Experience OBSEA: a web-based 3D virtual environment of a seafloor observatory

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Abstract— Oceanographic data such as wave conditions (height, period, direction), wind, and sea currents are often difficult to interpret. What is the sea state given a certain wave height, wave directional spreading, and wind speed (e.g., 2 m, 29º, 18 m/s)? An expert user might be able to imagine the sea conditions with such information, but this will be almost impossible for a non-expert user. The common approach for visualizing oceanographic data and its variability is usually through tables and 2D graphs, for example plots, bar diagrams, and latitude-longitude maps. These visualizations are often limited to displaying raw data values, which still require user interpretation. With the purpose of providing a more intuitive view of the marine environment and sea conditions to a widespread audience, this work presents an experimental web application. The open-source application represents in a realistic and intuitive way the observations from a meteo-oceanographic and seafloor observatory located in the Western Mediterranean; the OBSEA observatory. The user can visualize the marine observatory facilities within a 3D virtual environment that changes and evolves according to the data acquired. This work aims at a digital twin of the seafloor observatory using near-real-time and historical data.

Keywords—data visualization, 3D virtual environment, webGL, ocean simulation, digital twin

I. Introduction

In recent years, the term "digital twin" has appeared in the field of ocean data management, e.g., "Digital Twins of the Ocean (DITTO)" from UN [1], "European DTO" from the European Commission [2], "Digital Twin Ocean" from Mercator Ocean International [3]. The concept of a digital twin arose in industrial design and engineering to describe a virtual copy of a device, system, or process that can be updated in real time according to the data collected by the system's sensors [1][2][3][4]. The basic model of a digital twin described in [5] consists of a physical entity, its equivalent virtual entity, and a data connection between the two.

In ocean and earth sciences, major efforts for digital twins concentrate on the data connection, that is data acquisition, and the virtual entity, that is modelling, forecasting, and simulation (see [6] and EU Commission funding [4]). These efforts mainly focus on creating global and local models of physical and biochemical processes that are updated with real-time data. Oceanographic digital twins rarely consider to represent such data and processes in realistic and real-time 3D environments, which is relevant according to [5]: "What currently happens is that humans take visual information, reduce it to symbols of numbers and letters, and then re-conceptualize it visually. In the process, we lose a great deal of information, and we introduce inefficiencies in time. The capability of the digital twin lets us directly see the situation and eliminate the inefficient and counterproductive mental steps of decreasing the information and translating it from visual information to symbolic information and back to visually conceptual information." M. Grieves [5] then proposes to create a virtual 3D model of the physical entity that is updated with the data collected from the physical entity.

To disseminate and communicate meteo-oceanographic data, dashboards with 2D graphs are commonly used [7][8]. Although dashboards are useful for scientists and researchers, some data may be difficult to interpret. More intuitive visualization tools can be designed using these data: 3D realistic virtual environments can be used to represent oceanographic conditions and simulations according to the observed parameters. There are initiatives to create digital twins of the

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ocean, such as the Gilligan Project [5] and Digital Twin Antarctica [6] and Digital Twin Hydrology [7] projects from the European Space Agency (ESA), which are in their first steps. In this work, the term "CGI digital twin" is used to describe a 3D virtual environment and simulation based on data sent from its physical relative environment. CGI stands for computer-generated imagery commonly used in the film industry and videogames.

There are several challenges in the representation of oceanographic variables in realistic 3D environments. A clearly demanding feature is the representation of the sea state, which includes variables such as significant wave height, wave directional spread, and wave period. To build a 3D sea state representation, knowledge of mathematics, physics, and computer graphics is required. Fortunately, virtual representations of the ocean surface have been extensively used in the film and video game industries [9]. For these industries, the sea surface and its evolution over time must be realistic, attractive, and interactive. In other sectors such as naval engineering, sea state simulations are used to test the performance of vessels [10]. In this case, the virtual representation must be accurate and physically consistent with governing laws. For a CGI digital twin of the sea state from observational data, it is essential that the simulation is consistent with the observed sea state and that it is updated in real time according to the data delivered by the sensors.

