Article Title: Simulation of Underwater Excavation Using Dredging Procedures

Publication Date: 21 April 2018 **Deposit in to KTISIS Date:** 15 October 2020

Please cite the Publisher Version: https://doi.org/10.1109/MCG.2018.021951637

Publisher: IEEE Xplore

Version of article: Preprint

ISSN: 1558-1756

Simulation of Underwater Excavation using Dredging Procedures

Pavel Kouřil and Fotis Liarokapis

Abstract—Underwater excavation is still a very difficult and demanding task. One of the main problems is how to train inexperienced archaeologists. One of archaeology's most challenging tasks is known as dredging. This paper presents a novel system for simulating underwater excavation techniques using immersive virtual reality. The focus is not on simulating swimming but on excavating underwater while following established archaeological methods and techniques. In particular the use of dredging procedures was implemented by a realistic simulation of sand in real-time performance. The working area for performing dredging with the airlift is currently limited to 2x2 meters and users need to excavate it aiming to find artifacts within a specific amount of time.

Index Terms—virtual reality, sand simulation, underwater excavation, material modeling, fluid dynamics

INTRODUCTION

UNDERWATER cultural heritage assets are widely spread and unlike land archaeological sites, they are not accessible to the general public nor all experts, due to their environment and depth. Photos and surfaced artifacts exhibited in maritime museums provide fragmented aspects of such sites. Digital technologies have also been randomly used in museums as a supplementary information source, but not always very successfully. Virtual reality (VR) provides accessibility to both scholars and general public interested in having a better grasp of underwater sites and maritime archaeology in the form of digital encounters. They provide virtual underwater visit opportunities for children, the elderly or people with mobility problems, and enhance the actual underwater visit with augmented digital content.

VR can offer much more than underwater tours and it can be accessible using immersive technologies and Internet access. VR is also suitable for training simulations which is very difficult or impossible to perform in the real-world environment, flight simulators could be considered as a characteristic example of this. In terms of underwater archaeology, excavation is one of the most significant candidates for a training simulator. For example dredging, an underwater archaeology excavation technique, removes the sand and sediment from the seabed around the intake of the dredging device, e.g., an airlift. The collected objects are then either ejected into the current, or into a cage for further inspection. In most cases, accessing the underwater sites is difficult and expensive, both for general public and for archaeologists-in-training. There are a number of shipwrecks that are in very deep water and even very experienced divers have a number of problems. The aim of this paper is to provide a unique virtual experience to teach the basics of handling the airlift to future marine archaeologists. A system for simulating sand in immersive VR is presented allowing for real-time excavation.

• *P. Kouřil and F. Liarokapis are with Human Computer Interaction Laboratory, Faculty of Informatics Masaryk University, Brno 602 00, Czech Republic.*

RELATED WORK (COULD BE SIDEBAR)

Modeling Virtual Sand

There are several approaches to modeling virtual sand, with each one having advantages and disadvantages. One of the simplest approaches is to use a heightmap. The heightmap representations can be used for displacing soil, resulting in an interactable, animated sand, as shown by Beneš et al. [1], Li et al. [2], and Holz et al. [3]. Heightmaps however present some limitations, e.g., not being able to represent two different heights in one point, meaning the overlaps cannot be recorded, and the inability to record ”poured” sand. This limitation can be overcome by using multi-level heightfields that store additional piled soil on objects above the basic heightmap, as presented by Onoue et al. [4].

Alternatively, methods based on interacting rigid bodies and particles exist, but they are not suitable for real-time applications based on the literature. These simulations are for instance the work by Milenkovic [5], who showed 1000 spheres falling through a hour-glass, or the work done by Bell et al. [6]. Bell's approach does not model every grain of sand as a particle, but uses a grouping method, where each particle represents a group of grains.

Sand, and other granular materials, can be also simulated by modifying solvers used for simulating fluids. Zhu [7] presented such modification, to simulate the properties of a sand, using a PIC/FLIP (Particle-in-Cell and Fluid-Implicit Particle) method. However, the reported results by Zhu do not show interactive framerates. Finally, a real-time voxel-based approach to simulating soils was presented by Geiger [8], which demonstrates results that are suitable even for VR applications. However, this work was not implemented in immersive VR environments.

