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Workflows for Virtual Reality Visualisation and Navigation Scenarios in Earth Sciences

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Abstract: This paper presents generic guidelines for constructing customised workflows exploiting game engine technologies aimed at allowing scientists to navigate and interact with their own virtual environments. We have deployed Unity which is a cross-platform game engine freely available for educational and research purposes. Our guidelines are applicable to both onshore and offshore areas (either separately or even merged together) reconstructed from a variety of input datasets such as digital terrains, bathymetric and structure from motion models, and starting from either freely available sources or ad-hoc produced datasets. The deployed datasets are characterised by a wide range of resolutions, ranging from a couple of hundreds of meters down to single centimetres. We outline realisations of workflows creating virtual scenes starting not only from digital elevation models, but also real 3D models as derived from structure from motion techniques e.g. in the form of OBJ or COLLADA. Our guidelines can be knowledge transferred to other scientific domains to support virtual reality exploration, e.g. 3D models in archaeology or digital elevation models in astroplanetary sciences.

1 INTRODUCTION

Scientific visualisation can be an important aid for effective analysis and communication of complex

information that may be otherwise difficult to convey (Vitello et al., 2018, Dykes et al 2018). Visualisation is often a fundamental part of the research process, used for understanding, interpreting and exploring,

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and it can be helpful in guiding the direction of research, from fine-tuning individual parameters to posing entirely new research questions (Mitasova et al., 2012; Sciacca et al., 2015). Furthermore, Virtual reality (VR) can provide scientists with novel navigation mechanisms for exploring outcrops in a fully immersive way, offering the possibility to also interact and collect measurements thus replicating real world field activities (Fig. 1). The increasingly lower costs of new VR devices make it possible to easily access immersive VR environments in a variety of contexts e.g. for outreach, research, training, education and dissemination purposes (e.g. Nayyar et al., 2018; Freina and Ott, 2015; Oprean et al., 2018). Recently Gerloni et al. (2018) presented a VR platform enabling the survey of geological environments and assessment of related geo-hazards, targeting a widespread audience, ranging from early career scientists and civil planning organisations to academics (e.g. students and teachers) and the society at large for public outreach. The underlying idea is to provide users with a holistic view of particular geohazards by allowing exploration of specific features from several points of view and at different scales, to provide rich user experiences by realising exploration scenarios that may not even be possible to perform in the actual field in a real-world scenario. Such VR platforms can be valuable tools in earth-related sciences for developing skills in spatial awareness thus aiding users to comprehend complex geological features more easily. This paper reports our experiences in creating virtual scenes from different sources for reconstructing onshore and offshore 3D environments.

Due to the rapidly evolving technological advances there is currently an explosion in both the amount and complexity of scientific datasets manifested by several global Digital Elevation Models (DEMs)/Digital Terrain Models (DTMs) that are freely available (e.g. <http://srtm.csi.cgiar.org/>) but also high-quality DTMs/DEMs/Digital Surface Models (DSMs) coming from airborne acquisition such as LIDAR (e.g. Liu, 2008) and Aerial Structure from Motion approaches (ASfM) (e.g. Westoby et al., 2012; Turner et al., 2012). Freely available DTMs usually cover larger areas with a lower resolution whereas LIDAR and ASfM approaches are generally used to create smaller DTMs often characterised by higher resolutions and rich textures. Using dedicated Structure from Motion (SfM) software packages it is also possible to directly reconstruct VR environments

exploiting 3D model formats such as OBJ^a or COLLADA^b.



Figure 1: Exploration of Icelandic volcanoes through VR.

Freely available offshore datasets are provided by the General Bathymetric Chart of the Oceans supporting pixel sizes of 250m (GEBCO - <https://www.gebco.net/>) as well as EMODnet-Bathymetry providing harmonised DTMs (<http://www.emodnet-bathymetry.eu/>) for the European sea regions with a pixel size of 100m.

To achieve fine scales (e.g. 1m) scientists normally perform dedicated surveys based on customised multibeam echosounders or even small ROVs (Remote Operated Vehicles, e.g. Savini et al., 2014).

In the following sections we introduce all necessary steps to produce VR-enabled scenarios exploiting modern game engines focusing on Unity, which is the backbone upon which we have developed two workflows for onshore and offshore scenarios..

