



ViHAP3D Final Report

September 23, 2005

Contents

1	Executive Summary	7
2	Project Motivation	9
2.1	Background	11
2.1.1	Cultural Heritage in Europe	12
2.1.2	Need for European Cooperation	13
2.2	Scientific and Technical Challenges	16
2.2.1	3D Scanning	16
2.2.2	The Scanning Pipeline	17
2.2.3	Appearance Acquisition	20
2.2.4	Virtual Heritage Tools	21
2.3	Partners Involved	22
2.3.1	MPI Informatik	23
2.3.2	UPC	23
2.3.3	CNR	23
2.3.4	gedas	23
2.3.5	Konica Minolta	23
2.3.6	SBAAAS	24
3	Approach	25
3.1	Scientific and Technical Objectives	26
3.2	Work Plan	27
3.2.1	General Description	27
3.2.2	Workpackage List	28
3.2.3	Workpackage Objectives and Milestones	29
3.3	Deliverables	34
3.4	User Requirements	34
3.4.1	Selection criteria	34
3.4.2	General needs and requirements about the 3D Model	36
3.4.3	3D Model's and restoration activity	37
3.4.4	Visualization and communication in schools and museums	37
3.4.5	Disposition to investment	39
3.5	Evaluation of Results	39

3.5.1	The evaluation process	39
3.5.2	Expert end users' evaluation	40
3.5.3	Measuring satisfaction of Museum visitors	41
3.5.4	Restorers' evaluation	43
3.5.5	Schools' evaluation	43
4	Results and Achievements	45
4.1	Functional Specification	45
4.2	3D Scanning	45
4.2.1	Easy3DScan Software	45
4.3	Acquisition of Surface Properties	49
4.3.1	Introduction	49
4.3.2	Describing Surface Attributes	49
4.3.3	Data Acquisition	50
4.3.4	Data Preprocessing	52
4.3.5	BRDF Generation	52
4.3.6	Results and Conclusions	53
4.3.7	Application Areas	54
4.4	Integrated Scanner Prototypes	55
4.5	Software for Software for Post-Processing,	56
4.5.1	Mesh Align	56
4.5.2	Mesh Merge	60
4.5.3	Manipulation Tool "Mesh Repair"	65
4.6	Virtual Heritage Tools	66
4.6.1	Virtual Museum Builder	66
4.6.2	Virtual Museum Browser	68
4.6.3	Virtual Inspector	69
4.7	Repository of 3D-Models	73
4.8	Dissemination and System Evaluation	75
4.8.1	Exhibition 2003	75
4.8.2	Pisa Kiosk	76
4.8.3	Actions	77
4.8.4	Ferrara Restauro, 2003, 2004, 2005	78
4.8.5	"Minerva di Arezzo" Workshop, 2005	80
4.8.6	Florence, Kunsthistorisches Institut, 2005	81
4.9	Project Web Site	81
4.10	Project Impact	82
4.10.1	Scientific Impact	82
4.10.2	Impact on Cultural Heritage Community	83
4.10.3	Current System Users	83

<i>CONTENTS</i>	5
5 Prospects for Exploitation	87
5.1 Market Structure	87
5.2 Competitive Products and Services	88
5.3 Exploitation Routes	89
5.3.1 ‘Combined Partner’ Exploitation	89
5.3.2 ‘Individual Partner’ Exploitation	91
6 Perspectives for Further Research	93
7 Conclusion	95
Bibliography	97
A Contact Information	99
B Selected Scientific Publications by the ViHAP3D Partners	103
Bibliography	103

Chapter 1

Executive Summary

Nearly all of our cultural heritage is inherently three-dimensional. Recent hard- and software developments enabled 3D computer graphics to be one of the most powerful means to represent complex data sets. The ViHAP3D project (ViHAP3D is an acronym for *Virtual Heritage – High Quality 3D Acquisition and Presentation*) aimed therefore at preserving, presenting, accessing, and promoting cultural heritage using interactive, high-quality 3D graphics. The vision of the project was to create an exact digital copy of cultural heritage artifacts that can be examined by experts and laymen in various application scenarios using the full range of currently available virtual reality technology. The project objectives were to

- create 3D scanning tools for the acquisition of accurate and visually rich 3D models,
- enable post-processing, representation, and efficient rendering of the resulting data,
- develop virtual heritage tools for interactive visual presentation and navigation in high-quality digital model collections.

