

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 truly sophisticated project real world 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 obtained from that of NOAA ships that are publicly 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

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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 checkbox has not been filled. Since, for the filled ones, the filled scatter will shadow the others in 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 flat 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.

```
1 // header-files
2 #include <iostream>
3 #include <ostream>
4 #include <torch/torch.h>
5
6 #pragma once
7
8 // hash defines
9 #ifndef PRINTSPACE
10 #define PRINTSPACE    std::cout<<"\n\n\n\n\n\n\n\n\n\n"<<std::endl;
11 #endif
12 #ifndef PRINTSMALLLINE
13 #define PRINTSMALLLINE std::cout<<"-----"<<std::endl;
14 #endif
15 #ifndef PRINTLINE
16 #define PRINTLINE    std::cout<<"===== "<<std::endl;
17 #endif
18 #ifndef DEVICE
19     #define DEVICE    torch::kMPS
20     // #define DEVICE    torch::kCPU
21 #endif
22
23
24 #define PI    3.14159265
25
26
27 // function to print tensor size
28 void print_tensor_size(const torch::Tensor& inputTensor) {
29     // Printing size
30     std::cout << "[";
```



```

31     for (const auto& size : inputTensor.sizes()) {
32         std::cout << size << ", ";
33     }
34     std::cout << "\b]" <<std::endl;
35 }
36
37 // Scatterer Class = Scatterer Class
38 // Scatterer Class = Scatterer Class
39 // Scatterer Class = Scatterer Class
40 // Scatterer Class = Scatterer Class
41 // Scatterer Class = Scatterer Class
42 class ScattererClass{
43 public:
44
45     // public variables
46     torch::Tensor coordinates; // tensor holding coordinates [3, x]
47     torch::Tensor reflectivity; // tensor holding reflectivity [1, x]
48
49     // constructor = constructor
50     ScattererClass(torch::Tensor arg_coordinates = torch::zeros({3,1}),
51                   torch::Tensor arg_reflectivity = torch::zeros({3,1})):
52         coordinates(arg_coordinates),
53         reflectivity(arg_reflectivity) {}
54
55     // overloading output
56     friend std::ostream& operator<<(std::ostream& os, ScattererClass& scatterer){
57
58         // printing coordinate shape
59         os<<"\t> scatterer.coordinates.shape = ";
60         print_tensor_size(scatterer.coordinates);
61
62         // printing reflectivity shape
63         os<<"\t> scatterer.reflectivity.shape = ";
64         print_tensor_size(scatterer.reflectivity);
65
66         PRINTSMALLLINE
67
68         // returning os
69         return os;
70     }
71 }
72 };

```

8.1.2 Class: Transmitter

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

```

1 // header-files
2 #include <iostream>
3 #include <ostream>
4 #include <cmath>
5
6 // Including classes
7 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"
8
9 // Including functions
10 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fCart2Sph.cpp"
11 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
12 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fSph2Cart.cpp"
13
14 #pragma once
15
16 // hash defines
17 #ifndef PRINTSPACE
18 # define PRINTSPACE      std::cout<<"\n\n\n\n\n\n\n\n\n\n"<<std::endl;
19 #endif
20 #ifndef PRINTSMALLLINE
21 # define PRINTSMALLLINE std::cout<<"-----"<<std::endl;
22 #endif
23 #ifndef PRINTLINE
24 # define PRINTLINE      std::cout<<"===== "<<std::endl;
25 #endif
26
27 #define PI              3.14159265
28 #define DEBUGMODE_TRANSMITTER  false
29
30 #ifndef DEVICE
31 #define DEVICE          torch::kMPS
32 // #define DEVICE        torch::kCPU
33 #endif
34
35
36
37 // control panel
38 #define ENABLE_RAYTRACING      false
39
40
41
42
43
44
45
46
47 class TransmitterClass{
48 public:
49
50     // physical/intrinsic properties
51     torch::Tensor location;          // location tensor
52     torch::Tensor pointing_direction; // pointing direction
53
54     // basic parameters
55     torch::Tensor Signal;           // transmitted signal (LFM)
56     float azimuthal_angle;          // transmitter's azimuthal pointing direction
57     float elevation_angle;          // transmitter's elevation pointing direction
58     float azimuthal_beamwidth;      // azimuthal beamwidth of transmitter
59     float elevation_beamwidth;      // elevation beamwidth of transmitter
60     float range;                    // a parameter used for spotlight mode.
61
62     // transmitted signal attributes
63     float f_low;                    // lowest frequency of LFM
64     float f_high;                   // highest frequency of LFM
65     float fc;                       // center frequency of LFM
66     float bandwidth;                // bandwidth of LFM

```

```

67
68 // shadowing properties
69 int azimuthQuantDensity; // quantization of angles along the azimuth
70 int elevationQuantDensity; // quantization of angles along the elevation
71 float rangeQuantSize; // range-cell size when shadowing
72 float azimuthShadowThreshold; // azimuth thresholding
73 float elevationShadowThreshold; // elevation thresholding
74
75 // // shadowing related
76 // torch::Tensor checkBox; // box indicating whether a scatter for a range-angle pair has been
    found
77 // torch::Tensor finalScatterBox; // a 3D tensor where the third dimension represnets the vector length
78 // torch::Tensor finalReflectivityBox; // to store the reflectivity
79
80
81
82 // Constructor
83 TransmitterClass(torch::Tensor location = torch::zeros({3,1}),
84                 torch::Tensor Signal = torch::zeros({10,1}),
85                 float azimuthal_angle = 0,
86                 float elevation_angle = -30,
87                 float azimuthal_beamwidth = 30,
88                 float elevation_beamwidth = 30):
89     location(location),
90     Signal(Signal),
91     azimuthal_angle(azimuthal_angle),
92     elevation_angle(elevation_angle),
93     azimuthal_beamwidth(azimuthal_beamwidth),
94     elevation_beamwidth(elevation_beamwidth) {}
95
96 // overloading output
97 friend std::ostream& operator<<(std::ostream& os, TransmitterClass& transmitter){
98     os<<"\t> azimuth : "<<transmitter.azimuthal_angle <<std::endl;
99     os<<"\t> elevation : "<<transmitter.elevation_angle <<std::endl;
100     os<<"\t> azimuthal beamwidth: "<<transmitter.azimuthal_beamwidth<<std::endl;
101     os<<"\t> elevation beamwidth: "<<transmitter.elevation_beamwidth<<std::endl;
102     PRINTSMALLLINE
103     return os;
104 }
105
106 // overloading copyign operator
107 TransmitterClass& operator=(const TransmitterClass& other){
108
109     // checking self-assignment
110     if(this==&other){
111         return *this;
112     }
113
114     // allocating memory
115     this->location = other.location;
116     this->Signal = other.Signal;
117     this->azimuthal_angle = other.azimuthal_angle;
118     this->elevation_angle = other.elevation_angle;
119     this->azimuthal_beamwidth = other.azimuthal_beamwidth;
120     this->elevation_beamwidth = other.elevation_beamwidth;
121     this->range = other.range;
122
123     // transmitted signal attributes
124     this->f_low = other.f_low;
125     this->f_high = other.f_high;
126     this->fc = other.fc;
127     this->bandwidth = other.bandwidth;
128
129     // shadowing properties
130     this->azimuthQuantDensity = other.azimuthQuantDensity;
131     this->elevationQuantDensity = other.elevationQuantDensity;
132     this->rangeQuantSize = other.rangeQuantSize;
133     this->azimuthShadowThreshold = other.azimuthShadowThreshold;
134     this->elevationShadowThreshold = other.elevationShadowThreshold;
135
136     // this->checkBox = other.checkBox;
137     // this->finalScatterBox = other.finalScatterBox;
138     // this->finalReflectivityBox = other.finalReflectivityBox;

```

```

139
140     // returning
141     return *this;
142
143 };
144
145 /*=====
146 Aim: Update pointing angle
147 -----
148 Note:
149 > This function updates pointing angle based on AUV's pointing angle
150 > for now, we're assuming no roll;
151 -----*/
152 void updatePointingAngle(torch::Tensor AUV_pointing_vector){
153
154     // calculate yaw and pitch
155     if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 140 \n";
156     torch::Tensor AUV_pointing_vector_spherical = fCart2Sph(AUV_pointing_vector);
157     torch::Tensor yaw = AUV_pointing_vector_spherical[0];
158     torch::Tensor pitch = AUV_pointing_vector_spherical[1];
159     if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 144 \n";
160
161     // std::cout<<"\t TransmitterClass: AUV_pointing_vector = "<<torch::transpose(AUV_pointing_vector, 0,
162     // std::cout<<"\t TransmitterClass: AUV_pointing_vector_spherical =
163     // std::cout<<"\t TransmitterClass: AUV_pointing_vector_spherical =
164     // std::cout<<"\t TransmitterClass: AUV_pointing_vector_spherical =
165     // calculating azimuth and elevation of transmitter object
166     torch::Tensor absolute_azimuth_of_transmitter = yaw +
167     torch::tensor({this->azimuthal_angle}).to(torch::kFloat).to(DEVICE);
168     torch::Tensor absolute_elevation_of_transmitter = pitch +
169     torch::tensor({this->elevation_angle}).to(torch::kFloat).to(DEVICE);
170     if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 149 \n";
171
172     // std::cout<<"\t TransmitterClass: this->azimuthal_angle = "<<this->azimuthal_angle<<std::endl;
173     // std::cout<<"\t TransmitterClass: this->elevation_angle = "<<this->elevation_angle<<std::endl;
174     // std::cout<<"\t TransmitterClass: absolute_azimuth_of_transmitter =
175     // std::cout<<"\t TransmitterClass: absolute_elevation_of_transmitter =
176     // std::cout<<"\t TransmitterClass: absolute_elevation_of_transmitter =
177
178     // converting back to Cartesian
179     torch::Tensor pointing_direction_spherical = torch::zeros({3,1}).to(torch::kFloat).to(DEVICE);
180     pointing_direction_spherical[0] = absolute_azimuth_of_transmitter;
181     pointing_direction_spherical[1] = absolute_elevation_of_transmitter;
182     pointing_direction_spherical[2] = torch::tensor({1}).to(torch::kFloat).to(DEVICE);
183     if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 60 \n";
184
185     this->pointing_direction = fSph2Cart(pointing_direction_spherical);
186     if(DEBUGMODE_TRANSMITTER) std::cout<<"\t TransmitterClass: page 169 \n";
187
188 }
189
190 /*=====
191 Aim: Subsetting Scatterers inside the cone
192 -----
193 steps:
194 1. Find azimuth and range of all points.
195 2. Find azimuth and range of current pointing vector.
196 3. Subtract azimuth and range of points from that of azimuth and range of current pointing vector
197 4. Use tilted ellipse equation to find points in the ellipse
198 -----*/
199 void subsetScatterers(ScattererClass* scatterers,
200 float tilt_angle){
201
202     // translationally change origin
203     scatterers->coordinates = scatterers->coordinates - this->location; if(DEBUGMODE_TRANSMITTER)
204     std::cout<<"\t\t TransmitterClass: line 188 "<<std::endl;
205
206     /*
207     Note: I think something we can do is see if we can subset the matrices by checking coordinate values
208     right away. If one of the coordinate values is x (relative coordinates), we know for sure that
209     the distance is greater than x, for sure. So, maybe that's something that we can work with

