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

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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 the 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 system is able to operate close to or faster than the real-world devices. Also, our method generates visually realistic sonar images when compared with real-world sonar images of the same scenes.

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 simulate 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

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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 ultrasound 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 defined by series of acoustic tubes, being always orthogonal to the current sonar view, where the reverberation and objects surface irregularities are also addressed.

1.1. Contributions

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

The main goal here is to build quality and low time-consuming acoustic frames, according to underwater sonar image formation and operation modes (see Section 2). The pulse distance, the echo intensity and the sonar field-of-view parameters are extracted from the underwater scene during the rasterization pipeline, and subsequently fused to generate the simulated sonar data, as described in Section 3. Qualitative, quantitative and time evaluation results for the two different sonar devices are presented in Section 4, allowing the use of the proposed simulator by real-time applications. Conclusions and future work are drawn in Section 5.

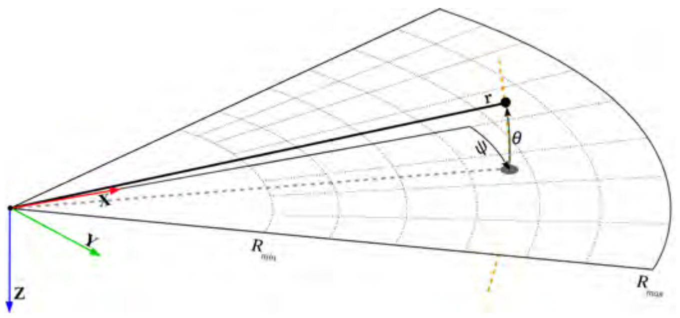


Figure 1: Imaging sonar geometry. By the projection process, all 3D points belonging to the same elevation arc (represented as dashed orange line) will be represented to the same image point in the 2D plane. Range r and azimuth angle ψ are measured, and elevation angle θ is lost. Sonar coverage area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

2. Imaging sonar operation

Sonars are echo-ranging devices that use acoustic energy to locate and survey objects in a desired area. The sonar transducer emits pulses of sound waves (or ping) until they hit any object or are completely absorbed. When the acoustic signal collides with a surface, part of this energy is reflected, while other is refracted. The sonar data is built by plotting the echo measured back versus time of acoustic signal. The transducer reading in a given direction forms a *beam*. A single beam transmitted from a sonar is illustrated in Fig. 1. The horizontal and vertical beamwidths are represented by the azimuth ψ and elevation θ angles, respectively, where each sampling along the beam is named as *bin*. The sonar coverage area is defined by R_{min} and R_{max}. Since the speed of sound underwater is known, or can be measured, the time delay between the emitted pulses and the respective echoes (named as *time of flight*) reveals how far the objects are (distance r), as well as how fast they are moving. The backscattered acoustic power in each bin determines the echo intensity value.

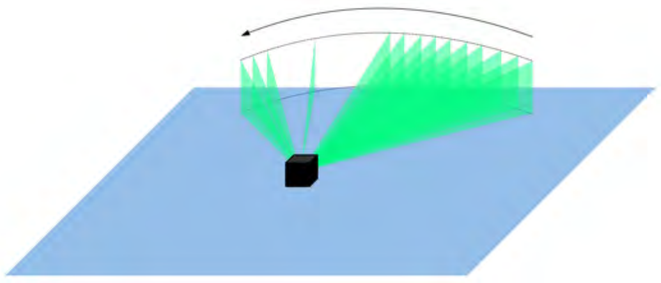
With different azimuth directions, the array of transducer readings forms the final sonar image. Since all incoming signals converge to the same point, the reflected echoes could have been originated anywhere along the corresponding elevation arc at a fixed range, as depicted in Fig. 1. In the acoustic representation, the 3D information is lost in the projection into a 2D image.

2.1. Sonar characteristics

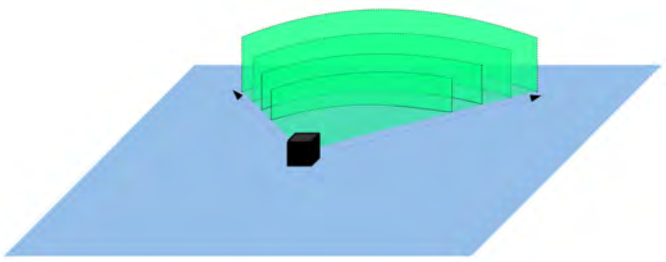
Although sonar devices overcome main limitations of optical sensors, they present more difficult data interpretation due to:

a) **Shadowing**: This effect is caused by objects blocking the sound waves transmission, and causing regions behind them, without acoustic feedback. These regions are defined by a black spot in the sonar image, occluding part of the scene;

b) **Non-uniform resolution**: The amount of pixels used to represent an echo intensity record in the Cartesian coordinate system grows as its range increases. This situation causes image distortions and object flatness;



(a)



(b)

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

c) **Changes in viewpoint**: Imaging the same scene from different viewpoints can cause occlusions, shadows movements and significant changes of observable objects [9]. For instance, when an outstanding object is insonified, its shadow is shorter, as the sonar becomes closer;

d) **Low signal-to-noise ratio (SNR)**: Sonars suffer from low SNR mainly due the very-long-range scanning, and the presence of speckle noise introduced by acoustic wave interferences [10];

e) **Reverberation**: This phenomenon is caused when multiple acoustic waves, returning from the same object, are detected over the same ping, producing duplicated objects.