2 GAME ENGINES FOR VR

Game engines provide sets of tools to build video games for consoles, mobile devices, and personal computers providing a rendering module for 2D or 3D graphics, a physics engine or collision detection (and collision response), sound, scripting, animation, but also functionalities for artificial intelligence, networking, streaming, memory management, threading, localization support, scene graphs, and may also include video support for cinematics. A game engine provides mechanisms to control the

^a <http://paulbourke.net/dataformats/obj/>

^b <https://www.khronos.org/collada/>

course of the game and is responsible for the visual appearance of the game rules. Examples of game engines available for free are Unity (<https://unity3d.com>) from Unity Technologies, CryEngine (<https://www.cryengine.com/>) from the German development studio Crytek, and Unreal (<https://www.unrealengine.com/>) from Epic Games. A current overview and comparison of different game engines can be found e.g. in O'Flanagan (2014) and Lawson (2016). In the context of this paper, for the creation of a virtual scenario applicable to Earth Sciences, Unity was selected. This game engine is best-suited for our development purposes considering its cross-platform integration allowing less development effort toward supporting different platforms such as desktops (Windows, MacOS, Linux), mobiles (Android, iOS) and WebGL based applications. Unity supports full object orientation in C#, supporting modularity and extensibility to build scalable assets that are easily expanded and sustained long term. Furthermore, Unity supports several file formats as used in industry-leading 3D applications e.g. 3DS Max, or Blender. Finally, Unity is well documented as it is supported by large numbers of communities of software developers.

3 WORKFLOWS MODELS

This section describes the two workflows (Fig. 2) developed to generate the VR scenes from different sources regarding onshore and offshore environments.

3.1 VR Scenes from DTM

Onshore and offshore data in DTM/DEM/DSM format can be imported in the game engine using Unity's terrain system based on 16-bit grayscale heightmaps. To prepare the proper input files the following information is needed: i) an elevation/bathymetric grid for user-selected area (the elevation/depth value z is reported in meters); ii) a raster/image file representing the texture for the selected area. These datasets must be georeferenced in metric units. The steps required to merge and process the datasets are detailed below.

STEP 1. Harmonisation: the texture and elevation grid have to match the same pixel size. If necessary, both must be resampled up to the best pixel size value. This is a critical and mandatory step in order to

manage assets so that they can be imported into Unity.

STEP 2. Reshaping: the elevation grid and the texture must have the same extent. Furthermore, the shape of the target area must be a square as it will have to be divided, in a further step, in square tiles.

STEP 3. Value Fixing: another important point is that both the elevation grid and the texture must be assigned with non-null or non-empty values. Each required value must be filled by interpolation or by a default value within the range of the elevation/depth values and RGB colours.

STEP 4. Grid Conversion: The elevation/depth grid must be adapted in order to be used with the Unity terrain based on an heightmap which is a black and white image that stores elevation data. Considering that Unity expects 16-bit unsigned integer (ranging from black to white to represent height, where black is the lowest point and white is the highest point) the elevation grid must be scaled within the range $0 - 2^{16}=65535$. This scaled data is then exported into a new elevation grid suitable for further processing.

STEP 5. Tiling Processing: due to the high resolution and large extension of the areas that are usually managed, we recommend production of a tiled set of the elevation/depth grid-texture. The Global Mapper software^c package has a function (Elevation Grid Format → UNITY RAW TERRAIN/TEXTURE) that tiles and exports (at the same time) both the texture and the elevation grid data. Users must set values for a number of parameters such as terrain size and texture image size in pixels, e.g. 4096 for the texture and 4097 for the terrain (one additional pixel is required by Unity). Global Mapper will then export the texture as .jpg file format and the elevation/depth grid (called terrain in Unity) as a 16-bit RAW file. Both of them are rotated and ready for the import process to start in stage 6. To facilitate the import process into Unity the following information must be given: i) x and y limits of the model (in the metric system - e.g. utm coordinates); ii) areal extents of the model; iii) min and max altitudes of the elevation/depth grid; iv) pixel size; v) number of tiles along x and y and finally vi) number of pixels per each tile.

