

Procedural Marine Landscape Synthesis for Swimming Exergame in Virtual Reality

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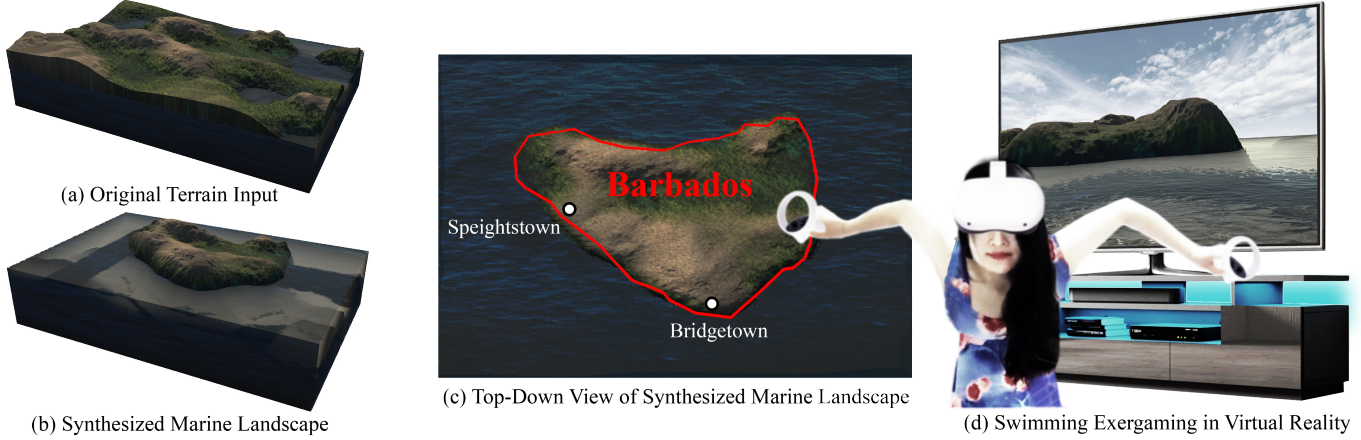


Fig. 1: Given original terrain input as shown in (a), we synthesize a realistic marine landscape shown in (b) according to the simulation-based procedural modeling approach we proposed in this paper. (c) shows the top-down view of our synthesized marine landscape that actually matches the shape of the island Barbados. (d) shows the player’s immersive VR swimming exergaming experience in our synthesized marine landscape.

Abstract—In this paper, we propose a simulation-based procedural modeling approach to automatically synthesize immersive marine landscapes for swimming exergame in virtual reality. Given arbitrary terrain as input, we transform it into a realistic marine landscape according to a novel simulation-based procedural modeling approach inspired by the geological phenomenon of tectonics. During the tectonic simulation, we apply another constraint that is specifying the water area so as to make the top-down view of our synthesized marine landscape match the shape expected from users. Besides, we apply physics rules to the VR controllers to immersively simulate players’ swimming experiences in virtual reality and collected feedback from the players who virtually swam in our synthesized marine landscapes.

Index Terms—procedural modeling, tectonics, physics, simulations, swimming, interactive user interface, virtual reality

I. INTRODUCTION

Exergaming, as an immersive virtual experience that bridges exercise with 3D gaming, becomes the trend of future entertainment and plays an important role in improving physical activity [1] by combining exertion with video games with respect to strength training, balance, and flexibility activities [2]. Exergaming potentially introduced a significant positive impact on players across the globe who are living more sedentary lifestyles [3]. More specifically, enhancing Exergaming with immersive interactive virtual environments results in more significant improvement in the concentration and motivation of players’ exertion activities, therefore, researchers show growing interest in exploring how to simulate exercise, sports, and gym activities in immersive virtual environments through Virtual Reality (VR) or Mixed Reality (MR) head-mounted

displays and interactive controllers. As one key observation, immersiveness is one of the most important reasons why VR exergames gain popularity. Players tend to be more excited, focused, and motivated on exercise activities in an immersive virtual environment rather than in a fake or tedious virtual environment. Therefore, improving the degree of immersiveness delivered both from the visual feedback, interactive feedback, and motion feedback from the display or exercise hardware is a promising research area that causes an increasing amount of attention from human-computer interaction researchers.

