



## D3.1

### Output-sensitive Rendering on Light Field Displays

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## 1 Executive Summary

This deliverable reports on the research results achieved in the field of Output Sensitive Rendering Techniques, covered in the project's Work Package 3. We list the contributions from the main involved partners, we summarize the project publications, classifying them in terms of the main data kind handled, list the awards received, and summarize the events that have used the developed technology.

## 2 Introduction

The DIVA project is aimed at training the next generation of visualization and analysis experts who will be equipped with the necessary skills to cope with the major challenges for visual presentation and understanding in data intensive application environments.

This deliverable reports on the research results achieved in the field of **Output Sensitive Rendering Techniques**, covered in the project's **Work Package 3**.

*The research goal set up in the project was “to aim at developing methodologies and techniques for presenting highly accurate and understandable depictions of local and remote massive geometric and volumetric models on both standard and novel 3D displays, fully harnessing human perceptual capabilities to enable users to gain an in-depth understanding of complex 3D models. The two main classes of targeted models are massive surface models, such as those created with laser scanners, and volumetric models, such as those created by simulations and medical acquisition devices.”*

The goal has been fully achieved, as demonstrated by the project tangible results in terms of publications, awards, and events organized.

Research and training activities have focused on specific sub-topics of the general research goal. In terms of massive data kinds, we have focused on volumetric models, with a special emphasis on rectilinear scalar volumes, surface models, especially meshes of triangles/quadrangles, and light fields, in connection with 3D displays. In terms of techniques, special emphasis has been given to adaptive methods to achieve output-sensitivity, compression and compression-domain rendering, to support streaming for out-of-core rendering and remote rendering, and user interfaces, to support exploration in a variety of settings. Results have been published in 24 peer-reviewed publications, and have led to the first two PhDs awarded to DIVA ESR fellows. In addition, two of these publications have been awarded a “Best Paper” prize. Finally, the developed techniques have been used for public events, especially in the area of Cultural Heritage.

In the following sections, we report on the results obtained.

### 3 Collaboration and fellow contributions

The research described in this deliverable is the result of collaborative work. While in the training aspects all DIVA groups have contributed through exchanges, supervision, and training events such as workshops and summer schools, the specific research that has led to the results described in this deliverable is the main output of the directly involved DIVA fellows. We list here the main roles:

- **Oliver Mattausch (ER, UZH)** – work on output sensitive techniques with main focus on scalable rendering
- **Jose Diaz Iriberry (ER, CRS4)** – work on volumetric models, with main focus on compression and perceptual testing
- **Marcos Balsa Rodriguez (ESR, CRS4)** – work on output sensitive techniques with main focus on scalable graphics, streaming, and user interaction, including calibration for light field displays
- **Alberto Jaspe Villanueva (ESR, CRS4)** – work on scalable graphics and user interaction in a variety of settings, including large projection based setups and light field displays
- **Vamsi Kiran Adikharla (ESR, HOL)** – work on retargeting live video and graphics for light field displays.

The collaboration among these fellows produced many high-quality publications. In addition, Vamsi and Marcos achieved the important goal of completing their PhD on the basis of their DIVA results.

Additional minor contributions to the work performed for this deliverable were given by fellows in Rostock on video capture, streaming, and display (ABM Tariqul Islam, ESR), and fellows in Zurich on geometry data capture and parallelization (Claudio Mura, ESR; David Steiner, ESR). These contributions are not discussed here, since they are already covered in the deliverables D2.1 (scalable processing), D.4.1 (parallel rendering), and D6.1 (tele-immersion).

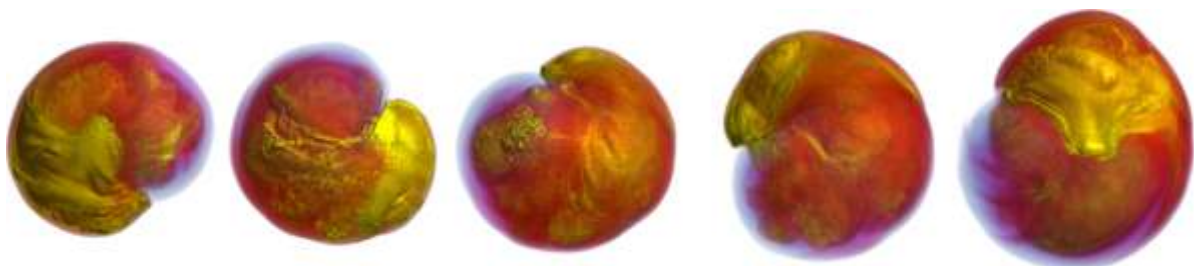
## 4 Research results

### 4.1 Volumes

Scientific visualization is the formal name given in computer science to the field that encompasses data representation and processing algorithms, user interfaces, visual and other sensory representations in order to transform data into sensory information. Scientists do so in order to glean insight from raw simulation data or data analysis. Rectilinear scalar volumes, i.e., scalar functions sampled on a 3D grid, are among the most common datasets in scientific visualization. Such volumetric information is generated by simulations as well as by acquisition devices like for example computerized tomography (CT), magnetic resonance imaging (MRI), and ultrasounds. New advances in computer simulation and in data acquisition devices are leading to a steady increase in the resolution of produced datasets. This is leading to research aimed at efficiently handling massive data.