2.2. *Types of underwater sonar devices*

The most common types of underwater acoustic sonars are MSIS and FLS. In the former, the sonar image is built for each pulse, with one beam per reading (see Fig. 2(a)); the resulting sonar images in MSIS are usually depicted on a display pulse by pulse, and the head position reader is rotated according to motor step angle. After a full 360° sector reading (or the desired sector defined by left and right limit angles), the accumulated sonar data is overwritten. The acquisition of a scanning image involves a relatively long time, introducing distortions caused by the vehicle movements. This sonar device is generally applied in obstacle avoidance [11] and navigation [12] applications. As illustrated in Fig. 2(b), the whole forward view of an FLS is scanned and the current data is overwritten by the next scan in a high frame rate, with all beams being read simultaneously; this is similar to a streaming video imagery for real-time applications; this imaging sonar is commonly used for navigation [13], mosaicing [9], target tracking [14] and 3D reconstruction [15].

3. GPU-based sonar simulation

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

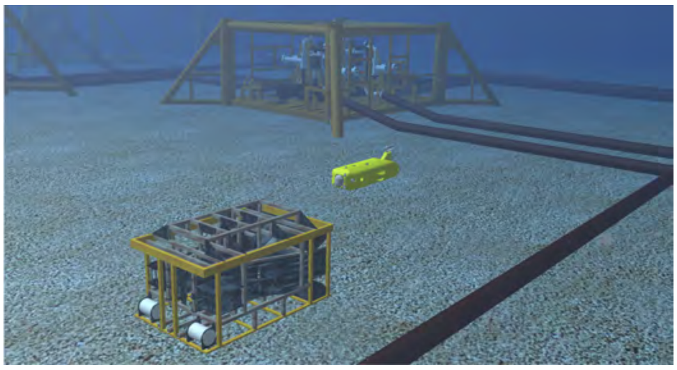


Figure 3: The virtual AUV in Rock-Gazebo underwater scene.

3.1. *Rendering underwater scene*

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

All scene aspects, such as world model, robot parts (including sensors and joints) and other virtual objects are defined by simulation description files (SDF), which use the SDFormat [18], an XML format used to describe simulated models and environments for Gazebo. Visual and collision geometries of vehicle and sensors are also described in specific file formats. Each component described in the SDF file becomes a Rock component, which is based on the Orocos real-time toolkit (RTT) [19], providing I/O ports, properties and operations as communication layers. When the models are loaded, Rock-Gazebo allows interaction between real world or simulated system components with the simulated models. A resulting scene sample of this integration is illustrated in Fig. 3.

3.2. *Sonar rendering*

A rendering pipeline can be customized by defining GPU shaders. A shader is written in OpenGL Shading Language (GLSL) [20], a high-level language with a C-based syntax, which enables more direct control of graphics pipeline, avoiding the

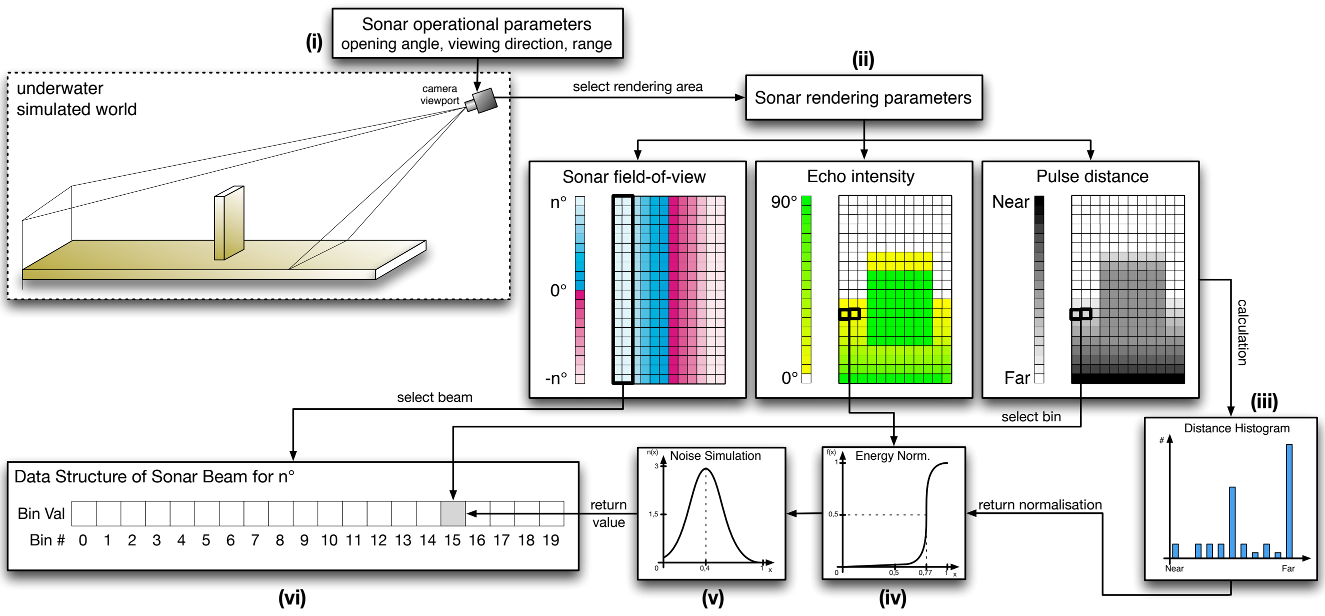


Figure 4: A graphical overview of the imaging sonar simulation process: (i) a virtual camera, specialized as the sonar device, samples the underwater scene; (ii) three 2D parameters are calculated by shader rendering on GPU: sonar field-of-view, echo intensity and pulse distance; the shader information 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.