Empirically speaking, by devoting a larger amount of time and effort to the 3D game design procedure, the immersiveness of VR programs can be significantly improved through repeating trials and errors from the game content designer. However, with the growing power of the computational design technologies that are inspired by the advanced computer graphics algorithms, procedural modeling approaches and be employed in the game design process to substitute lots of manual efforts demanded from the game content designers. Beyond this advantage, procedural modeling approaches can also integrate numerical simulation into the design process to make the result more natural, generalizable, and even scientifically accurate. Inspired by these observations, we explore procedural modeling technology within a special genre in exergame, swimming games, which has been underexplored by researchers from this perspective so far. We propose a simulation-based procedural modeling approach to automatically synthesize immersive marine landscapes for swimming exergame in virtual reality. Contributions of our work include:

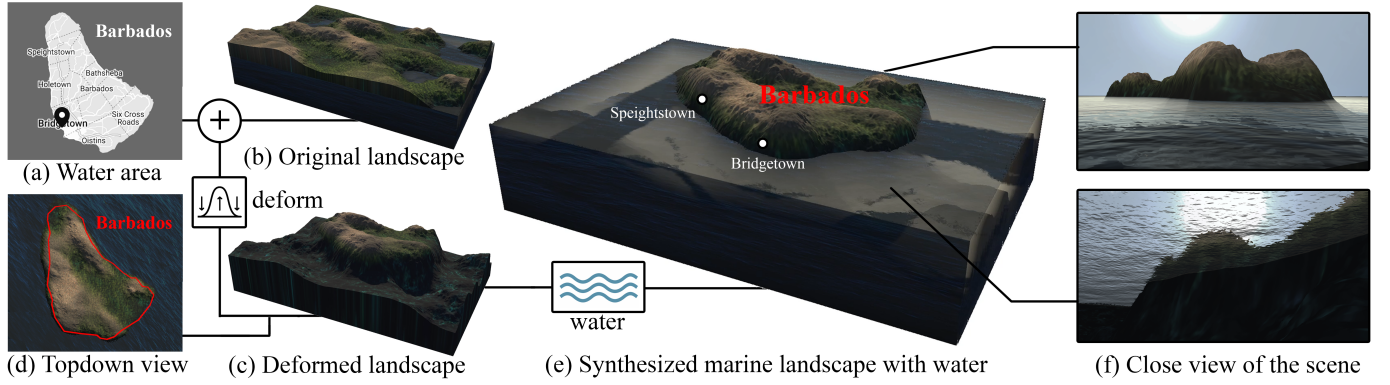


Fig. 2: Overview.

- We devise an efficient computational framework to mathematically simulate the formation process of a marine landscape through geological phenomena of tectonics. Video link is here: <https://youtu.be/ybYYzW52EoY>.
- We implement the proposed computational framework; Test, and validate it in the transformation process from arbitrary landscapes into marine landscapes through a series of numerical experiments.
- To test players' swimming experiences in our synthesized marine landscapes, we simulate physics rules on VR controllers and collect feedback from the players who virtually swam in our synthesized scenes.

II. RELATED WORK

Synthesizing realistic terrains is an essential skill for a game designer to create virtual content for 3D video games or virtual reality games. After the general-purpose GPU has been brought into the stage, advanced parallel computing technologies were applied to complex procedural terrain generation [4]. The increasing power of GPU computation makes the simulation-based terrain procedural modeling technologies win growing interest from the computer graphics research communities. Since 2010, Tucker et al. [5] thoroughly introduce the landscape evolution modeling approach through geomorphology which is currently in a period of resurgence that is aiming to explain the diversity, origins, and dynamics of terrain on the Earth and other planets in an era of increased environmental awareness. Later on, simulation-based terrain procedural modeling technologies have been widely employed in generating special terrain features such as spheroidal weathering [6], arches [7], canyons [8], desertscape [9], riverscapes [10], and glaciers terrains [11], since that period, geomorphology has been systematically studied and numerically simulated throughout this past decade. Date back to 2011, Yongsong et al. [12] improve the traditional terrain simulation with the problem of high computation cost and poor visual effect through a novel eroded terrain simulation technique using water map and sediment map to achieve more convincing simulated effects. In 2017, volumetric terrain features have been considered in the procedural generation process [13]. Most recently, given the limitation that example-based terrain