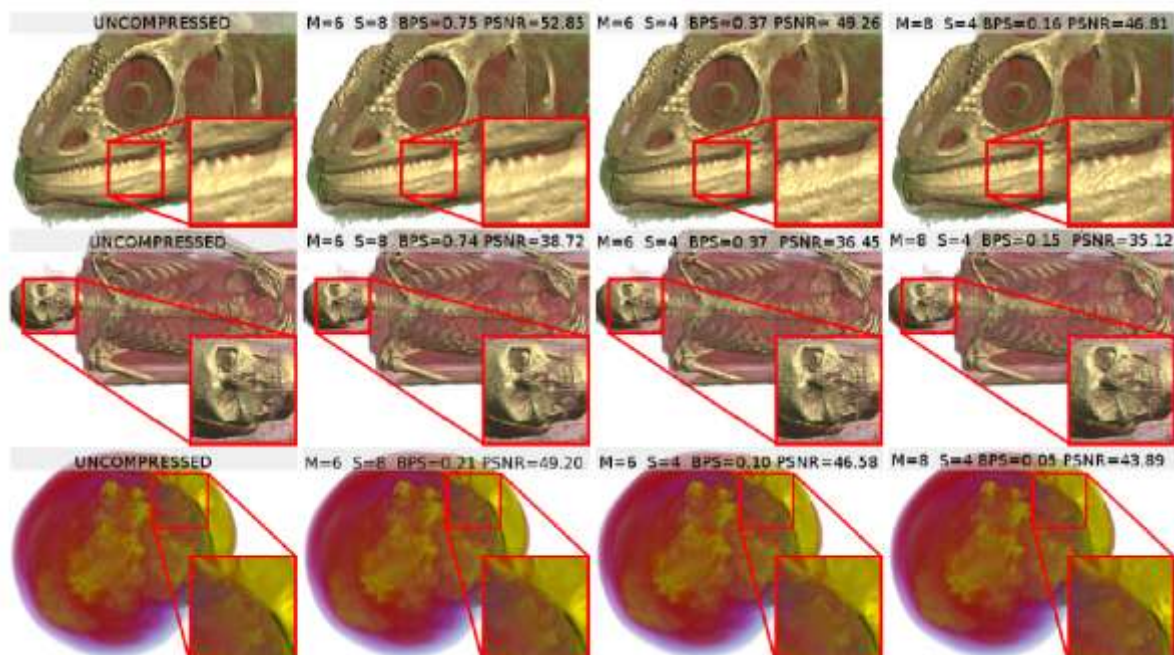
Work within DIVA has focused on the following subjects:

- Evaluating the possibility of direct volume rendering on mobile devices.** Volume rendering has been a relevant topic in scientific visualization for the last two decades. A decade ago the exploration of reasonably big volume datasets required costly workstations due to the high processing cost of this kind of visualization. In the last years, a high end PC or laptop was enough to be able to handle medium-sized datasets thanks, especially, to the fast evolution of GPU hardware. New embedded CPUs that sport powerful graphics chipsets make complex 3D applications feasible in such devices. However, besides the much marketed presentations and all its hype, no real empirical data is usually available that makes comparing absolute and relative capabilities possible. In this paper we analyze current graphics hardware in most high-end Android mobile devices and perform a practical comparison of a well-known GPU-intensive task: volume rendering. We have thus analyzed different aspects by implementing three different classical algorithms and showed how the current state-of-the-art mobile GPUs behave in volume rendering. A paper on the subject has been published at the International Symposium on Visual Computing 2012.
- Providing a comprehensive study of the state-of-the-art in compression-domain direct volume rendering.** Great advancements in commodity graphics hardware have favored GPU-based volume rendering as the main adopted solution for interactive exploration of



rectilinear scalar volumes on commodity platforms. Nevertheless, long data transfer times and GPU memory size limitations are often the main limiting factors, especially for massive, time-varying or multi-volume visualization, as well as for networked visualization on the emerging mobile devices. To address this issue, a variety of level-of-detail data representations and compression techniques have been introduced. In order to improve capabilities and performance over the entire storage, distribution and rendering pipeline, the encoding/decoding process is typically highly asymmetric, and systems should ideally compress at data production time and decompress on demand at rendering time. Compression and level-of-detail pre-computation does not have to adhere to real-time constraints and can be performed off-line for high quality results. In contrast, adaptive real-time rendering from compressed representations requires fast, transient, and spatially independent decompression. Within DIVA, we reviewed the existing compressed GPU volume rendering approaches, covering sampling grid layouts, compact representation models, compression techniques, GPU rendering architectures and fast decoding techniques. The result has led to state-of-the-art reports which have been first published and presented at Eurographics 2012, and later extended in a journal publication (Computer Graphics Forum, 2013).

- Advancing the state-of-the-art in compression-domain volume rendering.** We have introduced a novel multiresolution compression-domain GPU volume rendering architecture designed for interactive local and networked exploration of rectilinear scalar volumes on commodity platforms. In our approach, the volume is decomposed into a multiresolution hierarchy of bricks. Each brick is further subdivided into smaller blocks, which are compactly described by sparse linear combinations of prototype blocks stored in an overcomplete dictionary. The dictionary is learned, using limited computational and memory resources, by applying the K-SVD algorithm to a re-weighted non-uniformly sampled subset of the input volume, harnessing the recently introduced method of coresets. The result is a scalable high quality coding scheme, which allows very large volumes to be compressed off-line and then decompressed on-demand during real-time GPU-accelerated rendering. Volumetric information can be maintained in compressed format through all the rendering pipeline. In order to efficiently support high quality



filtering and shading, a specialized real-time renderer closely coordinates decompression with rendering, combining at each frame images produced by raycasting selectively decompressed portions of the current view- and transfer-function-dependent working set. The quality and performance of our approach has been demonstrated on massive static and time-varying datasets, leading to state-of-the-art results. In order to further improve visual quality at high compression rates, we have also extended the volume rendering pipeline to perform post-process deblocking at rendering time. The architecture has been presented in a publication at EuroVis 2012, while the deblocking extension has been published at VMV 2015.