Underwater Archaeology in Virtual Environments

In terms of augmented reality (AR), the first application using head-mounted display (HMD) for navy divers was presented by Gallagher in 1999 [9]. A more sophisticated system was presented in 2009 by Morales et al. [10] which provides visual aids to increase commercial divers' capability to detect, perceive, and understand elements in underwater environments. Moreover in 2009, Blum et al. 2009 [11] developed the AREEF system which allows people to discover an underwater world of corals and fish in a swimming pool in a comfortable and safe way. As current state of the art, swimming with holding a tablet device, enhanced with underwater position systems, can be considered; the tablet is used to guide the diver tourists during the diving session while providing information about the archaeological artifacts spotted during the visit [12].

As far as VR is concerned, the state of the art simulation is the Amphibian [13], which provides an immersive experience by simulating buoyancy, drag, and temperature changes through various sensors. In this system the participant is lying on a motion platform. Furthermore, there are two works that allow virtual visits of archaeological sites; our previous work [14], focusing on modeling the underwater environment of the Mazotos shipwreck and the work by Bruno et al. [15], presenting usage of photogrammetry to map the site of Cala Minnola. Also, there is a prototype of a serious excavation game by Kouřil [16], which also serves as a baseline work for this article.

SIMULATING SAND

For simulating the sand and performing the dredging procedure, we decided to implement the voxel-based approach presented by Geiger [8] and to further extend it with the dredging procedure using a device known as an *airlift*, which is a pipe that uses compressed air pulses to suck debris from a seabed. The simulation uses an Eulerian representation of the flow field, which means it models the flow of the fluid through a fixed three dimensional grid used as an underlying structure to perform the calculations. Since it is executed in parallel, each worker (thread) has write permission for the voxel at current indices (i, j, k), and read permissions for all 27 neighboring voxels (a, b, c) (the 26 adjacent voxels and itself). Each voxel stores information about its sand density $\rho_{i,j,k}$, sand velocity $\vec{u}_{i,j,k}$, applied forces on sand $\vec{f}_{i,j,k}$, rigid body density $\psi_{i,j,k}$, and rigid body velocity $\hat{v}^{\psi}_{i,j,k}$. The rigid body density value is used to store the density of any rigid body object present in our simulation, including but not limited to the user's hands, the airlift or the artifacts buried in the sand.

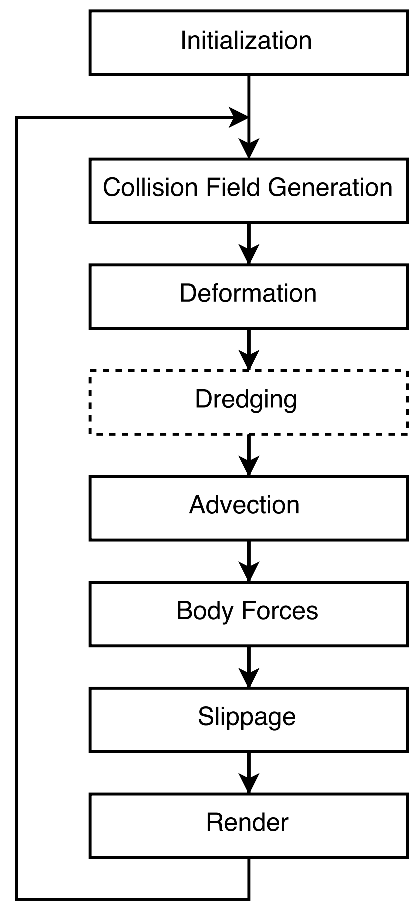


Figure 1. A flowchart of the computation steps of the sand simulation, as presented by Geiger [8], including our extension of the simulation in the form of the custom dredging step.