synthesis produces good local behavior but can have poor global behavior, Scott et al. [14] introduce fluid-flow solutions that can be overlaid on multi-resolution example-based terrain synthesis to improve global realism.

Even though there is plenty of valuable works on synthesizing realistic terrains and landscapes using the simulation-based approach, it still remains an open research area on marine environment synthesis. Nowadays, marine environment synthesis is getting popular among the environmental protection research community and causes growing attention from environmental scientists. However, environmental scientists are only focusing on how to simulate the growth of pollution. Also, none of the computer graphics scientists have considered the simulation-based approach to synthesizing realistic marine landscape features. On other hand, exertion video games in swimming [15] and VR swimming games [16] need realistic undersea virtual environments. Given the current game design technology, designing such a realistic marine landscape still needs a large amount of manual effort. Therefore, in this paper, we devise an efficient computational framework to mathematically simulate the formation process of a marine landscape through the geological phenomena of tectonics.

III. OVERVIEW

Figure 2 shows the overview of our approach. Given user-specified water area as shown in subfigure (a) and arbitrary landscape as original landscape as shown in subfigure (b), by applying an efficient computational procedural modeling process to mathematically simulate the formation process of a marine landscape through geological phenomena of tectonics, we deform the original landscape into a marine landscape as shown in subfigure (c). A detailed mathematical description of such a computational process is defined in Section IV. After adding water into the scene by using a real-time realistic water textured shader, our synthesized marine landscape with water is shown in subfigure (e). Subfigure (f) shows a close view of our synthesized marine landscape. After comparing Subfigure (a) with Subfigure (d), which is the topdown view of the finally marine landscape synthesized with our approach, we can observe that the water area in the synthesized marine landscape exactly matches the water area specified in Subfigure (a). In this example, the specified sea area is near Barbados Island.

