

# A novel GPU-based sonar simulator for real-time applications

## Abstract

Mainly when applied in the underwater environment, sonar simulation requires great computational effort due to the complexity of acoustic physics. Simulation of sonar operation allows evaluating algorithms and control systems without going to the real underwater environment; that reduces the costs and risks of in-field experiments. This paper tackles with the problem of real-time underwater imaging sonar simulation by using the OpenGL shading language chain on GPU. Our proposed system is able to simulate two main types of acoustic devices: mechanical scanning imaging sonars and forward-looking sonars. The underwater scenario simulation is performed based on three frameworks: (i) OpenSceneGraph reproduces the ocean visual effects, (ii) Gazebo deals with physical forces, and (iii) the Robot Construction Kit controls the sonar in underwater environments. Our system exploits the rasterization pipeline in order to simulate the sonar devices, which are simulated by means of three parameters: the pulse distance, the echo intensity and sonar field-of-view, being all calculated over [observable](#) objects shapes in the 3D rendered scene. Sonar-intrinsic operational parameters, speckle noise and object material properties are also considered as part of the acoustic image. [Our evaluation demonstrated that the proposed method is able to operate close to or faster than the real-world devices. Also, our method generates more visually realistic sonar images when compared with other approaches.](#)

**Key words:** Simulated sensor data, Sonar imaging, GPU-based processing, Robot Construction Kit (Rock), Underwater robotics.

## 1. Introduction

Simulation is an useful tool for designing and programming autonomous underwater vehicles (AUVs). That allows evaluating the vehicle behavior, without dealing with physical hardware or decision-making algorithms and control systems in real-time trials, as well as costly and time-consuming field experiments. AUVs usually demand expensive hardware and perform long-term data gathering operations, taking place in restrictive sites. When AUVs are not supported by an umbilical cable, and the underwater communication carries on by unreliable acoustic links, the vehicle should be able to make completely autonomous decisions, even with low-to-zero external assistance. While the analysis and interpretation of sensor data can be performed in a post-processing step, a real-time simulation is strongly necessary for testing and evaluation of vehicle's motion response, avoiding involved risks on real-world rides.

AUVs usually act below the photic zone, with high turbidity and huge light scattering. This makes the quality of image acquisition by optical devices limited by a short range, and artificially illuminated and clear visibility conditions. To tackle with that limitations, high-frequency sonars have been used primarily on AUVs' navigation and perception systems. Acoustic waves emitted by sonars are significantly less affected by water attenuation, aiding operation at greater ranges even as low-to-zero visibility conditions, with a fast refresh rate. Although sonar devices usually solve the main shortcomings of optical sensors in underwater conditions, they provide noisy data of lower resolution and more difficult interpretation.

By considering sonar benefits and singularities along with the need to evaluate AUVs, recent works proposed ray tracing- [1, 2, 3, 4, 5, 6] and tube tracing-based [7] techniques to simu-

late acoustic data with very accurate results, although presenting a high computational cost. Bell [1] proposed a simulator based on optical ray tracing for underwater side-scan sonar imagery; images are generated by acoustic signals represented by rays, which are repeatedly processed, forming a 2D-array. Coiras and Groen [2] used frequency-domain signal processing to produce synthetic aperture sonar frames; in that method, the acoustic image is created by computing the Fourier transform of the acoustic pulse used to insonify the scene. For forward-looking sonar simulations, Saç *et al.* [3] described a sonar model by computing the ray tracing in frequency domain; when a ray hits an object in 3D space, three parameters are calculated to process the acoustic data: the Euclidean distance from the sonar axis, the intensity of returned signal by Lambert illumination model and the surface normal; the reverberation and shadow phenomena are also considered in the scene rendering. DeMarco *et al.* [4] used Gazebo and Robot Operating System (ROS) [8] integration to simulate acoustic sound pulses by ray tracing technique, also producing a 3D point cloud of the coverage area; the reflected intensity takes into account the object reflectivity, and the amount of Gaussian and salt-and-pepper noises applied in the sonar image is empirically defined. Gu *et al.* [5] modeled a forward-looking sonar device, where the ultra-sound beams are formed by a set of rays; the acoustic image is significantly limited by a representation using only two colors: white, when the ray strikes an object, and black for shadow areas. Kwak *et al.* [6] improved the previous approach by adding a sound pressure attenuation to produce the gray-scale sonar frame, while the other physical characteristics related to sound transmission are disregarded. Guériot and Sintes [7] introduce a volume-based approach of energy interacting with the scene, and collected by the receiving sonar; the sound propagation is

64 defined by series of acoustic tubes, being always orthogonal to  
 65 the current sonar view, where the reverberation and objects sur-  
 66 face irregularities are also addressed.

### 67 1.1. Contributions

68 This paper introduces a novel imaging sonar simulator that  
 69 presents some contributions when compared to the existing ap-  
 70 proaches. Instead of simulating the sound pulse paths and the  
 71 effects of their hits with the virtual objects, as presented by ray  
 72 tracing and tube tracing-based methods [1, 2, 3, 4, 5, 6, 7], we  
 73 take advantage of precomputed data (e.g., normals, distances,  
 74 colors, angles) during the rasterization pipeline to compute the  
 75 acoustic frame. In addition, all raster data are handled on GPU,  
 76 accelerating then the simulation process with the guarantee of  
 77 real-time response, in contrast to the methods found in [1, 2, 3,  
 78 4]. Although the systems found in [1, 2, 3, 4, 5, 6, 7] focused  
 79 on the simulation of specific sonar device, our simulator is able  
 80 to reproduce two kinds of sonar devices: mechanical scanning  
 81 imaging sonar (MSIS) and forward-looking sonar (FLS). The  
 82 intensity measured back from the insonified objects depends  
 83 on surface normal directions and reflectivity, producing more  
 84 realistic simulated frames than binary representation, this lat-  
 85 ter found in [5, 6]. The speckle noise is modeled as a non-  
 86 uniform Gaussian distribution and applied to our final sonar  
 87 image, which approaches to real-world sonar operation, differ-  
 88 ently from [3, 4, 5, 6, 7]. On the other hand, we did not exploit  
 89 the additive noise as it was considered in [3, 4]. Finally, it is  
 90 noteworthy that our proposed system simulates physical phe-  
 91 nomena since they are constrained to real-time (e.g. decision-  
 92 making algorithms and control system tuning). Aware of this  
 93 real-time constraint, the high computational cost phenomena  
 94 such as reverberation is not included at this point, differently  
 95 from [3, 7].

96 The main goal here is to build quality and low time-con-  
 97 suming acoustic frames, according to underwater sonar image  
 98 formation and operation modes (see Section 2). The pulse dis-  
 99 tance, the echo intensity and the sonar field-of-view parameters  
 100 are extracted from the underwater scene during the rasteriza-  
 101 tion pipeline, and subsequently fused to generate the simulated  
 102 sonar data, as described in Section 3. Qualitative and time eval-  
 103 uation results for the two different sonar devices are presented  
 104 in Section 4, allowing the use of the proposed simulator by real-  
 105 time applications. Conclusions and future work are drawn in  
 106 Section 5.