Meteorological measurements such as surface winds can be approached in a CGI digital twin by interacting with objects present in the virtual environment, such as the water spray from the sea surface, rain, or clouds. Additionally, the sea state should already contain some information about the wind, as it affects the ocean-wave spectrum [11]. Adding virtual elements, such as directional arrows, animated flags, or flying particles in the air, is a common strategy to represent wind direction and intensity in virtual environments. Eulerian flow vectors, i.e., moving particles showing direction, can also be added to the ocean surface, as in the mixed reality solution of the SailGP competition [8].

Subsurface currents measured by a seafloor observatory are not easily perceptible by the human eye. Therefore, they must be represented with additional virtual elements for clarity, such as directional arrows or flying particles. Other meteo-oceanographic variables such as seawater temperature, water pressure, water conductivity and salinity are mostly detectable by sensors and are not perceptible to the naked eye. Thus, variables that do not have a clear visual representation should be represented with numbers and graphs in a digital twin.

In this work, we developed a web-based prototype to provide a CGI digital twin of a marine observational system composed of a seafloor node and a meteo-oceanographic buoy (https://bluenetcat.github.io/OBSEA/). The virtual environment corresponds to the OBSEA observatory, deployed at a depth of 20 m 4 km off the coast of Vilanova i la Geltrú in the Northwestern Mediterranean Sea (see Fig. 1). The OBSEA

observatory has been acquiring data on sea water temperature, salinity, water currents, waves, wind, and underwater sound and video for more than a decade [12]. Until now, the information provided by OBSEA instruments has been disseminated using the classical approach of a dashboard and 2D graphics5. This study introduces and describes how the collected variables are represented in a new web-based 3D virtual environment. The open-source code can be found at https://github.com/BlueNetCat/OBSEA.
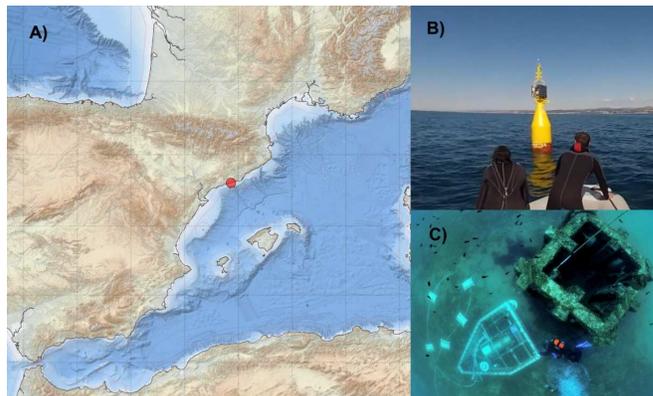
Fig. 1. *A) Geographical location of the seafloor observatory OBSEA. B) Meteo-oceanographic buoy. C) Seafloor observatory and artificial biotope.*

II. METHODS

A. Sea State Representation

Sea surface motion depends on a wide range of phenomena that act at multiple scales. While being a classical problem of fluid mechanics, sea surface motion is extremely complex and is an active research area (see [13] for an historic perspective of water wave theory and [14]).
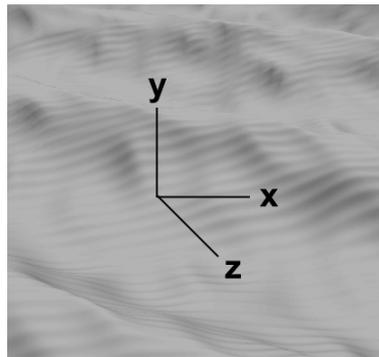
Fig. 2. *Axis of the sea state representation*

In this work, sea state dynamics are simulated using multiple Gerstner waves [15]. Given a point $\mathbf{r}$(x, y, z) in a reference system as shown in Fig. 2, the motion of a water parcel of the surface initially located at $r_0 = (x_0, 0, z_0)$ evolves according to:

$$x = x_0 + A\,u_x\cos(\theta); \quad y = A\sin(\theta); \quad z = z_0 + A\,u_z\cos(\theta) \qquad (1)$$

[5] https://news.clemson.edu/making-waves-jerry-tessendorf-creates-gilligan-to-teach-visual-effects/. Last accessed: 31st March 2023.

[6] Digital Twin Antarctica, 2021, Earthwave. https://www.youtube.com/watch?v=AWPD28FVQTA. Last accessed: 19th April 2023.