The project was coordinated by the German partner *Max-Planck-Institut für Informatik (MPII)* – one of the research institutions. The consortium included two additional research institutions: the Italian partner *Istituto Scienza e Tecnologie dell’Informazione, Consiglio Nazionale delle Ricerche (CNR)* and the Spanish partner *Universitat Politècnica de Catalunya (UPC)*. The industrial partners were the German *Konica Minolta Europe GmbH (KM)* and the Spanish company *gedas (gedas)*. The Italian partner *Soprintendenza per i Beni Ambientali, Architettonici, Artistici e Storici per le Province di Pisa, Livorno, Lucca, Massa Carrara (SBAAAS)* acted as end user in the project and provided a link to the cultural heritage community.

The project developed cutting-edge research results and transformed them into practical hardware and software tools. Various digitization efforts of important artifacts such as the *Minerva di Arezzo* were performed on-site or in the partner’s labs yielding

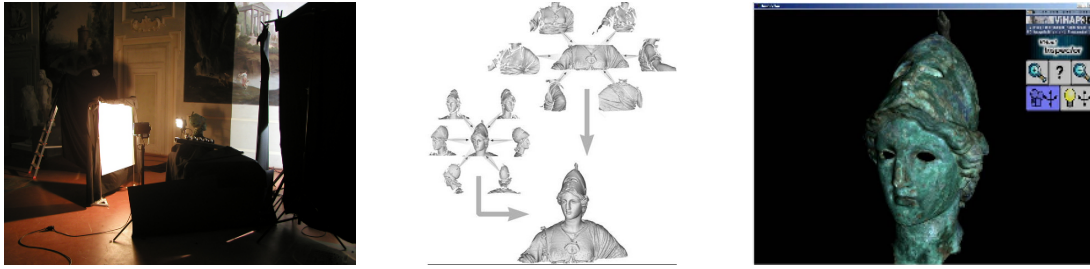


Figure 1.1: *Acquisition and presentation of the Minerva di Arezzo using the ViHAP3D pipeline. From left to right: Acquisition of the object appearance, merging of individual 3D scans in the post-processing phase, display using the project's Virtual Inspector.*

realistic and high quality object models. These models can be efficiently manipulated in the post-processing phase and stored on the project's custom-built database. Expert users such as museum curators and archaeologists were excited by the achieved quality and the new interaction possibilities of the presentation tools. Likewise, visitors of the demo installations such as the 2003 Saarbrücken exhibition and the Pisa kiosk provided enthusiastic feedback.

In summary, the ViHAP3D project has been highly successful in creating a unique pipeline to digitize the shape and appearance of cultural heritage objects, process and store the resulting data, and to present them to both laymen and expert audiences in a meaningful and visually appealing way. The project has met all of its objectives and produced all deliverables.

Chapter 2

Project Motivation

Computer Graphics evolution is motivating the use of graphical interaction. The number of fields where this technique is being implemented is increasing with the decreasing cost of the devices and the appearance of new interaction tools. New improvements in the virtual reality field have reached a point where a change is needed. Users request an evolution in visualization quality and user interfaces. Thus, the participation in this project helps in this race toward the evolution of computer graphics, mainly focusing the work on the creation of efficient, low cost, easy-to-use and high quality software systems. These tools help presenting 3D models as support for a better understanding of real artworks. This allows for a better knowledge of our Cultural Heritage and, in consequence for a broader diffusion of the knowledge. It can improve the general public interest in arts and culture.

It has to be mentioned that this project moves inside a European environment. This allows the partners to keep a feedback with other national and international institutions, which can improve the results in their studies and contributions to the project.

In addition, this project contributes to the scientific community with some doctoral thesis and the presentation of several papers during the development of the project.

Nearly our entire cultural heritage is inherently three dimensional, and 3D computer graphics appeared as the most apt and powerful medium for virtual representation of all kinds of complex data. However only a few attempts were made in this field (intended for big museums which can afford to invest in new technologies and skilled operators) and almost none did produce stable applications. Small museums tend to be neglected and not involved in any project, probably as a consequence of their difficulties in finding economic sponsors and supporters.