The simulation works in a series of time steps and transforms the result from previous time step (by applying multiple transformations in specified order). This implies that the data at the end of the transformation execution, β^{n+1}, are calculated from previously computed data, β^n. The order of transformations in each time step is shown in Figure 1. 'Initialization' and 'render' are not transformations, but creation of the sand volume to fill the sea bed, and extraction of the isosurface using the Marching cubes

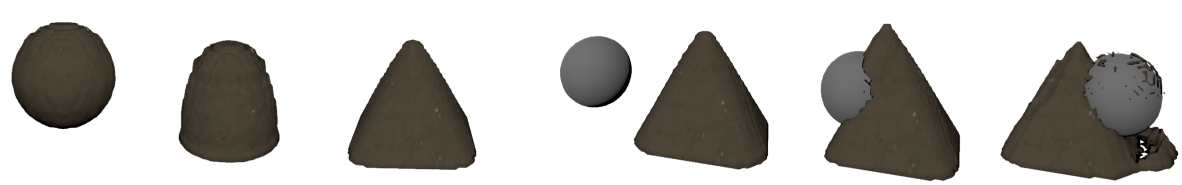


Figure 2. Showcase of a sand simulation, with falling volume of sand creating a pile and an arbitrary spherical rigid body colliding with the pile and deforming it as a result.

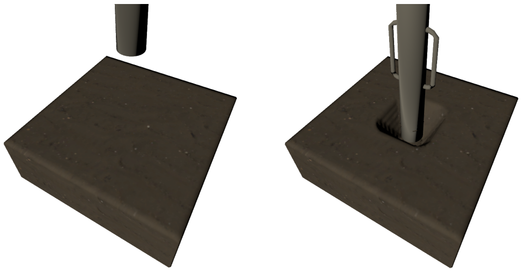


Figure 3. The sand volume can be removed using the dredging device, also called an 'airlift'.

algorithm and its rasterizaton.

Regarding the respective transformations, 'collision field generation' creates volumetric representation of the rigid bodies that are currently present in grid's bounding box (this process is usually called voxelization). 'Deformation' displaces the sand volume based on the forces from the rigid bodies colliding with the sand. Like deformation, 'advection' also displaces the sand volume, but instead bases its displacement on the velocity of the voxels containing the soil. 'Body forces' adds the gravitational forces to the whole body of the sand volume. 'Slippage' computes the soil slippage, allowing the sand to create slopes and not being displaced only based on the velocity and rigid body forces.

Our simulation was implemented based on the available descriptions of the steps by Geiger [8], with differences in the collision field generation and slippage procedures. Our physics simulation was implemented using the Unity game engine (https://unity3d.com/). The collision field generation was changed to fit the used physics engine of the Unity engine by voxelizing the colliders instead of the polygonal models. The slippage transformation uses a custom heuristic (see below), that computes the slippage directly on the grid, instead of requiring the conversion of the density field into a multi-level heightfield (MLH), computing the slippage on the MLH, and propagating the results back to the grid. The visual showcase of the simulation results can be seen in Figure 2 and Figure 3.

Slippage Heuristic

The custom heuristic checks the local differences between the grid columns of sand by comparing neighboring columns calculate the slippage. From the 27 neighboring voxels (a, b, c) only the voxels that are not in the same column are considered for displacing sand - that is, voxels which satisfy $a \neq i \wedge c \neq k$. The heuristic also specifies a maximum difference in the heights of columns, $d \in (0; 1)$. For the application, the value of $d = 0.5$ was chosen since it provided better empirical results.

To calculate difference of sand density leaving from and incoming to the current voxel, the following equations are used:

$$\rho^{tmp}_{i,j,k,} = \rho^{n}_{i,j,k} - (\rho^{n}_{x,y,z} + \psi^{n}_{x,y,z} + \rho^{n}_{x,y-1,z} + \psi^{n}_{x,y-1,z} + d)$$

$$\rho^{n+1}_{i,j,k,} = \rho^{tmp}_{i,j,k,} + \rho^{n}_{a,b,c} - (\rho^{n}_{i,j,k} + \psi^{n}_{i,j,k} + \rho^{n}_{i,j+1,k} + \psi^{n}_{i,j+1,k} + d)$$

For both equations, the maximum amount displaced for each neighboring column is limited to $(0, \frac{d}{8})$ to ensure the preservation of the sand volume, while computing the slippage in parallel. While this heuristic approach is not suitable for generic sand simulation due to the heuristic resulting in a pyramid instead of a cone after a sphere of sand is dropped, it is adequate for the use case of underwater excavation, where the sand is evenly distributed on a flat seabed, and the user interaction consists primarily of performing the dredging procedure.