```

```

203  */
204
205  // Finding spherical coordinates of scatterers and pointing direction
206  torch::Tensor scatterers_spherical = fCart2Sph(scatterers->coordinates);
    if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 191 "<<std::endl;
207  torch::Tensor pointing_direction_spherical = fCart2Sph(this->pointing_direction);
    if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 192 "<<std::endl;
208
209  // Calculating relative azimuths and radians
210  torch::Tensor relative_spherical = scatterers_spherical - pointing_direction_spherical;
    if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 199 "<<std::endl;
211
212  // clearing some stuff up
213  scatterers_spherical.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line
    202 "<<std::endl;
214  pointing_direction_spherical.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass:
    line 203 "<<std::endl;
215
216  // tensor corresponding to switch.
217  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;
218
219  // calculating length of axes
220  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;
221  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;
222
223  // part of calculating the tilted ellipse
224  torch::Tensor xcosa = relative_spherical[0] * torch::cos(tilt_angle_Tensor * PI/180);
225  torch::Tensor ysina = relative_spherical[1] * torch::sin(tilt_angle_Tensor * PI/180);
226  torch::Tensor xsina = relative_spherical[0] * torch::sin(tilt_angle_Tensor * PI/180);
227  torch::Tensor ycosa = relative_spherical[1] * torch::cos(tilt_angle_Tensor * PI/180);
228  relative_spherical.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 215
    "<<std::endl;
229
230  // finding points inside the tilted ellipse
231  torch::Tensor scatter_boolean = torch::div(torch::square(xcosa + ysina), torch::square(axis_a)) + \
232      torch::div(torch::square(xsina - ycosa), torch::square(axis_b)) <= 1;
    if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line
    221 "<<std::endl;
233
234  // clearing
235  xcosa.reset(); ysina.reset(); xsina.reset(); ycosa.reset(); if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t
    TransmitterClass: line 224 "<<std::endl;
236
237  // subsetting points within the elliptical beam
238  auto mask = (scatter_boolean == 1); // creating a mask
239  scatterers->coordinates = scatterers->coordinates.index({torch::indexing::Slice(), mask});
240  scatterers->reflectivity = scatterers->reflectivity.index({torch::indexing::Slice(), mask});
    if(DEBUGMODE_TRANSMITTER) std::cout<<"\t\t TransmitterClass: line 229 "<<std::endl;
241
242  // this is where histogram shadowing comes in (later)
243  if (ENABLE_RAYTRACING) {rangeHistogramShadowing(scatterers); std::cout<<"\t\t TransmitterClass: line
    232 "<<std::endl;}
244
245  // translating back to the points
246  scatterers->coordinates = scatterers->coordinates + this->location;
247
248  }
249
250  /*****
251  Aim: Shadowing method (range-histogram shadowing)
252  .....
253  Note:
254  > cut down the number of threads into range-cells
255  > for each range cell, calculate histogram
256  >
257  std::cout<<"\t TransmitterClass: "
258  -----*/
259  void rangeHistogramShadowing(ScattererClass* scatterers){
260
261  // converting points to spherical coordinates

```

```

262 torch::Tensor spherical_coordinates = fCart2Sph(scatterers->coordinates); std::cout<<"\t\t
    TransmitterClass: line 252 "<<std::endl;
263
264 // finding maximum range
265 torch::Tensor maxdistanceofpoints = torch::max(spherical_coordinates[2]); std::cout<<"\t\t
    TransmitterClass: line 256 "<<std::endl;
266
267 // calculating number of range-cells (verified)
268 int numrangecells = std::ceil(maxdistanceofpoints.item<int>()/this->rangeQuantSize);
269
270 // finding range-cell boundaries (verified)
271 torch::Tensor rangeBoundaries = \
272     torch::linspace(this->rangeQuantSize, \
273         numrangecells * this->rangeQuantSize, \
274         numrangecells); std::cout<<"\t\t TransmitterClass: line 263 "<<std::endl;
275
276 // creating the checkbox (verified)
277 int numazimuthcells = std::ceil(this->azimuthal_beamwidth * this->azimuthQuantDensity);
278 int numelevationcells = std::ceil(this->elevation_beamwidth * this->elevationQuantDensity);
    std::cout<<"\t\t TransmitterClass: line 267 "<<std::endl;
279
280 // finding the deltas
281 float delta_azimuth = this->azimuthal_beamwidth / numazimuthcells;
282 float delta_elevation = this->elevation_beamwidth / numelevationcells; std::cout<<"\t\t
    TransmitterClass: line 271"<<std::endl;
283
284 // creating the centers (verified)
285 torch::Tensor azimuth_centers = torch::linspace(delta_azimuth/2, \
286     numazimuthcells * delta_azimuth - delta_azimuth/2, \
287     numazimuthcells);
288 torch::Tensor elevation_centers = torch::linspace(delta_elevation/2, \
289     numelevationcells * delta_elevation - delta_elevation/2, \
290     numelevationcells); std::cout<<"\t\t TransmitterClass:
    line 279"<<std::endl;
291
292 // centering (verified)
293 azimuth_centers = azimuth_centers + torch::tensor({this->azimuthal_angle - \
294     (this->azimuthal_beamwidth/2)}).to(torch::kFloat);
295 elevation_centers = elevation_centers + torch::tensor({this->elevation_angle - \
296     (this->elevation_beamwidth/2)}).to(torch::kFloat);
    std::cout<<"\t\t TransmitterClass: line
    285"<<std::endl;
297
298 // building checkboxes
299 torch::Tensor checkbox = torch::zeros({numelevationcells, numazimuthcells}, torch::kBool);
300 torch::Tensor finalScatterBox = torch::zeros({numelevationcells, numazimuthcells,
    3}).to(torch::kFloat);
301 torch::Tensor finalReflectivityBox = torch::zeros({numelevationcells,
    numazimuthcells}).to(torch::kFloat); std::cout<<"\t\t TransmitterClass: line 290"<<std::endl;
302
303 // going through each-range-cell
304 for(int i = 0; i<(int)rangeBoundaries.numel(); ++i){
305     this->internal_subsetCurrentRangeCell(rangeBoundaries[i], \
306         scatterers, \
307         checkbox, \
308         finalScatterBox, \
309         finalReflectivityBox, \
310         azimuth_centers, \
311         elevation_centers, \
312         spherical_coordinates); std::cout<<"\t\t TransmitterClass: line
    301"<<std::endl;
313
314 // after each-range-cell
315 torch::Tensor checkboxfilled = torch::sum(checkbox);
316 std::cout<<"\t\t\t\t checkbox-filled = "<<checkboxfilled.item<int>()<<"/"<<checkbox.numel()<<" |
    percent = "<<100 * checkboxfilled.item<float>()/(float)checkbox.numel()<<std::endl;
317
318 }
319
320 // converting from box structure to [3, num-points] structure
321 torch::Tensor final_coords_spherical = \
322     torch::permute(finalScatterBox, {2, 0, 1}).reshape({3, (int)(finalScatterBox.numel()/3)});
323 torch::Tensor final_coords_cart = fSph2Cart(final_coords_spherical); std::cout<<"\t\t