- **Experimentally studying the effects of shading in 3D perception of volumetric models.**

Throughout the years, many shading techniques have been developed to improve the conveying of information in volume visualization. Some of these methods, usually referred to as realistic, are supposed to provide better cues for the understanding of volume data sets. While shading approaches are heavily exploited in traditional



monoscopic setups, no previous study has analyzed the effect of these techniques in virtual reality. To further explore the influence of shading on the understanding of volume data in such environments, we carried out a user study in a desktop-based stereoscopic setup. The goals of the study were to investigate the impact of well-known shading approaches and the influence of real illumination on depth perception. Participants had to perform three different perceptual tasks when exposed to static visual stimuli. 45 participants took part in the study, giving us 1152 trials for each task. Results show that advanced shading techniques improve depth perception in stereoscopic volume visualization. As well, external lighting does not affect depth perception when these shading methods are applied. As a result, we derived some guidelines that may help the researchers when selecting illumination models for stereoscopic rendering. The results of our study have been presented at CGI 2014 and later extended in a journal paper for *The Visual Computer* (2015).

## 4.2 Surfaces

Thanks to recent advances in 3D acquisition and modeling systems, high-quality 3D surface models are becoming increasingly common, as well as increasingly complex.

The main research objective within DIVA has been to enable the interactive exploration and better understanding of complex 3D models using commonly available 3D platforms. Advancing the state-of-the-art in this area requires solving the following problems:

- **Improving scalability of visualization methods for complex 3D surface models.** Nowadays, large amounts of highly detailed 3D models are becoming increasingly available, so there is a clear need for specialized and efficient methods for visualizing these data-sets. Therefore, we set as a goal to study compact data structures that exploit the characteristics of current



3D platforms (from high end rendering clusters to mobile devices) for improving scalability both in the visualization and the streaming of the data. This research has led to the following important results:

- **Methods for adaptive streaming of compressed meshes.**

Surfaces are most commonly represented using a mesh model. The most common representation is the triangle mesh. A large number of solutions have been presented in previous years to compactly represent objects in a multiresolution way in order to achieve adaptive rendering. Within DIVA, we have explored



how to efficiently combine multiresolution with compression in order to cope with strong bandwidth and hardware capabilities limitations. We have in particular presented a compression-domain adaptive multiresolution rendering approach capable to scale from desktop GPU rendering to mobile graphics. The basic idea behind the proposed approach is to use, as in previous work, a regular conformal hierarchy of tetrahedra to spatially partition the input 3D model and to arrange mesh fragments at different resolution. In this approach, we create compact GPU-friendly representations of these fragments by constructing cache-coherent strips that index locally quantized vertex data, exploiting the bounding tetrahedron for creating a local barycentric parametrization of the geometry. For the first time, this approach supports local quantization in a fully adaptive seamless 3D mesh structure. For web distribution, further compression is obtained by exploiting local data coherence for entropy coding. A paper on the subject has been presented at ACM Web3D 2013. While this approach works extremely well even on mobile devices, there is now, however, an increasing interest for techniques tuned for lightweight, interpreted, and scripted environments. The limitations of such platforms impose additional constraints on 3D streaming formats, which should be based as much as possible upon preexisting components in order to avoid the overhead of coding complex decoders and data structures in non-optimized programming environment, such as JavaScript. We have thus worked on a much simpler representation that can be obtained for particular kinds of objects, smooth and topologically simple, which comprise an important subset of the 3D models, e.g., in cultural heritage applications. We exploit these characteristics by proposing a solution based on an iso-parametric quad-parametrization of the 3D models, on top of which we construct a multiresolution structure. The resulting representation is extremely compact, and can be implemented on top of preexisting libraries. Thus, this scheme is well-suited for scripted environments such as Web browsers, where the limited CPU performance for interpreted code can be overcome by exploiting efficient implementations for image decoding already present in the API. The publication on this subject has received the best paper award at ACM Web3D 2012. At SIGGRAPH Asia 2013 we have also presented a contribution contrasting the two mentioned approaches.

- **Methods for adaptive streaming and rendering compressed point clouds.** Direct point-based rendering (PBR) is gradually emerging in industrial environments as a



viable alternative to the more traditional polygonal mesh methods for interactively inspecting very large geometric models. Points as rendering primitives are often a more efficient means for initial data processing and visual analysis of large raw 3D data. Furthermore, PBR is also advantageous compared to triangles especially in regions where a triangle might project to a pixel or less on the screen. Points also constitute a more compact representation, as the mesh connectivity of triangles is not required. Modern 3D scanning systems can generate massive datasets often exceeding hundreds of millions of points, and it is therefore important to provide adaptive solutions. Within DIVA, we have focused on introducing novel hierarchical representations and on improving compression. We have in particular introduced an efficient technique for out-of-core multi-resolution construction and high quality interactive visualization of massive point clouds. Our approach introduces a novel hierarchical level of detail (LOD) organization based on multi-way kd-trees, which simplifies memory management and allows control over the LOD-tree height. The LOD tree, constructed bottom up using a fast high-quality point simplification method, is fully balanced and contains all uniformly sized nodes. To this end, we introduced and analyzed three efficient point simplification approaches that yield a desired number of high-quality output points. For constant rendering performance, we proposed an efficient rendering-on-a-budget method with asynchronous data loading, which delivers fully continuous high quality rendering through LOD geomorphing and deferred blending. Our algorithm has been incorporated in a full end-to-end rendering system, which supports both local rendering and cluster-parallel distributed rendering. The method has been evaluated on complex models made of hundreds of millions of point samples. An article on the subject has been presented in Visual Computer in 2013. While this work has focused on the hierarchical representation, and considered a local out-of-core solution based on memory-mapping external-memory arrays, we have also in parallel worked on networked solutions capable to provide rendering on mobile devices. Instead of looking for maximum compression, we employ a compression algorithm which is fast enough to be decompressed on a low-powered device. The method is based on sorting in an order that minimize the Euclidean distance among adjacent points. The attributes of the points in the point strip are then stored in the rows of a 2D array. These rows are then transformed using a reversible n-bit to n-bit wavelet based on the Haar wavelet transform in order to reduce entropy, and the single base level and all the detail coefficients are finally encoded using a simple Elias gamma code. The method achieves 3-4 bytes/samples for colored models, and has been proved to be capable of streaming and rendering at interactive rates on low-end mobile

devices models with hundreds of millions of points. A publication on the subject has appeared at EG VAST 2012.

