Virtual Reality Visualization for Photogrammetric 3D Reconstructions of Cultural Heritage

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Abstract. In this paper the authors review the design of a self-build general-purpose Virtual Reality environment, which presents all relevant features of a full-size CAVE-like system, yet at a fraction of the financial and space requirements. Further, the application of this system to the development of a virtual museum is presented. The objects in the museum are models, reconstructed via photogrammetry from a set of pictures. For this process cost-free software is used. The presentation of the 3D models in the Virtual Environment is done using BlenderCAVE, a multi-screen extension of the Blender game engine. The main contributions of this paper are the discussion of the design choices for a small and low-budget but feature-rich virtual reality environment and the application of the system for cultural heritage. In this area tools for creation of 3D models and their presentation in a VR environment are presented.

Keywords: Virtual Reality · CAVE-like system · Cultural Heritage

1 Introduction

In the last year, affordable personal Virtual Reality devices like the Oculus Rift or Google Glasses pushed Virtual Reality, almost unexpectedly, in the public eye, suddenly reviving a trend that seemed to be ready to blossom already twenty years ago but that never did, giving the delusion that the topic was dead.

The truth is, that Virtual Reality never ceased to slowly move on with the development in research, far from the spotlights, patiently waiting for hardware to improve in power and decrease in price to support its features.

In 1993, with the Cruz-Neira CAVE [7], research institutes and private engineering companies slowly started building their own Virtual Environments, with a pace dictated mainly by the still high budget requirements those systems implied. Nowadays, a semi-immersive CAVE-like system price ranges from several hundred-thousand Euro up to several million Euro. The resolution, user interaction and quality of all their characteristics obviously improved enormously compared to their first ancestors from the 90s, but the price is still far from being an easily accessible one. Several research institution that could make use of the

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Fig. 1. The "Kyb3" Virtual Reality Environment, showing a 3D model in Blender-CAVE

potentialities of employing VR-oriented visualization systems, wouldn't still be able to afford a full CAVE system.

At the same time, the limitations of lower cost personal VR devices like Head Mounted Displays (HMD) are still hindering their use in environments meant for cooperative research involving multiple users.

From all this premises come the reasons that persuaded us to build our own customized VR system at the Institute of Cybernetics of Tallinn University of Technology in 2012, the Kyb3 [11], Fig. 1. The system has been designed to be a space and budget contained virtual environment with the flexibility of being both a tool to perform research on virtual reality itself and to employ it as a tool for scientific visualization. It took approximately one year and half to design and build the system but, once completed, its flexibility paid off, proving that the Kyb3 was open to an even wider range of applications than the ones it was devised for.

While mainly employed to visualize the results of microstructured materials analysis (Steel Fibre Reinforced Concrete [8,12,16]), a recent interest in 3D scanning and photogrammetry, led to the decision to employ the Kyb3 for a semi-immersive visualization of the scanned objects as well.

2 The Visualization System "Kyb3"

Being the first system of its kind in Estonia, the Kyb3 was conceived and built both as a tool for specific visualization tasks (Micro-structured materials analysis and visualization) and as a prototype to kick-start the research in the field of Virtual Reality in Estonia. The task of building a space and budget contained VR system that could also reproduce most of the real-size VE features, was not trivial and involved several months of accurate design. Every component of the system had to be chosen according to multiple constraint. While the budget-related ones might be obvious, the space related ones were instead the cause of more complex design choices. The full system had to fit into a space of no more than $2.5 \times 2.5 \times 2.5$ meters, while retaining a screen surface wide enough to grant a good semi-immersive visualization experience. Also, as mentioned, it had to be a scaled-down version of the features of real-size CAVE systems (table/floor screen, user tracking, etc).

2.1 Design Choices of the Kyb3 Related to Space

To deal with the space constraint, the fundamental choices have been: short throw projectors and a mirror system to further reduce the throw distance necessary for the projected image to achieve the chosen size. While with a traditional projection system, the projectors would have needed approximately 2.7 m distance to achieve a screen size of 110 cm $\times$ 80 cm, with the use of the short-throw projectors and mirrors, less that 75 cm where necessary. To properly position the hanging projectors, filters and mirrors, a special, configurable mounting was self-designed. This way it was possible to obtain a system fitting in a parallelepiped ($H \times W \times L$) of no more than 2.35 m $\times$ 2.04 m $\times$ 1.77 m, see Fig. 1.

