MoViE 3D: Modeling, visualization, animation and analysis of highly complex 3D environments in interactive virtual reality systems
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Abstract

In aiming to extend the virtual reality experience to ever larger models and scenes using low-cost devices and technologies, innovative, efficient and scalable solutions are required.

To this end, we propose to work on several fronts. On one side, we propose to expand the current state of the art in real time rendering to allow for the rendering of more detailed complex scenes, while incorporating techniques of physically-based animation and simulation of crowds to increase the impression of realism and autonomous existence of the virtual worlds. On a second front, we purport to facilitate the construction of immersed interfaces and to develop new and flexible VR devices that will allow for a richer, seamless and intuitive navigation of the virtual environments. Yet other aspect of the problem is devoted to the processing of geometry to make models amenable to be manipulated in VR systems.

In a complementary lines of research, we will also adapt and apply the GPU-driven techniques for realtime visualisation of volume models, and we intend to continue researching the application of information theory to give efficient solution of registration and segmentation problems. Moreover, we will study the representation and analysis of terrains through Triangulated Irregular Networks (TIN) obtained from irregularly-sampled terrain points.

Keywords: Virtual reality, Advanced interfaces, Geometry processing, Interactive visualization, Physically based animation, Crowds, Volume visualization, Terrain analysis, Applications of VR for medicine, Presence.

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1 Project Goals

The evolution and increasingly wide availability of new technologies are making huge digital models more and more prevalent. These models often exceed the capacity of the available interactive computer graphics systems to present and analyse those data.

This project is concerned with situations where very large models or scenes are created by sampling real objects, like in medical applications, laser-range scanner data, or terrain modelling. In all of these areas, the aforementioned growth in complexity is evident, due to both the advances in the digitalisation techniques (like the modern high density scanners and image-based devices in medicine), or by the need to have detailed models (in terrain modelling). We need to be able to, in each case, consolidate the data into an adequate model that addresses the functionalities demanded by each application area (be them visualisation, analysis or simulation). This gives rise to a slew of interesting, hard problems in the segmentation, registration and fusion of data from different sources or measurements, as well as in the visualization, compression, simplification, and development of specialised data structures. All these techniques, together with the use of high performance GPUs, have started to make way into the construction of robust and scalable solutions to these problems, and together represent one of the more active research areas in our field.

In dealing with these sets of data, Virtual Reality is an important and powerful tool. Virtual Reality systems are able to immerse an user into a synthetic world to a sufficient degree that the user is able to feel as if that synthetic world is real. It is thus very important to determine the exact extent to which realism is needed in order to convince the user that he is indeed immersed in that synthetic world. It is also necessary to provide mechanisms for the manipulation of the models and the control of the application, because the classical modes of interaction interfere severely with the illusion of immersion. Moreover, the development low cost VR systems is of great importance in improving the user experience and the applicability of the technology.

In summary, this project aims to develop scientific and technical knowledge that will allow for the interactive visualisation, manipulation and analysis of very complex data sets, using low-cost virtual reality devices and technologies. We will also strive to improve the sensation of presence and the transparent or least-invasive interaction with the applications.

The following specific objectives are envisioned:

- **Construction of very large models.**
  Data from data-capturing devices need to be processed to obtain viable models for interactive applications and analysis. This is true both in the case of range scanners and medical volume models. We seek to develop algorithms for the repair of naive triangle meshes and for their simplification. For medical images, we intend to perfect segmentation and registration techniques.

- **Real time visualization.**
  Given the size of the models we focus on, the rendering cannot be done by simplemindedly spewing geometry into the graphics pipeline. We intend to continue working on algorithms that exploit current GPUs performance to obtain interactive frame-rates in the presentation of highly complex data and developing specific models that can be partially evaluated for rendering at the GPU.
• **Transparent navigation and control.**
  The applications performance in itself will not be enough if the control of the application or the navigation are too intrusive, clumsy or distractive to the user. We intend to continue working on extending and adapting established interface paradigms to immersive environments, and to develop new mechanisms of user interaction.