use of low-level or hardware-specific languages. Shaders can describe the characteristics of either a vertex or a fragment (a single pixel). Vertex shaders are responsible by transforming the vertex position into a screen position by the rasterizer, generating texture coordinates for texturing, and lighting the vertex to determine each color. The rasterization results, in a set of pixels to be processed by fragment shaders, manipulate pixel location, depth and alpha values, and interpolated parameters from the previous stages, such as colors and textures.

In our work, the underwater scenes are sampled by a virtual camera (frame-by-frame), whose optical axis is aligned with the **opening angle**, the intended **viewing direction** and the coverage **range** of the simulated sonar device (see Fig. 4(i)). To reproduce the sonar imaging operation by using virtual camera frames, three parameters are computed in fragment and vertex 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° of field-of-view, the zero angle is in the center of the virtual camera, spanning 60° to the left and 60° to the right.

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

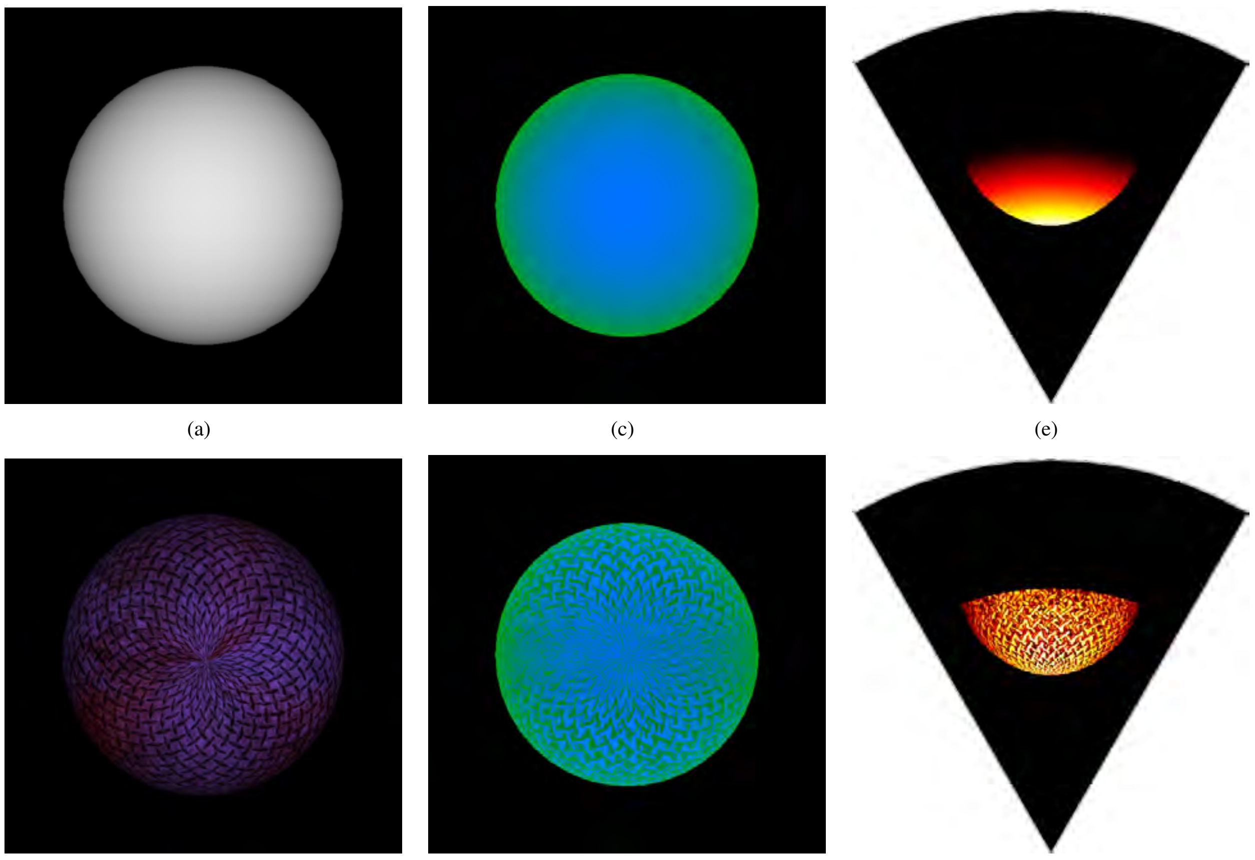


Figure 5: Example of shader rendering with normal mapping: A sphere without (a) and with texture (b); respective shader image representations of the spheres in (c) and (d), where the blue area represents the echo intensity parameter, while the green area means the pulse distance parameter. The final 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.