[7] Digital Twin Hydrology, 2021, ESA. https://www.youtube.com/watch?v=vf5wNv91nKA. Last accessed: 19th April 2023.

[8] 2022 France Sail Grand Prix | Day 1. https://www.youtube.com/live/L7NPqx5mV34?feature=share&t=829. Last accessed: 2nd April 2023

where x and z denote coordinates in the horizontal plane; y denotes the height above or below the mean sea level located at y=0; A is the wave amplitude; and u=(u_x, u_z) is the direction vector in the horizontal plane given by u_x=cos(α); u_z=sin(α), where α is the angular direction. Θ is the phase of the system given by:

$$\Theta \equiv \mathbf{k} \cdot \mathbf{r} - \omega t; \qquad |\mathbf{k}| = \frac{2\pi}{\lambda}; \qquad \omega = \frac{2\pi}{T}$$

where $\mathbf{k}$ = (k_x, k_z) = k·$\underline{\mathbf{u}}$ is the horizontal wavenumber; ω is the angular frequency; and λ and T are the wavelength and wave period, respectively. Both $\mathbf{k}$ and ω are related through the dispersion relation. Given the phase velocity c ≡ ω/λ and considering the linear wave theory under the limit of deep water approach (see, for example, [16]), we have:

$$h > \frac{\lambda}{2}; \qquad c = \sqrt{\frac{g}{k}}$$

where h is the mean water depth and g is the gravity constant, 9.8 m/s. Then we can rewrite the phase in (1) as:

$$\Theta = k \left(\cos(\alpha) \cdot x_0 + \sin(\alpha) \cdot z_0 - \sqrt{\frac{g}{k}}\, t \right) \qquad (2)$$

A final parameter to take into consideration is the *wave steepness, s*, defined as:

$$s \equiv k\, A; \qquad k = \frac{s}{A} \qquad (3)$$

This parameter accounts for the nonlinear properties of the wave solutions and the shape of the wave. To stay in the range of deep water approximation $s \ll 1$, otherwise corrections in powers of $(kA)^2$ should be retained (see [17] for an account of the validity of wave theories).

With these elements, one can proceed to build a realistic simulation of the sea state in a virtual environment at a reasonable computational cost. We consider a set of overlapping Gerstner waves, whose characteristic parameters (wave height, steepness, and direction) are set from the measurements. Our sea state is a combination of waves given by (1):

$$x = x_0 + \sum_{i=1}^{M} A_i \cos(\alpha_i)\, cos(\Theta_i);$$

$$y = \sum_{i=1}^{M} A_i\, sin(\Theta_i);$$

$$z = z_0 + \sum_{i=1}^{M} A_i \sin(\alpha_i)\, cos(\Theta_i); \qquad (4)$$

where i is the wave index and i=1,2,3…*M*, and *k*, *A*, and *s* depend on the wave index *i*.

Equation (4) provides the displacements of the wave surface points. To render the light properties of the surface, the normal to the surface must be calculated. For reproducibility, the formulas to obtain the normal direction N of a single wave using the tangent T and binormal directions B are given by (please refer to Jasper Flick (2018)[9] for a practical implementation).

$$N = B \times T; \qquad (5)$$

$$T = \begin{bmatrix} -(\cos(\alpha))^2 \cdot s \cdot sin(\Theta) \\ \cos(\alpha) \cdot s \cdot cos(\Theta) \\ -\cos(\alpha) \cdot \sin(\alpha) \cdot s \cdot sin(\Theta) \end{bmatrix}; \qquad B = \begin{bmatrix} -\cos(\alpha) \cdot \sin(\alpha) \cdot s \cdot sin(\Theta) \\ \sin(\alpha) \cdot s \cdot cos(\Theta) \\ -(\sin(\alpha))^2 \cdot s \cdot sin(\Theta) \end{bmatrix};$$