## 107 2. Imaging sonar operation

108 Sonars are echo-ranging devices that use acoustic energy to  
 109 locate and survey objects in a desired area. The sonar trans-  
 110 ducer emits pulses of sound waves (or ping) until they hit any  
 111 object or are completely absorbed. When the acoustic signal  
 112 collides with a surface, part of this energy is reflected, while  
 113 other is refracted. The sonar data is built by plotting the echo  
 114 measured back versus time of acoustic signal. The transducer  
 115 reading in a given direction forms a *beam*. A single beam trans-  
 116 mitted from a sonar is illustrated in Fig. 1. The horizontal and

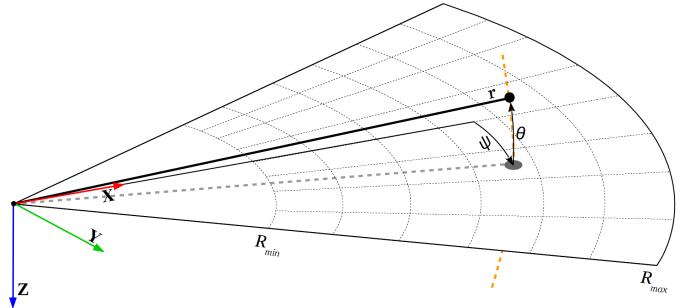


Figure 1: Imaging sonar geometry. By the projection process, all 3D points belonging to the same elevation arc (represented as dashed orange line) will be represented to the same image point in the 2D plane. Range  $r$  and azimuth angle  $\psi$  are measured, and elevation angle  $\theta$  is lost. Sonar coverage area is defined by  $R_{min}$  and  $R_{max}$ .

117 vertical beamwidths are represented by the azimuth  $\psi$  and el-  
 118 evation  $\theta$  angles, respectively, where each sampling along the  
 119 beam is named as *bin*. The sonar coverage area is defined by  
 120  $R_{min}$  and  $R_{max}$ . Since the speed of sound underwater is known,  
 121 or can be measured, the time delay between the emitted pulses  
 122 and the respective echoes (named as *time of flight*) reveals how  
 123 far the objects are (distance  $r$ ), as well as how fast they are mov-  
 124 ing. The backscattered acoustic power in each bin determines  
 125 the echo intensity value.

126 With different azimuth directions, the array of transducer  
 127 readings forms the final sonar image. Since all incoming sig-  
 128 nals converge to the same point, the reflected echoes could have  
 129 been originated anywhere along the corresponding elevation arc  
 130 at a fixed range, as depicted in Fig. 1. In the acoustic represen-  
 131 tation, the 3D information is lost in the projection into a 2D  
 132 image.

### 133 2.1. Sonar characteristics

134 Although sonar devices overcome main limitations of opti-  
 135 cal sensors, they present more difficult data interpretation due  
 136 to:

- 137 a) **Shadowing:** This effect is caused by objects blocking the  
 138 sound waves transmission, and causing regions behind them,  
 139 without acoustic feedback. These regions are defined by a  
 140 black spot in the sonar image, occluding part of the scene;
- 141 b) **Non-uniform resolution:** The amount of pixels used to  
 142 represent an echo intensity record in the Cartesian coordi-  
 143 nate system grows as its range increases. This situation  
 144 causes image distortions and object flatness;
- 145 c) **Changes in viewpoint:** Imaging the same scene from dif-  
 146 ferent viewpoints can cause occlusions, shadows move-  
 147 ments and significant changes of observable objects [9].  
 148 For instance, when an outstanding object is insonified, its  
 149 shadow is shorter, as the sonar becomes closer;
- 150 d) **Low signal-to-noise ratio (SNR):** sonars suffer from low  
 151 SNR mainly due the very-long-range scanning, and the  
 152 presence of speckle noise introduced by acoustic wave in-  
 153 terferences [10];
- 154 e) **Reverberation:** This phenomenon is caused when mul-  
 155 tiple acoustic waves, returning from the same object, are  
 156 detected over the same ping, producing duplicated objects.

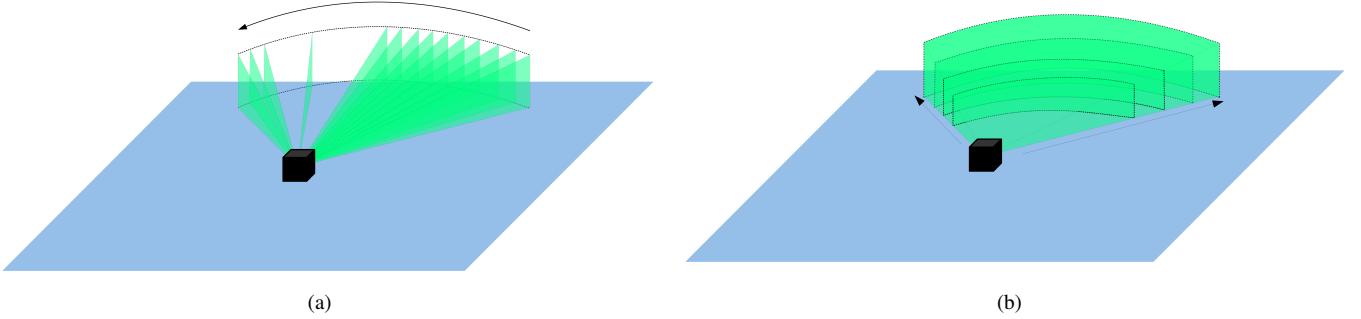


Figure 2: Different underwater sonar readings: (a) From a mechanical scanning imaging sonar and (b) from a forward-looking sonar.

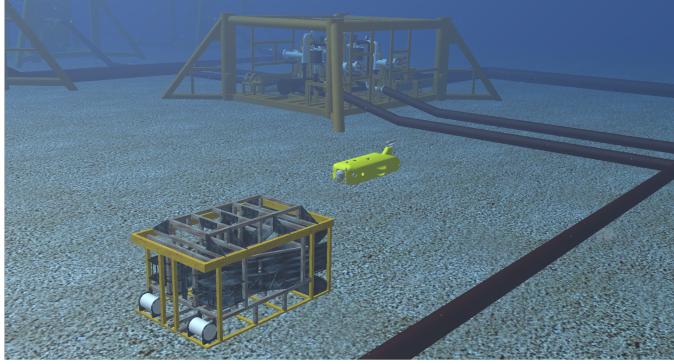


Figure 3: The AUV in Rock-Gazebo underwater scene.

## 157 2.2. Types of underwater sonar devices

158 The most common types of underwater acoustic sonars are  
 159 MSIS and FLS. In the former, the sonar image is built for each  
 160 pulse, with one beam per reading (see Fig. 2(a)); the resulting  
 161 sonar images in MSIS are usually depicted on a display pulse by  
 162 pulse, and the head position reader is rotated according to mo-  
 163 tor step angle. After a full  $360^\circ$  sector reading (or the desired  
 164 sector defined by left and right limit angles), the accumulated  
 165 sonar data is overwritten. The acquisition of a scanning image  
 166 involves a relatively long time, introducing distortions caused  
 167 by the vehicle movements. This sonar device is generally ap-  
 168 plied in obstacle avoidance [11] and navigation [12] applica-  
 169 tions. As illustrated in Fig. 2(b), the whole forward view of  
 170 an FLS is scanned and the current data is overwritten by the  
 171 next scanning in a high frame rate, with all beams being read  
 172 simultaneously; this is similar to a streaming video imagery for  
 173 real-time applications; this imaging sonar is commonly used  
 174 for navigation [13], mosaicing [9], target tracking [14] and 3D  
 175 reconstruction [15].