```

```

324     TransmitterClass: line 308"<<std::endl;
325     std::cout<<"\t\t finalReflectivityBox.shape = "; fPrintTensorSize(finalReflectivityBox);
326     torch::Tensor final_reflectivity = finalReflectivityBox.reshape({finalReflectivityBox.numel()});
327     std::cout<<"\t\t TransmitterClass: line 310"<<std::endl;
328     torch::Tensor test_checkbox = checkbox.reshape({checkbox.numel()}); std::cout<<"\t\t TransmitterClass:
329     line 311"<<std::endl;
330
331     // just taking the points corresponding to the filled. Else, there's gonna be a lot of zero zero zero
332     tensors
333     auto mask = (test_checkbox == 1); std::cout<<"\t\t TransmitterClass: line 319"<<std::endl;
334     final_coords_cart = final_coords_cart.index({torch::indexing::Slice(), mask}); std::cout<<"\t\t
335     TransmitterClass: line 320"<<std::endl;
336     final_reflectivity = final_reflectivity.index({mask}); std::cout<<"\t\t TransmitterClass: line
337     321"<<std::endl;
338
339     // overwriting the scatterers
340     scatterers->coordinates = final_coords_cart;
341     scatterers->reflectivity = final_reflectivity; std::cout<<"\t\t TransmitterClass: line 324"<<std::endl;
342 }
343
344 void internal_subsetCurrentRangeCell(torch::Tensor rangeupperlimit, \
345     ScattererClass* scatterers, \
346     torch::Tensor& checkbox, \
347     torch::Tensor& finalScatterBox, \
348     torch::Tensor& finalReflectivityBox, \
349     torch::Tensor& azimuth_centers, \
350     torch::Tensor& elevation_centers, \
351     torch::Tensor& spherical_coordinates){
352
353     // finding indices for points in the current range-cell
354     torch::Tensor pointsincurrentrangeCell = \
355     torch::mul((spherical_coordinates[2] <= rangeupperlimit) , \
356     (spherical_coordinates[2] > rangeupperlimit - this->rangeQuantSize));
357
358     // checking out if there are no points in this range-cell
359     int num311 = torch::sum(pointsincurrentrangeCell).item<int>();
360     if(num311 == 0) return;
361
362     // calculating delta values
363     float delta_azimuth = azimuth_centers[1].item<float>() - azimuth_centers[0].item<float>();
364     float delta_elevation = elevation_centers[1].item<float>() - elevation_centers[0].item<float>();
365
366     // subsetting points in the current range-cell
367     auto mask = (pointsincurrentrangeCell == 1); // creating a mask
368     torch::Tensor reflectivityincurrentrangeCell =
369     scatterers->reflectivity.index({torch::indexing::Slice(), mask});
370     pointsincurrentrangeCell = spherical_coordinates.index({torch::indexing::Slice(),
371     mask});
372
373     // finding number of azimuth sizes and what not
374     int numazimuthcells = azimuth_centers.numel();
375     int numelevationcells = elevation_centers.numel();
376
377     // go through all the combinations
378     for(int azi_index = 0; azi_index < numazimuthcells; ++azi_index){
379         for(int ele_index = 0; ele_index < numelevationcells; ++ele_index){
380
381             // check if this particular azimuth-elevation direction has been taken-care of.
382             if (checkbox[ele_index][azi_index].item<bool>()) break;
383
384             // init (verified)
385             torch::Tensor current_azimuth = azimuth_centers.index({azi_index});
386             torch::Tensor current_elevation = elevation_centers.index({ele_index});
387
388             // // finding azimuth boolean
389             // torch::Tensor azi_neighbours = torch::abs(pointsincurrentrangeCell[0] - current_azimuth);
390             // azi_neighbours = azi_neighbours <= delta_azimuth; // tinker with this.
391
392             // // finding elevation boolean
393             // torch::Tensor ele_neighbours = torch::abs(pointsincurrentrangeCell[1] - current_elevation);
394             // ele_neighbours = ele_neighbours <= delta_elevation;

```

```

389
390 // finding azimuth boolean
391 torch::Tensor azi_neighbours = torch::abs(pointsincurrentrange[0] - current_azimuth);
392 azi_neighbours = azi_neighbours <= this->azimuthShadowThreshold; // tinkering with
    this.
393
394 // finding elevation boolean
395 torch::Tensor ele_neighbours = torch::abs(pointsincurrentrange[1] - current_elevation);
396 ele_neighbours = ele_neighbours <= this->elevationShadowThreshold;
397
398
399 // combining booleans: means find all points that are within the limits of both the azimuth and
    boolean.
400 torch::Tensor neighbours_boolean = torch::mul(azi_neighbours, ele_neighbours);
401
402 // checking if there are any points along this direction
403 int num347 = torch::sum(neighbours_boolean).item<int>();
404 if (num347 == 0) continue;
405
406 // findings point along this direction
407 mask = (neighbours_boolean == 1);
408 torch::Tensor coords_along_aziele_spherical =
    pointsincurrentrange.index({torch::indexing::Slice(), mask});
409 torch::Tensor reflectivity_along_aziele =
    reflectivityincurrentrange.index({torch::indexing::Slice(), mask});
410
411 // finding the index where the points are at the maximum distance
412 int index_where_min_range_is = torch::argmin(coords_along_aziele_spherical[2]).item<int>();
413 torch::Tensor closest_coord = coords_along_aziele_spherical.index({torch::indexing::Slice(), \
    index_where_min_range_is});
414
415 torch::Tensor closest_reflectivity = reflectivity_along_aziele.index({torch::indexing::Slice(),
    \
    index_where_min_range_is});
416
417
418 // filling the matrices up
419 finalScatterBox.index_put_({ele_index, azi_index, torch::indexing::Slice()}, \
    closest_coord.reshape({1,1,3}));
420
421 finalReflectivityBox.index_put_({ele_index, azi_index}, \
    closest_reflectivity);
422
423 checkbox.index_put_({ele_index, azi_index}, \
    true);
424
425
426 }
427 }
428 }
429
430
431
432
433 };

```

8.1.3 Class: Uniform Linear Array

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

```

1  #include <cstdint>
2  #include <iostream>
3  #include <torch/torch.h>
4
5  #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
6  #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fConvolveColumns.cpp"
7  #include "ScattererClass.h"
8  #include "TransmitterClass.h"
9
10 #pragma once
11
12 // hash defines
13 #ifndef PRINTSPACE
14     #define PRINTSPACE    std::cout<<"\n\n\n\n\n\n\n\n"<<std::endl;
15 #endif
16 #ifndef PRINTSMALLLINE
17     #define PRINTSMALLLINE std::cout<<"-----"<<std::endl;
18 #endif
19 #ifndef PRINTLINE
20     #define PRINTLINE      std::cout<<"===== "<<std::endl;
21 #endif
22
23 #ifndef DEVICE
24     #define DEVICE        torch::kMPS
25     // #define DEVICE      torch::kCPU
26 #endif
27
28 #define PI                3.14159265
29
30 // #define DEBUG_ULA true
31 #define DEBUG_ULA false
32
33
34
35 class ULAClass{
36 public:
37     // intrinsic parameters
38     int num_sensors;           // number of sensors
39     float inter_element_spacing; // space between sensors
40     torch::Tensor coordinates; // coordinates of each sensor
41     float sampling_frequency;  // sampling frequency of the sensors
42     float recording_period;    // recording period of the ULA
43     torch::Tensor location;    // location of first coordinate
44
45     // derived stuff
46     torch::Tensor sensorDirection;
47     torch::Tensor signalMatrix;
48
49     // decimation-related
50     torch::Tensor lowpassFilterCoefficientsForDecimation; //
51
52     // constructor
53     ULAClass(int numsensors          = 32,
54              float inter_element_spacing = 1e-3,
55              torch::Tensor coordinates = torch::zeros({3, 2}),
56              float sampling_frequency = 48e3,
57              float recording_period   = 1,
58              torch::Tensor location   = torch::zeros({3,1}),
59              torch::Tensor signalMatrix = torch::zeros({1, 32}),
60              torch::Tensor lowpassFilterCoefficientsForDecimation = torch::zeros({1,10})):
61         num_sensors(numsensors),
62         inter_element_spacing(inter_element_spacing),
63         coordinates(coordinates),
64         sampling_frequency(sampling_frequency),
65         recording_period(recording_period),
66         location(location),

```

[illegible]

```

140     this->num_sensors}).to(torch::kFloat);
141     torch::Tensor integer_array = torch::linspace(0, \
142         this->num_sensors-1, \
143         this->num_sensors).reshape({1, this->num_sensors});
144     std::cout<<"integer_array = "; fPrintTensorSize(integer_array);
145     if(DEBUG_ULA) std::cout<<"\t ULAClass: line 116 \n";
146
147     // this->coordinates = torch::mul(torch::tile(integer_array, {3, 1}).to(torch::kFloat), \
148     //     torch::tile(this->sensorDirection, {1,
149         this->num_sensors}).to(torch::kFloat));
150     torch::Tensor test = torch::mul(torch::tile(integer_array, {3, 1}).to(torch::kFloat), \
151         torch::tile(this->sensorDirection, {1,
152             this->num_sensors}).to(torch::kFloat));
153     this->coordinates = this->location + test;
154     if(DEBUG_ULA) std::cout<<"\t ULAClass: line 120 \n";
155 }
156
157 // Signal Simulation
158 void nfdc_simulateSignal(ScattererClass* scatterers,
159     TransmitterClass* transmitterObj){
160
161     // creating signal matrix
162     int numsamples = std::ceil((this->sampling_frequency * this->recording_period));
163     this->signalMatrix = torch::zeros({numsamples, this->num_sensors}).to(torch::kFloat);
164
165     // getting shape of coordinates
166     std::vector<int64_t> scatterers_coordinates_shape = scatterers->coordinates.sizes().vec();
167
168     // making a slot out of the coordinates
169     torch::Tensor slottedCoordinates = \
170         torch::permute(scatterers->coordinates.reshape({scatterers_coordinates_shape[0], \
171             scatterers_coordinates_shape[1], \
172             1}), {2, 1, 0}).reshape({1, (int)(scatterers->coordinates.numel()/3), 3});
173
174     // repeating along the y-direction number of sensor times.
175     slottedCoordinates = torch::tile(slottedCoordinates, {this->num_sensors, 1, 1});
176     std::vector<int64_t> slottedCoordinates_shape = slottedCoordinates.sizes().vec();
177
178     // finding the shape of the sensor-coordinates
179     std::vector<int64_t> sensor_coordinates_shape = this->coordinates.sizes().vec();
180
181     // creating a slot tensor out of the sensor-coordinates
182     torch::Tensor slottedSensors = \
183         torch::permute(this->coordinates.reshape({sensor_coordinates_shape[0], \
184             sensor_coordinates_shape[1], \
185             1}), {2, 1, 0}).reshape({(int)(this->coordinates.numel()/3),
186             \
187             1, \
188             3});
189
190     // repeating slices along the y-coordinates
191     slottedSensors = torch::tile(slottedSensors, {1, slottedCoordinates_shape[1], 1});
192
193     // slotting the coordinate of the transmitter
194     torch::Tensor slotted_location = torch::permute(this->location.reshape({3, 1, 1}), \
195         {2, 1, 0}).reshape({1,1,3});
196     slotted_location = torch::tile(slotted_location, \
197         {slottedCoordinates_shape[0], slottedCoordinates_shape[1], 1});
198
199     // subtracting to find the relative distances
200     torch::Tensor distBetweenScatterersAndSensors = \
201         torch::linalg_norm(slottedCoordinates - slottedSensors, 2, 2, true, torch::kFloat);
202
203     // subtracting distance between relative fields
204     torch::Tensor distBetweenScatterersAndTransmitter = \
205         torch::linalg_norm(slottedCoordinates - slotted_location, 2, 2, true, torch::kFloat);
206
207     // adding up the distances
208     torch::Tensor distOfFlight = distBetweenScatterersAndSensors + distBetweenScatterersAndTransmitter;
209     torch::Tensor timeOfFlight = distOfFlight/1500;