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

3.3. Simulating operation of the sonar device

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

Due to the acoustic beam spreading and absorption in the water, the final bins have less echo strength than the first ones. This is so, because the energy is twice lost in the environment. To tackle with that issue, sonar devices use an energy normalization based on time-varying gain for range dependence compensation, which spreads losses in the bins. In our simulation approach, the accumulated intensity, I_{bin}, in each bin (see Fig.

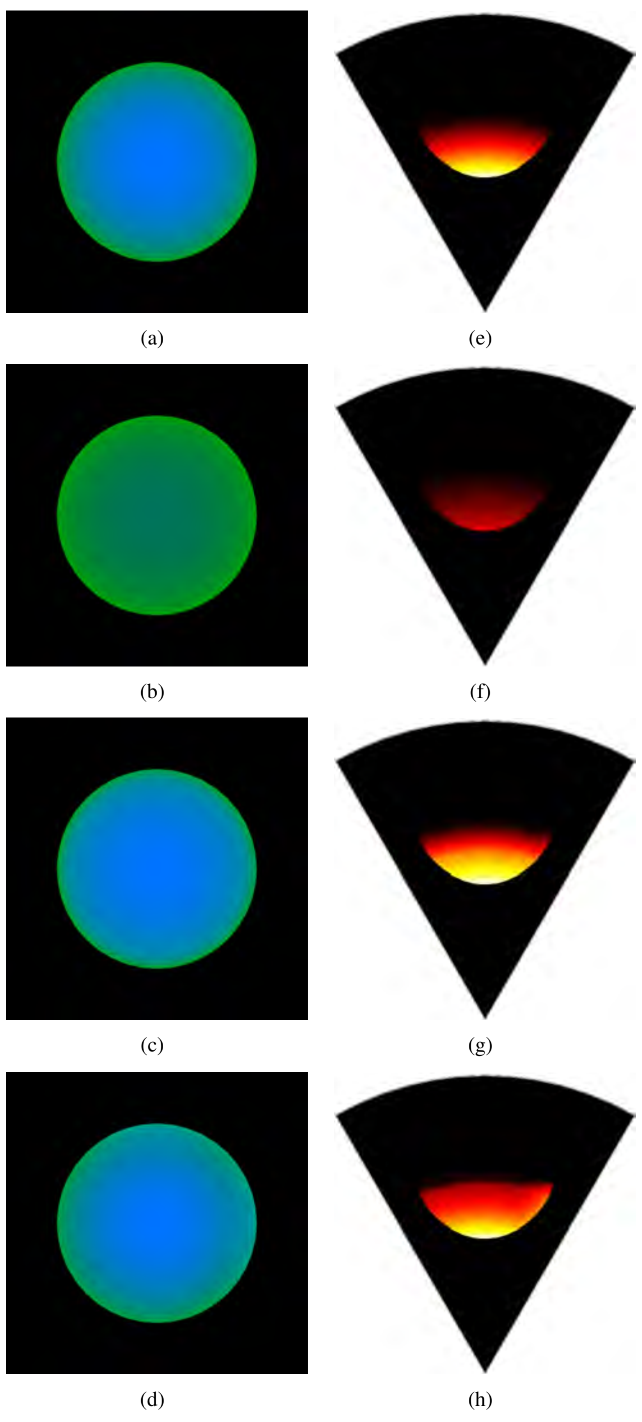


Figure 6: Examples of different reflectance values, ρ, applied in shader image representation of the same target, where blue is the echo intensity parameter and green is the pulse distance parameter: (a) raw image; (b) ρ = 0.35; (c) ρ = 1.40; and (d) ρ = 2.12. The following acoustic images are presented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

4(iv)) is normalized as

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

where x is the pixel location, N is the distance histogram value (number of pixels) of that bin, $S(i_x)$ is a sigmoid function, i_x is

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°

the echo intensity value of the pixel x, and $\times$ defines an element-wise multiplication.

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

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

$$y(t) = x(t) \times n(t), \tag{2}$$

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).