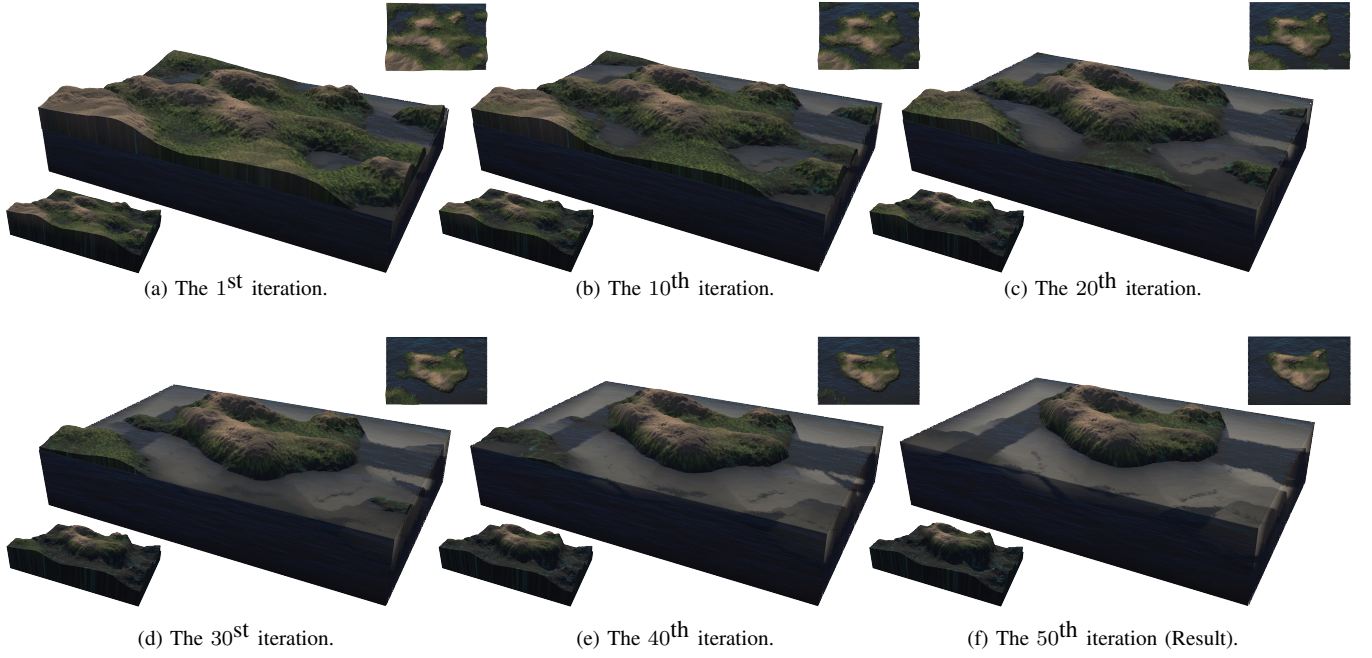


Fig. 3: Simulation Process. This figure shows an example of the marine landscape simulation process. Given arbitrary landscape in (a), (b-e) shows the intermediate results at the corresponding iterations. (f) shows the final synthesized marine landscape.

IV. MARINE LANDSCAPE SIMULATION

Figure 3 shows an example of a marine landscape simulation process implemented with our proposed approach. Simulation-based terrain procedural modeling is widely used in automatically synthesizing realistic terrain features by approximating the geological or natural phenomenon. In our approach, we simulate the marine landscape by deforming arbitrary terrain through the tectonics assumptions and approximation. Tectonics is a geological research domain that investigates the original research articles describing and explaining the evolution, structure, and deformation of Earth's lithosphere across the range of geologic time. we propose a general tectonics assumption in our proposed simulation process and synthesize the marine landscape in real-time and on a general-purpose computer that is specially used for synthesizing realistic marine landscapes for virtual reality entertainment.

Numerical Formulations. Tectonics are the processes that control the structure and properties of the Earth's crust and its evolution through time. Due to the span of the tectonics evolution process being over billions of years, all deformation of the landscape is simulated through assumptions. We conclude that the general tectonics assumptions for the formation of the marine landscape are caused by the difference between the oceanic crust density and the continental crust density, therefore, the heavier oceanic crust sinks at the same time pushing the lighter continental crust to rise. Therefore, the mass transfer between continental crust and oceanic crust must be equilibrium. Mathematically, let $h(\mathbf{p})$ denote the elevation of the terrain heightmap at position \mathbf{p} , let area W be the user-specified ocean (water) area of the marine landscape, then the

simulation process can be mathematically derived from the mass transfer equation defined as:

$$\int_0^t \left(\iint_W \frac{\partial h(\mathbf{p})}{\partial t} dW + \iint_{\bar{W}} \frac{\partial h(\mathbf{p})}{\partial t} d\bar{W} \right) dt = 0 \quad (1)$$

At the same time, due to the coastal hydraulic erosion near the water area, the sharpness nearby the continental margin area E must be below a threshold C , therefore, we have the smoothness constraint as:

$$\iint_E \nabla^2 h(\mathbf{p}) dE \leq C \quad (2)$$

After solving the mass transfer equation 1 under smoothness constraint 2, we have the numerical approximation for marine landscape deformation equation defined as below:

$$\frac{\partial h(\mathbf{p})}{\partial t} = \begin{cases} w(\mathbf{p}) \cdot (1-s) \cdot u \cdot e^{-kt} & \mathbf{p} \in W \\ w(\mathbf{p}) \cdot s \cdot u \cdot e^{-kt} & \mathbf{p} \in \bar{W}, \end{cases} \quad (3)$$