```

```

209 torch::Tensor samplesOfFlight = torch::floor(timeOfFlight.squeeze() * this->sampling_frequency);
210
211 // Adding pulses
212 for(int sensor_index = 0; sensor_index < this->num_sensors; ++sensor_index){
213     for(int scatter_index = 0; scatter_index < samplesOfFlight[0].numel(); ++scatter_index){
214
215         // getting the sample where the current scatter's contribution must be placed.
216         int where_to_place = samplesOfFlight.index({sensor_index, scatter_index}).item<int>();
217
218         // checking whether that point is out of bounds
219         if(where_to_place >= numsamples) continue;
220
221         // placing a point in there
222         this->signalMatrix.index_put_({where_to_place, sensor_index}, \
223                                     this->signalMatrix.index({where_to_place, sensor_index}) + \
224                                     torch::tensor({1}).to(torch::kFloat));
225
226         this->signalMatrix.index_put_({where_to_place, sensor_index}, \
227                                     this->signalMatrix.index({where_to_place, sensor_index}) + \
228                                     scatterers->reflectivity.index({0, scatter_index}) );
229     }
230 }
231
232 // Convolving signals with transmitted signal
233 torch::Tensor signalTensorAsArgument = \
234     transmitterObj->Signal.reshape({transmitterObj->Signal.numel(), 1});
235 signalTensorAsArgument = torch::tile(signalTensorAsArgument, \
236                                     {1, this->signalMatrix.size(1)});
237
238 // convolving the pulse-matrix with the signal matrix
239 fConvolveColumns(this->signalMatrix, \
240                 signalTensorAsArgument);
241
242 // trimming the convolved signal since the signal matrix length remains the same
243 this->signalMatrix = this->signalMatrix.index({torch::indexing::Slice(0, numsamples), \
244                                             torch::indexing::Slice()});
245
246 // printing the shape
247 std::cout<<"\t\t\t this->signalMatrix.shape (after signal sim) = ";
248     fPrintTensorSize(this->signalMatrix);
249
250 return;
251 }
252
253 // decimating the obtained signal
254 void nfdc_decimateSignal(TransmitterClass* transmitterObj){
255
256     if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal: entered "<<std::endl;
257
258     // basebanding the signal
259     torch::Tensor integerArray = torch::linspace(0, \
260         this->signalMatrix.size(0)-1, \
261         this->signalMatrix.size(0)).reshape({this->signalMatrix.size(0),
262         1}); if(DEBUG_ULA) std::cout<<"\t\t\t
263         ULAClass::nfdc_decimateSignal: 247"<<std::endl;
264
265     if(DEBUG_ULA) std::cout<<"integerArray.shape = "<<integerArray.sizes().vec()<<std::endl;
266     integerArray = torch::tile(integerArray, \
267         {1, this->num_sensors}); if(DEBUG_ULA) std::cout<<"\t\t\t
268         ULAClass::nfdc_decimateSignal: 249"<<std::endl;
269
270     if(DEBUG_ULA) std::cout<<"integerArray.shape = "<<integerArray.sizes().vec()<<std::endl;
271     integerArray = torch::exp(torch::complex(torch::zeros({1}), torch::ones({1})) * \
272         transmitterObj->fc * \
273         integerArray); if(DEBUG_ULA) std::cout<<"\t\t\t
274         ULAClass::nfdc_decimateSignal: 250"<<std::endl;
275
276     if(DEBUG_ULA) std::cout<<"this->signalMatrix.shape = "<<this->signalMatrix.sizes().vec()<<std::endl;
277     if(DEBUG_ULA) std::cout<<"integerArray.shape = "<<integerArray.sizes().vec()<<std::endl;
278     this->signalMatrix = torch::mul(this->signalMatrix, \
279         integerArray); std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal:
280         254"<<std::endl;
281
282     // low-pass filter
283     torch::Tensor lowpassfilter_impulseresponse = \

```

```

276         this->lowpassFilterCoefficientsForDecimation.reshape({this->lowpassFilterCoefficientsForDecimation.numel(),
277             1}); if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal: 263"<<std::endl;
278         lowpassfilter_impulseresponse = torch::tile(lowpassfilter_impulseresponse, \
279             {1, this->signalMatrix.size(1)}); if(DEBUG_ULA) std::cout<<"\t\t\t
280             ULAClass::nfdc_decimateSignal: 260"<<std::endl;
281
282         // Convolver
283         fConvolveColumns(this->signalMatrix, lowpassfilter_impulseresponse); if(DEBUG_ULA) std::cout<<"\t\t\t
284             ULAClass::nfdc_decimateSignal: 263"<<std::endl;
285
286         // downsampling
287         int decimation_factor = std::floor(this->sampling_frequency/transmitterObj->bandwidth); if(DEBUG_ULA)
288             std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal: 284"<<std::endl;
289         if(DEBUG_ULA) std::cout<<"\t\t\t\t\t decimation_factor = "<<decimation_factor<<std::endl;
290         int numsamples_after_decimation = std::floor(this->signalMatrix.size(0)/decimation_factor);
291         if(DEBUG_ULA) std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal: 285"<<std::endl;
292         torch::Tensor samplingIndices = \
293             torch::linspace(0, \
294                 numsamples_after_decimation * decimation_factor, \
295                 numsamples_after_decimation).to(torch::kInt); if(DEBUG_ULA) std::cout<<"\t\t\t
296                 ULAClass::nfdc_decimateSignal: 289"<<std::endl;
297
298         this->signalMatrix = \
299             this->signalMatrix.index({samplingIndices, torch::indexing::Slice()}); if(DEBUG_ULA)
300                 std::cout<<"\t\t\t ULAClass::nfdc_decimateSignal: 273"<<std::endl;
301
302         if(DEBUG_ULA) std::cout<<"this->signalMatrix.shape = "<<this->signalMatrix.sizes().vec()<<std::endl;
303     }
304 };

```

8.1.4 Class: Autonomous Underwater Vehicle

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

```

1  #include "ScattererClass.h"
2  #include "TransmitterClass.h"
3  #include "ULAClass.h"
4  #include <iostream>
5  #include <ostream>
6  #include <torch/torch.h>
7  #include <cmath>
8
9
10 // // including functions
11 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fGetCurrentTimeFormatted.cpp"
12
13 #pragma once
14
15 // function to plot the thing
16 void fPlotTensors(){
17     system("python /Users/vrsreeganesh/Documents/GitHub/AUV/Code/Python/TestingSaved_tensors.py");
18 }
19
20
21 void fSaveSeafloorScatteres(ScattererClass scatterer, \
22     ScattererClass scatterer_fl, \
23     ScattererClass scatterer_port, \
24     ScattererClass scatterer_starboard){
25
26     // saving the ground-truth
27     ScattererClass SeafloorScatter_gt = scatterer;
28     torch::save(SeafloorScatter_gt.coordinates,
29         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt.pt");
30     torch::save(SeafloorScatter_gt.reflectivity,
31         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt_reflectivity.pt");

```

```

31 // saving coordinates
32 torch::save(scatterer_fls.coordinates,
33             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates.pt");
34 torch::save(scatterer_port.coordinates,
35             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates.pt");
36 torch::save(scatterer_starboard.coordinates,
37             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates.pt");
38
39 // saving reflectivities
40 torch::save(scatterer_fls.reflectivity,
41             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates_reflectivity.pt");
42 torch::save(scatterer_port.reflectivity,
43             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates_reflectivity.pt");
44 torch::save(scatterer_starboard.reflectivity,
45             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates_reflectivity.pt");
46
47 // plotting tensors
48 fPlotTensors();
49
50 // // saving the tensors
51 // if (true) {
52 //     // getting time ID
53 //     auto timeID = fGetCurrentTimeFormatted();
54 //     std::cout<<"\t\t\t\t\t Saving Tensors (timeID: "<<timeID<<)"<<std::endl;
55 //     // saving the ground-truth
56 //     ScattererClass SeafloorScatter_gt = scatterer;
57 //     torch::save(SeafloorScatter_gt.coordinates, \
58 //                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt.pt");
59 //     torch::save(SeafloorScatter_gt.reflectivity, \
60 //                 "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_gt_reflectivity.pt");
61 // }
62
63 // // saving coordinates
64 // torch::save(scatterer_fls.coordinates, \
65 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates.pt");
66 // torch::save(scatterer_port.coordinates, \
67 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates.pt");
68 // torch::save(scatterer_starboard.coordinates, \
69 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates.pt");
70 // }
71
72 // // saving reflectivities
73 // torch::save(scatterer_fls.reflectivity, \
74 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_fls_coordinates_reflectivity.pt");
75 // torch::save(scatterer_port.reflectivity, \
76 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_port_coordinates_reflectivity.pt");
77 // torch::save(scatterer_starboard.reflectivity, \
78 //             "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/SeafloorScatter_starboard.coordinates_reflectivity.pt");
79 // }
80
81 // // plotting tensors
82 // fPlotTensors();
83
84 // // indicating end of thread
85 // std::cout<<"\t\t\t\t\t Ended (timeID: "<<timeID<<)"<<std::endl;
86 // }
87 }
88
89 // including class-definitions
90 #include "Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"
91
92 // hash defines
93 #ifndef PRINTSPACE
94 #define PRINTSPACE    std::cout<<"\n\n\n\n\n\n\n\n\n\n"<<std::endl;
95 #endif