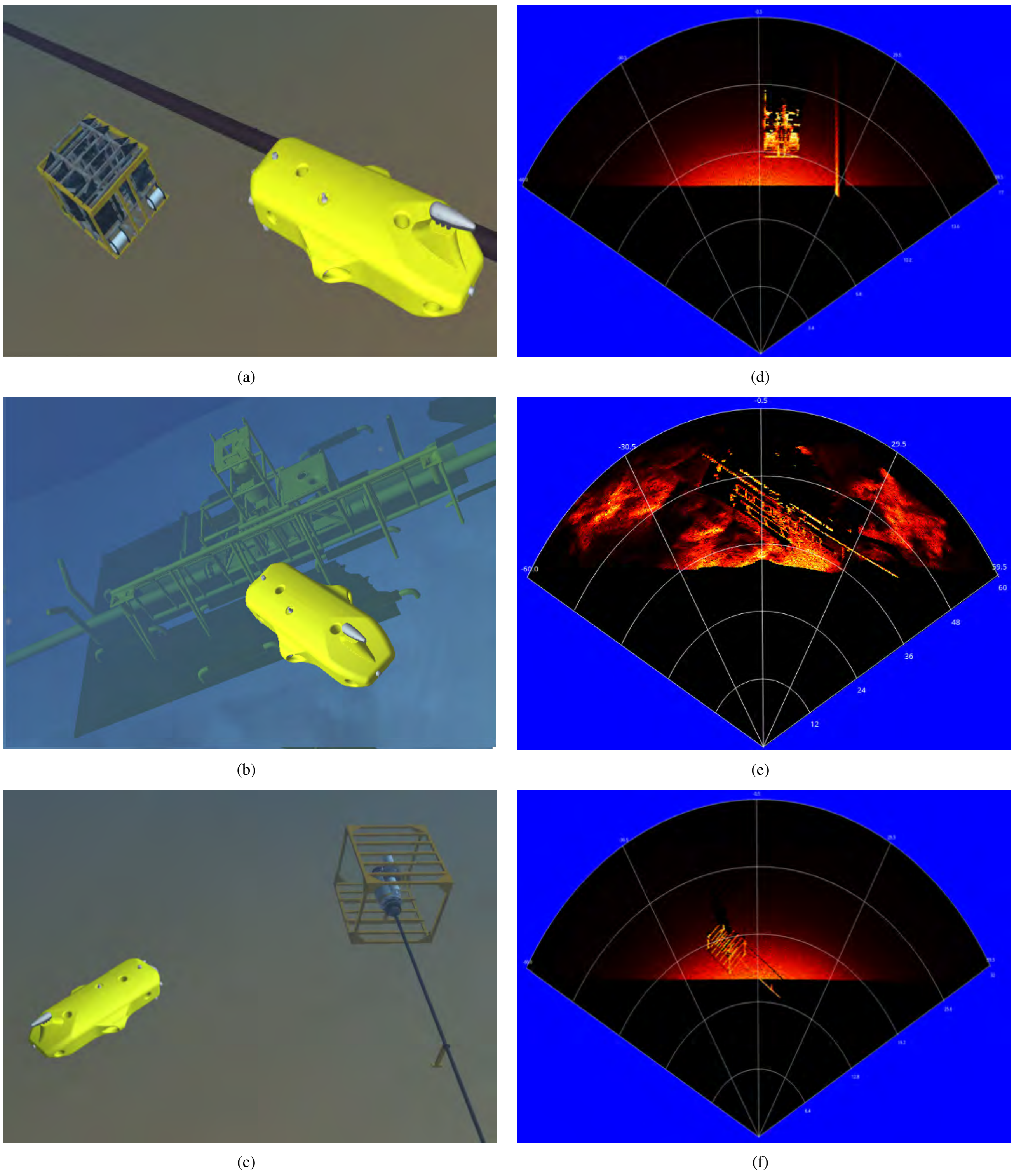
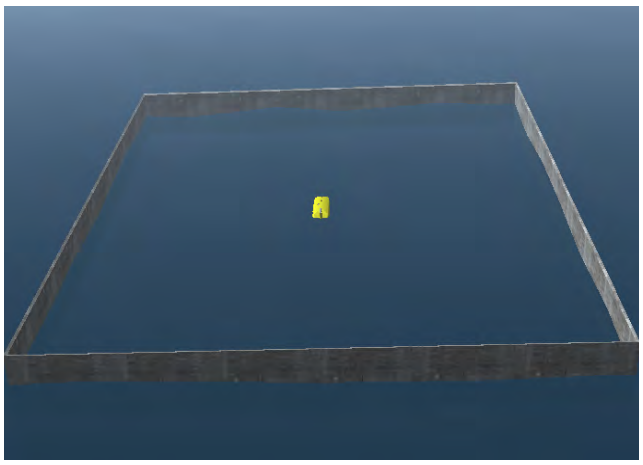


Figure 7: Forward-looking sonar simulation experiments: (a), (b) and (c) present the virtual underwater trials, while (d), (e) and (f) are the correspondent acoustic representations of each scenario, respectively.

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



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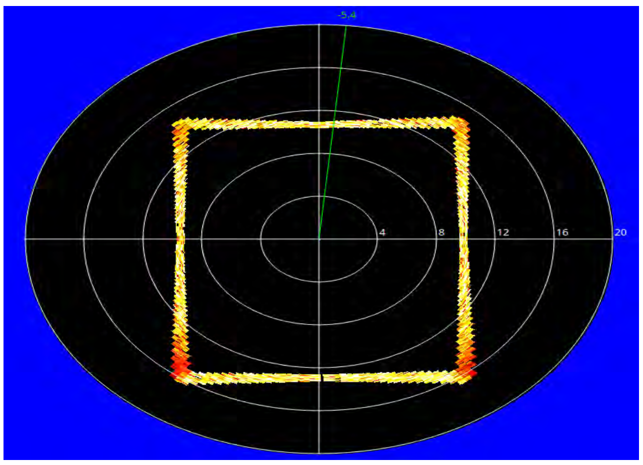

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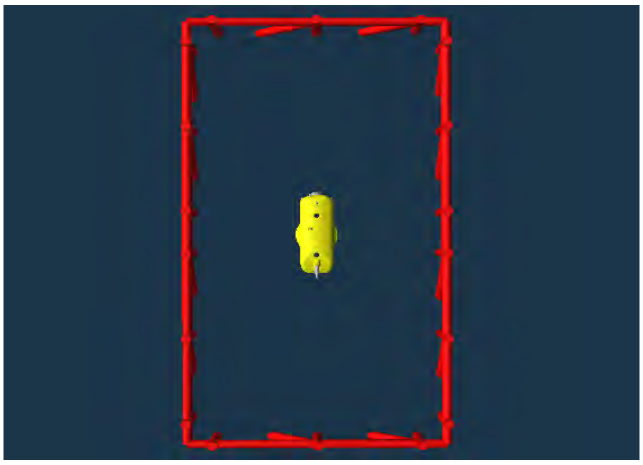