STEP 6. Metadata Association: the produced tiled elevation/depth grid-texture is finally associated with a descriptive text file, which adds information about the real environment depicted in the data mentioned in step 5. The essential information these files must contain are easting, northing and elevation. These text

^c <https://tinyurl.com/y62w52ao>

files are formatted as JSON strings, used to calculate the position of the player in the real-world coordinates.

STEP 7. Tiles Importing: this step is required for large extensions and/or high resolutions where the number of resulting tiles can be prohibitively large. As an example, in Gerloni et al. (2018) importing a high-resolution terrain and texture with 2 cm/pixel resulted in a total number of 1681 of tiles with 512x512 pixels each. To automate the import and alignment of such numbers of tiles the Unity editor functionality has been extended with an ad-hoc code made available on GitHub (<https://tinyurl.com/y268jsg2>).

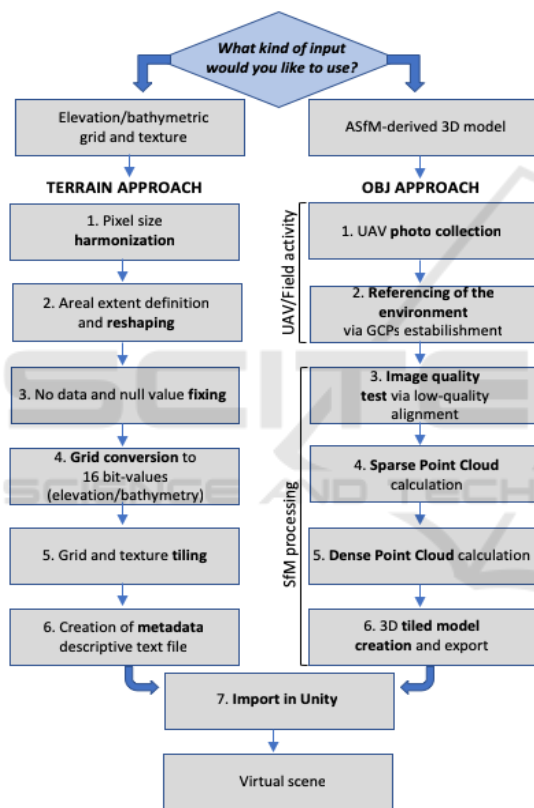


Figure 2: Conceptual overview summarising the workflows.

3.2 VR Scenes from ASfM 3D Models

This section describes the main steps needed for reconstruction, processing and rendering from the real environment into the VR scene using a 3D tiled OBJ model. The environment can be reconstructed using the ASfM approach (e.g. Westoby et al., 2012), providing centrimetric pixel size resolution of the texture. The SfM technique allows the identification of matching features in different images, captured

along proper UAV flight paths (Fig. 3), the combination between them to create a sparse and dense cloud, the creation of a mesh, a texture and, much more importantly for VR, a high-resolution 3D tiled model (e.g. Westoby et al., 2012).

STEP 1. Photo Collection: UAV-captured photos have been collected in order to have an overlap of 90% along the path and 80% in lateral direction, useful to have a good alignment of images and to reduce the distortions on the resulting orthomosaics and have been processed with the use of Agisoft PhotoScan (<http://www.agisoft.com/>), a commercial Structure from Motion (SfM) software. We used a quadcopter (DJI Phantom 4 Pro) for image acquisition every 2 seconds (equal time interval mode), with a constant velocity of 3 m/s to minimize the motion blur, as well as to achieve well-balanced camera settings (exposure time, ISO aperture) and ensure sharp and sufficiently exposed images with low noise. The UAV flight path has been planned and managed using DJI Ground Station Pro software (<https://www.dji.com/ground-station-pro>).

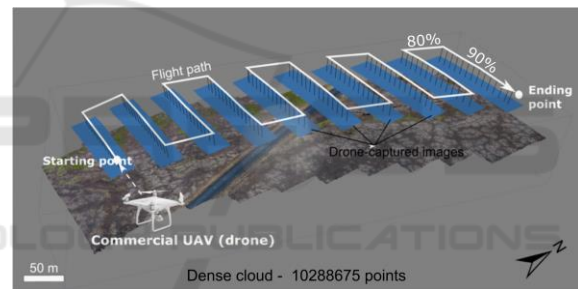


Figure 3: UAV flight path (white line) at 50 m of flight height. The dense SfM-resulting cloud is represented.