```

```

91 #ifndef PRINTSMALLLINE
92 #define PRINTSMALLLINE std::cout<<"-----"<<std::endl;
93 #endif
94 #ifndef PRINTLINE
95 #define PRINTLINE      std::cout<<"===== "<<std::endl;
96 #endif
97
98 #ifndef DEVICE
99 #define DEVICE          torch::kMPS
100 // #define DEVICE        torch::kCPU
101 #endif
102
103 #define PI              3.14159265
104 // #define DEBUGMODE_AUV true
105 #define DEBUGMODE_AUV false
106
107
108 class AUVClass{
109 public:
110     // Intrinsic attributes
111     torch::Tensor location;           // location of vessel
112     torch::Tensor velocity;           // current speed of the vessel [a vector]
113     torch::Tensor acceleration;       // current acceleration of vessel [a vector]
114     torch::Tensor pointing_direction; // direction to which the AUV is pointed
115
116     // uniform linear-arrays
117     ULAClass ULA_fls;                 // front-looking SONAR ULA
118     ULAClass ULA_port;                // mounted ULA [object of class, ULAClass]
119     ULAClass ULA_starboard;           // mounted ULA [object of class, ULAClass]
120
121     // transmitters
122     TransmitterClass transmitter_fls; // transmitter for front-looking SONAR
123     TransmitterClass transmitter_port; // mounted transmitter [obj of class, TransmitterClass]
124     TransmitterClass transmitter_starboard; // mounted transmitter [obj of class, TransmitterClass]
125
126     // derived or dependent attributes
127     torch::Tensor signalMatrix_1;     // matrix containing the signals obtained from ULA_1
128     torch::Tensor largeSignalMatrix_1; // matrix holding signal of synthetic aperture
129     torch::Tensor beamformedLargeSignalMatrix; // each column is the beamformed signal at each stop-hop
130
131     // plotting mode
132     bool plottingmode; // to suppress plotting associated with classes
133
134     // spotlight mode related
135     torch::Tensor absolute_coords_patch_cart; // cartesian coordinates of patch
136
137     // Synthetic Aperture Related
138     torch::Tensor ApertureSensorLocations; // sensor locations of aperture
139
140
141     /*=====
142     Aim: stepping motion
143     -----*/
144     void step(float timestep){
145
146         // updating location
147         this->location = this->location + this->velocity * timestep;
148         if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 81 \n";
149
150         // updating attributes of members
151         this->syncComponentAttributes();
152         if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 85 \n";
153     }
154
155     /*=====
156     Aim: updateAttributes
157     -----*/
158     void syncComponentAttributes(){
159
160         // updating ULA attributes
161         if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 97 \n";
162
163         // updating locations

```



```

164     this->ULA_fls.location      = this->location;
165     this->ULA_port.location     = this->location;
166     this->ULA_starboard.location = this->location;
167
168     // updating the pointing direction of the ULAs
169     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 99 \n";
170     torch::Tensor ula_fls_sensor_direction_spherical = fCart2Sph(this->pointing_direction); //
        spherical coords
171     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 101 \n";
172     ula_fls_sensor_direction_spherical[0]           = ula_fls_sensor_direction_spherical[0] - 90;
173     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 98 \n";
174     torch::Tensor ula_fls_sensor_direction_cart     = fSph2Cart(ula_fls_sensor_direction_spherical);
175     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 100 \n";
176
177     this->ULA_fls.sensorDirection      = ula_fls_sensor_direction_cart; // assigning sensor direction for
        ULA-FLS
178     this->ULA_port.sensorDirection     = -this->pointing_direction; // assigning sensor direction for
        ULA-Port
179     this->ULA_starboard.sensorDirection = -this->pointing_direction; // assigning sensor direction for
        ULA-Starboard
180     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line 105 \n";
181
182     // // calling the function to update the arguments
183     // this->ULA_fls.buildCoordinatesBasedOnLocation(); if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line
        109 \n";
184     // this->ULA_port.buildCoordinatesBasedOnLocation(); if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: line
        111 \n";
185     // this->ULA_starboard.buildCoordinatesBasedOnLocation(); if(DEBUGMODE_AUV) std::cout<<"\t AUVClass:
        line 113 \n";
186
187     // updating transmitter locations
188     this->transmitter_fls.location      = this->location;
189     this->transmitter_port.location     = this->location;
190     this->transmitter_starboard.location = this->location;
191     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 102 \n";
192
193     // updating transmitter pointing directions
194     this->transmitter_fls.updatePointingAngle( this->pointing_direction);
195     this->transmitter_port.updatePointingAngle( this->pointing_direction);
196     this->transmitter_starboard.updatePointingAngle( this->pointing_direction);
197     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 108 \n";
198 }
199
200 /*=====
201 Aim: operator overriding for printing
202 -----*/
203 friend std::ostream& operator<<(std::ostream& os, AUVClass &auv){
204     os<<"\t location = "<<torch::transpose(auv.location, 0, 1)<<std::endl;
205     os<<"\t velocity = "<<torch::transpose(auv.velocity, 0, 1)<<std::endl;
206     return os;
207 }
208
209
210 /*=====
211 Aim: Subsetting Scatterers
212 -----*/
213 void subsetScatterers(ScattererClass* scatterers,\
214                      TransmitterClass* transmitterObj,\
215                      float tilt_angle){
216
217     // ensuring components are synced
218     this->syncComponentAttributes();
219     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 120 \n";
220
221     // calling the method associated with the transmitter
222     if(DEBUGMODE_AUV) {std::cout<<"\t\t scatterers.shape = "; fPrintTensorSize(scatterers->coordinates);}
223     if(DEBUGMODE_AUV) std::cout<<"\t\t tilt_angle = "<<tilt_angle<<std::endl;
224     transmitterObj->subsetScatterers(scatterers, tilt_angle);
225     if(DEBUGMODE_AUV) std::cout<<"\t AUVClass: page 124 \n";
226 }
227
228
229 // pitch-correction matrix

```



```

230 torch::Tensor createYawCorrectionMatrix(torch::Tensor pointing_direction_spherical, \
231                                       float target_azimuth_deg){
232
233     // building parameters
234     torch::Tensor azimuth_correction =
235         torch::tensor({target_azimuth_deg}).to(torch::kFloat).to(DEVICE) - \
236         pointing_direction_spherical[0];
237     torch::Tensor azimuth_correction_radians = azimuth_correction * PI / 180;
238
239     torch::Tensor yawCorrectionMatrix = \
240         torch::tensor({torch::cos(azimuth_correction_radians).item<float>(), \
241                       torch::cos(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
242                                azimuth_correction_radians).item<float>(), \
243                       (float)0, \
244                       torch::sin(azimuth_correction_radians).item<float>(), \
245                       torch::sin(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
246                                azimuth_correction_radians).item<float>(), \
247                       (float)0, \
248                       (float)0, \
249                       (float)0, \
250                       (float)1}).reshape({3,3}).to(torch::kFloat).to(DEVICE);
251
252     // returning the matrix
253     return yawCorrectionMatrix;
254 }
255
256 // pitch-correction matrix
257 torch::Tensor createPitchCorrectionMatrix(torch::Tensor pointing_direction_spherical, \
258                                         float target_elevation_deg){
259
260     // building parameters
261     torch::Tensor elevation_correction =
262         torch::tensor({target_elevation_deg}).to(torch::kFloat).to(DEVICE) - \
263         pointing_direction_spherical[1];
264     torch::Tensor elevation_correction_radians = elevation_correction * PI / 180;
265
266     // creating the matrix
267     torch::Tensor pitchCorrectionMatrix = \
268         torch::tensor({(float)1, \
269                       (float)0, \
270                       (float)0, \
271                       (float)0, \
272                       torch::cos(elevation_correction_radians).item<float>(), \
273                       torch::cos(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
274                                elevation_correction_radians).item<float>(), \
275                       (float)0, \
276                       torch::sin(elevation_correction_radians).item<float>(), \
277                       torch::sin(torch::tensor({90}).to(torch::kFloat).to(DEVICE)*PI/180 +
278                                elevation_correction_radians).item<float>()}).reshape({3,3}).to(torch::kFloat);
279
280     // returning the matrix
281     return pitchCorrectionMatrix;
282 }
283
284 // Signal Simulation
285 void simulateSignal(ScattererClass& scatterer){
286
287     // making three copies
288     ScattererClass scatterer_fls = scatterer;
289     ScattererClass scatterer_port = scatterer;
290     ScattererClass scatterer_starboard = scatterer;
291
292     // printing size of scatterers before subsetting
293     std::cout<< " > AUVClass: Beginning Scatterer Subsetting"<<std::endl;
294     std::cout<<"\t AUVClass: scatterer_fls.coordinates.shape (before) = ";
295     fPrintTensorSize(scatterer_fls.coordinates);
296     std::cout<<"\t AUVClass: scatterer_port.coordinates.shape (before) = ";
297     fPrintTensorSize(scatterer_port.coordinates);
298     std::cout<<"\t AUVClass: scatterer_starboard.coordinates.shape (before) = ";
299     fPrintTensorSize(scatterer_starboard.coordinates);
300
301     // finding the pointing direction in spherical
302     torch::Tensor auv_pointing_direction_spherical = fCart2Sph(this->pointing_direction);