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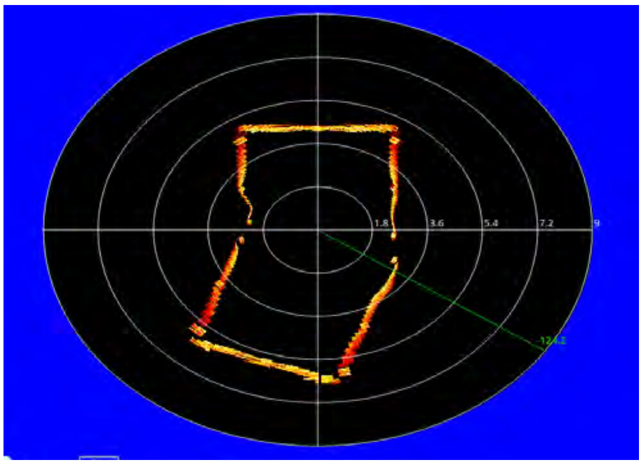

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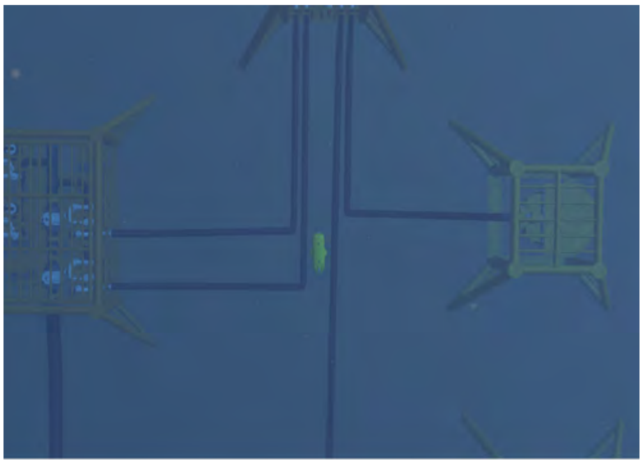

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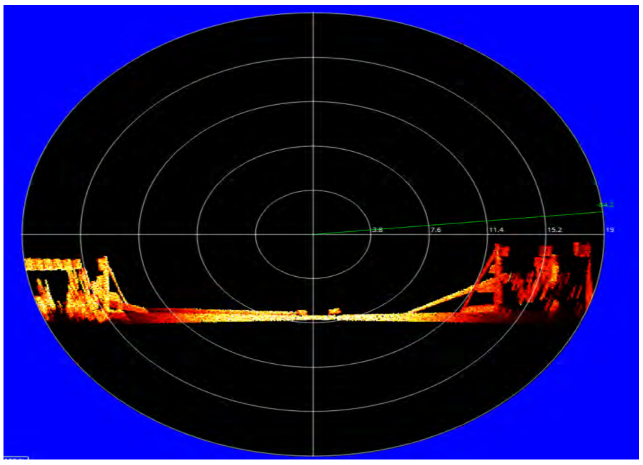

(f)

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).

model in a non-uniform seabed (see Fig. 7(b)); the target model was insonified to generate the sonar frame from the underwater scene (see Fig. 7(e)); the frontal face of the target, as well the portion of the seabed and the degraded data by noise, are clearly visible in the FLS image; also, a long acoustic shadow is formed behind the manifold, occluding part of the scene. **The third scenario** contains a subsea isolation valve (SSIV) structure, connected to a pipeline in the bottom (see Fig. 7(c)); the simulated acoustic image, depicted in Fig. 7(f), also present shadows, material properties and speckle noise effects. Due to

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

sensor configuration and robot position, the initial bins usually present a blind region in the three simulated scenes, caused by absence of objects at lower ranges, similar to real sonar images. It is noteworthy that the brightness of seafloor decreases as it is farther from sonar, because of the normal orientation of the surface.

The MSIS was also simulated in three different experiments. The robot in a big textured tank composes **the first scene** (see Fig. 8(a)); similar to the first scenario of FLS experiment, the reflectivity and texture were set to the target; the rotation of the sonar head position, by a complete 360° scanning, produced the acoustic frame of tank walls (see Fig. 8(d)). **The second scene** involves the vehicle's movement during the data acquisition process; the scene contains a grid around the AUV (see Fig. 8(b)), captured by a front MSIS mounted horizontally; this trial induces a distortion in the final acoustic frame, because the relative sensor position with respect to the surrounding object changes, as the sonar image is being built (see Fig. 8(e)); in this case, the robot rotates 20° left during the scanning. **The last scene** presents the AUV over oil and gas structures on the sea bottom (see Fig. 8(c)); using an MSIS located in the back of the AUV with a vertical orientation, the scene was scanned to produce the acoustic visualization; as illustrated in Fig. 8(f), object surfaces present clear definition in the slice scanning of the sea-floor.