The whole system is supported by a self-designed aluminum frame (the material was chosen to avoid excessive interference with the electromagnetic fields of the tracking system), tailored on the specific configuration needs of the Kyb3, and built with the practical support of Dimentio OÜ.

2.2 Design Choices of the Kyb3 Related to Budget

The budget constraint influenced all the design choices made: A single tower computer with 4 high-end NVIDIA 4000 graphics card was chosen instead of the now common setup with one computer per screen. A low cost electromagnetic user tracking system, the WintrackerIII is employed instead of the more commonly used, but high price, optical systems. Consumer hardware (Nintendo Wiimote and Razer Hydra 6-DOF joysticks) is used to manage the user interaction.

Both, to keep the price low and to have a research-friendly system, only open-source freely-available software was installed on the machine. The whole input is managed through VRPN [17] and VRUI [10] Device Daemon, while the main software used for the applications are: ParaView for visualization of several types of scientific data-sets (vectors and tensors fields, CFD simulations, volumetric data), and VRUI, a VR platform supporting a wide set of software to visualize mesh data, LIDAR data, scalar/vectorial/tensorial volume data, VRML scenes and more. Further VMD and jReality are currently being configured to extend the fields of application to molecular dynamics and mathematical geometry.

A recent addition is BlenderCAVE. This list of software offers a wide choice of supported data-sets to researchers and users from various fields to visualize their data on the 3D screens of the Kyb3.

3 Application Within Cultural Heritage

One possible application of Virtual Reality and 3D scanning is, of course, in cultural heritage. It can be used to share information about and discuss artifacts with colleagues online, or to build a virtual museum for the public. In some cases it may not be possible for visitors to access the historic site, due to a remote location or the risk of damage, but nevertheless it would be beneficial to show it to the public to create interest in its preservation and exploration. Another possibility is that virtual exhibitions can be easily transferred from one place around the world to another and can take place in several locations at the same time and could be arranged in small towns or even villages, therefore being accessible by more people.

During the course of the academic year 2013 and 2014, having several MS Kinect camera available from previous user-tracking experiments, and being interested in further increasing the interaction between the Kyb3 and the real world, we turned our attention to 3D scanning options.

For the use of VR in a museum, several other points need consideration:

– The usability of applications by visitors to the museum
– The need to create different user interfaces depending on the target group
– The ability to integrate multimedia content, creating moments of edutainment effective
– The maintenance cost of the solution
– The cost of staff training

Most of these points are not addressed by our study, however some of the design choices we made have proven to be beneficial to maintanance costs.

The backprojection screens used by us are scratch resistant and washable, which is a large benefit when dealing with user groups and children. Also the Razer Hydra, used as a wand, is relatively cheap and as being gaming equipment also robust. It doesn't get damaged immediately when accidentally falling down and could be replaced without large costs if damaged. The optically tracked wands, used in large commerical VR environments, need readjusting of the tracker markers by the manufacturer after falling down, which causes downtime of the system and is expensive.

The main aim here is to show, how a general purpose VRE can be opened up for cultural heritage as a new application field, thus increasing the amount of possible users of the system and therefore increasing its value for the institution maintaining it.

(a) Photo of the sculpture (b) 3D model without texture

Fig. 2. Kinect scan of a meerkat sculpture

4 3D Scanning with a Depth Sensor

Due to the available equipment, the most obvious one seemed to be the reconstruction of an object through the automatic registration and merging of multiple point clouds derived from the depth sensor of the Kinect, using the Point Cloud Library (PCL) [15].

Three months of experiments that involved a BSc thesis, resulted in a partial success. Through the use of key-points registration and loop-closure detection to reduce errors, we obtained a self-developed software able to scan a small object (up to 30x30x30 cm), Fig. 2, or a human bust, with no textures and a limited level of depth resolution. The whole process, including scanning and reconstruction took approximately 20 minutes, resulting in a mesh file compatible with most of the 3D Visualization software.