• **Low cost virtual reality devices.**
  In order to make VR applications readily available, it is paramount to decrease the cost of implementing them, both in terms of the cost of the devices as in terms of the costs of very specialised calibration and set-up. We plan to study and to develop low-cost VR systems that take care of its own calibration.

• **Illustrative volume visualization.**
  Illustrative volume visualisation endeavours to facilitate the user’s evaluation of the data by stressing some features or elements of the data, while making others less salient. This is of great relevance, in particular, in the rendering of medical images for diagnosis, and we intend to develop efficient algorithms that are capable of achieving acceptable frame-rates, even with high-density models now starting to appear in this context.

• **Physically-convincing animation.**
  In order to present credible reactions of the virtual world to our actions, we need to simulate the physics of these interactions in an effective way. Some tradeoffs are acceptable as they do not break the illusion of immersion, but high latencies are not. We continue in this line our work in computing such animations in the GPUs to achieve acceptable frame-rates and realism.

• **Crowd simulation.**
  Our goal here is to develop a system that we can use to evaluate the impact on human participants of their participation in immersive crowd scenes. In order to achieve this for large crowds (tens of thousands of avatars), we will study image techniques for economical but credible avatar animation.

  The scheduling of the project contemplates tasks that extend for the full duration of the project, as they encompass doctoral dissertations in progress and the research of the teams involved. We will strive to have adequate results for the construction of the test bed software in the areas of medical applications, in preservation of cultural heritage and avatar animation.

2 **Degree of success**

Goals that have been attained so far are presented by briefly explaining some of the contributions, grouped by project activities which are directly related to the main objectives of the proposed research.

2.1 **3D User Interface Engineering and Interaction Techniques**

The main goal of this activity is to improve VR applications with fully-interactive, usable user interfaces while maximizing performance, security and user comfort. Some of the results that have been achieved follow:
• We have studied user performance in 3D pointing selection when interacting with complex virtual environments. We have identified the eye-hand visibility mismatch problem as a major factor which hinders user performance when interacting with cluttered environments using VR input devices [33]. Moreover, we have proposed a new control mapping for pointing selection [2] which clearly outperforms competing approaches in cluttered virtual environments. In addition, we have improved user performance in selection tasks through Expanding Targets and Forced Disocclusion [31].

• We have analyzed visual feedback techniques for accurate pointing on stereoscopic displays. We have shown both analytically and empirically that current approaches provide poor feedback on stereoscopic displays, resulting in low user performance. We have also proposed a new feedback technique following a camera viewfinder metaphor [32] which outperforms competing techniques in terms of speed and binocular fusion.

• We have developed new algorithms for complexity and occlusion management on densely-occluded scenes. We have proposed algorithms for selecting the region of the scene to be covered by a hand-held miniature replica of the scene and algorithms for handling occlusion from an exocentric viewpoint [60]. Our technique greatly improves user performance on spatial tasks in densely-occluded scenes [24]. In addition, we have proposed new tools and interaction techniques for multi-scale manipulation of indoor scenes [61].

• We have proposed a new representation of rugosity for efficient rendering of fine haptic detail [58]. The representation uses displacement maps over a coarse mesh to encode rugosity details.

2.2 Geometry Processing

This activity attempts diverse problems related to the processing of large geometric models that includes reconstructing triangular meshes from sample data, repairing holes, simplification and analysis. We have been achieved the following results:

• In [8] we present a technique that automatically recovers solids from their binary grid representations. The result is a surface that is guaranteed to contain the samples of the volume classified as interior and exclude those classified as exterior. Also, the surface obtained is divided into patches separated by features. This technique is built upon a novel parameterization of planes and a voting scheme to find large flats on the boundary with acceptable runtimes.

• Complementing the previous contribution, a feature extraction algorithm that works on discrete models was developed [38]. This method is based on the observation that one can characterize local properties of the surface based on what can be seen by an imaginary creature on the surface. The algorithm can extract meaningful boundaries and features from the minimal input data.