New technology still had to be developed in order to reduce data model construction time, data download time and to be easily accessible and usable on-line by non-expert users. A dialogue between computer science experts and museum staff was highly desirable in order to create really useful and affordable tools which fulfill the cultural heritage community's needs. Even if a number of public and European-funded projects devoted to the development of advanced tools for authoring and browsing

virtual museums were starting (e.g. the MOSAIC project, PURE-FORM, . . .), working solutions of 3D tools and 3D online facilities were quite scarce. Some advanced tools were being developed at the Guggenheim Museum (New York, USA) and at the National Gallery of Art (Washington, D.C., USA), but in none of them additional information on the selected objects could be given. At that time, no tools similar to the ones envisioned by the ViHAP3D project had been actually available. But a clear need for virtual museum builders together with acquisition, browser and inspector tools has been identified.

The project aimed to meet these various needs by exploring the possibility of producing and presenting digital 3D models: Specifically, the goal was to produce technologies for acquiring, post-processing and visualizing 3D models that are

- faithful and accurate so that they could be used instead of traditional photography to support academic research, cataloguing and archiving activities or the restoration of artwork
- cheap enough to be affordable
- apt to be presented inside a multimedia kiosk dedicated to museum visitors.

No system fulfilling all of these requirements was present on the market. Moreover, we were convinced that as long as 3D scanning remains a technical procedure involving many separate and inter-dependent steps this technology could never have a wide diffusion in real applications. This problem was even more complex in fields where the average experience in IT is not very high – the cultural heritage area is a good example of such a field.

Several technological advances were needed to transform 3D scanning from a niche-market technology into a commodity technology used on a day-to-day basis. Driven by the requests and needs of the end users, the following objectives were identified at the beginning of the ViHAP3D project:

- Improvement of the functionalities of 3D scanning devices by providing technologies for scanning both shape and surface attributes at different levels of quality. In particular, surface attributes can be a simple surface color (low-end approach) or a complete surface appearance model (BRDF, high-end).
- Reduction of the time required to scan an object in order to decrease the production cost of a single model. This can be done by designing more automatic systems (reducing user's contribution) and/or designing new software solutions demand less resources (faster processing).
- Increased scalability, the technology should be able to process the complete spectrum of application cases – from a small object to any complex and/or large masterpiece.¹

¹In effect, the tools developed have been tested and assessed on a number of different cases, ranging

- The tools should run on inexpensive platforms (low cost PC-based machines).

2.1 Background

After the revolutionary invention of photography in the nineteenth century, we are now on the edge of a second revolution, where interactive 3D graphics will complement or even replace other classical media as a comprehensive and powerful way of presenting rich digital content. 3D digital models are the ideal archiving solution for long-term preservation. They allow permanent digital archival of fragile or endangered artwork, visual presentation to a widely-distributed user community, reproduction of physical replicas, scientific or historical analysis and restoration procedure planning.

However, as stated by the DigiCULT Survey (an European research started in 1996 to investigate the state of the art in today's archives, libraries, museums and other cultural Institutions), the spread of new technologies among Cultural Institutions was still unsatisfactory. Between 1996 and 2001 the European Community and the National Governments removed some obstacles to the accessibility of Cultural Heritage data to future e-business markets; this major change was done since the publishing, entertainment and content provider companies were seen as fundamental actors in the development of new products and services to be delivered over digital networks.

The analysis performed in January 2002 demonstrated that the situation was still far from what the specialists expected it to be in 1996 when the survey began: no new mass markets in electronic publishing had been consolidated; just a few examples of success in the cultural industries and even fewer in the cultural heritage sector emerged.

This could depend on the high costs to sustain services and the consequent lack of demand by common users. The tools applied in the cultural sector were too complex and used only in management systems.

Eventually, the introduction in the art world of multimedia and digital technologies was mainly concerned with museums' web sites, audio-guides and video kiosks, but none of them did make use of 3D models. Again the main reason was that the existing 3D applications were specifically designed for expert users such as computer scientists. This situation was also confirmed by an examination of the literature: Although a number of books and articles were published on the subject, they were always written by technologists and intended for similar readers. There was no specific literature on the application of 3D digital data (including modeling and rendering aspects) targeted at the cultural heritage domain.