The limitation of the method appeared though quite obvious when we tried using the same software to scan much larger objects and environments. On room-sized indoor areas, after tweaking of the parameters it was possible to obtain reasonable meshes, despite several external factors. Some examples are the type and intensity of lights and the color of the objects, conditioning negatively the quality of the Kinect depth image. Outdoors, these problems amplify, including the limitations due to having a cable-bound camera. More traditional LIDAR outdoor methods had on the other hand the serious disadvantage of really high prices (and some of the same reconstruction problems encountered with the Kinect depth-cloud reconstruction).

We therefore turned our attention to photogrammetry, whose recent evolution led to astonishing results in outdoor reconstruction.

5 Photogrammetric Reconstruction

The (re-)construction of a 3D model from photos is commonly also referred to as *Structure from Motion* (SfM). The general process for the reconstruction is, in principal, independent of the used software, but the degree of required user-interaction differs drastically. The online tool 123D Catch for example hides some of the different steps completely from the user, while the open-source programs require the user to perform each of the following steps separately:

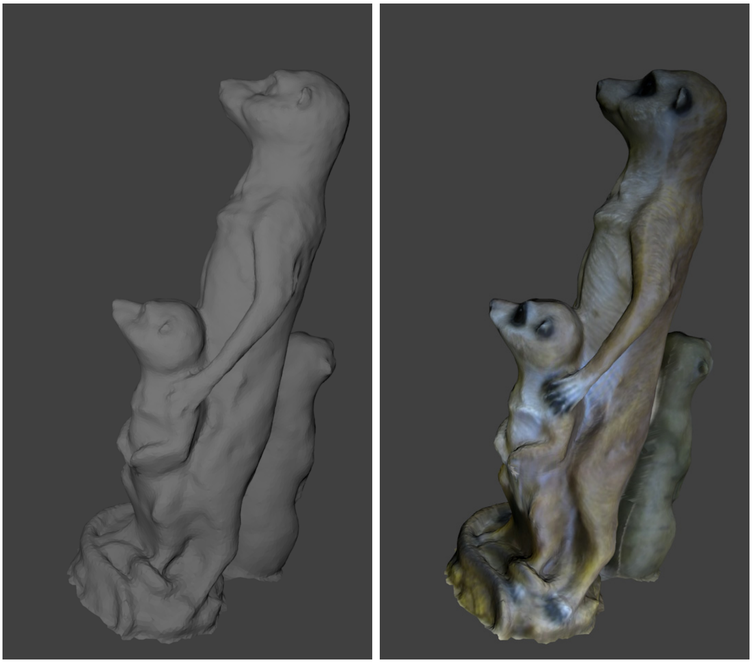
- taking a sequence of pictures of the object
- loading images into software, resp. scaling down
- possibly enter camera parameters (or use EXIF data)
- aligning of images, determining camera positions
- obtaining of point cloud (mesh vertices)
- mesh generation

There are several commercial and free software tools available, some of the more popular ones seem to be:

- Agisoft PhotoScan: commercial
- Autodesk Smart3DCapture: commercial, can use GPS position
- Autodesk 123D Catch: free online tool using the core of Smart3DCapture, amount of pictures limited, restrictive license (content belongs to whom?)
- Python Photogrammetry ToolBox [3]: open-source front-end for OSM-Bundler, CMVS, PMVS [2]
- VisualSFM [18]: open-source, graphical user-interface
- OpenMVG [1]: open-source library
- MeshLab [5,6]: open-source mesh creation and processing software

As the rest of our 3D system is build on free and open-source software (FOSS), it is natural for us to concentrate on free software, meaning preferably open-source or at least usable free of charge.

In order to create a three-dimensional representation of an object of interest it is necessary to cover the subject with a good photo set, taking between 50 and 70 photographs of the subject from different angles and with overlap. During the process the lighting conditions should stay the same, it is preferable not to have anything blocking the view and the subject should not be moved as features from the whole photograph are used to stitch together the model. It is also preferable not to have any disturbances in the background.