```

```

294
295 // asking the transmitters to subset the scatterers by multithreading
296 std::thread transmitterFLSSubset_t(&AUVClass::subsetScatterers, this, \
297     &scatterer_fls,\
298     &this->transmitter_fls, \
299     (float)0);
300 std::thread transmitterPortSubset_t(&AUVClass::subsetScatterers, this, \
301     &scatterer_port,\
302     &this->transmitter_port, \
303     auv_pointing_direction_spherical[1].item<float>());
304 std::thread transmitterStarboardSubset_t(&AUVClass::subsetScatterers, this, \
305     &scatterer_starboard, \
306     &this->transmitter_starboard, \
307     - auv_pointing_direction_spherical[1].item<float>());
308
309 // joining the subset threads back
310 transmitterFLSSubset_t.join(); transmitterPortSubset_t.join(); transmitterStarboardSubset_t.join();
311
312 // printing the size of these points before subsetting
313 PRINTDOTS
314 std::cout<<"\t AUVClass: scatterer_fls.coordinates.shape (after) = ";
315     fPrintTensorSize(scatterer_fls.coordinates);
316 std::cout<<"\t AUVClass: scatterer_port.coordinates.shape (after) = ";
317     fPrintTensorSize(scatterer_port.coordinates);
318 std::cout<<"\t AUVClass: scatterer_starboard.coordinates.shape (after) = ";
319     fPrintTensorSize(scatterer_starboard.coordinates);
320
321 // multithreading the saving tensors part.
322 std::thread savetensor_t(fSaveSeafloorScatterers, \
323     scatterer, \
324     scatterer_fls, \
325     scatterer_port, \
326     scatterer_starboard);
327
328 // asking ULAs to simulate signal through multithreading
329 std::thread ulafls_signalsim_t(&ULAClass::nfdc_simulateSignal, \
330     &this->ULA_fls, \
331     &scatterer_fls, \
332     &this->transmitter_fls);
333 std::thread ulaport_signalsim_t(&ULAClass::nfdc_simulateSignal, \
334     &this->ULA_port, \
335     &scatterer_port, \
336     &this->transmitter_port);
337 std::thread ulastarboard_signalsim_t(&ULAClass::nfdc_simulateSignal, \
338     &this->ULA_starboard, \
339     &scatterer_starboard, \
340     &this->transmitter_starboard);
341
342 // joining them back
343 ulafls_signalsim_t.join(); // joining back the thread for ULA-FLS
344 ulaport_signalsim_t.join(); // joining back the signals-sim thread for ULA-Port
345 ulastarboard_signalsim_t.join(); // joining back the signal-sim thread for ULA-Starboard
346 savetensor_t.join(); // joining back the signal-sim thread for tensor-saving
347
348 // saving the tensors
349 if (true) {
350     // saving the ground-truth
351     torch::save(this->ULA_fls.signalMatrix,
352         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_fls.pt");
353     torch::save(this->ULA_port.signalMatrix,
354         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_port.pt");
355     torch::save(this->ULA_starboard.signalMatrix,
356         "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Assets/signalMatrix_starboard.pt");
357 }
358
359 // Imaging Function
360 void image(){
361     // asking ULAs to decimate the signals obtained at each time step
362     std::thread ULA_fls_image_t(&ULAClass::nfdc_decimateSignal, &this->ULA_fls, \

```

```
361         &this->transmitter_fls);
362     // std::thread ULA_port_image_t(&ULAClass::nfdc_decimateSignal, &this->ULA_port, \
363     //                               &this->transmitter_port);
364     // std::thread ULA_starboard_image_t(&ULAClass::nfdc_decimateSignal, &this->ULA_starboard, \
365     //                                   &this->transmitter_starboard);
366
367     // joining the threads back
368     ULA_fls_image_t.join();
369     // ULA_port_image_t.join();
370     // ULA_starboard_image_t.join();
371
372
373     // this->ULA_fls.nfdc_decimateSignal(this->transmitter_fls);
374
375 }
376
377
378 // // decimating the signal
379 // void nfdc_decimate(){
380 //     ;
381 // }
382
383
384 };
```

8.2 Setup Scripts

8.2.1 Seafloor Setup

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

```

1  /* =====
2  Aim: Setup sea floor
3  =====*/
4  #include <torch/torch.h>
5  #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/include/ScattererClass.h"
6
7  #ifndef DEVICE
8      // #define DEVICE      torch::kMPS
9      #define DEVICE      torch::kCPU
10 #endif
11
12
13 // adding terrain features
14 #define BOXES      false
15 #define TERRAIN      false
16 #define DEBUG_SEAFLOOR false
17
18
19
20 // Adding boxes
21 void fCreateBoxes(float across_track_length, \
22                  float along_track_length, \
23                  torch::Tensor& box_coordinates, \
24                  torch::Tensor& box_reflectivity){
25
26     // converting arguments to torch tensors
27
28     // setting up parameters
29     float min_width      = 2;      // minimum across-track dimension of the boxes in the sea-floor
30     float max_width      = 5;      // maximum across-track dimension of the boxes in the sea-floor
31
32     float min_length     = 2;      // minimum along-track dimension of the boxes in the sea-floor
33     float max_length     = 5;      // maximum along-track dimension of the boxes in the sea-floor
34
35     float min_height     = 3;      // minimum height of the boxes in the sea-floor
36     float max_height     = 20;     // maximum height of the boxes in the sea-floor
37
38     int meshdensity      = 10;     // number of points per meter.
39     float meshreflectivity = 2;     // average reflectivity of the mesh
40
41     int num_boxes        = 10;     // number of boxes in the sea-floor
42     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 41\n";
43
44     // finding center point
45     torch::Tensor midxypoints = torch::rand({3, num_boxes}).to(torch::kFloat).to(DEVICE);
46     midxypoints[0]            = midxypoints[0] * across_track_length;
47     midxypoints[1]            = midxypoints[1] * along_track_length;
48     midxypoints[2]            = 0;
49     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 48\n";
50
51     // assigning dimensions to boxes
52     torch::Tensor boxwidths = torch::rand({num_boxes})*(max_width - min_width) + min_width; // assigning
53     // widths to each boxes
54     torch::Tensor boxlengths = torch::rand({num_boxes})*(max_length - min_length) + min_length; // assigning
55     // lengths to each boxes
56     torch::Tensor boxheights = torch::rand({num_boxes})*(max_height - min_height) + min_height; // assigning
57     // heights to each boxes
58     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 54\n";
59
60     // creating mesh for each box
61     for(int i = 0; i<num_boxes; ++i){
62
63         // finding x-points
64         torch::Tensor xpoints = torch::linspace(-boxwidths[i].item<float>()/2, \
65         boxwidths[i].item<float>()/2, \

```

```

63         (int)(boxwidths[i].item<float>() * meshdensity));
64     torch::Tensor ypoints = torch::linspace(-boxlengths[i].item<float>()/2, \
65         boxlengths[i].item<float>()/2, \
66         (int)(boxlengths[i].item<float>() * meshdensity));
67     torch::Tensor zpoints = torch::linspace(0, \
68         boxheights[i].item<float>(), \
69         (int)(boxheights[i].item<float>() * meshdensity));
70     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 69\n";
71
72     // meshgridding
73     auto mesh_grid = torch::meshgrid({xpoints, ypoints, zpoints}, "xy");
74     auto X = mesh_grid[0];
75     auto Y = mesh_grid[1];
76     auto Z = mesh_grid[2];
77     X = torch::reshape(X, {1, X.numel()});
78     Y = torch::reshape(Y, {1, Y.numel()});
79     Z = torch::reshape(Z, {1, Z.numel()});
80     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 79\n";
81
82     // coordinates
83     torch::Tensor boxcoordinates = torch::cat({X, Y, Z}, 0).to(DEVICE);
84     boxcoordinates[0] = boxcoordinates[0] + midxypoints[0][i];
85     boxcoordinates[1] = boxcoordinates[1] + midxypoints[1][i];
86     boxcoordinates[2] = boxcoordinates[2] + midxypoints[2][i];
87     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 86\n";
88
89     // creating some reflectivity points too.
90     torch::Tensor boxreflectivity = meshreflectivity + torch::rand({1, boxcoordinates[0].numel()}) - 0.5;
91     boxreflectivity = boxreflectivity.to(DEVICE);
92     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 90\n";
93
94     // adding to larger matrices
95     if(DEBUG_SEAFLOOR) {std::cout<<"box_coordinates.shape = "; fPrintTensorSize(box_coordinates);}
96     if(DEBUG_SEAFLOOR) {std::cout<<"box_coordinates.shape = "; fPrintTensorSize(boxcoordinates);}
97
98     if(DEBUG_SEAFLOOR) {std::cout<<"box_reflectivity.shape = "; fPrintTensorSize(box_reflectivity);}
99     if(DEBUG_SEAFLOOR) {std::cout<<"boxreflectivity.shape = "; fPrintTensorSize(boxreflectivity);}
100
101     box_coordinates = torch::cat({box_coordinates.to(DEVICE), boxcoordinates}, 1);
102     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 95\n";
103     box_reflectivity = torch::cat({box_reflectivity.to(DEVICE), boxreflectivity}, 1);
104     if(DEBUG_SEAFLOOR) std::cout<<"\t fCreateBoxes: line 97\n";
105 }
106 }
107
108
109
110 // functin that setups the sea-floor
111 void SeafloorSetup(ScattererClass* scatterers) {
112
113     // sea-floor bounds
114     int bed_width = 100; // width of the bed (x-dimension)
115     int bed_length = 100; // length of the bed (y-dimension)
116
117     // multithreading the box creation
118
119     // creating some tensors to pass. This is put outside to maintain scope
120     bool add_boxes_flag = BOXES;
121     torch::Tensor box_coordinates = torch::zeros({3,1}).to(torch::kFloat).to(DEVICE);
122     torch::Tensor box_reflectivity = torch::zeros({1,1}).to(torch::kFloat).to(DEVICE);
123     // std::thread boxes_t(fCreateBoxes, \
124     //     bed_width, bed_length, \
125     //     &box_coordinates, &box_reflectivity);
126     fCreateBoxes(bed_width, \
127         bed_length, \
128         box_coordinates, \
129         box_reflectivity);
130
131     // scatter-intensity
132     // int bed_width_density = 100; // density of points along x-dimension
133     // int bed_length_density = 100; // density of points along y-dimension
134     int bed_width_density = 10; // density of points along x-dimension
135     int bed_length_density = 10; // density of points along y-dimension