• We have applied the ideas from the previous papers, together with the results in [13] and with new developments, to develop an algorithm [6] that is capable of automatically repairing small to medium-sized defects in a massive mesh model. This technique was successfully applied to a mesh of 173M triangles resulting from a scan of a large twelfth century monument with close to twenty thousand holes because of inevitable occlusions in the digitizing process.
• We have also introduced a model repair tool which accepts as input an arbitrary 3D model and returns the surface of a valid solid, allowing the user to identify areas with potential topological errors and to choose how to fix them in a user-friendly manner [20].

• We have presented a new image-based representation of geometric and appearance details which consists of a set of cubic cells (providing a coarse representation of the object) together with a collection of distance maps (encoding fine geometric detail inside each cell) [30].

2.3 Terrain modeling and analysis

Within this activity we have been working on the design and implementation of algorithms for: (a) modeling terrains of quality; (b) solving proximity and matching problems.

Modelling quality Triangulated Irregular Networks

• We have proposed a framework that combines improvement and Delaunay refinement techniques for incrementally adapting a refined mesh by interactively inserting and removing domain elements, so that the number of Steiner points added during the process remains low [9].

• We have presented a method for triangulating grid terrain data. The method produces triangular approximations that capture well the relevant features of the terrain surface by naturally producing well-shaped triangles [39], [68].

• We have proposed algorithms that combine Delaunay approaches with area/aspect-ratio constraints for generating a refined Delaunay mesh of a domain, with applications [40].

• We have studied the problems of matching: (a) two colored point sets in 3D under the bottleneck distance [45]; two road networks [44].

Terrain analysis

• We have proposed algorithms for efficiently solving proximity [47], [14], [7] and visibility problems in terrains [41], [42].

• We have designed algorithms for efficiently: (a) computing distance functions on road networks [15]; (b) solving reverse nearest neighbor queries on road networks [70]; (c) determining shortest routes [11].

• We have presented algorithms for detecting movement patterns in spatio-temporal data bases using the GPU [48].

2.4 Volume modeling and Visualization

The objective of this activity is to provide general, automatic and scalable algorithms for improving the 3D inspection and analysis of medical images. Following a summary of the main results that we have obtained:

Data Volume Registration and Segmentation

We have studied registration in order to extract the relevant information of registered models for segmentation purposes. We also propose a novel information-theoretic approach for
thresholding-based segmentation that uses the excess entropy to measure the structural information of a 2D or 3D image and to locate the optimal thresholds. All developed techniques have been evaluated in real clinical environment in collaboration of medical experts [36], [59], [5], [4], [3].

Interactive visualization for medicine

- We have studied diffusion tensor images from which white matter fiber maps can be reconstructed. We have presented an obscurance-based framework that allows us to obtain realistic and illustrative volume visualizations in an interactive manner. Moreover, we obtain a saliency map from the gradient of obscurances and we show its application to enhance volume visualization and to select the most salient views. The proposed techniques have been evaluated in clinical environments [56], [57].

- We have developed a measure for selecting a set of representative views of a 3D volume dataset and, finally, the automatic construction of exploration paths around it [52]. This may help the doctors to obtain a general view of the 3D model being inspected [53].

- We have also focused on improving the perception of the medical doctors on the models being analyzed. This has been achieved by designing a fast algorithm for the generation of high quality view-dependent ambient occlusion together with halo generation [43]. We are currently working on a fully GPU-accelerated algorithm that needs no precomputation.

- We have proposed the Magic Virtual Lantern which consists in an interaction metaphor that mimics the behavior of a lantern whose projection cone renders the medical model under a second transfer function. This way, VR exploration becomes very intuitive. The algorithm is very easy to integrate with a GPU ray tracing of volume data [52].

- In [27] a framework for the aid in anatomical education is presented. The core idea is to connect textual and visual information through links created by using Information Retrieval technologies. The result can be seen as an electronic book that renders the textual information and a 3D view of the model.