Dredging Procedure

The approach to excavation is dividing the site into smaller sections by the means of a grid, with each square constituting a trench. The trenches are excavated stratigraphically, meaning they are dug layer by layer. The airlift is one of the primary equipment employed in underwater excavation. The archaeologist holds the airlift at a distance of c. 100mm from the artifact or the seabed and directs the sand towards the airlift in order for the sand to be sucked in and removed from the site or artifact; there are various techniques of "feeding" the sand into the airlift, with hand-fanning being the safest but also the slowest [17].

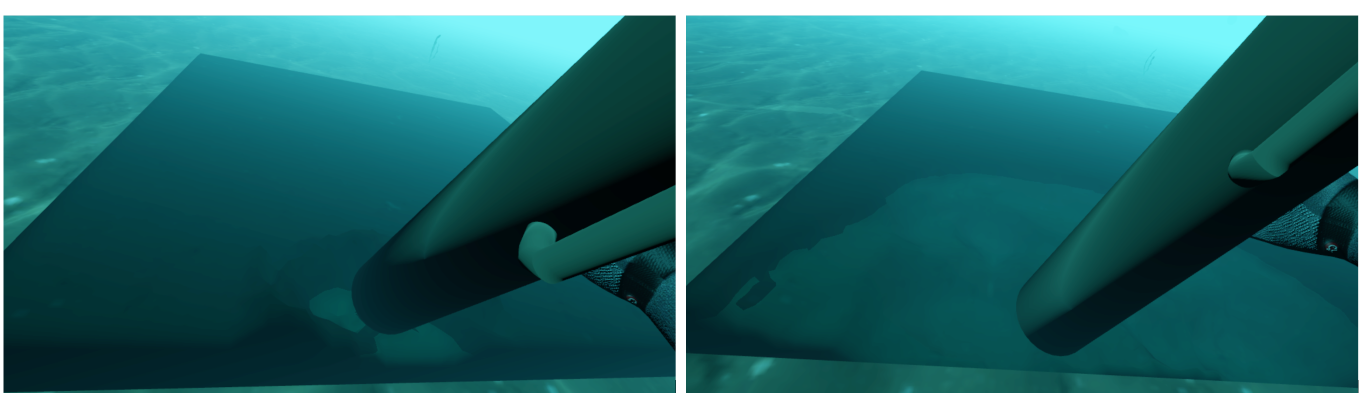
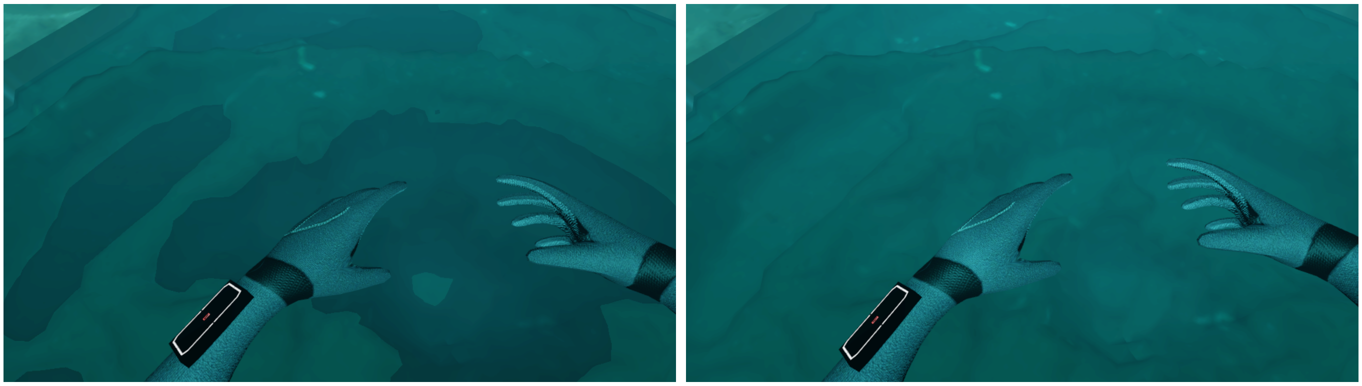