```

```

136
137 // setting up coordinates
138 auto xpoints = torch::linspace(0, \
139                               bed_width, \
140                               bed_width * bed_width_density).to(DEVICE);
141 auto ypoints = torch::linspace(0, \
142                               bed_length, \
143                               bed_length * bed_length_density).to(DEVICE);
144
145 // creating mesh
146 auto mesh_grid = torch::meshgrid({xpoints, ypoints}, "ij");
147 auto X          = mesh_grid[0];
148 auto Y          = mesh_grid[1];
149 X              = torch::reshape(X, {1, X.numel()});
150 Y              = torch::reshape(Y, {1, Y.numel()});
151
152 // creating heights of scatterers
153 torch::Tensor Z = torch::zeros({1, Y.numel()}).to(DEVICE);
154
155 // setting up floor coordinates
156 torch::Tensor floorScatter_coordinates = torch::cat({X, Y, Z}, 0);
157 torch::Tensor floorScatter_reflectivity = torch::ones({1, Y.numel()}).to(DEVICE);
158
159 // populating the values of the incoming argument.
160 scatterers->coordinates = floorScatter_coordinates; // assigning coordinates
161 scatterers->reflectivity = floorScatter_reflectivity; // assigning reflectivity
162
163 // // rejoining if multithreading
164 // boxes_t.join(); // bringing thread back
165
166 // combining the values
167 if(DEBUG_SEAFLOOR) std::cout<<"\t SeafloorSetup: line 166 \n";
168 if(DEBUG_SEAFLOOR) {std::cout<<"\t scatterers->coordinates.shape = ";
169                     fPrintTensorSize(scatterers->coordinates);}
170 if(DEBUG_SEAFLOOR) {std::cout<<"\t box_coordinates.shape = "; fPrintTensorSize(box_coordinates);}
171 if(DEBUG_SEAFLOOR) {std::cout<<"\t scatterers->reflectivity.shape = ";
172                     fPrintTensorSize(scatterers->reflectivity);}
173 if(DEBUG_SEAFLOOR) {std::cout<<"\t box_reflectivity = "; fPrintTensorSize(box_reflectivity);}
174
175 scatterers->coordinates = torch::cat({scatterers->coordinates, box_coordinates}, 1);
176 PRINTLINE
177 scatterers->reflectivity = torch::cat({scatterers->reflectivity, box_reflectivity}, 1);
178 PRINTSMALLLINE
179
180 }

```

8.2.2 Transmitter Setup

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

```

1  /* =====
2  Aim: Setup sea floor
3  =====*/
4  #include <torch/torch.h>
5  #include <cmath>
6
7  #ifndef DEVICE
8      // #define DEVICE      torch::kMPS
9      #define DEVICE      torch::kCPU
10 #endif
11
12
13
14 // function to calibrate the transmitters
15 void TransmitterSetup(TransmitterClass* transmitter_fls,
16                       TransmitterClass* transmitter_port,
17                       TransmitterClass* transmitter_starboard) {

```

```

18
19 // Setting up transmitter
20 float sampling_frequency = 160e3;           // sampling frequency
21 float f1 = 50e3;                           // first frequency of LFM
22 float f2 = 70e3;                           // second frequency of LFM
23 float fc = (f1 + f2)/2;                    // finding center-frequency
24 float bandwidth = std::abs(f2 - f1); // bandwidth
25 float pulselength = 0.2;                   // time of recording
26
27 // building LFM
28 torch::Tensor timearray = torch::linspace(0, \
29                                           pulselength, \
30                                           floor(pulselength * sampling_frequency)).to(DEVICE);
31 float K = (f2 - f1)/pulselength;           // calculating frequency-slope
32 torch::Tensor Signal = K * timearray;       // frequency at each time-step, with f1 = 0
33 Signal = torch::mul(2*PI*(f1 + Signal), \
34                  timearray);               // creating
35 Signal = cos(Signal);                      // calculating signal
36
37
38 // Setting up transmitter
39 torch::Tensor location = torch::zeros({3,1}).to(DEVICE); // location of transmitter
40 float azimuthal_angle_fls = 0;             // initial pointing direction
41 float azimuthal_angle_port = 90;           // initial pointing direction
42 float azimuthal_angle_starboard = -90;     // initial pointing direction
43
44 float elevation_angle = -60;               // initial pointing direction
45
46 float azimuthal_beamwidth_fls = 20;        // azimuthal beamwidth of the signal cone
47 float azimuthal_beamwidth_port = 20;       // azimuthal beamwidth of the signal cone
48 float azimuthal_beamwidth_starboard = 20;  // azimuthal beamwidth of the signal cone
49
50 float elevation_beamwidth_fls = 20;        // elevation beamwidth of the signal cone
51 float elevation_beamwidth_port = 20;       // elevation beamwidth of the signal cone
52 float elevation_beamwidth_starboard = 20;  // elevation beamwidth of the signal cone
53
54 int azimuthQuantDensity = 10; // number of points, a degree is split into quantization density
55 // along azimuth (used for shadowing)
56 int elevationQuantDensity = 10; // number of points, a degree is split into quantization density
57 // along elevation (used for shadowing)
58 float rangeQuantSize = 10; // the length of a cell (used for shadowing)
59
60 float azimuthShadowThreshold = 1; // azimuth threshold (in degrees)
61 float elevationShadowThreshold = 1; // elevation threshold (in degrees)
62
63 // transmitter-fls
64 transmitter_fls->location = location; // Assigning location
65 transmitter_fls->Signal = Signal; // Assigning signal
66 transmitter_fls->azimuthal_angle = azimuthal_angle_fls; // assigning azimuth angle
67 transmitter_fls->elevation_angle = elevation_angle; // assigning elevation angle
68 transmitter_fls->azimuthal_beamwidth = azimuthal_beamwidth_fls; // assigning azimuth-beamwidth
69 transmitter_fls->elevation_beamwidth = elevation_beamwidth_fls; // assigning elevation-beamwidth
70 // updating quantization densities
71 transmitter_fls->azimuthQuantDensity = azimuthQuantDensity; // assigning azimuth quant density
72 transmitter_fls->elevationQuantDensity = elevationQuantDensity; // assigning elevation quant density
73 transmitter_fls->rangeQuantSize = rangeQuantSize; // assigning range-quantization
74 transmitter_fls->azimuthShadowThreshold = azimuthShadowThreshold; // azimuth-threshold in shadowing
75 transmitter_fls->elevationShadowThreshold = elevationShadowThreshold; // elevation-threshold in shadowing
76 // signal related
77 transmitter_fls->f_low = f1; // assigning lower frequency
78 transmitter_fls->f_high = f2; // assigning higher frequency
79 transmitter_fls->fc = fc; // assigning center frequency
80 transmitter_fls->bandwidth = bandwidth; // assigning bandwidth
81
82
83
84 // transmitter-portside
85 transmitter_port->location = location; // Assigning location
86 transmitter_port->Signal = Signal; // Assigning signal
87 transmitter_port->azimuthal_angle = azimuthal_angle_port; // assigning azimuth angle
88 transmitter_port->elevation_angle = elevation_angle; // assigning elevation angle

```



```

89 transmitter_port->azimuthal_beamwidth = azimuthal_beamwidth_port; // assigning azimuth-beamwidth
90 transmitter_port->elevation_beamwidth = elevation_beamwidth_port; // assigning elevation-beamwidth
91 // updating quantization densities
92 transmitter_port->azimuthQuantDensity = azimuthQuantDensity; // assigning azimuth quant density
93 transmitter_port->elevationQuantDensity = elevationQuantDensity; // assigning elevation quant density
94 transmitter_port->rangeQuantSize = rangeQuantSize; // assigning range-quantization
95 transmitter_port->azimuthShadowThreshold = azimuthShadowThreshold; // azimuth-threshold in shadowing
96 transmitter_port->elevationShadowThreshold = elevationShadowThreshold; // elevation-threshold in shadowing
97 // signal related
98 transmitter_port->f_low = f1; // assigning lower frequency
99 transmitter_port->f_high = f2; // assigning higher frequency
100 transmitter_port->fc = fc; // assigning center frequency
101 transmitter_port->bandwidth = bandwidth; // assigning bandwidth
102
103
104
105 // transmitter-starboard
106 transmitter_starboard->location = location; // assigning location
107 transmitter_starboard->Signal = Signal; // assigning signal
108 transmitter_starboard->azimuthal_angle = azimuthal_angle_starboard; // assigning azimuthal signal
109 transmitter_starboard->elevation_angle = elevation_angle;
110 transmitter_starboard->azimuthal_beamwidth = azimuthal_beamwidth_starboard;
111 transmitter_starboard->elevation_beamwidth = elevation_beamwidth_starboard;
112 // updating quantization densities
113 transmitter_starboard->azimuthQuantDensity = azimuthQuantDensity;
114 transmitter_starboard->elevationQuantDensity = elevationQuantDensity;
115 transmitter_starboard->rangeQuantSize = rangeQuantSize;
116 transmitter_starboard->azimuthShadowThreshold = azimuthShadowThreshold;
117 transmitter_starboard->elevationShadowThreshold = elevationShadowThreshold;
118 // signal related
119 transmitter_starboard->f_low = f1; // assigning lower frequency
120 transmitter_starboard->f_high = f2; // assigning higher frequency
121 transmitter_starboard->fc = fc; // assigning center frequency
122 transmitter_starboard->bandwidth = bandwidth; // assigning bandwidth
123
124 }