where u is deformation speed, $k = 0.2$ is speed decay, water area coefficient s is:

$$s = 1 / \left(1 + \frac{\iint_{\bar{W}} d\bar{W}}{\iint_W dW} \right), \quad (4)$$

and water map function $w(\mathbf{p})$ is calculated as:

$$w(\mathbf{p}) = \begin{cases} -1 & \mathbf{p} \in W \cap \bar{E} \\ -e^{-4(\|\mathbf{p}-\mathbf{q}\|/d)^2} & \mathbf{p} \in W \cap E \\ e^{-4(\|\mathbf{p}-\mathbf{q}\|/d)^2} & \mathbf{p} \in \bar{W} \cap E \\ 1 & \mathbf{p} \in \bar{W} \cap \bar{E}, \end{cases} \quad (5)$$

where $\mathbf{q} \in E$ is the closest point to \mathbf{p} and d is the average width of the continental margin area E .

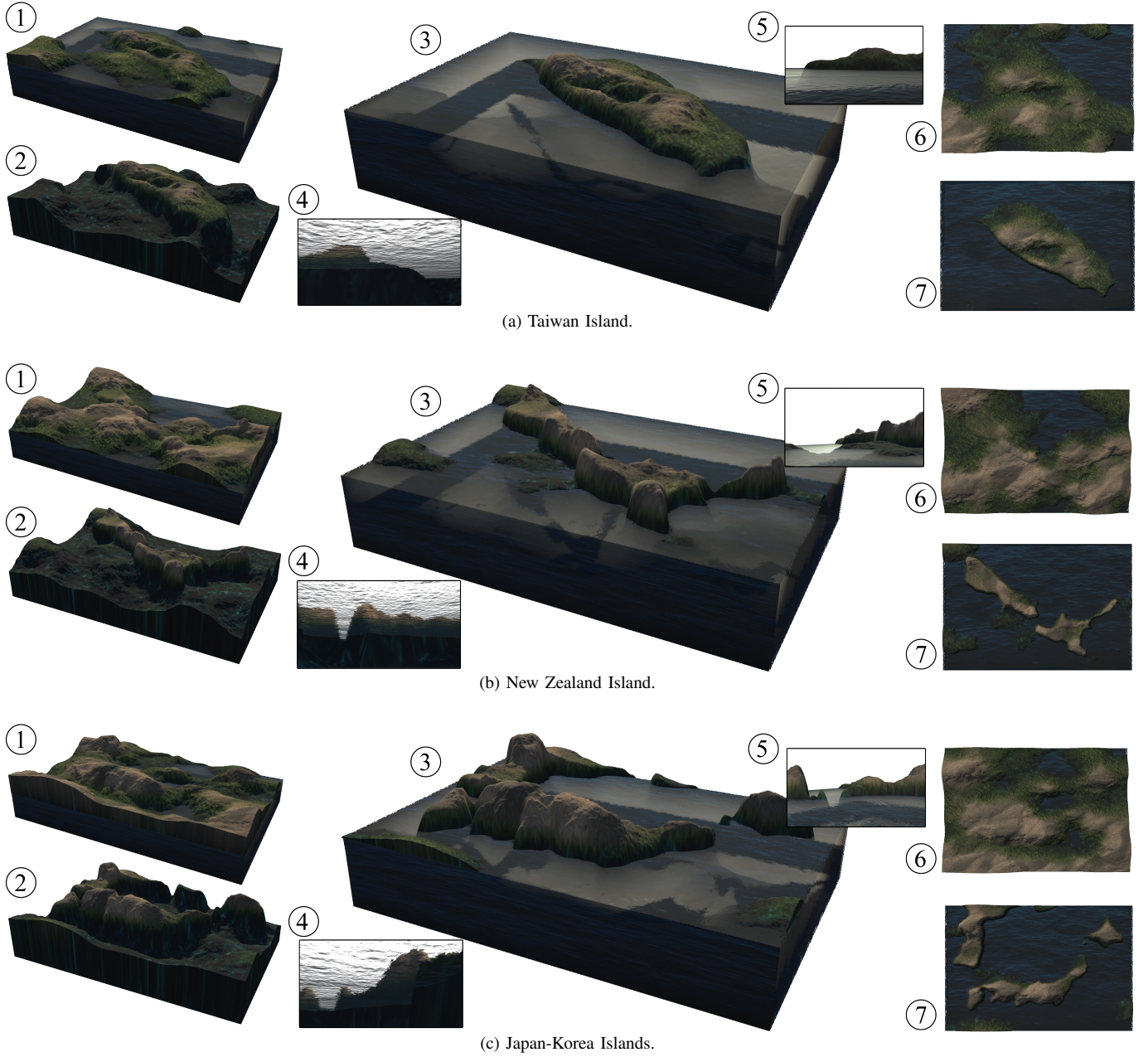


Fig. 4: Numerical Experiments.

Numerical Experiments. Figure 4 shows the numerical experiments that validate our proposed approach to synthesizing different marine landscapes given different water areas. In this experiment, we define the water area constraints based on some famous islands in the real world, they are (a) Taiwan Island, (b) New Zealand Island, and (c) Japan-Korea Islands. For each example, there are 7 subfigures labeled through 1-7. Subfigure 1 shows a random landscape (with water) procedurally generated as input. Subfigure 2 shows a marine landscape (without water) procedurally