## 176 3. GPU-based sonar simulation

177 The goal of our work is to simulate two types of underwater  
 178 sonar with low computational cost. The complete pipeline of  
 179 the proposed simulator (from the virtual scene to the simulated  
 180 acoustic data) is detailed in the following sections. The sonar  
 181 simulator is written in C++ with OpenCV [16] support as Rock  
 182 packages.

### 183 3.1. Rendering underwater scene

184 In Rock-Gazebo framework [17], Gazebo handles with phys-  
 185 ical forces, while Rock's visualization tools are responsible by  
 186 the scene rendering. The graphical data in Rock are based  
 187 on OpenSceneGraph framework, an open source C/C++ 3D  
 188 graphics toolkit built on OpenGL. The osgOcean library is used  
 189 to simulate the ocean visual effects. In our case, Rock-Gazebo  
 190 integration provides the underwater scenario, allowing also real-  
 191 time hardware-in-the-loop simulation with a virtual AUV.

192 All scene aspects, such as world model, robot parts (in-  
 193 cluding sensors and joints) and other virtual objects are defined  
 194 by simulation description files (SDF), which use the SDFFor-  
 195 mat [18], an XML format used to describe simulated models  
 196 and environments for Gazebo. Visual and collision geometries  
 197 of vehicle and sensors are also described in specific file for-  
 198 mats. Each component described in the SDF file becomes a  
 199 Rock component, which is based on the Orococos real-time tool-  
 200 kit (RTT) [19], providing I/O ports, properties and operations  
 201 as communication layers. When the models are loaded, Rock-  
 202 Gazebo allows interaction between real world or simulated sys-  
 203 tem components with the simulated models. A resulting scene  
 204 sample of this integration is illustrated in Fig. 3.

### 205 3.2. Sonar rendering

206 A rendering pipeline can be customized by defining GPU  
 207 shaders. A shader is written in OpenGL Shading Language  
 208 (GLSL) [20], a high-level language with a C-based syntax, which  
 209 enables more direct control of graphics pipeline, avoiding the  
 210 use of low-level or hardware-specific languages. Shaders can  
 211 describe the characteristics of either a vertex or a fragment (a  
 212 single pixel). Vertex shaders are responsible by transforming  
 213 the vertex position into a screen position by the rasterizer, gen-  
 214 erating texture coordinates for texturing, and lighting the vertex  
 215 to determine each color. The rasterization results, in a set of  
 216 pixels to be processed by fragment shaders, manipulate pixel  
 217 location, depth and alpha values, and interpolated parameters  
 218 from the previous stages, such as colors and textures.

219 In our work, the underwater scenes are sampled by a virtual  
 220 camera (frame-by-frame), whose optical axis is aligned with the  
 221 **opening angle**, the intended **viewing direction** and the cover-  
 222 age **range** of the simulated sonar device (see Fig. 4(i)). To  
 223 reproduce the sonar imaging operation by using virtual camera  
 224 frames, three parameters are computed in fragment and vertex

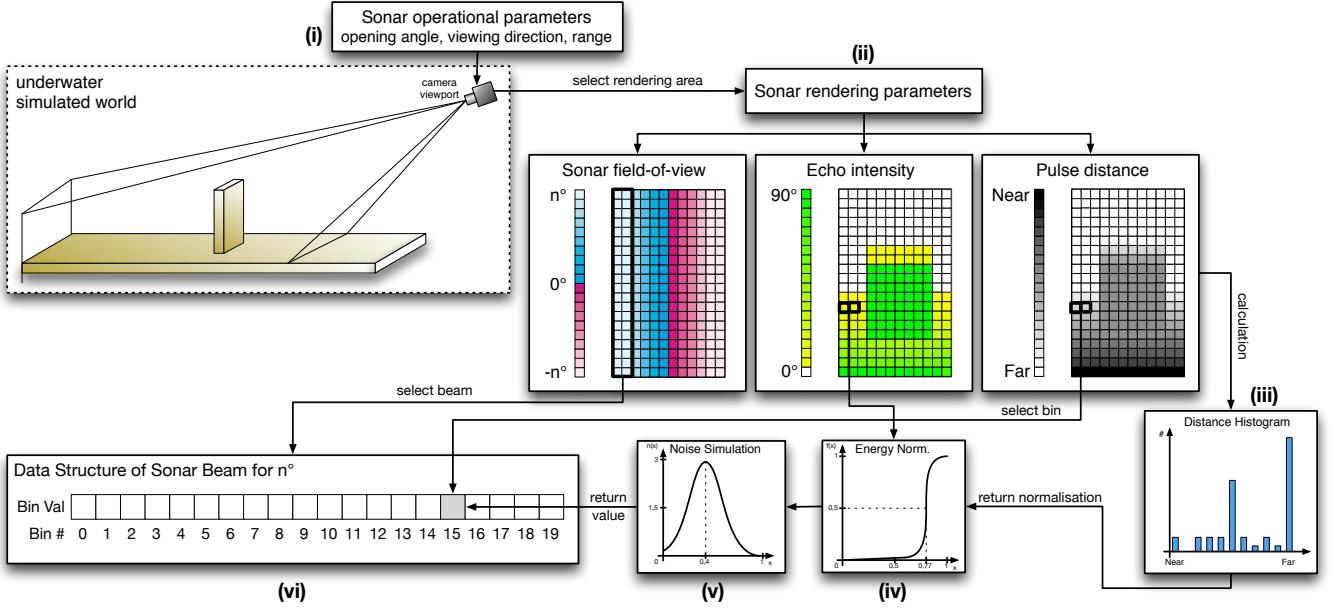


Figure 4: A graphical overview of the imaging sonar simulation process: (i) a virtual camera, specialized as the sonar device, samples the underwater scene; (ii) three 2D parameters are calculated by shader rendering on GPU: sonar field-of-view, echo intensity and pulse distance; the shader information is split into beam parts, according to the angle values, and the bin distance and echo intensity are defined by: (iii) distance histogram and (iv) energy normalization, respectively; (v) the speckle noise is applied to the final sonar data; (vi) and the simulated acoustic data is presented as Rock's data type.

shaders, during the rendering pipeline. This way, we are able to use the precomputed geometric information during the image rasterization process on GPU. The three parameters to render the sonar device using a virtual camera are illustrated in Fig. 4(ii), and are described as follows:

- **Pulse distance** simulates the time of flight of the acoustic pulse, being calculated by the Euclidean distance between the camera center and the object surface;
- **Echo intensity** represents the energy reflection of the sound wave, calculated from the object surface normal regarding the camera;
- **Sonar field-of-view** is represented by the camera field-of-view in the horizontal direction.

By default, the shader encodes the raster data in 8-bit color channels for red, green, blue and alpha (RGBA). In our simulator, RGB channels are used to store the echo intensity, pulse distance and sonar field-of-view parameters to render the sonar from a virtual camera. The echo intensity parameter follows a real sonar common representation as 8-bit values. The pulse distance is replaced by the native GLSL 32-bit depth buffer to avoid precision limitation during the calculation of the distance histogram (see Fig. 4(iii)). As the field-of-view angle varies from the image center to both side directions, the sonar field-of-view is represented by 8-bit values without loss of precision. All of these three parameters are normalized into the interval  $[0,1]$ . For the echo intensity parameter, zero means no energy, while one means maximum echo energy. For pulse distance, the minimum value denotes a close object, while the maximum value represents a far one, limited by the sonar maximum range.