All the experimental scenarios was defined in order to provide enough variability of specific phenomena usually found in real sonar images, such as acoustic shadows, noise interference, surface irregularities and properties, distortion during the acquisition process and changes of acoustic intensities. However, the speckle noise application is restricted to regions with acoustic intensity, as shown in Figs. 7(f) and 8(d). This fact is due to our sonar model be multiplicative (defined in Eq. 2). In real sonar images, the noise also granulates the shadows and blind regions. The sonar simulator can be improved by inserting an additive noise to our model. The impact of incorporating additive noise on the image is more severe than that of multiplicative, and we decided to collect more data before including a specific additive noise in our simulator, at this moment. A second feature missing in our simulated acoustic images are the ghost effects caused by reverberation. This lacking part can be addressed by implementation of a multi-path propagation model [23], where the signal propagates along several different paths, resulting in fading and reverberation effects. Simulating the multi-path reflection is computationally costly, thus we need more time to model and include the reverberation phenomenon, considering the real-time constraints.

4.2. *Computational time*

Performance evaluation of the simulator was assessed by considering the suitability to run real-time applications. The experiments were performed on a Intel Core i7 3540M processor, running at 3 GHz with 16GB DDR3 RAM memory and NVIDIA NVS 5200M video card, with Ubuntu 16.04 64 bits operating system. The elapsed time of each sonar data is stored to compute the average time, standard deviation and frame rate metrics, after 500 iterations. The results found is summarized in Tables 2 and 3. After changing the sonar rendering parameters, such as number of bins, number of beams and field-of-view, the proposed approach generated the sonar samples with a high frame rate, for both sonar types, in comparison to real-world sonars. For instance, the Tritech Gemini 720i, a real forward-looking sonar sensor, with a field-of-view of 120° by 20° and 256 beams, presents a maximum update rate of 15 frames per second; so, the obtained results allow the use of the sonar simulator for real-time applications. Also, the MSIS produced data