In the simulation environment, the three parameters to generate the sea state, i.e., the amplitudes A, s and α, are set from the observed oceanographic variables. Wave data are measured by an acoustic wave and current profiler (ADCP) sensor looking upward from the seafloor. It provides average wave height (H_{m0}), highest one-tenth of wave height (H_{10}), mean wave direction (α), and angular dispersion (σ_α) which accounts for the wave directional spreading. As a first approach, the wave heights are chosen from a Gaussian distribution parametrized by the average wave height (H_{m0}) and the highest one-tenth of waves (H_{10}). The standard deviation of the wave height (σ_H) is determined using H_{10} and the standard normal table (Z table). Similarly, the wave directions are determined by assuming a Gaussian distribution characterized by the measured values of α and σ_α. Gaussian distributions are sampled by random numbers using the Box-Muller transform [18]. The steepness of the waves is dependent on the wind speed, a linear relationship that was defined empirically (more wind results in steeper waves).

The sea surface plane is defined using a 3D polygon mesh. The above wave equations represent the position and normal of the vertices of the mesh and are calculated in the GPU. The vertex density of the mesh is higher at the center where the buoy is located. To avoid artifacts due to low vertex resolution when the waves move away from the center, a distance factor reduces the size of the waves and white fog is added. Capillary waves are simulated with specular reflections of the sea surface and not by the wave motions of the geometry, as the resolution of the surface geometry is not sufficient for such small waves. These capillary waves are generated offline as a video texture using Blender [10] and do not change during the simulation. The parameters of the wave equations are uploaded to the GPU as a data texture. In the current state of implementation, the shader considers diffuse color, specular reflections from the sun, the Fresnel effect, and fog (above and below water). Finally, the 3D representation of the buoy is animated by computing the motion provided by the three largest waves of the sea state. These three Gerstner equations are calculated in the CPU to determine the position and normal direction of the sea surface.

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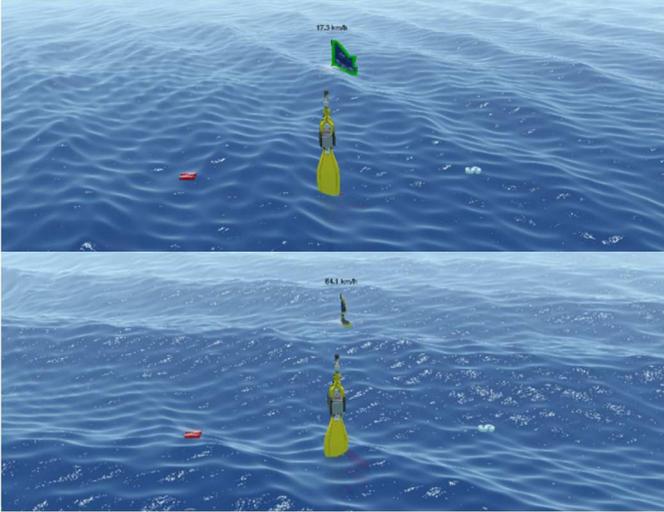
Fig. 3. *3D representation of the sea state conditions corresponding to March 3, 2019, at 03:00 UTC (top) and November 27, 2020, at 16:30 UTC (bottom). The 3D buoy model is shown with a flag added on the top. The labels (N and S) indicate the cardinal directions. Observed values are (left and right): average wave height 0.5 m and 2.0 m, maximum wave height 0.8 m and 3.4 m, mean wave direction 159.0° (SSE) and 108.0 (ESE), wave directional spreading 44.6° and 29.0°, wind speed 4.8 m/s and 17.8 m/s, and wind direction 16.1° (NNE) and 88.1° (E).*

B. Wind Representation

Wind direction and speed are measured using a weather station installed on the buoy (200WX WeatherStation®, Aimar Technology Corporation, USA). To visualize the wind data, a flag is added to the virtual environment (Fig. 3). The animation of the flag is procedurally generated using Verlet integration [19], which considers the inertial motion of a particle when applying a new force to it. Wind and gravity are the forces acting on the cloth. This algorithm was first used in game development in the early 2000s to procedurally animate lifeless human bodies and clothes in real time (see [20] and Jared Counts' tutorial[11] for theoretical and practical implementations). The flag surface is controlled via skeletal animation with bones distributed as a grid. These bones, linked between themselves, move according to the wind speed and direction and the elasticity and mass of the textile material. In addition, the wind speed and the four cardinal points are indicated by labels located over the surface and on top of the buoy representation. The application interface allows the user to change wind speed and direction.