STEP 2. Environment Referencing: Furthermore, in order to allow the co-registration of datasets and the calibration of the 3D model, World Geodetic System (WGS84) coordinates of, at least, four artificial Ground Control Points (GCPs) have been established near each corner within each surveyed area and one in the central part for reducing the so called doming effect resulting from SfM processing (e.g. James and Robson, 2012).

STEP 3. Image Quality Test: the first step was to obtain an initial low-quality image alignment, only considering measured camera locations (Reference preselection mode). After that, images with quality value of <0.5 , or out of focus, have been disabled and thus excluded from further photogrammetric processing, as suggested in the user manual of the software.

STEP 4. Sparse Point Cloud Calculation: after this first quality check, ground control points were added in all images, where available, in order to: *i)* scale and georeference the point cloud (and thus the resulting model); *ii)* optimise extrinsic parameters, such as estimated camera locations and orientations; *iii)* improve the accuracy of the final model. Furthermore, realignment of photos using high accuracy settings was completed, resulting in a better establishment of camera location and orientation, and then the sparse point cloud was computed.

STEP 5. Dense Point Cloud Calculation: Dense point cloud (e.g. Fig. 3) is then calculated from the sparse point cloud, using a Mild depth filtering and high-quality settings.

STEP 6. Tiled Model Creation: a tiled model with a very high resolution that represents all 3D objects and vertical surfaces (Fig. 5B) can be built and exported in Wavefront OBJ format that is compatible with Unity. We suggest a tile size of 4096x4096 pixels as a compromise between performance and quality.

STEP 7. Model Rendering Optimization: in order to optimize the rendering performance of the scene we suggest using Levels of Detail (LODs) to reduce the number of details shown when the model is far away from the camera.

To make the model robust for navigation purposes each tile must have its own collider generated and to match the same north between the real and the virtual world the 3D objects must be rotated by 180° along the y axis. Finally, the virtual scene has to be properly referenced and scaled by employing information derived from SfM processing and thus the scene dimension (in meters) and the corresponding geographic coordinates must be defined, as well as the altitude referred to the 3D reconstructed model. After these steps, the scene is ready to be navigated (e.g. Fig. 5B).

4 USE CASES

This section describes the application of the mentioned workflows through two different cases.

4.1 VR Scene from DTM

In this use case we demonstrate the workflow discussed in Section 3.1 (Fig. 2) using a large area of the Hellenic arc with WGS 84 / UTM zone 35N spatial reference system (Fig. 4).

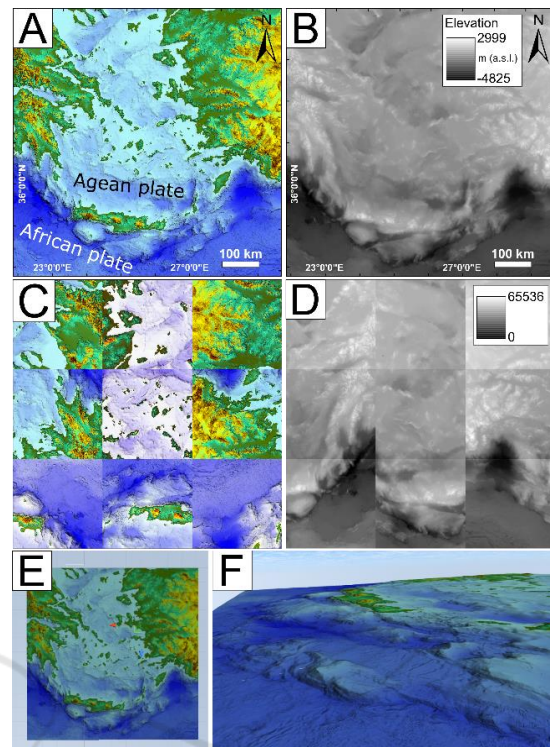


Figure 4: (A) texture; (B) elevation grid; (C) tiled texture; (D) raw tiled terrain ready to be imported in Unity; (E) tiled model in Unity and (F) VR navigation.