- Adaptive Quad Patches: an Adaptive Regular Structure for Web Distribution and Adaptive Rendering of 3D Models
- Coarse-grained Multiresolution Structures for Mobile Exploration of Gigantic Surface Models
- Compression-domain Seamless Multiresolution Visualization of Gigantic Meshes on Mobile Devices

○ **Methods for coherent hierarchical culling in ray tracing.**

While previous methods have focused on representations that are tuned for pure rasterization, rendering complex lighting effects is often more easily obtained through a ray tracing approach. Within DIVA, we have thus proposed a new



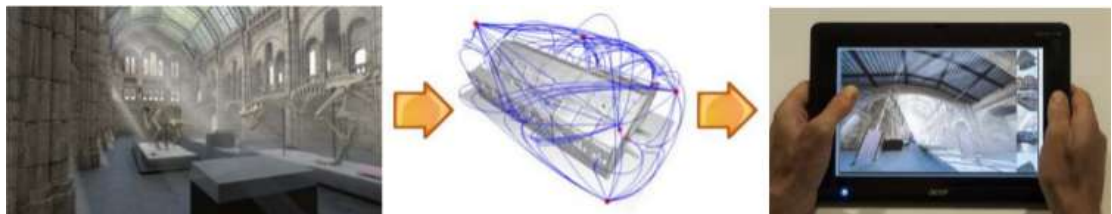
technique for in-core and out-of-core GPU ray tracing using a generalization of hierarchical occlusion culling in the style of the CHC++ method. Our method exploits the rasterization pipeline and hardware occlusion queries in order to create coherent batches of work for localized shader-based ray-tracing kernels. By combining hierarchies in both ray space and object space, the method is able to share intermediate traversal results among multiple rays. We exploit temporal coherence among similar ray sets between frames and also within the given frame. A suitable management of the current visibility state makes it possible to benefit from occlusion culling for less coherent ray types like diffuse reflections. Since large scenes are still a challenge for modern GPU ray tracers, our method is most useful for scenes with medium to high complexity, especially since our method inherently supports ray tracing highly complex scenes that do not fit in GPU memory. For in-core scenes our method is comparable to CUDA ray tracing and performs up to six times better than pure shader-based ray tracing. A paper on the subject has been presented at Eurographics 2015 and has appeared in the Computer Graphics Forum special issue.

○ **Methods for ray-tracing massive models from a compressed data representation.**

Voxelized representations of complex 3D scenes are widely used nowadays to accelerate visibility queries in many GPU rendering techniques. Since GPU memory is limited, it is important that these data structures can be kept within a strict memory budget. Recently, directed acyclic graphs (DAGs) have been successfully introduced to compress sparse voxel octrees (SVOs), but they are limited to sharing identical regions of space. In this paper, we show that a more efficient lossless compression of geometry can be achieved, while keeping the same visibility-query

performance, by merging subtrees that are identical through a similarity transform, and by exploiting the skewed distribution of references to shared nodes to store child pointers using a variable bit-rate encoding. We also describe how, by selecting plane reflections along the main grid directions as symmetry transforms, we can construct highly compressed GPU-friendly structures using a fully out-of-core method. Our results demonstrate that state-of-the-art compression and real-time tracing performance can be achieved on high-resolution voxelized representations of real-world scenes of very different characteristics, including large CAD models, 3D scans, and typical gaming models, leading, for instance, to real-time GPU in-core visualization with shading and shadows of the full Boeing 777 at sub-millimetric precision. A paper on the subject has been accepted to i3D 2016.

- **Automatic generation of image-based representations.** When dealing with scenes with complex lighting, real-time constraints impose hard limits on the achievable quality. We have therefore worked on methods to ensure visual quality in all kinds of environments by presenting precomputed imagery rather than real-time-renderings. In order to do so, we have introduced a novel efficient technique for automatically transforming a generic renderable 3D scene into a simple graph representation named ExploreMaps, where nodes are nicely placed point of views, called probes, and arcs are smooth paths between neighboring probes. Each probe is associated with a panoramic image enriched with preferred viewing orientations, and each path with a panoramic video. Our GPU-accelerated unattended construction pipeline distributes probes so as to guarantee coverage of the scene while accounting for perceptual criteria before finding smooth, good looking paths between neighboring probes. Images and videos are precomputed at construction time with off-line photorealistic rendering engines, providing a convincing 3D visualization beyond the limits of current real-time graphics techniques. At run-