(a) Mesh (b) with texture

Fig. 3. Photogrammetric model of a meerkat sculpture obtained with 123D Catch

5.1 123D Catch

Autodesk 123D Catch provides a simple and user-friendly way to record three-dimensional data without the need for specialized equipment or technical skills. It is accessible to anybody with a consumer camera. Autodesk 123D Catch finds common features on all the photographs and uses them to reconstruct a three-dimensional scene. To create a model of the statue of *Juulius*, the eternal student (Fig. 4) and the mascot of our university, we took about 50 photographs sequentially around the statue, each showing the whole statue, uploaded them to 123D Catch and received a three-dimensional scene representing the statue. Such a three-dimensional scene can easily be exported as a mesh object and opened in Blender where it can be modified, and represented interactively to a user using Blender game engine.

As mentioned before, the process is straightforward, the reconstruction in 123D Catch requires no adjustments by the user. In our case, it took about half an our to upload the pictures and obtain the model, the result is very detailed and presented in Fig. 5 for Juulius and in Fig. 3 for the meerkat skulpture for comparison with the Kinect scan in Fig. 2.

Fig. 4. Photo of Juulius, the eternal student, mascot of Tallinn University of Technology

5.2 Python Photogrammetry ToolBox

The Python Photogrammetry ToolBox (PPT) is a GUI for several tools to simplify the reconstruction process. Using PPT only some mouse-clicks are necessary to obtain structure from the images, however the process is not as automatized as with 123D Catch. The components invoked by the GUI are Bundler and PMVS, CMVS. After MeshLab needs to be invoked to create the mesh. PPT can take a mix of pictures from different cameras, but for all cameras the width of the CCD sensor needs to be known.

The following steps are performed:

- check camera database and enter parameters if necessary
- run Bundler, in this case we used the siftvlfeat for feature matching and the images have been scaled down to 1200 pixels
- then PVMS was used to create the point cloud
- in MeshLab the Poisson Surface reconstruction is used, here it may be necessary to remove points belonging to the surrounding

The result of the reconstruction is shown in Fig. 6. The result is slightly less precise as the one obtained by 123D Catch, but this might be due to a non-optimal choice of parameters or the scaling of the pictures.

(a) Mesh (b) With texture

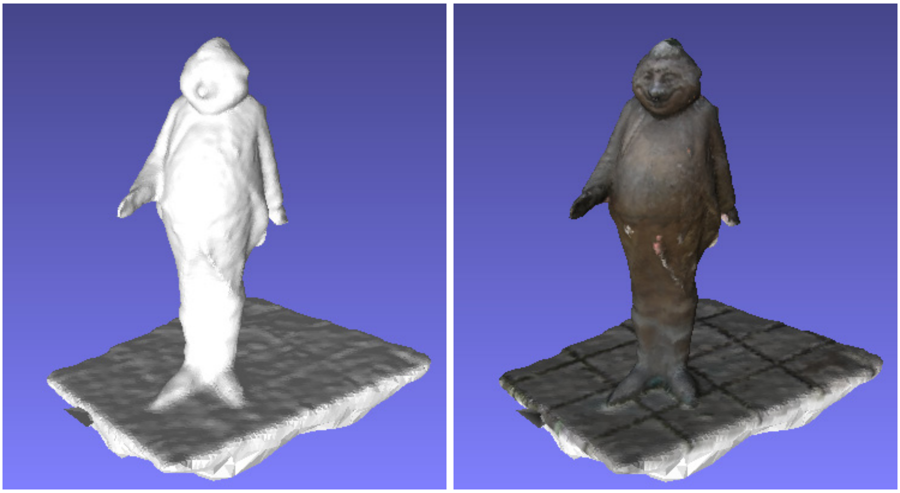
Fig. 5. Mesh of Juulius obtained with 123D Catch

5.3 VisualSFM

Creating three-dimensional reconstructions using VisualSFMs graphical user interface is similar to using 123D Catch. First, the user needs to select the photographs to work with, then, with two button clicks, it is possible to receive a sparse reconstruction based on those. With one more button click it is possible to receive a dense reconstruction, computing which takes time -? for us it took about two hours to compute a dense reconstruction of the statue of Juulius. It is possible to run VisualSFM on the command line and change some of its parameters, giving the user more control over the steps of the reconstruction process. The resulting point cloud with the camera positions is shown in Fig. 7. Being able to see the camera positions gives the possibility to see possible reasons in case the model has holes or lacks details in some areas, due to sparse photo coverage.