Every sonar device has a maximum field-of-view; to represent this parameter in the rendering pipeline, the zero angle is in the center of the image, increasing until it reaches the half value of the maximum field-of-view of the simulated sonar device, for both sided borders; for example, if a sonar device has  $120^\circ$  of field-of-view, the zero angle is in the center of the virtual camera, spanning  $60^\circ$  to the right and  $60^\circ$  to the left.

In real-world sensing, surfaces usually present irregularities and different reflectance values. To render these surfaces in a virtual scene, the echo intensity values can also be defined by normal maps (see Fig. 5) and material property information (see Fig. 6). Normal mapping is a rendering technique, based on normal perturbation, that is used to simulate wrinkles and dents on the object surface by using RGB textures on shaders. This approach consumes less computational resources for the same level of detail, compared with the displacement mapping technique, because the geometry remains unchanged. Since normal maps are built in tangent space, interpolating the normal vertex and the texture, tangent, bi-tangent and normal (TBN) matrices are computed to convert the normal values into the world space. The visual differences of applying normal mapping in the actual scenes are illustrated in Figs. 5(a) and 5(c); in the shader representation, in Figs. 5(e) and 5(b); and the final sonar image, in Figs. 5(d) and 5(f). The reflectance allows properly describing the intensity received back from observable objects in shader processing, according to the material properties (for instance, aluminum has more reflectivity than wood and plastic). When an object has the reflectivity property defined, the reflectance value  $\rho$  is passed to the fragment shader and processed on GPU. So, the final pixel intensity represents the product of surface normal angle by the reflectance value  $\rho$ .

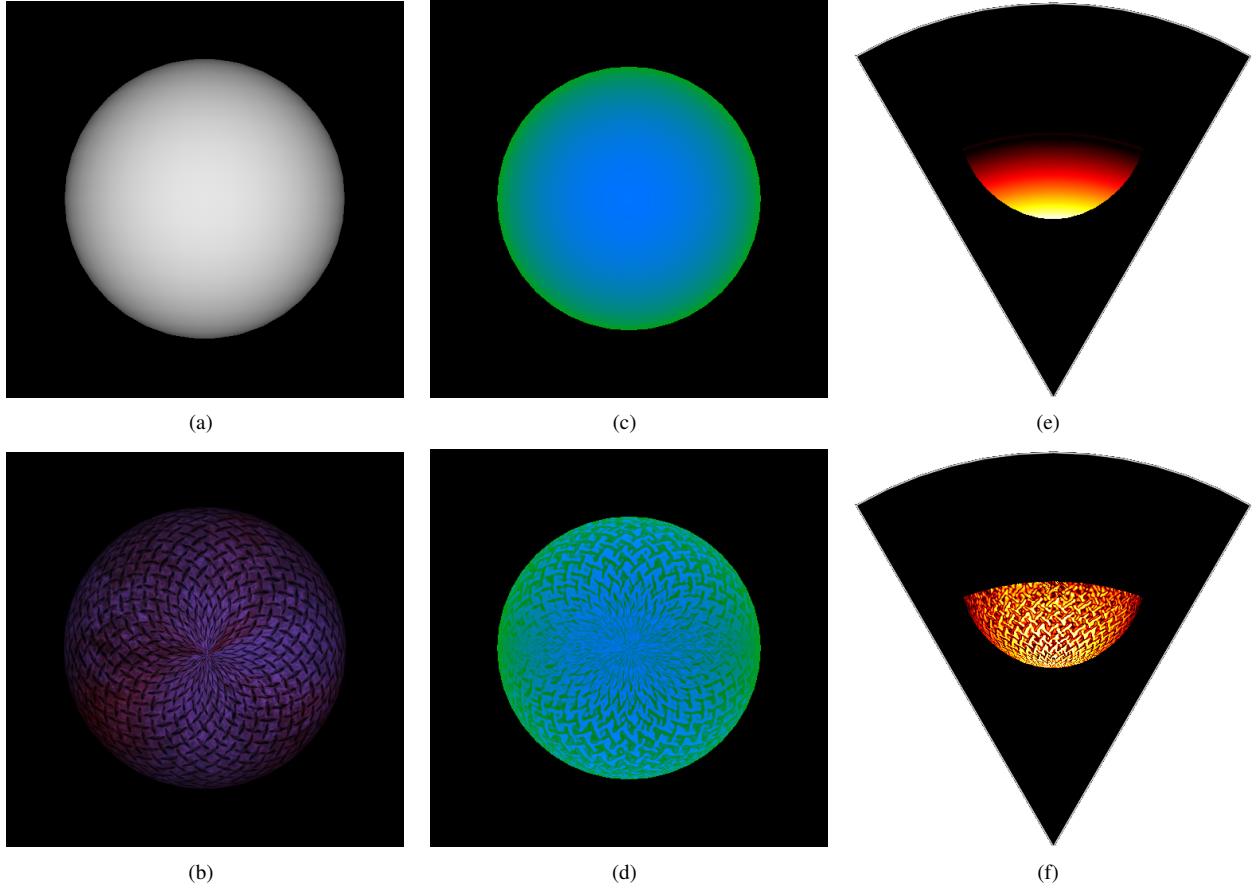


Figure 5: Example of shader rendering with normal mapping: A sphere without (a) and with texture (b); respective shader image representations of the spheres in (c) and (d), where the blue area represents the echo intensity parameter, while the green area means the pulse distance parameter. The final acoustic images are depicted in (e) and (f). By using normal mapping technique, the textures changes the normal directions, and the sonar image details the appearance of object surface, like in real world sensing.

285 The reflectance affects the shader representation, as depicted in  
 286 Figs. 6(a), 6(b), 6(c) and 6(d)), with a final sonar image shown  
 287 in Figs. 6(e), 6(f), 6(g) and 6(h).

### 288 3.3. Simulating operation of the sonar device

289 The sonar rendering parameters are used to compute the  
 290 corresponding acoustic representation. Since the sonar field-  
 291 of-view is radially spaced over the horizontal field-of-view of  
 292 the virtual camera (where all pixels in the same column have  
 293 the same angle), the first step is to split the image into a num-  
 294 ber of beams (beamed sub-images). Each column of the sonar  
 295 field-of-view parameter is related with a respective beam vector,  
 296 according to sonar bearings, as illustrated in Fig. 4(vi). In turn,  
 297 one beam represents one or more columns. Each beamed sub-  
 298 image is converted into bin intensities using the pulse distance  
 299 and the echo intensity parameters. In a real imaging sonar, the  
 300 echo measured back is sampled over time, and the bin number  
 301 is proportional to the sensor range. In other words, the initial  
 302 bins represent the closest distances, while the latest bins repre-  
 303 sent the farthest ones. Therefore a distance histogram (see Fig.  
 304 4(iii)) is computed in order to group the sub-image pixels with  
 305 the respective bins, according to the pulse distance parameter

306 and number of bins, and calculate the accumulated intensity in  
 307 each bin.