generated through our proposed deformation equation 3. Subfigure 3 shows the corresponding procedurally generated marine landscape with water rendered, which is used during the user study as the

3D virtual environment where players swim in virtual reality. Subfigures 4 and 5 show the under-water view and above-water view of our synthesized marine landscape. Subfigures 6 and 7 show the top-down views of the original random landscape and the synthesized marine landscape respectively. As we can see in the top-down view in subfigure 7, the synthesized islands' shapes look like the shapes of the corresponding islands on the world map. All experimental experiments presented here are finished in 10 seconds, which validates the efficiency of our approach in synthesizing realistic marine landscapes. Full animation of procedural marine landscape synthesis process can be found through the supplementary video link which is shown here: <https://youtu.be/OdQKymcYNF8>.

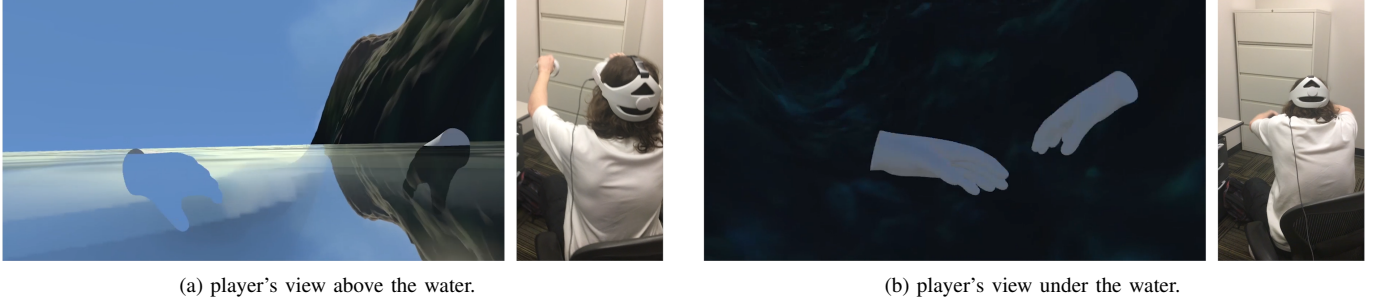


Fig. 5: Virtual Swimming. This picture shows a player's virtual swimming experience in our synthesized marine landscape. (a) and (b) show the player's view above the water and under the water respectively. At this moment, the player is breaststroking.