6 BlenderCAVE

One possible category of software to create an interactive museum are game engines (e.g. the CryEngine has been used before [9]), and within this category, Blender [4] with the BlenderCAVE [13,14] is an interesting candidate. Blender was an in-house tool of the Dutch animation studio Neo Geo and Not a Number Technologies (NaN), in 2002 it was released under the GNU General Public License. While the learning curve is steep, the work-flow within Blender has been designed by modeling and animation professionals, and is very efficient.



(a) Mesh (b) With texture

Fig. 6. Mesh of Juulius obtained with Python Photogrammetry ToolBox and MeshLab

Implemented in 2012/2013 at the Computer Science Laboratory for Mechanics and Engineering Science (LIMSI), a CNRS Laboratory associated with Paris-Sud University, BlenderCAVE (BC) offers an adaptation to the open-source Blender Game Engine (BGE) module of Blender able to run in a scaleable way on any Virtual Reality architecture (N hosts, K screens), supporting stereoscopic viewing in all the most common techniques (passive, active, side-by-side, etc) and integrating a VRPN plugin to manage user tracking and interaction.

The flexibility of the BGE, together with the powerful features of Blender itself, provides the user an interactive 3D scene manager that is both simple to setup and flexible in the format of data that can be displayed. By integrating a physics engine (Bullet Engine), BGE can take, under the BC control, extremely interesting interactive scenes to a wide range of devices, from simple desktop environments to full-sized CAVE systems.

Thanks to a flexible implementation, BC allows most of the existing BGE scenes to work on a VE with barely a couple of lines of additional codes to their logic managers.

During the starting phase of Cultural Heritage visualization on Virtual Reality Environments, despite a wide selection of existing software, BC became our chosen one due to several reasons. First of all thanks to Blender's own features, that allow us to import almost every existing format of meshes and additionally perform some post-processing and refinement of the meshes obtained through the photogrammetric reconstruction. Having the BGE integrated in the same working environment means that the process to bring interaction to the static objects is extremely straightforward, allowing therefore to immediately be able to navigate the meshes in immersive ways (as for example walking around and inside them).

Fig. 7. Point cloud with camera positions obtained with VisualSFM

Additionally, the scaleability of BC, allows the preparation of the scenes to be easily be performed on desktop and laptop computers, and then taken to the already configured BC on the Kyb3 system, without requiring any additional configuration.

Fig. 8. Showing the obtained model with BlenderCAVE in our 3D system

An ideal setup for prototyping, working and displaying results of the work done in the quickest possible way. Fig. 8 shows the 3D model of Juulius obtained by photogrammetry integrated into one of the example scenes of BlenderCAVE.

7 Conclusions and Outlook

In this paper we have discussed the main design choices for a low-budget VR system, that has the main features of a CAVE-like environment, and that is used for both, VR development and applications in material science, civil engineering and cultural heritage. For the application in cultural heritage, we presented a tool-chain to create 3D models from real objects from small artifacts to statues and possibly to houses. The tool-chain included either free-of-charge or open-source software and covered the full range from 3D scanning over model creation to modeling and presentation with BlenderCAVE in our VR environment.

In the future the authors plan to develop interactive physical games using the physics engine of Blender. The physics engine could also be used to animate objects and therefore create more lively representations.

Another plan is to try to use of remote controlled multi-copters to take aerial photos, e.g. to create models of houses, castles or churches. The whole process described in Section 5 implies one thing: that pictures are taken from all the directions around the subject of interest, to cover every possible exposed surface. This can be relatively easy in case of small objects whose size is no larger than a human body, but what happens if the necessity of completely reconstructing a building arises? One possibility that we consider for the future are multi-copters, which are readily available now, many of them already endowed with HD cameras.

By combining the pictures taken from the ground and those taken from the copter of the otherwise unreachable parts, it is possible to gather all of the pictures necessary for a high resolution and accurate 3D model of a building. Due to the copter maneuverability, it is also possible to focus on extruding features of the building (as small towers or gargoyles) and include them realistically in the final reconstruction.

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