308 Due to the acoustic beam spreading and absorption in the  
 309 water, the final bins have less echo strength than the first ones.  
 310 This is so, because the energy is twice lost in the environment.  
 311 To tackle with that issue, sonar devices use an energy normal-  
 312 ization based on time-varying gain for range dependence com-  
 313 pensation, which spreads losses in the bins. In our simulation  
 314 approach, the accumulated intensity,  $I_{bin}$ , in each bin (see Fig.  
 315 4(iv)) is normalized as

$$316 \quad I_{bin} = \sum_{x=1}^N \frac{1}{N} \times S(i_x), \quad (1)$$

317 where  $x$  is the pixel location,  $N$  is the distance histogram value  
 318 (number of pixels) of that bin,  $S(i_x)$  is a sigmoid function, and  $i_x$   
 319 is the echo intensity value of the pixel  $x$ .  $\times$  defines an element-  
 320 wise multiplication.

321 Finally, the sonar image resolution must be big enough to  
 322 contain all information of the bins. For that, the number of bins  
 323 involved is directly proportional to the sonar image resolution.

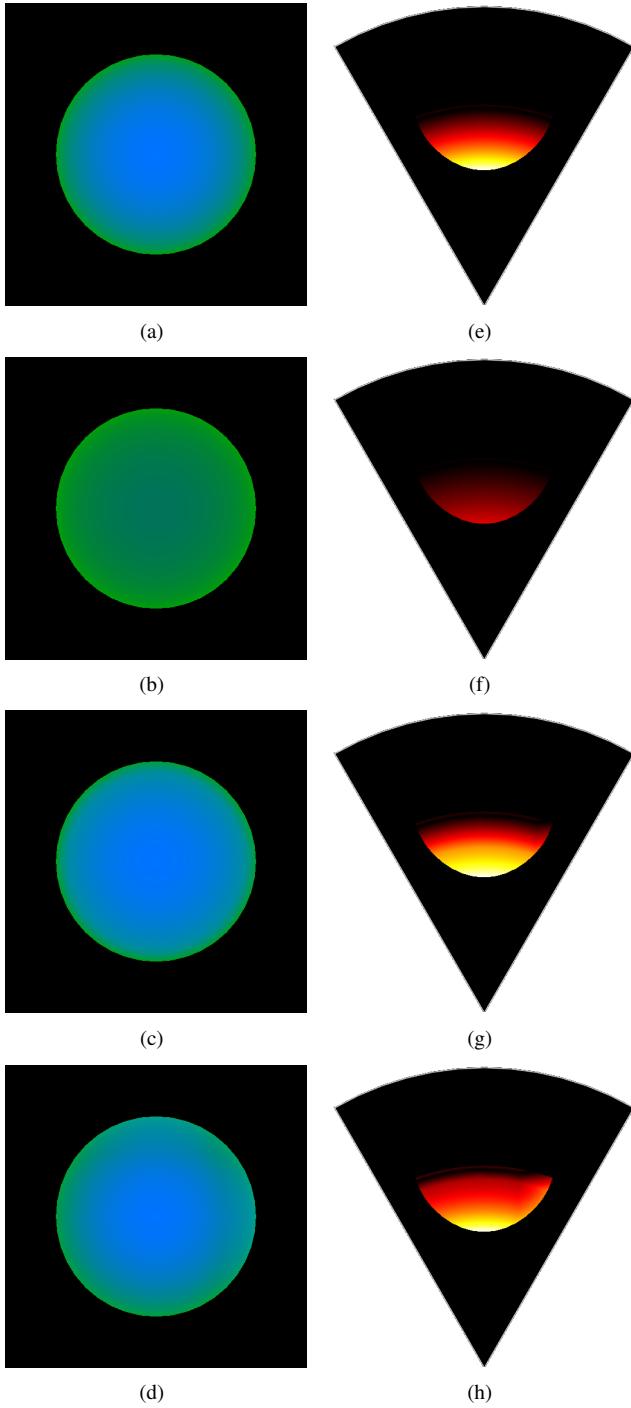


Figure 6: Examples of different reflectance values,  $\rho$ , applied in shader image representation of the same target, where blue is the echo intensity parameter and green is the pulse distance parameter: (a) raw image; (b)  $\rho = 0.35$ ; (c)  $\rho = 1.40$ ; and (d)  $\rho = 2.12$ . The following acoustic images are presented in (e), (f), (g) and (h).

### 3.3.1. Noise model

Imaging sonar systems are disturbed by a multiplicative noise known as speckle, which is caused by coherent processing of backscattered signals from multiple distributed targets. This effect degrades image quality and visual evaluation. Speckle noise results in constructive and destructive interferences, which

Table 1: Sonar device configurations used on experimental evaluation.

Device	# of beams	# of bins	Field of view	Down tilt	Motor Step
FLS	256	1000	120° x 20°	20°	-
MSIS	1	500	3° x 35°	0°	1.8°

are shown as bright and dark dots in the image. The noisy image has been expressed, following [21]:

$$y(t) = x(t) \times n(t), \quad (2)$$

where  $t$  is the time instant,  $y(t)$  is the noised image,  $x(t)$  is the free-noise image,  $n(t)$  is the speckle noise matrix, and  $\times$  defines an element-wise multiplication.

This type of noise is well-modeled as a Gaussian distribution. The physical explanation is provided by the central limit theorem, which states that the sum of many independent and identically distributed random variables tends to behave as a Gaussian random variable [22]. A Gaussian distribution is defined by following a non-uniform distribution, skewed towards low values, and applied as speckle noise in the simulated sonar image (see Fig. 4(v)). This noise simulation is repeated for each virtual acoustic frame.

### 3.3.2. Integrating sonar device with Rock

After the imaging sonar simulation process, from the virtual underwater scene to the representation of the degraded acoustic sonar data by noise, the resulting sonar data is encapsulated as Rock's sonar data type (see Fig. 4(vi)). This data type is provided as I/O port of a Rock's component, allowing the interaction with other simulated models and applications.

## 4. Simulation results and experimental analysis

To evaluate our simulator, experiments were conducted by using a 3D model of an AUV equipped with an MSIS and an FLS. Different scenarios were casted and studied, considering the sonar device configurations summarized in Table 1. In the experimental analysis, as the scene frames are being captured by the sonars, the resulting acoustic images are sequentially presented, on-the-fly (see Figs. 7 and 8).

### 4.1. Experimental evaluation

The virtual FLS from AUV was used to insonify the scenes from three distinct scenarios. A docking station, in parallel with a pipeline on the seabed, composes **the first scenario** (see Fig. 7(a)); the target surface is well-defined in the simulated acoustic frame (see Fig. 7(d)), as well as the shadows and speckle noise; given that the docking station is metal-made, the texture and reflectivity were set such that a higher intensity shape was resulted in comparison with the other observable targets. **The second scenario** presents the vehicle in front of a manifold model in a non-uniform seabed (see Fig. 7(b)); the target model