Interactive simulation of surgery planning

In collaboration with medical doctors we have developed a system that simulates the different conditions involved in a subcondyle fracture repairing surgeon. This project has three different aspects: the modeling of the geometry involved in the surgery, the rendering of the surgery itself, and finally, the haptic interaction in order to make the surgery more realistic. We have successfully performed steps one and two, and we are currently facing the third problem [51].

2.5 Physically-convincing animation

In order to improve realism in our VR applications, it is important to include animated objects. We have been achieved the following results:

- Facial and dynamical character animation. We have developed an automatic system to reuse an initial animation rigg to different characters. This way reached a method that automatize the tedious problem of rigging each character appearing in an animation production [10]. We have just started also a new research path in order to obtain an automatic method for building an animation skeleton and rigg from initial general poses [55].
**Muscle Contraction Model.** We have studied, together with medical doctors, the dynamical simulation of the human inguinal region. This is almost the first work in this area trying to simulate the muscle contraction to explain why an inguinal hernia is produced. We have developed a Finite Element Model and an anatomically based geometrical model for simulating the different anatomical units that plays a role in the dynamics of this area. We have published the results in some journal papers [17, 16, 21, 18].

**We have designed an algorithm for the simulation of falling leaves on graphics hardware. The core idea is to encode a falling path in a texture and apply pseudo-random modifications per each leaf. We have studied different ways of rendering the falling leaves by using some of the GPU features such as render-to-vertex buffer or geometry shaders [26].**

**In [23], we study systematically the motions in two and three dimensions that have certain properties regarding the evolution of speed at each point. These motions give rise to smooth and pleasant animations that present a minimal distortion along the trajectory in a very concrete and measurable way. The paper includes closed-form expressions to compute the motion joining two given states in constant time.**

### 2.6 Interaction with virtual crowds

This activity concerns with the determination of crowd behaviour based on psychological properties of individual crowd members and determining the degree of Presence, and with the study of real-time rendering of very large crowds. We have been achieved the following results:

- We have continued our collaboration with Prof. Badler (Univ. Pennsylvania) to introduce personality components to improve the realism of crowds animation, and the results achieved so far have been reported in [12]. We have also pursued the validation of crowd-animation-algorithms by measuring the degree of presence felt by a user embedded in them, a novel approach that we presented in [54].

- In [22] are described the main challenges and limitations of crowd simulation models for high rise building evacuation simulation. Also it is proposed a model that incorporates human psychological and physiological factors to simulate human movement closer to real movements of people, where interaction between bodies emerges and flow rates and speeds become the result of those interactions instead of some predefined value.

- We have presented the design of our platform for improving the realism of the motion and animation of immersive crowds at the Spanish conference on Computer Graphics ([73]), and have applied our techniques to a didactic application that presents a reconstruction of Tarraco in the roman times [65].

### 2.7 Interactive visualization of highly complex models

In this activity we have studied hardware-accelerated techniques for the fast rendering of complex models. We have based our research in using hierarchical data structures supporting relief impostors. We have been achieved the following results:

- We have derived efficient and scalable navigation algorithms for gigantic data models. In our scheme, the scene is represented through an octree model, from which we can obtain the required set of triangle meshes corresponding to view-dependent LODs. We
have used this approach for the immersive, interactive visualization of the 173 Mtriangle, high resolution digital reconstruction of the entrance of the Ripoll Monastery (North of Barcelona). The corresponding project has been described in [35], while [66] details the real-time navigation strategy.

• We have designed specific Multiresolution trees of Relief Impostors, MRIs, [1] that are specially suited for the inspection of urban environments [29], [28]. MRIs inherently support multiresolution and partial visibility culling, as occluded parts are not captured by the impostors. The algorithm combines a hierarchical representation having a complexity that is independent from the initial data, the use of virtual and compact tree levels through wavelet compression, a simple view-dependent impostor selection heuristics and a very efficient use of the GPU resources. The initial results and tests with this new data structure are highly promising.