Figure 4. Users work with the dredging device (airlift) to remove a layer of sand. After removal of sand, lower (lighter-colored) layer of sand is exposed.



(a) (b)

Figure 5. The colorization of the layers is optional and can be turned on (a) or off (b) by the users, helping the users to perform the excavation stratigraphically.

To simulate the dredging procedure, the sand simulation was extended by inserting an extra transformation between the deformation and advection transformations. The dredging procedure removes any sand density in a cylindrical area around the intake of the airlift, with radius r and height h. The parameters r and h have to be chosen based on the resolution of the grid, size of the grid in world space units, and the diameter of the airlift's intake. The input end of the airlift is located at position $\vec{x}$. First, we calculate the parameter e, to determine the circular area of the cylinder.

$$e = (i - \vec{x}_x)^2 + (k - \vec{x}_z)^2$$

Then, the density field ρ and velocity field $\vec{u}$ are updated as follows:

$$\rho^{n+1}_{i,j,k} = \begin{cases} 0 & e \leq r^2 \wedge j \in [\vec{x}_y - h, \vec{x}_y] \\ \rho^n_{i,j,k} & otherwise \end{cases}$$

$$\vec{u}^{n+1}_{i,j,k} = \begin{cases} 0 & e \leq r^2 \wedge j \in [\vec{x}_y - h, \vec{x}_y] \\ \frac{(i,j,k)-\vec{x}}{||(i,j,k)-\vec{x}||} & e \leq (r+1)^2 \wedge j \in [\vec{x}_y - h - 1, \vec{x}_y] \\ \vec{u}^n_{i,j,k} & otherwise \end{cases}$$

Colored Layers

One of the requirements of this work was to allow users to remove the sand layer by layer. To address this issue the sand is visually separated into layers as a visual aid to perform the dredging procedure correctly. The layers are visualized by darkening the even layers, as shown in Figure 6. The stripes are easily readable even in the limited visibility conditions imposed by the underwater environment. This was implemented to increase the realism of the excavation. The entire grid is separated into 10 layers and the colors are assigned in the fragment shader based on the fragment's position on the y axis in the model space. The rendering of the layers can be toggled on and off during the run time of the application, meaning the user can try the excavation with or without the visual guides, e.g., for self-evaluation of removing the current layer.

Figure 6. The sand in the grid can be separated into 10 layers, serving as a visual aid for the users.

VR Underwater Excavation Simulation

Users can interact in real-time with the excavation of objects (artifacts) based on the sand simulation designed for underwater environments [14], [16]. The simulation tracks the user in the context of the physical environment, allowing for natural movement in the virtual environment. To overcome limitations imposed by the physical environment, the user can also teleport in VR (jump from one virtual position to another without physically moving).

The environment is enhanced with caustics and fog, to simulate the lightning conditions underwater. For enhancing the immersion, the terrain is populated with procedurally generated vegetation and rocks. In the background, outside of the playing area, there are schools of fish, simulated by the boids algorithm [18]. The area for performing dredging with the airlift is currently limited to 2x2 meters, with the airlift available for 'grab' and 'use' near the area. The usage of the airlift results in haptic feedback, which also improves the immersion of the simulation. Screenshots of the application are shown on Figure 4 and Figure 5.

Figure 7. A user with the HTC Vive VR headset in the room-scale experience using the application.