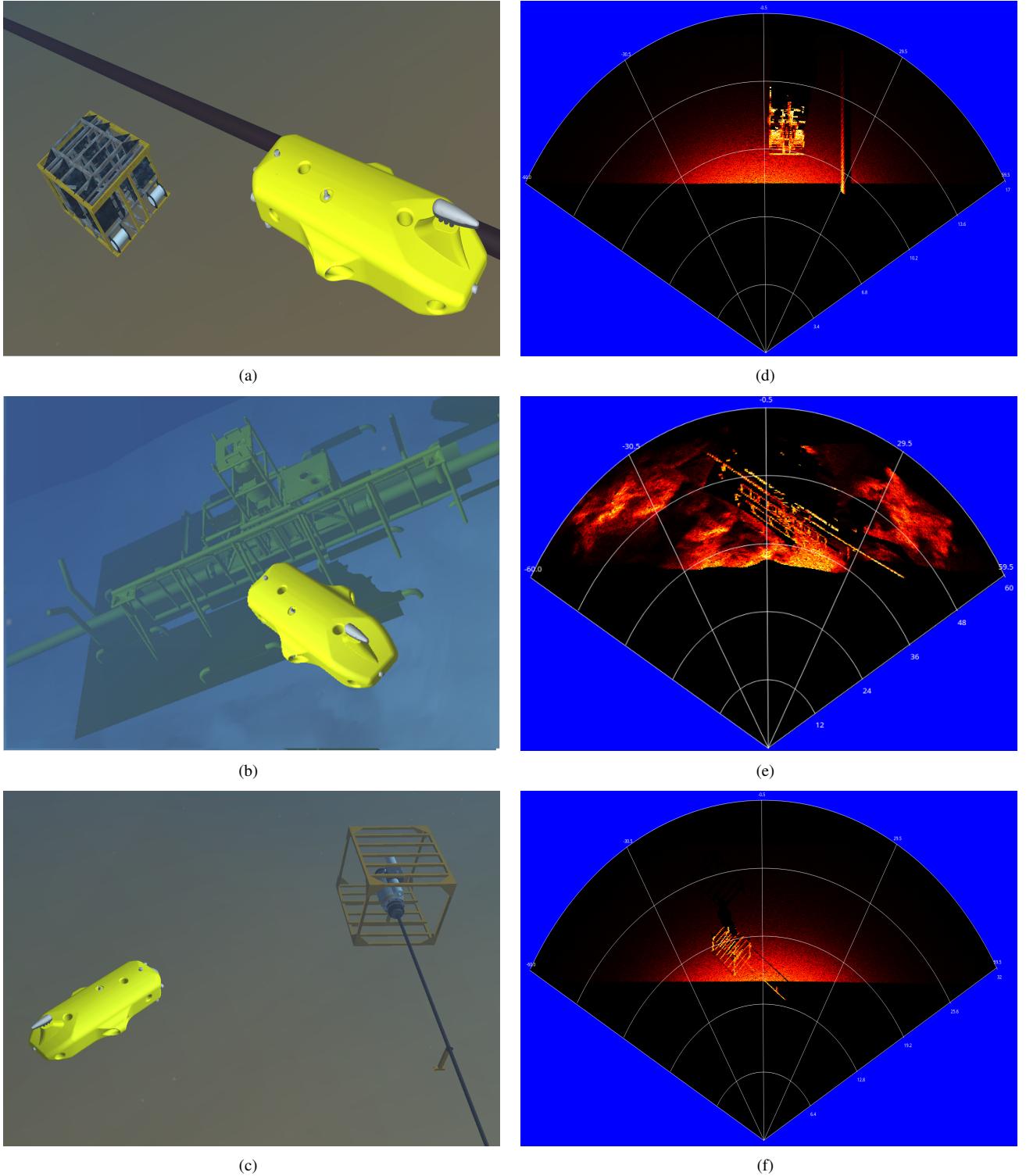


Figure 7: Forward-looking sonar simulation experiments: (a), (b) and (c) present the virtual underwater trials, while (d), (e) and (f) are the correspondent acoustic representations of each scenario, respectively.

371 was insonified to generate the sonar frame from the underwa-  
 372 ter scene (see Fig. 7(e)); the frontal face of the target, as well  
 373 the portion of the seabed and the degraded data by noise, are  
 374 clearly visible in the FLS image; also, a long acoustic shadow  
 375 is formed behind the manifold, occluding part of the scene. The

376 **third scenario** contains a sub-sea isolation valve (SSIV) struc-  
 377 ture, connected to a pipeline in the bottom (see Fig. 7(c)); the  
 378 simulated acoustic image, depicted in Fig. 7(f), also present  
 379 shadows, material properties and speckle noise effects. Due to  
 380 sensor configuration and robot position, the initial bins usually

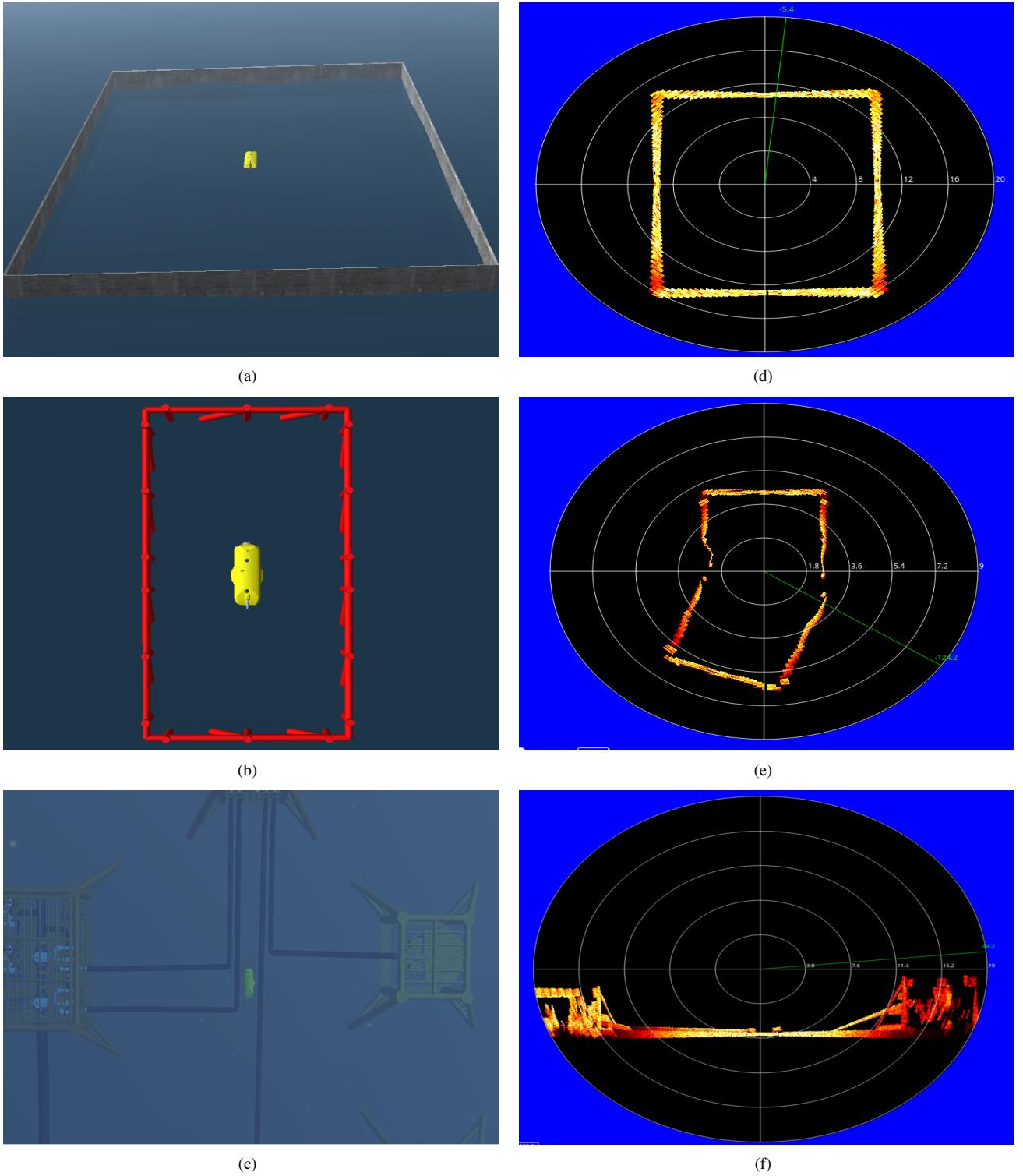


Figure 8: Experiments using mechanical scanning imaging sonar in three different scenarios (a), (b) and (c), and the respective processed simulated frames in horizontal orientation in (d) and (e), and vertical orientation in (f).