• An approach using relief impostors and perfect hash textures, has been used in a navigation software for the inspection of the digital reconstruction of Tarraco [65].

2.8 Virtual reality systems

The objective of this technological activity is to provide new low-cost VR systems. We have worked on the following topics:

• We have designed a new portable VR system [37]. It uses back-projection with passive stereo being managed with a single PC. It has been patented, and it is now being commercially exploited by Sener Ingenieria y Sistemas S.A. under two different variants: a medium-size, wheel-tracked portable system (display screen of 1.2 x 0.9 meters) that can be disassembled and transported in a private car, and a larger (also transportable) system featuring a vertical display screen of 2.7 x 2 meters and a precise, ultrasound-based tracking system. The visualization and interaction software in both cases has been completely developed under the project. Our VR systems have been tested and compared with the older VR systems in our Lab [67].

• We have designed and constructed a new VR system with active stereo for surgical planning in medicine. It uses shutter glasses, one high-frequency Samsung monitor display and a haptic robot. The interactive registration and interaction software has also been designed and implemented. The prototype has been successfully tested by a local Hospital and by one of the project EPOs (Alma IT Systems).

• We have designed and produced a prototype system that uses two different units with one PC, one projector and one camera each. The system automatically calibrates itself, offering a virtual projection display area which is partially covered by each one of the units. The calibration algorithm includes a first geometric matching followed by a pixel-based luminance calibration.

• We are working (in this last phase of the project) on the design of a new, autocallibrating projection system for the 4-wall Cave system in our Lab. The new system will use passive stereo and 12 standard projectors for each vertical Cave wall, with overlapping projection areas of about 1.5 x 1 meters. We are presently involved in the design and implementation of the calibration and visualization software and in the design and construction of the physical projection system.
2.9 Demonstrators

This activity was scheduled for the last year of the project. Nonetheless, we have already developed some prototypes in the context of some of the papers published, for evaluating their results.

We have developed a software platform for visualizing complex scenes using the VR systems (with one wall of projection). The whole system is designed in a layered fashion. It uses VR Juggler and Qt3D to achieve a portable VR application. We have already integrated on this platform some of the visualization algorithms and interaction techniques proposed in this project. For example, we have a cultural heritage application. We are integrating other applications such as avatar animation and extending the framework for the 4-walls VR system that we are developing.

In the medical area, we are developing a similar platform for visualizing and manipulating volume data. This application includes almost all the modules related with medical data treatment and visualization. Medical doctors use this application for evaluating our results.

3 Performance indicators

The project’s objectives are being met as expected. Both the quality and the relevance of the results so far are witnessed by the quality of the publications of both teams, most of which are listed (classified by their kind) at the end of this document. The next two subsections discuss other indicators of the project’s success up to this point (thesis, relations with EPOs, etc.), and the following subsection (see Section 3.3) briefly visits the issues around the coordination between both teams.

3.1 UPC subproject

PhD and MSc students

One PhD thesis was completed during the project:


Eight students, enrolled in the PhD Program in Computing of the UPC, are developing their research within the project: F. Argelaguet, A. Brogni, M.A. Cervero, J. Díaz, X. Lligades, J. Ojeda, V. Theoktisto and J. Surinyac. Six of them have already presented their thesis proposal and it is expected that F. Argelaguet and V. Theoktisto will complete their PhD in 2010.

Nine MSc thesis have been completed in the Graphics speciality of the MSc Program in Computing. A number of these students (and the three students that have left the PhD Program after obtaining their DEA diploma) are working at companies of related areas.

Publications

The Bibliography section lists both publications already published or accepted, and those recently submitted. The first set include 16 papers in peer reviewed journals, 23 in international conferences with peer reviews and 9 papers in national conferences with peer reviews.