Bathymetry comes from EMODnet-Bathymetry and DEM from the Srtm v4.1 DEM database (<http://srtm.csi.cgiar.org/>), having a different areal extent and pixel size. They have been harmonized to the same (best) pixel size, merged and reshaped to a square area, and incorrect values have been fixed (Steps 1, 2 and 3; Fig. 4B); The texture (Fig. 4A) has been created from the resulting elevation grid and it is representative of the elevation. Grid conversion and tiling processing (Steps 4-5) is depicted in Figures 4C-D. Finally, Figure 4E shows the resulting tiled model in Unity whereas the VR navigation is depicted in Figure 4F.

4.2 VR Scene from OBJ Model

In this use case we demonstrate the workflow discussed in Section 3.2, focusing on the western part of the Metaxa Mine, Santorini, Greece. The first UAV flight was dedicated specifically in capturing a set of photos in nadir camera view (Fig. 5A) with the suggested overlap (Bonali et al., 2019). The photos have been captured every 2 seconds, at an altitude of 20 m from the highest point of the ground (Home point) and with a constant velocity of 2 m/s. The second flight was for collecting photos of the vertical

outcrops and the camera was oriented orthogonal to vertical cliff, in order to add details to the model. A set of 20 GCPs have also been included in order to co-register the 3D model to the WGS84 reference system. The resulting 3D model is as large as 349 x 383 m, is composed of 170 tiles, each of them is 4096x4096 pixels, and the pixel resolution is 8 mm; it has been imported in Unity engine (Fig. 5B).

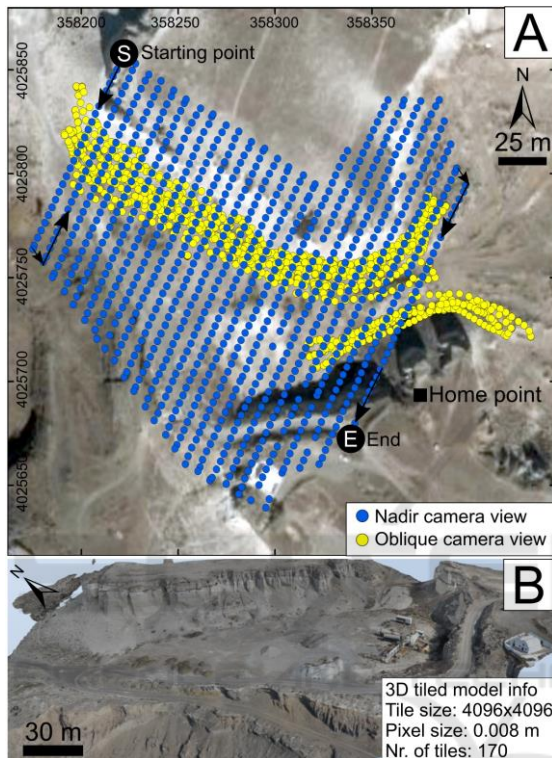


Figure 5: (A) Location of UAV-captured images, spatial reference: WGS 84 / UTM zone 35N. (B) 3D tiled model of the western part of the mine, explored in virtual reality.

5 DISCUSSION

We deployed the workflows presented in earlier sections (Fig. 2) to create Unity scenes for the purposes of visual exploration through immersive VR. Both approaches (terrain and OBJ) enable immersive user interaction scenarios based on previously reconstructed 3D models. This section reports on our experiences with various models with both approaches and discusses briefly possible improvements and pointers to future work developments. The terrain approach is suitable for DTM/DSM-textures both from freely available sources and ad-hoc created models for onshore/offshore environments, individually or combined.