381 present a blind region in the three simulated scenes, caused by  
 382 absence of objects at lower ranges, similar to real sonar images.  
 383 It is noteworthy that the brightness of sea-floor decreases as it  
 384 is farther from sonar, because of the normal orientation of the  
 385 surface.

386 The MSIS was also simulated in three different experiments.  
 387 The robot in a big textured tank composes **the first scene** (see  
 388 Fig. 8(a)); similar to the first scenario of FLS experiment, the  
 389 reflectivity and texture were set to the target; the rotation of the  
 390 sonar head position, by a complete  $360^\circ$  scanning, produced

Table 2: Processing time to generate forward-looking sonar samples with different parameters.

# of samples	# of beams	# of bins	Field-of-view	Average time (ms)	Std dev (ms)	Frame rate (fps)
500	128	500	120° x 20°	54.7	3.7	18.3
500	128	1000	120° x 20°	72.3	8.9	13.8
500	256	500	120° x 20°	198.7	17.1	5.0
500	256	1000	120° x 20°	218.2	11.9	4.6
500	128	500	90° x 15°	77.4	11.8	12.9
500	128	1000	90° x 15°	94.6	10.2	10.6
500	256	500	90° x 15°	260.8	18.5	3.8
500	256	1000	90° x 15°	268.7	16.7	3.7

Table 3: Processing time to generate mechanical scanning imaging sonar samples with different parameters.

# of samples	# of bins	Field-of-view	Average time (ms)	Std dev (ms)	Frame rate (fps)
500	500	3° x 35°	8.8	0.7	113.4
500	1000	3° x 35°	34.5	1.6	29.0
500	500	2° x 20°	10.3	0.6	96.7
500	1000	2° x 20°	41.7	3.7	24.0

391 the acoustic frame of tank walls (see Fig. 8(d)). **The second**  
392 **scene** involves the vehicle’s movement during the data acqui-  
393 sition process; the scene contains a grid around the AUV (see  
394 Fig. 8(b)), captured by a front MSIS mounted horizontally; this  
395 trial induces a distortion in the final acoustic frame, because the  
396 relative sensor position with respect to the surrounding object  
397 changes, as the sonar image is being built (see Fig. 8(e)); in  
398 this case, the robot rotates 20° left during the scanning. **The**  
399 **last scene** presents the AUV over oil and gas structures on the  
400 sea bottom (see Fig. 8(c)); using an MSIS located in the back  
401 of the AUV with a vertical orientation, the scene was scanned  
402 to produce the acoustic visualization; as illustrated in Fig. 8(f),  
403 object surfaces present clear definition in the slice scanning of  
404 the sea-floor.

405 All the experimental scenarios was defined in order to pro-  
406 vide enough variability of specific phenomena usually found in  
407 real sonar images, such as acoustic shadows, noise interference,  
408 surface irregularities and properties, distortion during the acqui-  
409 sition process and changes of acoustic intensities. However, the  
410 speckle noise application is restricted to regions with acoustic  
411 intensity, as shown in Figs. 7(f) and 8(d). This fact is due to our  
412 sonar model be multiplicative (defined in Eq. 2). In real sonar  
413 images, the noise also granulates the shadows and blind regions.  
414 The sonar simulator can be improved by inserting an additive  
415 noise to our model. The impact of incorporating additive noise  
416 on the image is more severe than that of multiplicative, and we  
417 decided to collect more data before including a specific addi-  
418 tive noise in our simulator, at this moment. A second feature  
419 missing in our simulated acoustic images are the ghost effects  
420 caused by reverberation. This lacking part can be addressed by  
421 implementation of a multi-path propagation model [23], where  
422 the signal propagates along several different paths, resulting in  
423 fading and reverberation effects. Simulating the multi-path re-

424 flection is computationally costly, thus we need more time to  
425 model and include the reverberation phenomenon, considering  
426 the real-time constraints.

#### 427 4.2. Computational time

428 Performance evaluation of the simulator was assessed by  
429 considering the suitability to run real-time applications. The  
430 experiments were performed on a Intel Core i7 3540M proce-  
431 sor, running at 3 GHz with 16GB DDR3 RAM memory and  
432 NVIDIA NVS 5200M video card, with Ubuntu 16.04 64 bits  
433 operating system. The elapsed time of each sonar data is stored  
434 to compute the average time, standard deviation and frame rate  
435 metrics, after 500 iterations. The results found is summarized in  
436 Tables 2 and 3. After changing the sonar rendering parameters,  
437 such as number of bins, number of beams and field-of-view,  
438 the proposed approach generated the sonar samples with a high  
439 frame rate, for both sonar types, in comparison to real-world  
440 sonars. For instance, the Tritech Gemini 720i, a real forward-  
441 looking sonar sensor, with a field-of-view of 120° by 20° and  
442 256 beams, presents a maximum update rate of 15 frames per  
443 second; so, the obtained results allow the use of the sonar sim-  
444 ulator for real-time applications. Also, the MSIS produced data  
445 in the simulator is able to complete a 360° scan sufficiently fast  
446 in comparison with a real sonar as Tritech Micron DST. For the  
447 FLS device, these rates are superior to the rates lists by De-  
448 Marco *et al* [4] (330ms) and Saç *et al* [3] (2.5min). For MSIS  
449 type, to the best of our knowledge, there is no previous work  
450 for comparison.