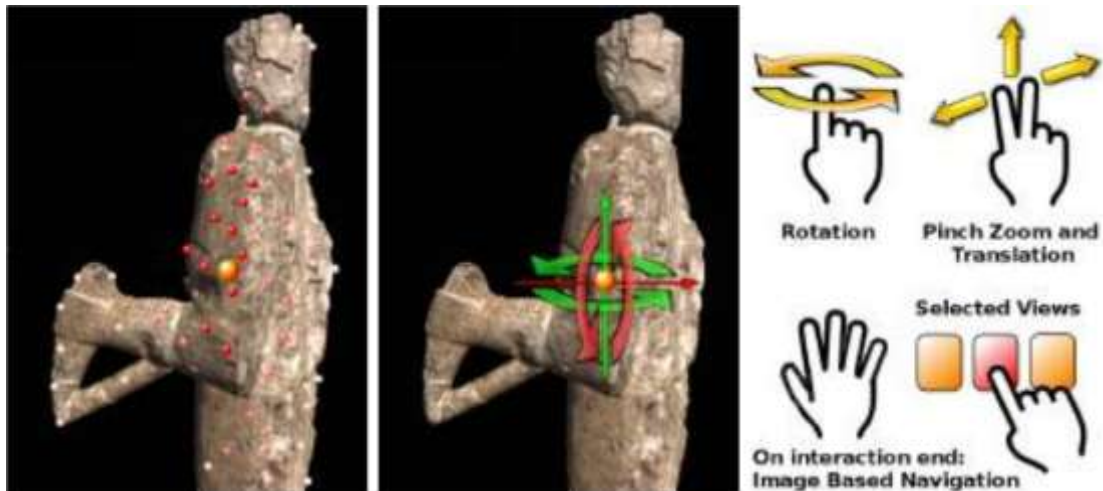


time, the graph is exploited both for creating automatic scene indexes and movie previews of complex scenes and for supporting interactive exploration through a low-DOF assisted navigation interface and the visual indexing of the scene provided by the selected viewpoints. Due to negligible CPU overhead and very limited use of GPU functionality, real-time performance is achieved on emerging web-based environments based on WebGL even on low-powered mobile devices. A paper on the subject has been presented at Eurographics 2015 and has appeared in the Computer Graphics Forum special issue.

- **Improving navigation techniques for complex 3D surface models.** The exploration of complex 3D models with multi-scale information requires a simple and effective navigation interface that enables the user to explore and study both global shape and very fine details. We therefore focused on studying interactive methods which are easy to use and provide enough freedom, enabling the exploration of the whole virtual object, while, at the same time, helping the user to retain the spatial context. We have in particular introduced

a novel user interface and system for exploring extremely detailed 3D models using constrained navigation techniques. Our contributions include the following:

- **Auto-centering trackball.** In order to address the problem of complex 3D model exploration, we start with a free movement camera controller with automatic pivot definition in order to simplify the interaction. In particular, this greatly improves the usability on small screen devices where the task of pivot selection is difficult due to precise picking limitations. In addition, by automatically computing the interaction



pivot, our approach provides smooth and continuous navigation between far and close views. The method is based on the idea of centering the pivot by analyzing the current view of the object. We have presented both screen-space and model-space adaptive techniques to do so in real-time while rendering massive models using our adaptive techniques. A paper on the subject has been presented at ACM Web3D 2014.

- **Constrained Navigation Methods for Interactive Visual Exploration of Massive 3D Models on Large Projection Setups.**

In this approach, 3D models and associated information are presented on a large projection surface controlled by a touch-enabled surface placed at a suitable distance in front of it. Our indirect user interface, dubbed IsoCam, combines an object-aware interactive camera controller with an interactive point-of-interest selector and is implemented within a scalable implementation based on multiresolution structures shared between the rendering and user interaction subsystems. The collision-free camera controller automatically supports the smooth transition from orbiting to proximal navigation, by exploiting a distance-field representation of the 3D object. The point-of-interest selector exploits a specialized view similarity computation to propose a few nearby easily reachable interesting 3D views from a large database, move the camera to the user-selected point of interest, and provide extra information through overlaid annotations of the target view. The capabilities of our



approach have been demonstrated in a public event attended by thousands of people, which were offered the possibility to explore sub-millimetric reconstructions of 38 stone statues of the Mont'e Prama Nuragic complex, depicting larger-than-life human figures, and small models of prehistoric Nuraghe (cone-shaped stone towers). A follow-up of this work, using 2.5m-high projection screens, is now included in permanent exhibitions at two Archeological Museums. Results of a thorough user evaluation, involving quantitative and subjective measurements, are discussed in an article appear in ACM JOCCH 2014. A similar approach has also been introduced for light field displays.

- **Systems for scalable exploration.**

A number of systems incorporating the above-mentioned approaches have been realized and tested in the cultural heritage area. In particular, a scalable approach for exploring cultural 3D objects by mixing scalable rendering, compression, and constrained navigation has been applied to the Mont'e Prama statues dataset. The paper describing this approach has been awarded the Best Paper prize at Digital Heritage 2015.



- **Improving understanding of complex 3D surface models.** Providing effective 3D content presentation is particularly relevant when the goal is to allow people to appreciate, understand, and interact with intrinsically 3D virtual objects. In this context, it is important to go beyond visual replication, providing contextual information that integrates and enhances the 3D model view. We set as a goal, thus, to study new methods for presenting the user with additional spatially coherent information, while avoiding cluttering the 3D view or requiring the user to focus on the interaction or the contextual information instead of the 3D virtual object. Our major contribution is a novel approach for letting casual viewers explore detailed 3D models integrated with structured spatially associated descriptive information organized in a graph. Each node associates a subset of the 3D



Suggestion Display

3D scene

Touch-enabled Surface

surface seen from a particular viewpoint to the related descriptive annotation, together with its author-defined importance. Graph edges describe, instead, the strength of the dependency relation between information nodes, allowing content authors to describe the preferred order of presentation of information. At run-time, users navigate inside the 3D scene using a camera controller, while adaptively receiving unobtrusive guidance towards interesting viewpoints and history- and location-dependent suggestions on important information, which is adaptively presented using 2D overlays displayed over the 3D scene. The capabilities of our approach are demonstrated in a real-world cultural heritage application involving the public presentation of sculptural complex on a large projection-based display. A user study has been performed in order to validate our approach. A paper on the subject has been presented at EuroVis 2015 and has appear in the conference special issue of Computer Graphics Forums.

