Autonomous Underwater Vehicle: A Surveillance Protocol

S.V. Rajendran

January 30, 2025

Preface

This project is an attempt at combining all of my major skills into creating a truly sophisticated project. The aim of this project is to come up with a perception and control pipeline for AUVs for maritime surveillance. As such, the work involves creating a number of sub-pipelines.

The first is the signal simulation and geometry pipeline. This pipeline takes care of creating the underwater profile and the signal simulation that is involved for the perception stack.

The perception stack for the AUV is one front-looking-SONAR and two side-scan SONARs. The parameters used for this project are obtaine from that of NOAA ships that are publically available. No proprietary parameters or specifications have been included as part of this project. The three SONARs help the AUV perceive the environment around it. The goal of the AUV is to essentially map the sea-floor and flag any new alien bodies in the "water"-space.

The control stack essentially assists in controlling the AUV in achieving the goal by controlling the AUV to spend minimal energy in achieving the goal of mapping. The terrains are randomly generated and thus, intelligent control is important to perceive the surrounding environment from the acoustic-images and control the AUV accordingly. The AUV is currently granted six degrees of freedom. The policy will be trained using a reinforcement learning approach (DQN is the plan). The aim is to learn a policy that will successfully learn how to achieve the goals of the AUV while also learning and adapting to the different kinds of terrains the first pipeline creates. To that end, this will be an online algorithm since the simulation cannot truly cover real terrains.

The project is currently written in C++. Despite the presence of significant deep learning aspects of the project, we choose C++ due to the real-time nature of the project and this is not merely a prototype. In addition, to enable the learning aspect, we use LibTorch (the C++ API to PyTorch).

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.

Chapter 2

Underwater Environment Setup

Overview

- The underwater environment is modelled using discrete scatterers.
- They contain two attributes: coordinates and reflectivity.

2.1 Seafloor Setup

- The sea-floor is the first set of scatterers we introduce.
- A simple flat or flat-ish mesh of scatterers.
- Further structures are simulated on top of this.
- The seafloor setup script is written in section 8.2.1;

2.2 Additional Structures

- We create additional scatters on the second layer.
- For now, we stick to simple spheres, boxes and so on;

Chapter 3

Hardware Setup

Overview

3.1 Transmitter

3.2 Uniform Linear Array

3.3 Marine Vessel

Chapter 4

Geometry

Overview

4.1 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.

4.1.1 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.

4.1.2 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 1 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

Signal Simulation

Overview

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

5.1 Transmitted Signal

- We use a linear frequency modulated signal.
- The signal is defined in setup-script of the transmitter. Please refer to section: 8.1.2;

5.2 Signal Simulation

1. First we obtain the set of scatterers that reflect the transmitted signal.
2. The distance between all the sensors and the scatterer distances are calculated.
3. The time of flight from the transmitter to each scatterer and each sensor is calculated.
4. This time is then calculated into sample number by multiplying with the sampling-frequency of the uniform linear arrays.
5. 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.
6. 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.

7. 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.

Chapter 6

Imaging

Overview

- Present different imaging methods.

Decimation

1. The signals received by the sensors have a huge number of samples in it. Storing that kind of information, especially when it will be accumulated over a long time like in the case of synthetic aperture SONAR, is impractical.
2. Since the transmitted signal is LFM and non-baseband, this means that making the signal a complex baseband and decimating it will result in smaller data but same information.
3. So what we do is once we receive the signal at a stop-hop, we baseband the signal, low-pass filter it around the bandwidth and then decimate the signal. This reduces the sample number by a lot.
4. Since we're working with spotlight-SAS, this can be further reduced by beamforming the received signals in the direction of the patch and just storing the single beam. (This needs validation from Hareesh sir btw)

Match-Filtering

- A match-filter is any signal, that which when multiplied with another signal produces a signal that has a flag frequency-response = an impulse basically. (I might've butchered that definition but this will be updated later)
- This is created by time-reversing and calculating the complex conjugate of the signal.
- The resulting match-filter is then convolved with the received signal. This will result in a sincs being placed where impulse responses would've been if we used an infinite bandwidth signal.

