auv.ula_starboard            = ula_starboard;     // attaching starboard-ULA to the AUV



// // Setting up Projector: front, portside and starboard
// Projector projector_portside(torch::zeros({3,1}).to(torch::kMPS), // location
//                              fDeg2Rad(90),                     // azimuthal angle
//                              fDeg2Rad(-30),                    // elevation angle
//                              fDeg2Rad(30),                     // azimuthal beamwidth
//                              fDeg2Rad(20));                    // elevation beamwidth
// Projector projector_fbls(torch::zeros({3,1}).to(torch::kMPS), // location
//                          fDeg2Rad(0),                          // azimuthal angle
//                          fDeg2Rad(-30),                        // elevation angle
//                          fDeg2Rad(120),                        // azimuthal beamwidth
//                          fDeg2Rad(60));                        // elevation beamwidth;
// Projector projector_starboard(torch::zeros({3,1}).to(torch::kMPS), // location
//                               fDeg2Rad(-90),                   // azimuthal angle
//                               fDeg2Rad(-30),                   // elevation angle
//                               fDeg2Rad(30),                    // azimuthal beamwidth
//                               fDeg2Rad(20));                   // elevation beamwidth;

// auv.projector_portside = projector_portside;        // Attaching projectors to AUV
// auv.projector_fbls    = projector_fbls;             // Attaching projectors to AUV
// auv.projector_starboard = projector_starboard;      // Attaching projectors to AUV






// // testing projection
// torch::Tensor coordinates = torch::tensor({ 1, 2, 3, 4,
//                                             0,  0,  0,  0,
```

```
  //                                       -1, -1, -1, -1}).view({3,4}).to(torch::kFloat).to(torch::kMPS);
  // torch::Tensor coordinates_normalized = fColumnNormalize(coordinates);
  // torch::Tensor coordinates_projected = coordinates.clone();
  // coordinates_projected[2] = torch::zeros({coordinates.size(1)});

  // torch::Tensor innerproduct = coordinates * coordinates_projected;
  // innerproduct = torch::sum(innerproduct, 0, true);



  // PRINTLINE
  // torch::Tensor xy = coordinates.clone();
  // xy[2] = torch::zeros({xy.size(1)});
  // std::cout<<"coordinates = \n"<<coordinates<<std::endl;
  // PRINTSMALLLINE
  // std::cout<<"xy = \n"<<xy<<std::endl;
  // torch::Tensor xylengths = torch::norm(xy, 2, 0, true, torch::kFloat);
  // std::cout<<"xylengths = \n"<<xylengths<<std::endl;
  // PRINTLINE






  // returning
  return 0;
}
```

Chapter 9

Reading

9.1 Primary Books

1.

9.2 Interesting Papers