### 4.3 Light fields

The term light field is mathematically defined as a function that describes the amount of light fared in all directions from every single point in space at a given time instance. Over a continuous time, the collection of light rays emitted at all the points in space continuously defines a scene and the set of objects in it. Presenting a scene in 3D thus involves capturing wavelengths of light at all points in all directions at all time instances and displaying this captured information within a given region of interest of a scene. However, it is not possible in reality due to practical limitations such as complex capturing procedure, enormous amount of data every single time instant, unavailability of means to capture and display the smooth and continuous light field information. Many attempts were made in the past for simplifying and displaying a light field.

Within DIVA, we have studied light fields in the context of projection-based light field displays, which recreate the 3D scene structure in a more natural way using multiple projection engines. A special hologram screen used to do the optical transformation of directing the light beams to different directions. Thus the light rays are described with reference to a 2D screen and there is no multiplexing involved in the whole system. In contrast to lens based autostereoscopic displays, there is no light barrier and this allows continuous motion parallax. Also the optical properties of the screen allow proper adjacent view isolation and increased FOV, supporting multiple users at the same time.

While the display technology itself has been studied within WP5, in WP3 we have focused on specific problems concerning the rendering of massive data, focusing in particular on the problems of geometric calibration, content retargeting, and user interaction. Our specific results have been the following:

- **Automatic geometric calibration of projector-based light-field displays.** Continuous multiview (light-field) projection-based displays employ an array of projectors, mirrors, and a selectively transmissive screen to produce a light field. By appropriately modeling the display geometry, the light beams can emulate the emission from physical objects at fixed spatial locations, providing multiple freely moving viewers the illusion of interacting with



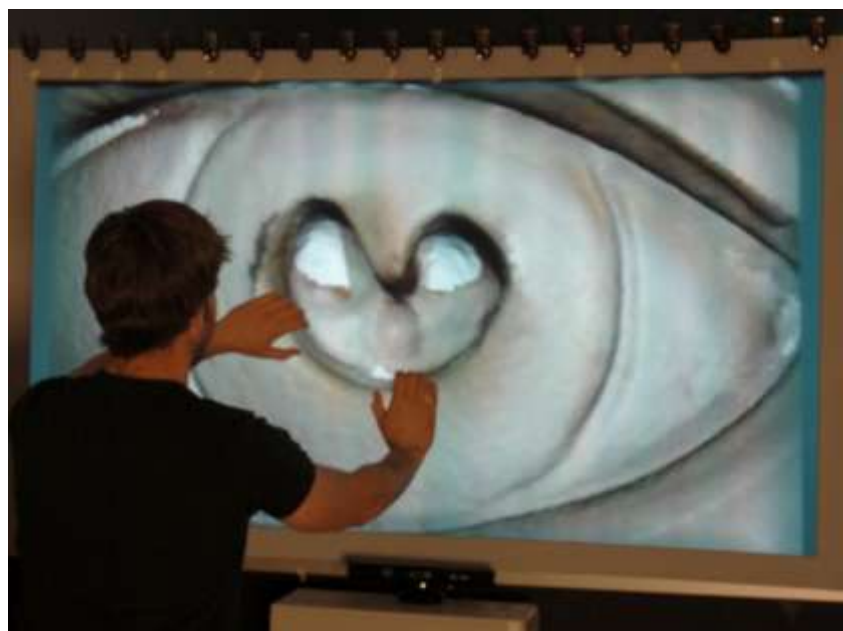
floating objects. Within DIVA, we have worked on a novel calibration method for this class of displays using a single uncalibrated camera and four fiducial markers. Calibration starts from a simple parametric description of the display layout. First, individual projectors are calibrated through parametric optimization of an idealized pinhole model. Then, the overall display and projector parameterization is globally optimized. Finally, independently for each projector, remaining errors are corrected through a rational 2D warping function. The final parameters are available to rendering engines to quickly compute forward and backward projections. The technique has been demonstrated in the calibration of a large-scale horizontal-parallax-only 35MPixels light field display developed by the Holografika project partner. A short paper on the technique has been presented at EuroVis 2013.

- **Real-time adaptive content retargeting for light field displays.** The discrete nature of multiprojector light field displays results in aliasing when rendering scene points at depths outside the supported depth of field causing visual discomfort. Within DIVA, we have thus proposed an efficient on-the-fly content-aware real-time depth retargeting algorithm for



live content, apply it to 3D light field video or graphics data, to increase the quality of visual perception on a cluster-driven multiprojector light field display. In the case of light field video, the proposed algorithm is embedded in an end-to-end real-time system capable of capturing and reconstructing light field from multiple calibrated cameras on a full horizontal parallax light field display. By automatically detecting salient regions of a scene, we solve an optimization to derive a non-linear operator to fit the whole scene within the comfortable viewing range of the light field display. We have evaluated the effectiveness of our approach on synthetic and real world scenes. A paper on the subject has been presented at CGI 2015 and an extended version of the article has appeared in The Visual Computer journal. In addition, a Eurographics 2015 poster has described the application of the approach to general 3D scenes.