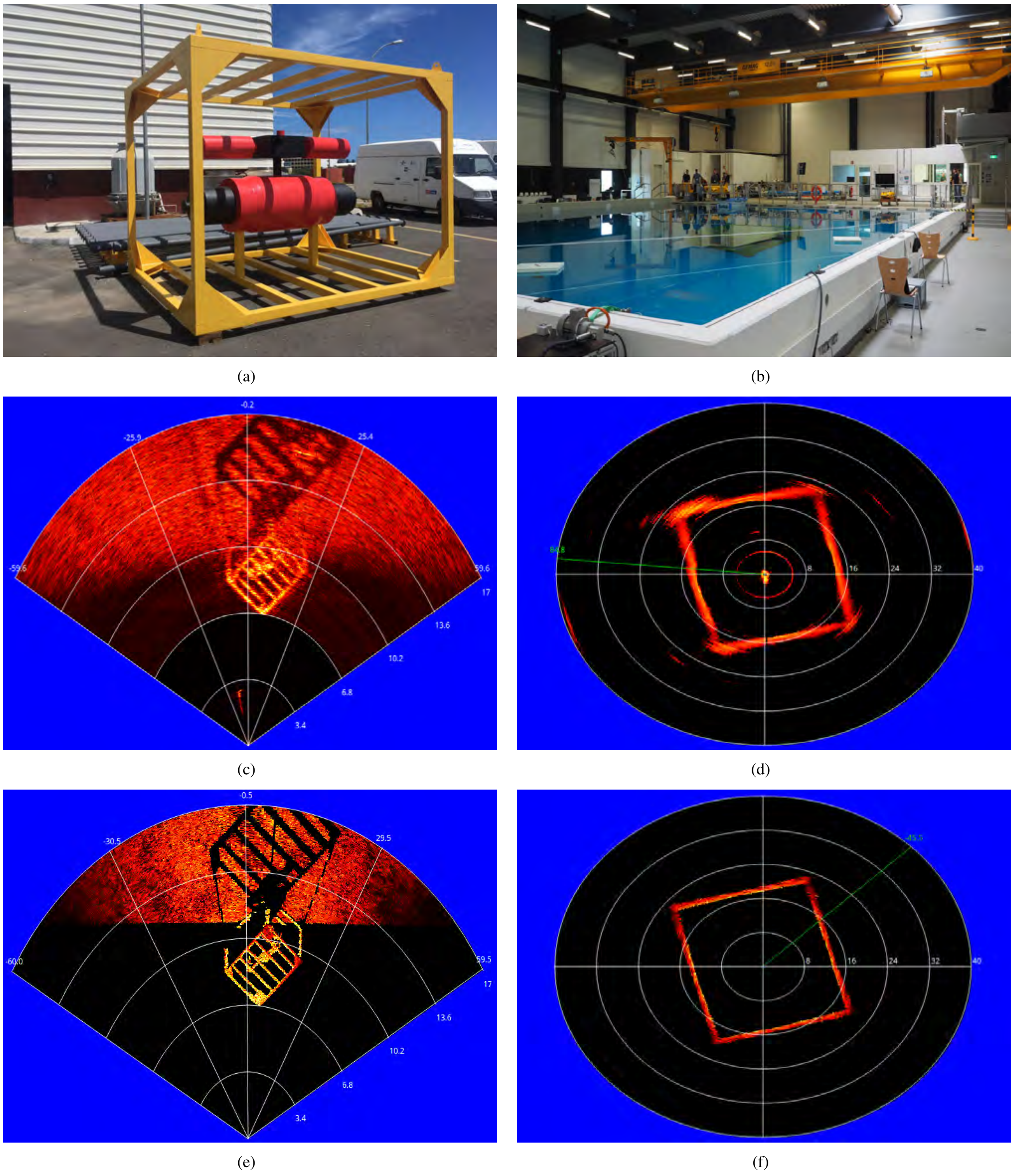

Figure 9: Target objects used in real and simulated experiments, insonified by Tritech Gemini 720i (FLS) and Tritech Micron DST (MSIS) sensors: (a) a subsea isolation valve (SSIV) and (b) a big tank. Real-world sonar and virtual images generated by our system: (c) sonar image of the SSIV captured with the FLS device and (e) the simulated image; (d) tank walls captured by the MSIS device and (f) the simulated representation.

in the simulator is able to complete a 360° scan sufficiently fast in comparison with a real sonar as Tritech Micron DST. For the FLS device, these rates are superior to the rates lists by De-Marco *et al* [4] ($330ms$) and Saç *et al* [3] ($2.5min$). For MSIS type, to the best of our knowledge, there is no previous work for comparison.

According to previous results, since the number of bins is directly proportional to sonar image resolution, we can conclude that the number of bins used affects the computational time; when the number of bins increases, the simulator will have a bigger scene frame to compute and to generate the sonar data.

4.3. Quantitative evaluation of the simulated sonar image

Numerically assessing the performance of a sonar simulator is a non-trivial task. As sonar simulators are expected to work as trustworthy environment to avoid in-field experiments, the 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 simulated sonar devices, respectively, at the same conditions. In other words, it means that we have to guarantee the same pose 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 simulated) 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, among which, five were chosen to be used here: Mean-squared error (MSE), peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM), multi-scale structural similarity index measure (MS-SSIM), and scale invariant feature transform (SIFT). MSE calculates the cumulative square error between the reference and estimated images; values closer to zero are better. PSNR measures the peak error, expressed in terms of logarithmic scale; by handling with 8-bit grayscale images, the closer PSNR is to $99dB$, the greater is similarity between the two images. SSIM evaluates the similarity of two images by performing a corresponding sliding window in the images; the more similar the images are, the average of window differences is closer to one. MS-SSIM is calculated as a weighted mean of SSIM rates, obtained for different scales of the reference and estimated images; as SSIM, the greater the values, the better is the results. SIFT compares the extracted interesting keypoints for both images; while the distance between the two set of descriptors over the keypoints in the two images approaches to zero, the greater the similarity degree. Here, all the metrics are normalized between zero and one range.

To evaluate the quality of the sonar images generated by our simulator, two real-world scenarios were modeled containing two target objects, which were insonified by an FLS and an MSIS: A SSIV (see Fig. 9(a)) submerged at Todos os Santos Bay, Salvador, Brazil; and the tank walls at DFKI Maritime Exploration Hall (see Fig. 9(b)). Figs. 9(c) and 9(e) are the results of the real and simulated sonar images of the SSIV, while Figs. 9(d) and 9(f)) illustrate the real and simulated acoustic representations of the tank walls. The real sonar images were acquired using the FlatFish AUV [24]. After modeling the two scenarios, the five metrics were applied in order to compute the degree of similarity between each pair of sonar images. Table 4 summarizes the results.

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

Scene	MSE	PSNR	SSIM	MS-SSIM	SIFT
SSIV (Figs. 9(c), 9(e))	0.010	0.463	0.361	0.654	0.042
Tank (Figs. 9(d), 9(f))	0.004	0.489	0.834	0.895	0.288

Since the viewpoints in the real and the virtual scenes are approximated, the simulated images did not suffer from significant changes in the insonified objects, as explained in Section 2.1. However, the acoustic details and effects missing in the simulated images, such as reverberation and additive noise, probably influenced the results of PSNR, which did not even reach 50%, for the similarity of two scenes. SSIM and MS-SSIM take into account visual attributes of the images, such as luminance, contrast and structural terms, rather than pixel location; since the tank scene is an object simpler than the SSIV, in terms of insonified regions, and the FLS is more sensitive to the additive noise than MSIS, the results of the SSIM-based metrics presented higher similarity for MSIS images than FLS ones. SIFT has a limited performance when directly applied in images corrupted by multiplicative speckle noise [25]; this fact explains why the SIFT presented the worst similarity results for both sonar devices. MSE evaluates the two images in general, by considering the position of the elements in the scene; also, the two scenes were insonified by sonars presenting approximately the same poses, as well as, the simulator depicts the sonar image with echo intensity close to the real-world sonar image; these situations can explain why MSE was the metric with the best results, although a clear visual difference can still be observed in these latter two sonar images, due to the lack of the additive noise.

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 acoustic images. The resulting acoustic representation of shadows are so accurate as the insonified objects. 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 simulated sonar image, providing an average time close to or better than real-world imaging devices. These results allow the use of this imaging sonar simulator in 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. We expect that the addition of these two effects in the simulated sonar model will certainly improve the quantitative results, as well as, the visual perception of the resulting simulated images.

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