Implementation

The sand simulation was implemented using computer shaders and executed in parallel on the GPU, with the data for voxels being stored in several 3D textures - for each data (e.g., the density ρ, the velocity $\vec{u}$, ...) separate textures are used, with the index (i, j, k) corresponding to the same voxel across multiple textures. The simulation is executed in synchronization with the physics engine, that is, 50 times a second.

Regarding the dredging area, our location for excavating constitutes only from one trench. The size of the area in world space units is 2 by 2 meters, with the resolution of the grid being 64^3. The dredging parameters r and h were chosen as 4 voxels and 5 voxels (approximately 6.25 cm and 8 cm) respectively. The application was developed exclusively for the HTC Vive VR headset, supporting the room-scale experience, where the user's head position and rotation, as well as his hands using the tracked controllers, are transformed into the virtual space. The haptic feedback is based on the controller's vibration capabilities. An example of the user interacting with the system can be seen on Figure 7.

Benchmarking

The VR simulation was tested on two computers suitable for running VR applications - a computer with Intel® Core™ i5-6500 CPU @ 3.20 GHz, 16GB of RAM and NVIDIA GeForce GTX 1070 with 8GB of memory and a computer with Intel® Xeon® E5-2620 v2 CPU @ 2.1 GHz, 16GB of RAM and NVIDIA GeForce GTX 980 with 4GB of memory. The benchmarking was performed twice on each setup using the FRAPS software, and each benchmark consisted of one minute of running the application. Results demonstrate that the application is able to maintain stable 90 FPS, which is the requirement for VR applications for HTC Vive to match the refresh rate of HTC Vive displays of 90 Hz. It is worth noting that the application is locked at 90 FPS using vertical synchronization (V-Sync), which prevents from reaching higher framerates.

Since the FPS benchmarking is not representative of a smooth experience, a frametime analysis was also performed to explore the render time for each frame. The graphical results of first run for each computer can be seen on Figure 8. Notice that while the average framerates and frametimes were identical, the second computer shows more rendering spikes. This result was expected due to the present of slower and older components of the second computer - both GPU and CPU.

Conclusion

Informal user evaluation was already performed with more than 30 users at an internal event. Feedback received reported that the underwater simulation is fun and enjoyable. In the near future, a formal user evaluation with expert users (marine archaeologists) is planned. This will examine differences on the learning rate for users who exercise the airlift operation in the virtual environment, compared to a more traditional learning method, e.g., a video showcase, or study texts.

Additionally, this work offers numerous future research topics - improvement of the underwater simulation itself, either by solving the limitations of the current approach (e.g., support for multiple trenches or voxelization of more types of colliders) or simulating the diffusion of the sand underwater and modifying body forces transformation to correctly simulate underwater physics properties, or any of the future work presented in the work by Geiger [8]. Also, an improvement to the slippage heuristic, or benchmarking of the differences between the slippage heuristic and approach presented by Geiger approach can be done.

Acknowledgments

This research was part of the i-MareCulture project (Advanced VR, iMmersive Serious Games and Augmented REality as Tools to Raise Awareness and Access to European Underwater CULTURal heritagE, Digital Heritage) that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727153. Authors would like to thank Prof. Stella Demesticha and her team for her guidance towards the archaeological aspects of this research.

References

[1] B. Beneš, E. Dorjgotov, L. Arns, and G. Bertoline, "Granular material interactive manipulation: Touching sand with haptic feedback," ser. WSCG'2006, 2006. [Online]. Available: http://hpcg.purdue.edu/bbenes/papers/Benes06WSCG.pdf

[2] X. Li and J. M. Moshell, "Modeling soil: Realtime dynamic models for soil slippage and manipulation," in *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '93. New York, NY, USA: ACM, 1993, pp. 361–368. [Online]. Available: http://doi.acm.org/10.1145/166117.166162

[3] D. Holz, T. Beer, and T. Kuhlen, "Soil Deformation Models for Real-Time Simulation: A Hybrid Approach," pp. 21–30. [Online]. Available: http://dx.doi.org/10.2312/PE/vriphys/vriphys09/021-030