C. Sea Water Velocity and Hydrological Data

Sea water velocity is measured in one-meter cells in the vertical direction from the seafloor. The vector velocity captured using the acoustic Doppler current profiler (ADCP) and is decomposed into the three components along the horizontal and vertical axes. The water velocity is represented by 3D arrows, one for each cell, scaled according to the measured sea water speed. The rest of the hydrological measurements, as temperature and salinity, close to the seafloor are represented, as

a first approach, by their numerical values in the form of labels projected over the seafloor plane.

The digital twin is accessible via the web browser, as it uses the Three.js library[12] to render the 3D virtual environment with WebGL and the framework Vue.js[13] to build the user interface. The data are fed in real time through the SensorThings API (Liang et al., 2016), where both real-time and historical data are archived. The open-source code can be found at https://github.com/BlueNetCat/OBSEA.
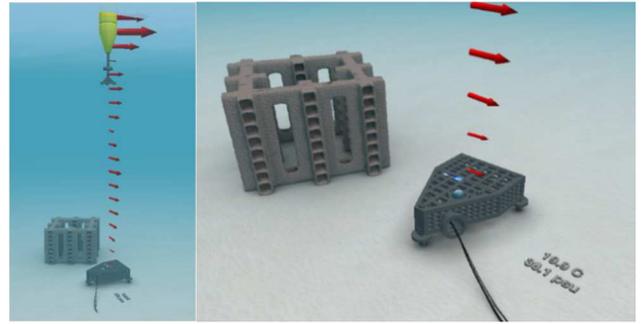
Fig. 4. *Underwater view of the virtual environment. Left: arrows represent sea water velocity profile. Right: underwater base and artificial biotope. Sea water temperature and salinity at the sea bottom are shown in the seafloor plane.*

III. RESULTS

The virtual environment (Fig. 3-4) includes a 3D digital model of the real equipment deployed in the observatory, such as the buoy, the seafloor station, and the artificial biotope. The complete appearance of the CGI digital twin of the observatory is accomplished through an animated representation allowing the user to explore and navigate from the surface to the bottom in a continuous manner. Additionally, the user can generate and modify the sea state with three sliders (H_{m0}, direction, and steepness) and the wind direction and intensity. A single wave can also be configured by the user to simulate a swell.

The application was evaluated in terms of real-time performance. In this paper, no user evaluation was done. The application was tested in different configurations and two devices. The most demanding item in terms of rendering is the rendering of the sea surface, which depends on the number of vertices in the sea surface geometry and the number of waves (Table 1).

TABLE I. FRAMES PER SECOND OF THE SEA SURFACE ANIMATION ON TWO DIFFERENT COMPUTERS.

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[11] Jared Counts (2012). Simulate Tearable Cloth and Ragdolls With Simple Verlet Integration. https://gamedevelopment.tutsplus.com/tutorials/simulate-tearable-cloth-and-ragdolls-with-simple-verlet-integration--gamedev-519. Last accessed: 4th April 2023.

[12] Three.js, https://threejs.org/, last accessed: 19th December 2022.

[13] Vue.js, https://vuejs.org/, last accessed: 19th December 2022.

Windows 10 Pro, Intel(R) Core(TM) i7 CPU, 16 GB RAM, NVIDIA GeForce GTX 1060 GPU, Chrome version 112.0.5615.121 Gaming laptop (HP Omen 15 – 2017)			
		Number of waves	
		1K	*4K*
Nº sea surface vertices	*160K*	55 fps	24 fps
	125K	59 fps	36 fps
	100K	59 fps	46 fps
Ubuntu 18.04.6 LTS, Intel(R) Core(TM) i5 CPU , 16 GB RAM, NVIDIA Quadro K420 GPU, Chrome version 111.0.5563.110 Desktop PC (2014)			
		Number of waves	
		4	*16*
Nº sea surface vertices	*125K*	3 fps	4 fps
	100K	4 fps	5 fps
	10K	10 fps	7 fps