Technology transfer

We have continued a fluid collaboration with the companies and institutions who showed their interest for the project from its proposal phase (Sener Ingeniería y Sistemas, GeoVirtual...
and Alma I.T. Systems). The collaboration has been particularly fruitful with Sener, which commercializes our patented portable stereoscopic system. We have also signed a technology transfer agreement with Alma for developing a VR system for neuro surgical planning based on the prototype developed in the project.

Besides the above institutions, the Museu Nacional d’Art de Catalunya (MNAC) have also been interested in the results of the project in the area of cultural heritage. We have built two immersive setups for the virtual inspection of the portal of the Ripoll Monastery, which were available to the public during the “The Romanic Art and the Mediterraneum” exhibition (February-May 2008).

**European projects**

Our group has been involved in the projects: Presence: Research encompassing sensory enhancement, neuroscience, cerebral-computer interfaces and applications (PRESENCCIA) and Immersive multi-modal interactive presence (IMMERSENCE) led by professor Mel Slater.

**Collaboration with other research groups**

We have cooperated, in the framework of the project, with a number of foreign groups and researchers. Among them, we would like to cite the following ones: J. Rossignac (Georgia Tech, USA), R. Scopigno (CNUCE, CNR, Pisa, Italy), B. Froehlich (VR Systems Group, Bauhaus-Universität, Germany), H.P. Seidel (Max Plank Inst. for CG, Saarbruecken, Germany), N. Badler (Univ. Pennsylvania, USA) and T. Gotzelmann (U. Magdeburg Univ., Germany).

### 3.2 UdG subproject

**PhD and MSc students**

Four PhD thesis were completed during the project:

- Y. Diez, “2D and 3D Noisy Colored Point Set Matching under the Bottleneck Distance”, Octubre 2008, Universitat Politècnica de Catalunya.

Currently, 7 PhD students are enrolled in our PhD programmes and are developing their thesis within the project: N. Madern, F. Prados, T. Paradinas, M. Ruiz, R. Bramón, E. Bonmat, N. Valladares. It is expected that N. Madern will complete his PhD in 2010.

Four Master thesis were completed during the project.

**Publications**

The Bibliography section lists the publications produced so far within the project. They include 8 papers in indexed journals, 12 in international conferences with peer reviews and 2 papers in national conferences with peer reviews.

**Technology transfer**

We have a fruitful collaboration with: Nexus Geografics, Laboratory of Experimental Images,
Service of neurology of Hospital Clínic de Barcelona, Facultat de Medicina de la Universitat de Girona, Services of radiology of the Hospital of the Vall d’Hebró, Joan XIII and Arnau de Vilanova, Service of Neuroradiology of U. Hamburg and Departament of Physics of U. Freiburg.

Collaboration with other research groups
We have collaborations with: J. Urrutia (Independent National University of Mexico), J.M. Díaz-Báez, Future I. (University of Seville), M.C. Rivara (University of Chile), M. Lopez (Denver University, the USA) and F. Anton (Tech. Univ. of Denmark), Ivan Viola (Visualization Group, University of Bergen), Stefan Bruckner (Computer Graphics Group, Vienna University of Technology), Meritxell member Bach of the Signal Processing Laboratory, BioMedical Imaging Center (Ecole Polytechnique Fédérale de Lausanne - EPFL).

3.3 Coordination
For the coordination of the activities and tasks, the subproject coordinators have had joint meetings with semester regularity in addition to specific meetings between other researches that participate in tasks with a related goal. Moreover, once a year, we have organized a “Workshop of the Project” where the main results have been presented and discussed. The coincidence and complementarily of research lines of both groups have provided a suitable working framework. The research of the UPC has been centered in geometry processing, animation, crowds simulation, visualization of complex scenes and the development of virtual reality systems and interfaces. The research group of the UdG has a major experience in computational geometry and geographic information systems, providing a formal framework to the project. Both groups shared their interest in medical applications although in some complementary areas. This fact has produced a tight cooperation between both groups.

Papers in peer-reviewed international journals


Papers in peer-reviewed international conferences


Papers in peer-reviewed national conferences