V. VIRTUAL SWIMMING INTERFACE

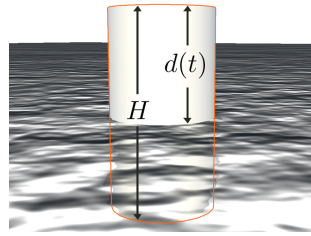
In order to provide players with a natural virtual experience in swimming, we implement the fluid dynamics in virtual reality by applying physics laws. As the applied real-time fluid simulation is a computation-intensive task for GPU programming, that is easily got stuck on the screen, especially, when considering computing high-dimensional fluid simulation. Therefore, in our user study, we simplify the fluid simulation into fluid dynamics formulas to address two dominant features of swimming, which are drag and buoyancy.

Drag. In fluid dynamics, drag (also called fluid resistance or fluid friction) is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid. This means when the player has a speed, drag force will slow down the player's motion, on other hand, drag force will push the player forward when the player's hands are pushing the water back. Mathematically, let $A = 0.05\text{m}^2$ be the hand's average surface area, let $\mathbf{n}(t)$ be the hand's normal direction, let $\mathbf{v}(t)$ be the hand's velocity at time t , then the drag of the player caused by the hand is $\mathbf{f}_D(t)$ calculated as:

$$\mathbf{f}_D(t) = -\frac{1}{2}\rho\|\mathbf{v}(t)\|^2 C_D A \cos(\alpha(t)) \hat{\mathbf{v}}(t), \quad (6)$$

where water density $\rho = 1\text{g/cm}^3$, drag coefficient $C_D = 2.3$, and $\cos(\alpha(t))$ is dot product of normal $\mathbf{n}(t)$ and normalized velocity $\hat{\mathbf{v}}(t) = \mathbf{v}(t)/\|\mathbf{v}(t)\|$. If $\cos(\alpha(t)) \leq 0$, $\mathbf{f}_D(t) = 0$.

Buoyancy. Buoyancy is an upward force exerted by a fluid that opposes the weight of a partially or fully immersed object. It is important to simulate this buoyancy during the virtual swimming so that the players can have an immersive experience of the feeling that they are floating in the water. In our approach, we simulate the player as a column, let $H = 1.75\text{m}$ be the player's height, let $V = 0.07\text{m}^3$ be the player's height, let $\mathbf{g} = (0, -9.8, 0)\text{m/s}^2$ be the gravity acceleration, player's



depth above the water as $d(t)$, then the buoyancy $\mathbf{f}_B(t)$ is calculated through the following formulas:

$$\mathbf{f}_B(t) = -\hat{\mathbf{g}} \left(1 - \left[\frac{d(t)}{H} \right]_{[0,1]} \right) \rho g V, \quad (7)$$

where water density $\rho = 1\text{g/cm}^3$ and clamp operation $[f(x)]_{[a,b]}$ means $f(x)$ is clamped between a and b .

VI. USER STUDY EXPERIMENTS

Implementation. We have implemented the virtual swimming interactive user interface using Unity 3D with the 2019 version. We have implemented this VR interactive interface using the Steam VR 2.0 plugin. Our proposed marine terrain synthesis algorithm is implemented in Unity 3D. The hardware configurations contain Intel Core i5 CPU, 32GB DDR4 RAM, and NVIDIA GeForce GTX 1650 4GB GDDR6 Graphics Card. The VR program is configured on Oculus Quest 2.0.

Participants. We recruited 12 undergraduate students for this virtual swimming experiment in our synthesized marine terrain as shown in Figure 4. All of the participants are male and aged between 20 and 24. All of the participants claimed that have learned to swim before and they like VR games. But only 7.7% among them have tried VR games that are about VR swimming before.

Study Procedures. During the user study experiment, each player is asked to virtually swim in our synthesized marine terrain for about 5 to 10 mins. Figure 5 shows the player's view on the VR headset. Unlike some research work that simulates VR skimming in the swimming pool, our swimming interface is simulated through the VR controllers in mid-air, therefore, in our study, the players try virtual swimming experiences within the office. Subfigures (a) and (b) show the player's view above the water and under the water respectively. In this example, the player is breaststroking. After the virtual swimming experiments, we ask players to fill in a questionnaire to evaluate the VR experience. According to the standard questionnaire testing users' perceived enjoyment level, every question is asking about one perceptive evaluation to rate their VR swimming experience and asks for some general feedback.