[4] K. Onoue and T. Nishita, "Virtual sandbox," in *Proceedings of the 11th Pacific Conference on Computer Graphics and Applications*, ser. PG '03. Washington, DC, USA: IEEE Computer Society, 2003, pp. 252–. [Online]. Available: http://dl.acm.org/citation.cfm?id=946250.946949

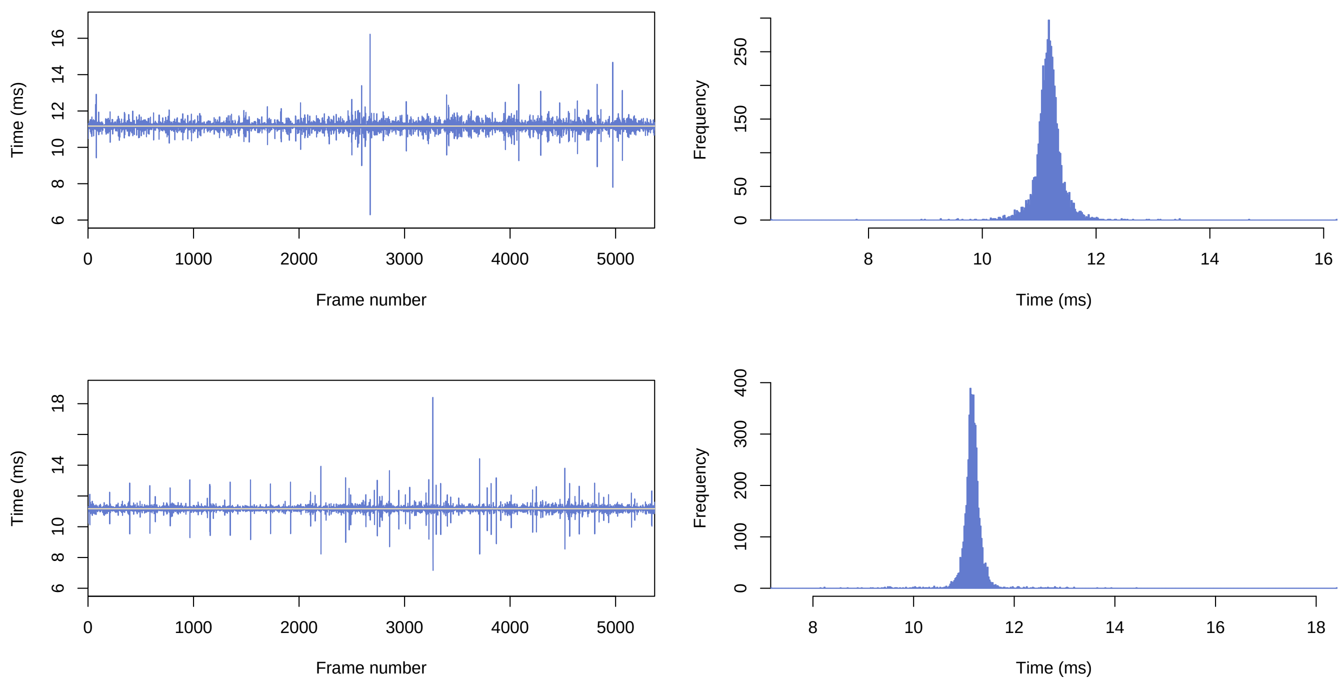


Figure 8. Frametime analysis of the application on the two tested computers. Notice the comparable frame rate but more spikes on the second computer featuring NVIDIA GeForce GTX 980.