- **Natural exploration of 3D massive models on large-scale light field displays.** Interacting on light field displays allows users to naturally see 3D models and operate on them. However, interaction techniques must take into account that these displays have a spatially varying resolution and must maintain objects within their display hotspot to avoid causing visual





discomfort. As a complement or an alternative to retargeting techniques, we have thus studied approaches to constrain object motion. Our solution is a virtual environment for natural immersive exploration of extremely detailed surface models on multi-projector light field displays, which give multiple, freely moving, naked-eye viewers the illusion of seeing and manipulating 3D objects with continuous horizontal parallax. Our specialized 3D user interface, dubbed FOX (Focus Sliding Surface), allows inexperienced users to inspect 3D objects at various scales, integrating panning, rotating, and zooming controls into a single low-degree-of-freedom operation. At the same time, FOX takes into account the requirements for comfortable viewing on the light field display hardware, which has a limited field-of-view and a variable spatial resolution. Specialized multi-resolution structures, embedding a fine-grained, per-patch spatial index within a coarse-grained patch-based mesh structure, are exploited for fast batched I/O, GPU-accelerated rendering, and user-interaction-system-related geometric queries. The capabilities of the system were demonstrated by the interactive inspection of a giga-triangle dataset on a large-scale, 35 MPixel light field display controlled by wired or vision-based devices. The method and results of a thorough user evaluation, involving quantitative and subjective measurements are discussed in an article that has appeared in the journal *Computers & Graphics* in 2012.

## 5 Awards

The work on *Adaptive Quad Patches: an Adaptive Regular Structure for Web Distribution and Adaptive Rendering of 3D Models* has won **Best Long Paper Award** at **ACM Web3D International Symposium 2012**.

The work on *Digital Mont'e Prama: 3D cultural heritage presentations in museums and anywhere* has won the **Best Paper Award** at **Digital Heritage 2015**.

Both papers are co-authored by DIVA ESR Marcos Balsa Rodriguez.

## 6 Public events

The technology developed within WP3 has been used in (or has been the basis for) public demonstrations. We list the following work:

- Eurographics 2012 technical demo.** In May 2012 CRS4 co-organized in Cagliari the Eurographics 2012 conference (EG 2012) and the Eurographics Symposium on Parallel Graphics (EGPGV 2012), who was also a DIVA event. The scalable graphics technology (volume graphics and surface graphics) developed at CRS4 was showcased in a demo room at the conference. DIVA fellows participated to outreach activities by giving talks and demonstrations to the general public.



- Sardinia Trade Fair Visual Computing technical demo.** In April 2013, CRS4 organized in Cagliari, during the 65th International Trade Fair, a large technological event on Visual Computing Technology for Cultural Heritage. Thousands of people had the opportunity to see large-scale projections of dynamic contents and to interactively explore extremely detailed 3D models.



- Demonstrations included the latest results obtained within the DIVA project for low-DOF camera control and 3D model streaming. DIVA fellows participated to outreach activities by giving talks and demonstrations to the general public. The event was also supported by AG Multivision and Digital Projections (which kindly provided advanced projector setups), and Soprintendenza per i Beni Archeologici per le Province di Cagliari e Oristano, who collaborated with CRS4 on the 3D digitization of ancient statues.

- Digital Mont'e Prama exhibitions.** CRS4 has developed an advanced system for acquisition, reconstruction and presentation of the color and shape of cultural heritage objects. The developed approach has been successfully applied to the acquisition and exploration of a set of 3D models derived from the 3D scan acquisition of the statues of Mont'e Prama, ancient stone sculptures created by the Nuragic



civilization of Sardinia, Italy. The system has been set up in Cagliari, Oristano, Rome, and Milan. DIVA fellows have actively participated in research and evaluation activities, which led to some of the papers included in this report.

## 7 Conclusions

In work package WP3 on Output Sensitive Techniques we have successfully completed our goal of developing methodologies and techniques for presenting highly accurate and understandable depictions of local and remote massive geometric and volumetric models on both standard and novel 3D displays, fully harnessing human perceptual capabilities to enable users to gain an in-depth understanding of complex 3D models. The two main classes of targeted models are massive surface models, such as those created with laser scanners, and volumetric models, such as those created by simulations and medical acquisition devices.

The goal has been fully achieved, as demonstrated by the project tangible results in terms of publications, software systems developed and demonstrated, awards, and events organized.

We can herewith report the completion of deliverable D3.1.

## 8 References

In the following, we list the publications resulting from work on output sensitive rendering. DIVA fellows are highlighted in **bold**.

### 8.1 Volumes

- 1 **Marcos Balsa Rodriguez**, Enrico Gobbetti, José Antonio Iglesias Guitián, Maxim Makhinya, Fabio Marton, Renato Pajarola, and Susanne Suter. State-of-the-art in Compressed GPU-Based Direct Volume Rendering. *Computer Graphics Forum*, 33(6): 77-100, September 2014.
- 2 **Jose Díaz**, Timo Ropinski, Isabel Navazo, Enrico Gobbetti, and Pere-Pau Vázquez. An experimental study on the effects of shading in 3D perception of volumetric models. *Volume 31*, 2015. To appear.
- 3 **Jose Díaz**, Timo Ropinski, Isabel Navazo, Enrico Gobbetti, and Pere-Pau Vázquez. Perceptual effects of volumetric shading models in stereoscopic desktop-based environments. In *Proc. Computer Graphics International*, 2015.
- 4 Fabio Marton, José Antonio Iglesias Guitián, **Jose Diaz**, and Enrico Gobbetti. Real-time deblocked GPU rendering of compressed volumes. In *Proc. 19th International Workshop on Vision, Modeling and Visualization (VMV)*. Pages 167-174, October 2014.
- 5 **Marcos Balsa Rodriguez**, Enrico Gobbetti, José Antonio Iglesias Guitián, Maxim Makhinya, Fabio Marton, Renato Pajarola, and Susanne Suter. A Survey of Compressed GPU-based Direct Volume Rendering. In *Eurographics State-of-the-art Report*. Pages 117-136, May 2013.
- 6 Pere Pau Vazquez Alcocer and **Marcos Balsa Rodriguez**. Practical Volume Rendering in mobile devices. In *Proc. International Symposium on Visual Computing*. Volume 7431 of *Lecture Notes in Computer Science (LNCS)*. Pages 708-718, Springer Verlag, 2012.
- 7 Enrico Gobbetti, José Antonio Iglesias Guitián, and Fabio Marton. COVRA: A compression-domain output-sensitive volume rendering architecture based on a sparse representation of voxel blocks. *Computer Graphics Forum*, 31(3pt4): 1315-1324, 2012. *Proc. Eurovis 2012*.