```

8.2.3 Uniform Linear Array

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

```

1  /* =====
2  Aim: Setup sea floor
3  NOAA: 50 to 100 KHz is the transmission frequency
4  we'll create our LFM with 50 to 70KHz
5  =====*/
6
7
8  // Choosing device
9  #ifndef DEVICE
10 // #define DEVICE torch::kMPS
11 #define DEVICE torch::kCPU
12 #endif
13
14
15 // the coefficients for the low-pass filter.
16 #define LOWPASS_DECIMATE_FILTER_COEFFICIENTS 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0001, 0.0003,
17 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,
18 0.1180, 0.1212, 0.1179, 0.1078, 0.0914, 0.0699, 0.0451, 0.0192, -0.0053, -0.0262, -0.0416, -0.0504,
19 -0.0522, -0.0475, -0.0375, -0.0239, -0.0088, 0.0057, 0.0179, 0.0263, 0.0303, 0.0298, 0.0253, 0.0177,
20 0.0086, -0.0008, -0.0091, -0.0153, -0.0187, -0.0191, -0.0168, -0.0123, -0.0065, -0.0004, 0.0052, 0.0095,
21 0.0119, 0.0125, 0.0112, 0.0084, 0.0046, 0.0006, -0.0031, -0.0060, -0.0078, -0.0082, -0.0075, -0.0057,
22 -0.0033, -0.0006, 0.0019, 0.0039, 0.0051, 0.0055, 0.0050, 0.0039, 0.0023, 0.0005, -0.0012, -0.0025,
23 -0.0034, -0.0036, -0.0034, -0.0026, -0.0016, -0.0004, 0.0007, 0.0016, 0.0022, 0.0024, 0.0023, 0.0018,
24 0.0011, 0.0003, -0.0004, -0.0011, -0.0015, -0.0016, -0.0015
25
26
27
28
29
30

```



```

21 void ULASetup(ULAClass* ula_fls,
22              ULAClass* ula_port,
23              ULAClass* ula_starboard) {
24
25     // setting up ula
26     int num_sensors = 64; // number of sensors
27     float sampling_frequency = 160e3; // sampling frequency
28     float inter_element_spacing = 1500/(2*sampling_frequency); // space between samples
29     float recording_period = 0.1; // sampling-period
30
31     // building the direction for the sensors
32     torch::Tensor ULA_direction = torch::tensor({-1,0,0}).reshape({3,1}).to(torch::kFloat).to(DEVICE);
33     ULA_direction = ULA_direction/torch::linalg_norm(ULA_direction, 2, 0, true,
34               torch::kFloat).to(DEVICE);
35     ULA_direction = ULA_direction * inter_element_spacing;
36
37     // building the coordinates for the sensors
38     torch::Tensor ULA_coordinates = torch::mul(torch::linspace(0, num_sensors-1, num_sensors).to(DEVICE), \
39               ULA_direction);
40
41     // the coefficients for the decimation filter
42     torch::Tensor lowpassfiltercoefficients =
43       torch::tensor({LOWPASS_DECIMATE_FILTER_COEFFICIENTS}).to(torch::kFloat);
44
45     // assigning values
46     ula_fls->num_sensors = num_sensors; // assigning number of sensors
47     ula_fls->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
48     ula_fls->coordinates = ULA_coordinates; // assigning ULA coordinates
49     ula_fls->sampling_frequency = sampling_frequency; // assigning sampling frequencys
50     ula_fls->recording_period = recording_period; // assigning recording period
51     ula_fls->sensorDirection = ULA_direction; // ULA direction
52     ula_fls->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;
53
54     // ula_fls->num_sensors = num_sensors; // assigning number of sensors
55     // ula_fls->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
56     // ula_fls->coordinates = ULA_coordinates; // assigning ULA coordinates
57     // ula_fls->sampling_frequency = sampling_frequency; // assigning sampling frequencys
58     // ula_fls->recording_period = recording_period; // assigning recording period
59     // ula_fls->sensorDirection = ULA_direction; // ULA direction
60
61     // assigning values
62     ula_port->num_sensors = num_sensors; // assigning number of sensors
63     ula_port->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
64     ula_port->coordinates = ULA_coordinates; // assigning ULA coordinates
65     ula_port->sampling_frequency = sampling_frequency; // assigning sampling frequencys
66     ula_port->recording_period = recording_period; // assigning recording period
67     ula_port->sensorDirection = ULA_direction; // ULA direction
68     ula_port->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;
69
70     // ula_port->num_sensors = num_sensors; // assigning number of sensors
71     // ula_port->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
72     // ula_port->coordinates = ULA_coordinates; // assigning ULA coordinates
73     // ula_port->sampling_frequency = sampling_frequency; // assigning sampling frequencys
74     // ula_port->recording_period = recording_period; // assigning recording period
75     // ula_port->sensorDirection = ULA_direction; // ULA direction
76
77     // assigning values
78     ula_starboard->num_sensors = num_sensors; // assigning number of sensors
79     ula_starboard->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
80     ula_starboard->coordinates = ULA_coordinates; // assigning ULA coordinates
81     ula_starboard->sampling_frequency = sampling_frequency; // assigning sampling frequencys
82     ula_starboard->recording_period = recording_period; // assigning recording period
83     ula_starboard->sensorDirection = ULA_direction; // ULA direction
84     ula_starboard->lowpassFilterCoefficientsForDecimation = lowpassfiltercoefficients;
85
86     // ula_starboard->num_sensors = num_sensors; // assigning number of sensors
87     // ula_starboard->inter_element_spacing = inter_element_spacing; // assigning inter-element spacing
88     // ula_starboard->coordinates = ULA_coordinates; // assigning ULA coordinates
89     // ula_starboard->sampling_frequency = sampling_frequency; // assigning sampling frequencys
90     // ula_starboard->recording_period = recording_period; // assigning recording period
91     // ula_starboard->sensorDirection = ULA_direction; // ULA direction

```

92 }

8.2.4 AUV Setup

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

```

1  /* =====
2  Aim: Setup sea floor
3  NOAA: 50 to 100 KHz is the transmission frequency
4  we'll create our LFM with 50 to 70KHz
5  =====/
6
7  #ifndef DEVICE
8      #define DEVICE      torch::kMPS
9      // #define DEVICE      torch::kCPU
10 #endif
11
12 // =====
13 void AUVSetup(AUVClass* auv) {
14
15     // building properties for the auv
16     torch::Tensor location      = torch::tensor({0,50,30}).reshape({3,1}).to(torch::kFloat).to(DEVICE); //
17     // starting location of AUV
18     torch::Tensor velocity      = torch::tensor({5,0, 0}).reshape({3,1}).to(torch::kFloat).to(DEVICE); //
19     // starting velocity of AUV
20     torch::Tensor pointing_direction = torch::tensor({1,0, 0}).reshape({3,1}).to(torch::kFloat).to(DEVICE);
21     // pointing direction of AUV
22
23     // assigning
24     auv->location      = location;          // assigning location of auv
25     auv->velocity      = velocity;          // assigning vector representing velocity
26     auv->pointing_direction = pointing_direction; // assigning pointing direction of auv
27 }

```

8.3 Function Definitions

8.3.1 Cartesian Coordinates to Spherical Coordinates

```

1  /* =====
2  Aim: Setup sea floor
3  =====*/
4  #include <torch/torch.h>
5  #include <iostream>
6
7  // hash-defines
8  #define PI          3.14159265
9  #define DEBUG_Cart2Sph false
10
11 #ifndef DEVICE
12     #define DEVICE      torch::kMPS
13     // #define DEVICE    torch::kCPU
14 #endif
15
16
17 // bringing in functions
18 #include "/Users/vrsreeganesh/Documents/GitHub/AUV/Code/C++/Functions/fPrintTensorSize.cpp"
19
20 #pragma once
21
22 torch::Tensor fCart2Sph(torch::Tensor cartesian_vector){
23
24     // sending argument to the device
25     cartesian_vector = cartesian_vector.to(DEVICE);
26     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 26 \n";
27
28     // splatting the point onto xy plane
29     torch::Tensor xysplat = cartesian_vector.clone().to(DEVICE);
30     xysplat[2] = 0;
31     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 31 \n";
32
33     // finding splat lengths
34     torch::Tensor xysplat_lengths = torch::linalg_norm(xysplat, 2, 0, true, torch::kFloat).to(DEVICE);
35     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 35 \n";
36
37     // finding azimuthal and elevation angles
38     torch::Tensor azimuthal_angles = torch::atan2(xysplat[1], xysplat[0]).to(DEVICE) * 180/PI;
39     azimuthal_angles = azimuthal_angles.reshape({1, azimuthal_angles.numel()});
40     torch::Tensor elevation_angles = torch::atan2(cartesian_vector[2], xysplat_lengths).to(DEVICE) * 180/PI;
41     torch::Tensor rho_values = torch::linalg_norm(cartesian_vector, 2, 0, true, torch::kFloat).to(DEVICE);
42     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 42 \n";
43
44
45     // printing values for debugging
46     if (DEBUG_Cart2Sph){
47         std::cout<<"azimuthal_angles.shape = "; fPrintTensorSize(azimuthal_angles);
48         std::cout<<"elevation_angles.shape = "; fPrintTensorSize(elevation_angles);
49         std::cout<<"rho_values.shape = "; fPrintTensorSize(rho_values);
50     }
51     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 51 \n";
52
53     // creating tensor to send back
54     torch::Tensor spherical_vector = torch::cat({azimuthal_angles, \
55                                                  elevation_angles, \
56                                                  rho_values}, 0).to(DEVICE);
57     if (DEBUG_Cart2Sph) std::cout<<"\t fCart2Sph: line 57 \n";
58
59     // returning the value
60     return spherical_vector;
61 }

```

Chapter 9

Reading

9.1 Primary Books

- 1.

9.2 Interesting Papers