VII. RESULTS AND DISCUSSION

Questions in our questionnaire are asking about perceptive evaluations to rate their VR swimming experience. For example, how realistic is the VR swimming experience compared to the real-world swimming experience? For each question, we let players select a number between 1 to 5 as the Likert score. Figure 6 shows the bar plots of the player's evaluations of the virtual swimming experiences conducted in our user study. Here are the statistical results of the Likert scores for each question: VR swimming is realistic (AVG=3.07, STDEV=1.02, MD=3); VR swimming is comfortable (AVG=4.15, STDEV=0.78, MD=4); VR environment is immersive (AVG=3.77, STDEV=0.90, MD=4); VR Marine landscape looks natural (AVG=4.23, STDEV=0.80, MD=4); VR interaction is comfortable (AVG=3.85, STDEV=1.03, MD=4); VR swimming follows physics laws (AVG=3.46, STDEV=1.22, MD=4); VR swimming experience is fun (AVG=4.61, STDEV=0.50, MD=5); VR swimming help learn swimming (AVG=3.31, STDEV=1.38, MD=3); According to the Likert scores voted by the players, they generally agree that the swimming experience in VR is very comfortable (AVG=4.15) and fun (AVG=4.61). Also, most players agree the marine landscape in the VR swimming program looks natural (AVG=4.23).

According to players' general feedback, someones believe that this was the most realistic swimming simulation they have ever played and believe this work deserves well recognition. Some players believe that, for people who don't have the ability to jump into the water with proper safety equipment or those who find it hard to overcome the fear of being submerged, this VR swimming experience is really a life saver as it can help get people used to the motions of the different strokes. Some players indicate that when they paddle in the water with different strengths and postures, the feedback, such as the movement speed, given by the VR simulation is very realistic. Some players comment that the generation of the marine environment is very distinctive, the structure of the underwater and the feedback of the body touching the obstacles are very immersive.

Future Work. Players from this study provide some valuable suggestions on improving this synthesized virtual environment and the virtual swimming experience. For example, they suggest adding bubbles and having water sloshing noising whenever move their hands in the water. Someones recommend adding a "breath timer" that limits the amount of time a player can stay underwater without resurfacing. Someones suggest connecting players to a VR system that allows for leg tracking would allow this crucial part of swimming to be simulated. Some suggest adding the effect of rippling waves on the surrounding water when the character's head leaves the water, etc. According to these valuable suggestions collected from the first-hand data, and the validation of our proposed approach to synthesizing realistic marine landscape, we believe our work has a great potential impact on virtual swimming exergame authoring research in the future.

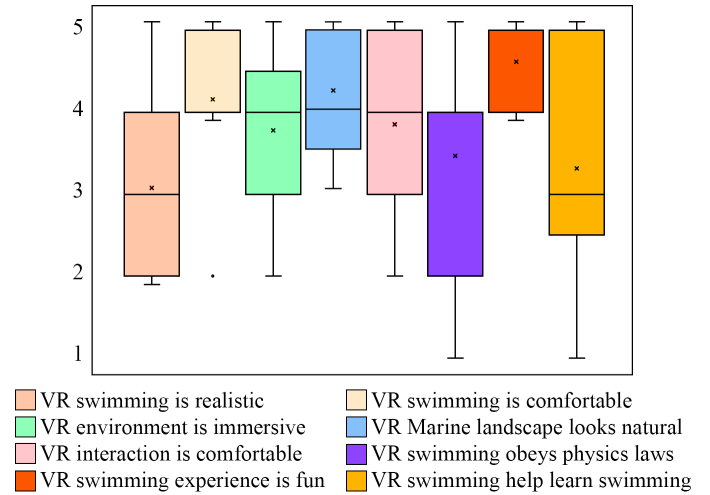


Fig. 6: User Study Result.

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