Questions

- Do we match-filter before beamforming or after. I do realize that theoretically they're the same but practically, does one conserve resolution more than the other.

Chapter 7

Results

Chapter 8

Software

Overview

-

8.1 Class Definitions

8.1.1 Class: Scatter

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

```cpp
// 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);

        PRINTSMALLLINE

        // returning os
        return os;
    }

};
```

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


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;

        // 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;

    // Finding spherical coordinates of scatterers and pointing direction
    torch::Tensor scatterers_spherical      = fCart2Sph(scatterers->coordinates);
    torch::Tensor pointing_direction_spherical = fCart2Sph(this->pointing_direction);

    // sending them to the right device
    scatterers_spherical         = scatterers_spherical.to(DEVICE);
    pointing_direction_spherical = pointing_direction_spherical.to(DEVICE);

    // Calculating relative azimuths and radians
    torch::Tensor relative_spherical = scatterers_spherical - pointing_direction_spherical;

    // clearing some stuff up
    scatterers_spherical.reset();
    pointing_direction_spherical.reset();

    // tensor corresponding to switch.
```

```
        torch::Tensor tilt_angle_Tensor = torch::tensor({tilt_angle}).to(torch::kFloat).to(DEVICE);

        torch::Tensor axis_a  = torch::tensor({this->azimuthal_beamwidth / 2}).to(torch::kFloat).to(DEVICE);
        torch::Tensor axis_b  = torch::tensor({this->elevation_beamwidth / 2}).to(torch::kFloat).to(DEVICE);

        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();

        // findings points inside the cone
        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;

        // clearing
        xcosa.reset(); ysina.reset(); xsina.reset(); ycosa.reset();

        // 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});

        // // this is where histogram shadowing comes in (later)
        // rangeHistogramShadowing(scatterers);


        // 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
        >
    --------------------------------------------------------------------------*/
    void rangeHistogramShadowing(ScattererClass* scatterers){

        // converting points to spherical coordinates
        torch::Tensor spherical_coordinates = fCart2Sph(scatterers->coordinates);

        // finding maximum range
        torch::Tensor maxdistanceofpoints = torch::max(spherical_coordinates[2]);

        // finding range-cell boundaries
        torch::Tensor rangeBoundaries = torch::linspace(this->rangeQuantSize, \
                                              maxdistanceofpoints + this->rangeQuantSize,\
                                              (int)(maxdistanceofpoints.item<int>()/this->rangeQuantSize)
                                                  + 1);

        // creating the checkbox
        int numazimuthcells   = std::ceil(this->azimuthal_beamwidth * this->azimuthQuantDensity);
        int numelevationcells = std::ceil(this->elevation_beamwidth * this->elevationQuantDensity);

        // finding the deltas
        float delta_azimuth  = this->azimuthal_beamwidth / numazimuthcells;
        float delta_elevation = this->elevation_beamwidth / numazimuthcells;

        // finding the centers
        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);

        // building checkboxes
```

```
    torch::Tensor checkbox          = torch::zeros({numazimuthcells, numelevationcells}, torch::kBool);
    torch::Tensor finalScatterBox   = torch::zeros({numazimuthcells, numelevationcells, 3}).to(torch::kFloat);
    torch::Tensor finalReflectivityBox = torch::zeros({numazimuthcells, numelevationcells}).to(torch::kFloat);

    // 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);
    }

    // converting from box structure to [3, num-points] structure
    torch::Tensor final_coords_spherical = torch::permute(finalScatterBox, \
                                                          {3, 1, 2}).reshape({3, (int)(finalScatterBox.numel()/3)});
    torch::Tensor final_coords_cart = fSph2Cart(final_coords_spherical);
    torch::Tensor final_reflectivity = torch::permute(finalReflectivityBox, \
                                                      {3,1,2}).reshape({finalReflectivityBox.numel()});
    torch::Tensor test_checkbox = torch::permute(checkbox, {3, 1, 2}).reshape({checkbox.numel()});