[5] V. J. Milenkovic, "Position-based physics: Simulating the motion of many highly interacting spheres and polyhedra," in *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '96. New York, NY, USA: ACM, 1996, pp. 129–136. [Online]. Available: http://doi.acm.org/10.1145/237170.237222

[6] N. Bell, Y. Yu, and P. Mucha, *Particle-based simulation of granular materials*, 2005, pp. 77–86. [Online]. Available: https://dx.doi.org/10.1145/1073368.1073379

[7] Y. Zhu and R. Bridson, "Animating sand as a fluid," in *ACM SIGGRAPH 2005 Papers*, ser. SIGGRAPH '05. New York, NY, USA: ACM, 2005, pp. 965–972. [Online]. Available: http://doi.acm.org/10.1145/1186822.1073298

[8] A. D. Geiger, "A voxel-based approach to the real-time simulation of sands and soils," Master's thesis, University of Regina, 2015. [Online]. Available: http://ourspace.uregina.ca/handle/10294/6563

[9] D. G. Gallagher, "Development of miniature, head-mounted, virtual image displays for navy divers," in *OCEANS '99 MTS/IEEE. Riding the Crest into the 21st Century*, vol. 3, 1999, pp. 1098–1104 vol.3. [Online]. Available: http://dx.doi.org/10.1109/OCEANS.1999.800143

[10] R. Morales, P. Keitler, P. Maier, and G. Klinker, "An underwater augmented reality system for commercial diving operations," in *OCEANS 2009*, 2009, pp. 1–8. [Online]. Available: http://ieeexplore.ieee.org/abstract/document/5422365/

[11] L. Blum, W. Broll, and S. Müller, "Augmented reality under water," in *SIGGRAPH '09: Posters*, ser. SIGGRAPH '09. New York, NY, USA: ACM, 2009, pp. 97:1–97:1. [Online]. Available: http://doi.acm.org/10.1145/1599301.1599398

[12] F. Bruno, A. Lagudi, L. Barbieri, M. Muzzupappa, G. Ritacco, A. Cozza, M. Cozza, R. Peluso, M. Lupia, and G. Cario, *Virtual and Augmented Reality Tools to Improve the Exploitation of Underwater Archaeological Sites by Diver and Non-diver Tourists*. Cham: Springer International Publishing, 2016, pp. 269–280. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-48496-9_22

[13] D. Jain, M. Sra, J. Guo, R. Marques, R. Wu, J. Chiu, and C. Schmandt, "Immersive terrestrial scuba diving using virtual reality," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, ser. CHI EA '16. New York, NY, USA: ACM, 2016, pp. 1563–1569. [Online]. Available: http://doi.acm.org/10.1145/2851581.2892503

[14] F. Liarokapis, P. Kouřil, P. Agrafiotis, S. Demesticha, J. Chmelík, and D. Skarlatos, "3D Modelling and Mapping For Virtual Exploration of Underwater Archaeology Assets," in *Proc. of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS), XLII-2/W3*, 2017, pp. 425–431. [Online]. Available: http://doi.org/10.5194/isprs-archives-XLII-2-W3-425-2017

[15] F. Bruno, A. Lagudi, L. Barbieri, M. Muzzupappa, M. Mangeruga, F. Pupo, M. Cozza, A. Cozza, G. Ritacco, R. Peluso, and S. Tusa, "Virtual diving in the underwater archaeological site of cala minnola," vol. XLII-2/W3, pp. 121–126, 2017. [Online]. Available: http://doi.org/10.5194/isprs-archives-XLII-2-W3-121-2017

[16] P. KOUŘIL, "Underwater excavation serious game," Master's thesis, Faculty of Informatics, Masaryk University, Brno, 2017. [Online]. Available: https://is.muni.cz/th/396550/fi_m/

[17] J. Green, *Maritime Archaeology: A Technical Handbook*. Elsevier/Academic Press, 2004. [Online]. Available: https://books.google.cz/books?id=sFUinBpSWx8C

[18] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '87. New York, NY, USA: ACM, 1987, pp. 25–34. [Online]. Available: http://doi.acm.org/10.1145/37401.37406

Pavel Kouřil graduated from Faculty of Informatics Masaryk University in Brno, Czech Republic and currently works at the Research and Development department at Bohemia Interactive.

Contact him at: pavelkouril@mail.muni.cz

Fotis Liarokapis is an Associate Professor at the Human-Computer Interaction Laboratory at Masaryk University, Faculty of Informatics in Brno, Czech Republic.

Contact him at: liarokap@fi.muni.cz