According to Table 1, rendering times were too long for a 9-year old computer with a low-grade GPU to have a valid user experience. With a 6-year old gaming laptop, the frame rates started to be affected when using 4.000 waves. The sea state representation in Fig. 3 uses $M=16$ waves. The loading time of the web application is a factor to consider in the user experience. If high-quality meshes and textures are used, the website takes longer to load. To provide a better experience, low-resolution textures and meshes are first loaded and later replaced with high-resolution assets. As it is not feasible to load the hourly data set of 10 years of OBSEA, the data must be served on demand. In this work, hourly data are packed in 6-month static files. These files, which can take up to 5 MB, are served when the user zooms in on a date. To quickly visualize the data availability over 10 years, daily maximums are stored in a static file that is downloaded on start-up. Real-time and recent data are served through the SensorThings API with a PostgreSQL database in the backend.

IV. Discussion And Conclusions

To the best of our knowledge, this is the first prototype of a CGI digital twin of a meteo-oceanographic observatory to represent the site and the oceanographic data in a realistic and intuitive way. CGI initiatives to create digital twins of the ocean are not new, but are not connected to live oceanographic data, interactive, or open to the public. Developments made in the entertainment industry (e.g., the Gilligan Project) are very straightforward in terms of the degree of realism but make use of high computational resources beyond the capabilities of web-based environments. A similar initiative, which may fall into the category of a virtual environment, is the SmartBay observatory in Ireland [21]. The website shows a virtual 3D interactive view of the facilities, devices and data collection system[14]. This initiative shows an interest in creating virtual environments for the dissemination of data from marine observatories.

In this work, we presented a CGI digital twin of the seafloor observatory OBSEA as a tool to visualize oceanographic data and transfer knowledge. The interactive 3D virtual environment changes the sea state, wind effects, and sea water velocities according to the data provided by the seafloor observatory.

According to the rendering results, modern computers can render the 3D virtual environment at acceptable frame rates (above 30 fps). The application should adapt its specifications to achieve acceptable frame rates for different devices. An alternative would be to render videos offline and create short clips at the cost of losing real-time interactivity, which is usually desired in a digital twin.

Multiple improvements and strategies can be developed to improve the sea state representation. Here, only a combination of 16 waves was used for an equilibrated performance in terms of realism and computation resources. A better approach to increase the number of wave modes would be to use the inverse fast Fourier transform (IFFT) in the GPU to calculate the vertex's positions and normals according to thousands of waves, as described in [9][22]. An advantage of using the IFFT is that the resulting textures can be used as tiles, making it possible to create an endless sea surface (in this work, the sea surface was limited to the location of the seafloor observatory). A better distribution of wave parameters should be provided: instead of using a gaussian distribution, skewed distributions should be used to match more appropriate ocean spectrum as the Pierson-Moskowitz and JONSWAP spectra [23][24].

Adding water spray, bubbles, and foam is one way to improve the realism of the representation. CGI strategies for the color of the sea surface, which require light reflection, refraction, reflectance, absorption, scattering, god rays, and caustics, can also be improved. It is worth mentioning that the chemical and biological properties of water affect the water color [25] and that it could be included in a digital twin. The relationship between the color and the chemical and biological properties of water is hardly understood by non-experts. If users can manipulate such parameters in a digital twin they can test how the water color changes.

Another challenge that other researchers and developers may face is how to interpret the wave parameters and transfer that information to the sea state representation. In this work, we used H_{m0}, H_{10}, wave direction, and wave directional spreading, but the sensor provided other parameters that we did not use, such as wave period, maximum wave height H_{max} (VZMX), highest wave one third H_3 (VAVH), period and direction at spectral maximum (VTPK, VPED), and zero-crossing period (VTZA). Other sensors and data services provide wave parameters in different ways. For example, CMEMs wave products [26] provide other parameters such as swells and wind waves. These variables and different models should be considered to improve the generation of wave parameters.

Future planned improvements include a more realistic representation of the local environment, including effects and data such as the sun's position, cloudiness, fog, rainfall, surrounding vessels, water turbidity, underwater sound, and the presence of species around the underwater camera. Additionally, the status and signals of the sensors and systems will be displayed, such as the status of the batteries or the hydrophone's signal. Other planned activities involve the validation of the sea state representation with real footage linked to oceanographic observations. Marine observatories and other digital twin

initiatives could benefit from the work presented here, as the code is available and open source.

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