Specifically, this approach works within a wide range of resolutions from hundreds down to single meters. Although other works (e.g. Gerloni et al., 2018) have applied a similar approach down to cms scale, this may require scalings within Unity posing excessive memory requirements resulting in prohibitively low frame rates. Figure 6A shows an example of the Cratered Cones Near Hephaestus Fossae (in Mars) based on the publicly available HiRISE Digital Terrain Models (<https://www.uahirise.org/>). The resolution of the area shown is 1m whereas the areal extent is 4800 x 4800 m. Figure 6B shows an ad-hoc bathymetric model created from data collected during two oceanographic cruises, with the use of a Reson Seabat 8160 Multibeam Echosounder (Savini et al., 2010; Savini et al., 2014). The resulting DTM is of 40 m resolution and provides a wide range of bathymetric depth information from 120m to 1400m. The 3D OBJ approach was also tested with several models of different areal extents and resolutions (see Figs. 6C-D) covering from 8mm to 1m. This approach allows improved representations of geometry especially around features that are vertical to the terrain as shown in Figure 6D where an outcrop from Vlychada beach, Santorini, Greece, shows several volcanic layers related to the Minoan eruption (e.g. Nomikou et al., 2016). To our experience so far both approaches work well in creating VR scenes. A number of optimisations are planned for future developments. Firstly, we would like to avoid any dependencies upon proprietary software packages (such as Agisoft Photoscan, Global Mapper or ArcGIS). Currently the open-source alternatives such as QGIS (<https://www.qgis.org/it/site/>) and VisualSFM (<http://ccwu.me/vsfm/>) suffer from a number of limitations, e.g. non-streamlined user interface for data processing for the former, and low quality of point clouds for the latter (e.g. Burns et al., 2017). Additionally, for VisualSFM further post-processing through other third party software is needed (Falkingham, 2013). Regarding the use of VR in Earth Sciences, this technology provides a series of positive feedbacks for geological and geo-hazards studies. Firstly, it facilitates the survey of geological environments and related geo-hazards assessment: i) travel time and associated costs to study remote areas are cut off, for example from Europe to South America or Asia (Lanza et al., 2013; Tibaldi et al., 2015); ii) all logistic issues that must be taken into account during mission preparation are overcome, as well as VR allows to access remote or dangerous areas (e.g. Tibaldi et al., 2008).

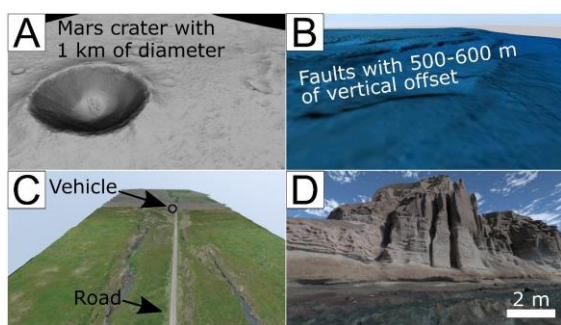


Figure 6: VR scenes from elevation / bathymetric grid-texture format (A-B) and 3D OBJ models (C-D).

This technology is also very innovative and can be used for research, teaching and outreach activities, encompassing a wide audience that spans from early career scientists and civil planning organisations, to academic and non-academic people. Finally, it is possible to establish a virtual geological lab where the reconstructed key sites are permanently available for geological exploration and studies, thus providing the possibility of geological exploration also to people affected by motor disabilities.

6 FUTURE DEVELOPMENTS

Our future vision is to build fully open-source workflows avoiding completely any dependencies upon proprietary software. To this extent we will work in integrating existing open source packages while injecting into them any additional functionalities as required. Specifically, for the terrain approach to streamline the process for end users, as automatic as possible procedures are needed. We envisage development of a collection of Python scripts to handle tasks such as areal extent definition and pixel homogenization of both elevation grids and textures or the conversion to RAW format and successive tiling process. Although the development of our workflows was based on the Unity game engine we have focused on the generic functionalities of game engines abstracting from specific realisations thus following a modular approach so that in future we would be able to support other engines. Our future development plan also includes a formal assessment of user interaction mechanisms under various scenarios to ascertain potential VR experiences fully tailored to specific teaching, training and research activities, including scenarios coming from geophysical and lab-scaled studies (Tortini et al., 2014; Russo et al., 2017).

7 CONCLUSIONS

We have outlined generic workflow approaches for creating virtual reality scenes based on a variety of sources. We have demonstrated onshore and offshore (including combined) examples using different sources and deploying different. The vision is to build fully automated workflows without any dependencies upon proprietary software packages. The work presented in this paper has followed a generic approach applicable to creating virtual scenarios in other disciplines such as geophysics, astro planetary sciences and archaeology.

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