    // 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);
    final_coords_cart = final_coords_cart.index({torch::indexing::Slice(), mask});
    final_reflectivity = final_reflectivity.index({torch::indexing::Slice(), mask});

    // overwriting the scatterers
    scatterers->coordinates = final_coords_cart;
    scatterers->reflectivity = final_reflectivity;


}














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){

    // converting points to their spherical coordinates
    torch::Tensor spherical_coordinates = fCart2Sph(scatterers->coordinates);

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

    // testing number of points
    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                    = scatterers->coordinates.index({torch::indexing::Slice(), mask});

        // histogramming
        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 already filled
                // if (checkbox.index({azi_index, ele_index}) == torch::tensor({true})) break;
                if (checkbox[azi_index][ele_index].item<bool>()) break;

                // init
                torch::Tensor current_azimuth = azimuth_centers[azi_index];
                torch::Tensor current_elevation = elevation_centers[ele_index];

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

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

                // combining booleans
                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) break;

                // 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_({azi_index, ele_index, torch::indexing::Slice()}, closest_coord.reshape({1,1,3}));
                finalReflectivityBox[ele_index][azi_index] = closest_reflectivity;
                checkbox[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.

```cpp
#include <iostream>
#include <torch/torch.h>

#include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.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 DEBUG_ULA true


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;

   // 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):
           num_sensors(numsensors),
           inter_element_spacing(inter_element_spacing),
           coordinates(coordinates),
           sampling_frequency(sampling_frequency),
           recording_period(recording_period) {
              // 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;
    }

    // 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();

        // returning
        return *this;
    }

    /* ===========================================================================
    Aim: Build coordinates on top of location.
    ...........................................................................
    Note:
        > This function builds the location of the coordinates based on the location and direction member.
    ---------------------------------------------------------------------------*/
    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";


        // this->coordinates = torch::mul(torch::tile(integer_array, {3, 1}).to(torch::kFloat), \
        //                           torch::tile(this->sensorDirection, {1, this->num_sensors}).to(torch::kFloat));
        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";

    }
};
```

8.1.4 Class: Autonomous Underwater Vehicle

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

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

#pragma once

// 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]

    // 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;
    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";
}


// pitch-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;
    }


};
```

8.2 Setup Scripts

8.2.1 Seafloor Setup

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

```
/* ====================================
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     true
#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        = 10;    // 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       = 20;    // 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       = 10;    // maximum height of the boxes in the sea-floor

    int meshdensity        = 5;     // number of points per meter.
    float meshreflectivity = 2;     // average reflectivity of the mesh

    int num_boxes          = 20;    // 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);}


    scatterers->coordinates  = torch::cat({scatterers->coordinates, box_coordinates}, 1);
    PRINTLINE
    scatterers->reflectivity = torch::cat({scatterers->reflectivity, box_reflectivity}, 1);
    PRINTSMALLLINE


}
```

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       = -70;                // initial pointing direction

float azimuthal_beamwidth    = 20;                // azimuthal beamwidth of the signal cone
float elevation_beamwidth    = 20;                // elevation beamwidth of the signal cone

float azimuthShadowThreshold = 0.5;               // azimuth threshold
float elevationShadowThreshold = 0.5;             // elevation threshold

int azimuthQuantDensity   = 20;  // quantization density along azimuth (used for shadowing)
int elevationQuantDensity = 20;  // quantization density along elevation (used for shadowing)
float rangeQuantSize     = 20;  // cell-dimension (used for shadowing)



// 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; // assigning azimuth-beamwidth
transmitter_fls->elevation_beamwidth = elevation_beamwidth; // 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; // assigning azimuth-beamwidth
transmitter_port->elevation_beamwidth = elevation_beamwidth; // 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;
    transmitter_starboard->elevation_beamwidth = elevation_beamwidth;
    // 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




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   = 1;                         // 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);
```

```

    // 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->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

    // 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->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


    // 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->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

}
```

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({0,50,50}).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

```cpp
/* ====================================
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;
}
```

Chapter 9

Reading

9.1 Primary Books

1.

9.2 Interesting Papers