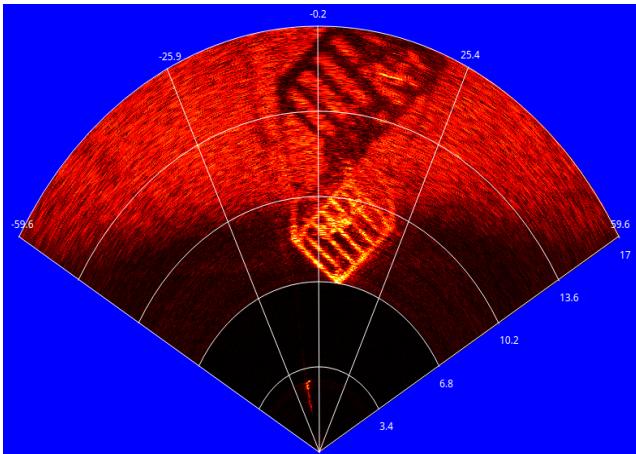
451 According to previous results, since the number of bins is  
452 directly proportional to sonar image resolution, we can con-  
453 clude that the number of bins used affects the computational  
454 time; when the number of bins increases, the simulator will



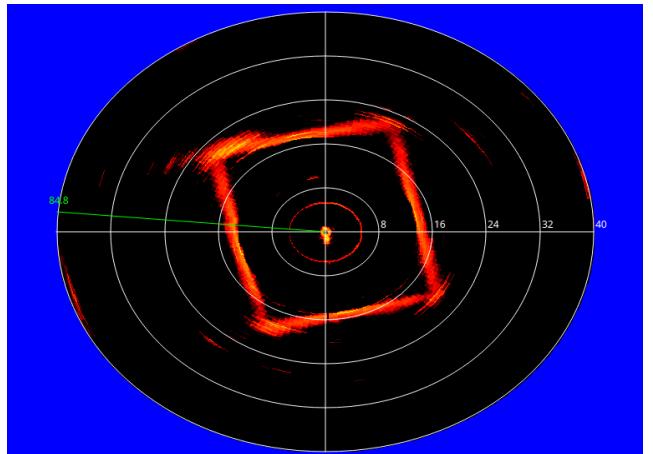
(a)



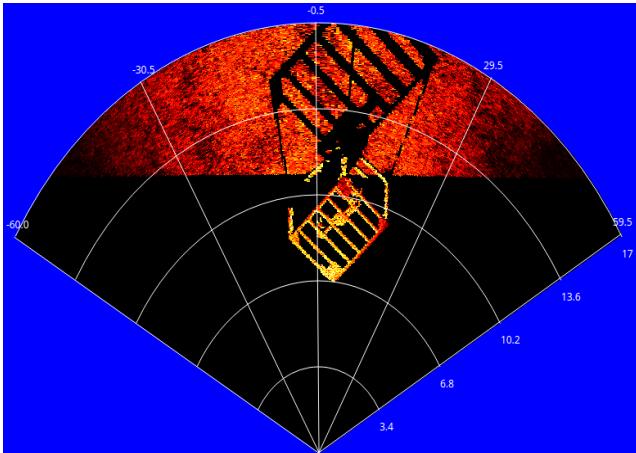
(d)



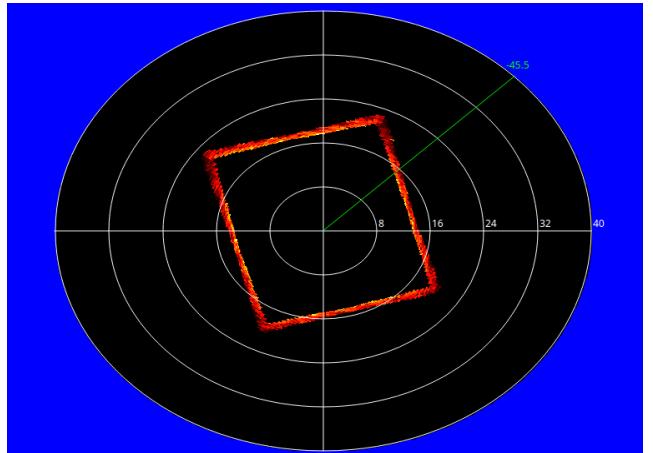
(b)



(e)



(c)



(f)

Figure 9: Target objects used in the qualitative experimental evaluation: subsea isolation valve (SSIV) (a) and big tank (d). Real-world sonar images and the virtual images generated by our approach, with the same device configurations: SSIV taken with Tritech Gemini 720i (b) and the corresponding simulated FLS image (c); tank walls taken with Tritech Micron DST (e) and the following simulated MSIS representation (f).

455 have a bigger scene frame to compute and to generate the sonar  
456 data.

#### 457 4.3. Quality evaluation of the simulated sonar image

458 Numerically assessing the performance of a sonar simulator  
459 is a non-trivial task. As sonar simulators are expected to work  
460 as trustworthy environment to avoid in-field experiments, the

Table 4: Similarity evaluation results between real-live and simulated sonar images.

Scene	MSE	PSNR	SSIM	MS-SSIM	SIFT
SSIV	0.01	20.002	0.361	0.654	4.19%
Tank	0.01	23.787	0.834	0.895	28.8%

goal of quantitative evaluation should be to demonstrate that the real-world sonar image can be aligned with the synthetic one. Just two [3, 4] out of the seven works analyzed in Section 1 perform quantitative evaluation of the proposed simulators, although restricted only to computational time assessment.

Similarity should be carried out by considering a real-world and a virtual scene, both insonified by real and virtual sonar devices, respectively, in the exact same conditions. In other words, it means that we have to guarantee the same poses of the AUV in the real and virtual scenarios, which, in turn, should present the same elements being insonified; measuring the alignment of the images (real and virtual) works as comparing how much the simulated sonar image is similar to the real one with respect to pixel intensity and location and image components.

The process of measuring the image quality can be performed by a set of metrics, such as: mean-squared error (MSE), peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM), multi-scale structural similarity index measure (MS-SSIM), and interesting point detectors and distances (e.g., scale invariant feature transform - SIFT). To evaluate the quality of our approach, we attempted to model two real objects insonified by our AUV using FLS and MSIS, illustrated in Figs. 9(a) and 9(d): a subsea isolation valve (SSIV) under the sea; and the big tank walls. Once the scenes were modeled, a pair of sonar images were produced: one from the real sonar device and another from the simulated sonar device, for each scene (Figs. 9(b), 9(c), 9(e) and 9(f)). After that, we applied the five aforementioned metrics to compute the degree of similarity between each pair of sonar images, presented in Table 4.

By the mathematical metrics (MSE and PSNR) results, based on pixel location and intensity differences, the simulated images presented a low error rate against the real images. Once the viewpoints in real and virtual scenes are approximated, the simulated images did not suffer from significant changes of insonified objects, as explained in Section 2.1. Also, the additive noise in real images contains low intensity values, which did not interfere on these metrics evaluations. The perceptual metrics (SSIM and MS-SSIM), based on human visual system, take into account visual attributes of images, such as luminance, contrast and structural terms. Since the tank scene has less insonified regions than the SSIV, and the FLS is more sensitive to the additive noise, the perceptual metrics results presented higher similarity for MSIS images than FLS. By the end, the point-based methods do not work properly in noised images. So, it is expected that the SIFT presented low similarity results for both sonar devices.

## 5. Conclusion and future work

A GPU-based simulator for imaging sonar was proposed here. The system is able to reproduce the operation mode of two different types of sonar devices (FLS and MSIS) in real-time. The real sonar image singularities, such as multiplicative noise, surface properties and acoustic shadows are addressed, and represented in the simulated frames. Specially for the shadows, the acoustic representation can present information as useful as the insonified object. Considering the qualitative and quantitative results, the sonar simulator can be used by feature detection algorithms, based on corners, lines and shapes. Also, the computational time to build one sonar frame was calculated using different device settings. The vertex and fragment processing during the underwater scene rendering accelerates the rendered sonar image, providing an average time close or better than real-world imaging devices. These results allow the use of this imaging sonar simulator by real-time applications, such as obstacle detection and avoidance, and object tracking. We are working now on a way to add the reverberation effect to perform a more close-to-real sensing, without significantly affecting the computational time. We are also working on how to include an additive noise in the simulation of the acoustic images. Future works will focus on qualitative and time consuming comparison with other sonar simulators.

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