### 8.2 Surfaces

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- 2 Marco Di Benedetto, Fabio Ganovelli, **Marcos Balsa Rodriguez**, **Alberto Jaspe Villanueva**, Roberto Scopigno, and Enrico Gobbetti. ExploreMaps: Efficient Construction and Ubiquitous Exploration of Panoramic View Graphs of Complex 3D Environments. *Computer Graphics Forum*, 33(2): 459-468, 2014. *Proc. Eurographics 2014*.
- 3 **Marcos Balsa Rodríguez**, Enrico Gobbetti, Fabio Marton, and Alex Tinti. Coarse-grained Multiresolution Structures for Mobile Exploration of Gigantic Surface Models. In *Proc. SIGGRAPH Asia Symposium on Mobile Graphics and Interactive Applications*. Pages 4:1-4:6, November 2013. ACM.
- 4 **Marcos Balsa Rodriguez**, Enrico Gobbetti, Fabio Marton, and Alex Tinti. Compression-domain Seamless Multiresolution Visualization of Gigantic Meshes on Mobile Devices. In

- Proc. ACM Web3D International Symposium. Pages 99-107, June 2013. ACM Press. New York, NY, USA.
- 5 **Marcos Balsa Rodriguez**, Marco Agus, Fabio Bettio, Fabio Marton, and Enrico Gobbetti. Digital Mont'e Prama: 3D cultural heritage presentations in museums and anywhere. In Proc. Digital Heritage, September 2015. **(Best paper award)**.
  - 6 **Marcos Balsa Rodriguez**, Marco Agus, Fabio Marton, and Enrico Gobbetti. Adaptive Recommendations for Enhanced Non-linear Exploration of Annotated 3D Objects. Computer Graphics Forum, 34(3): 41-50, 2015. Proc. EuroVis 2015.
  - 7 Fabio Marton, **Marcos Balsa Rodriguez**, Fabio Bettio, Marco Agus, **Alberto Jaspe Villanueva**, and Enrico Gobbetti. IsoCam: Interactive Visual Exploration of Massive Cultural Heritage Models on Large Projection Setups. ACM Journal on Computing and Cultural Heritage, 7(2): Article 12, June 2014.
  - 8 **Marcos Balsa Rodriguez**, Marco Agus, Fabio Marton, and Enrico Gobbetti. HuMoRS: Huge models Mobile Rendering System. In Proc. ACM Web3D International Symposium. Pages 7-16, August 2014. ACM Press. New York, NY, USA.
  - 9 Enrico Gobbetti, Ruggero Pintus, Fabio Bettio, Fabio Marton, Marco Agus, and **Marcos Balsa Rodriguez**. Digital Mont'e Prama: dalla digitalizzazione accurata alla valorizzazione di uno straordinario complesso statuario. Archeomatica, 6(1): 10-14, 2015.
  - 10 Oliver Mattausch, Jiri Bittner, **Alberto Jaspe Villanueva**, Enrico Gobbetti, Michael Wimmer, and Renato Pajarola. CHC+RT: Coherent Hierarchical Culling for Ray Tracing. Computer Graphics Forum, 34(2): 537-548, 2015. Proc. Eurographics 2015.
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  - 13 Enrico Gobbetti, Fabio Marton, **Marcos Balsa Rodriguez**, Fabio Ganovelli, and Marco Di Benedetto. Adaptive Quad Patches: an Adaptive Regular Structure for Web Distribution and Adaptive Rendering of 3D Models. In Proc. ACM Web3D International Symposium. Pages 9-16, August 2012. ACM Press. New York, NY, USA. **(Best Long Paper Award)**.

### 8.3 Light fields

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- 2 **Vamsi Kiran Adhikarla**, Fabio Marton, Tibor Balogh, and Enrico Gobbetti. Real-time adaptive content retargeting for live multi-view capture and light field display. The Visual Computer, 31(6--8): 1023-1032, 2015.
- 3 **Vamsi Kiran Adhikarla**, Fabio Marton, Attila Barsi, Enrico Gobbetti, Peter Tamas Kovacs, and Tibor Balogh. Real-time Content Adaptive Depth Retargeting for Light Field Displays. In Eurographics Posters, 2015.

- 4 Fabio Marton, Marco Agus, Enrico Gobbetti, Giovanni Pintore, and **Marcos Balsa Rodriguez**. Natural exploration of 3D massive models on large-scale light field displays using the FOX proximal navigation technique. *Computers & Graphics*, 36(8): 893-903, December 2012.

#### 8.4 PhDs awarded to DIVA fellows

- 1 **Marcos Balsa Rodriguez**. Scalable Exploration of Highly Detailed and Annotated 3D Models. PhD thesis. PhD School of Mathematics and Computer Science, University of Cagliari, Italy, 2015.
- 2 **Vamsi Kiran Adikahrla**. Light Field Rendering and Interaction, Faculty of Information Technology, Multidisciplinary Technical Sciences Doctoral School, Pázmány Péter Catholic University, Budapest, Hungary, 2015.