One of the goals of the ViHAP3D project was to respond to this situation by providing tools for the cultural heritage community. Other projects dealing with the same

from small artifacts (ceramic vases, small statuettes, etc) to more complex objects (large statues or architectures). Major examples of complex scanning have been the funeral monument of Arrigo VII (15 full-size statues), the Parthenon friezes (scanned by the University of Southern California (USC) with triangulation-based scanning and processed with the ViHAP3D tools) and the Pisa Cathedral (scanned with time-of-flight technology and processed with the ViHAP3D tools).

issues include

- SCULPTEUR (Semantic and content-based multimedia exploitation for European benefit – IST-2001-35372), a three-year European project that started in May 2002. The goal of the project was to develop both the technology and the expertise to help create, manage and present cultural archives of 3D models and associated multimedia objects, exploiting the semantic web technology, and make cultural heritage available worldwide.
- ARCO (Augmented Representation of Cultural Objects – IST-2000-28336) - a research project, funded by the European Union, aimed at developing technology for museums to create 3D virtual exhibitions on the web. Virtual exhibitions are created by digitising museum artefacts, which are then transformed into virtual representations, which can be X3D or VRML models or scenes.

2.1.1 Cultural Heritage in Europe

The official web site of the Council of Europe states that cultural heritage has always been recognised as a major factor in the development of human knowledge, understanding and values, and hence, along with democracy and human rights, is a necessary substratum for a fulfilling life. In its different expressions it has helped successive generations throughout history to find a meaning, an identity, a vision.

The cultural and natural heritage provides a sense of identity and helps to differentiate communities in a climate of globalisation. It allows cultural communities to discover and understand one another and, at the same time, constitutes a development asset.

If these are the traditional main attributes of culture, others have been added in recent decades and the list seems to grow steadily. Making European citizens aware of their cultural heritage is seen as the support of sustainable development, the cement of social cohesion, the drive for creative entrepreneurship and employment, the fertile soil for civil society, the leading force of new-technology driven innovation, the lymph of the knowledge society. As a result culture is moving upwards on political agendas: the reference publication by the Council of Europe on culture and development *In from the Margins* states that "a new alliance between culture and development" is underway to respond to "two interlocking priorities: to bring the millions of dispossessed and disadvantaged Europeans in from the margins of society, and cultural policy in from the margins of governance".

Nowadays, culture is believed to be able to prevent and treat some of the emerging tensions of our society; to help understand the many facets of sustainability; to bring about a new sense of solidarity, to positively inspire the new economy, especially act as a means of empowerment and entitlement, to promote public-private links, to be the bed rock we need to reach out from to understand and respect other cultures with self-reliance. In other words, culture is looked at as an ingredient of society and policy

which needs to be brought in from the margins, because for many decades it has not received the attention it deserves by policy-makers.

All these functions had been embedded in a policy that promotes identity, respects diversity, supports creativity and stimulates participation, the four key principles the Council of Europe's Culture Committee has been defending since its creation.

To foster and facilitate dialogue, activities concerning building up common archives of our heritage and granting access to them, in particular for historians and researchers, have been launched, as well as others aimed to disseminate this knowledge among the general public and to link this dissemination with a development of the European economic development, to empower cultural producers and facilitate partnerships and networks with markets.

2.1.2 Need for European Cooperation

Cultural institutions in charge of preserving and exploiting heritage all over Europe play an important role on behalf of the public because they all hold a share of our common heritage.

European ministers or representatives of culture in the European Union have stated that culture is instrumental in promoting mutual respect for and understanding of different ideas and identities, and that such mutual understanding can be developed further through improved access to information in the framework of digital projects. Consequently a strong effort has been made in the last years to build an information society for all European citizens that reflects the wealth of European cultural creation and heritage, and quality initiatives in cultural websites were encouraged.

Because the information society is based upon knowledge, cultural websites have a great deal to offer to all citizens. The availability of high-quality websites encourages European citizens to discover, to explore and to benefit from online material representing the unique diversity of European culture. Such websites will enable maximum value to be derived from Europe's cultural treasures, which enrich the European information society, by the citizens of Europe and beyond.

It is important that the quality of such online offerings be of the highest standard, in order to deliver the best possible service to European citizens, who can therefore develop a common sense of membership and a shared identity, both prerequisites indispensable for a genuinely united Europe.

In accordance with the Europe initiative "An information society for all", the European Commission and the member states have established trans-European coordination mechanisms for digitisation policies and programs in the field of cultural content and applications.

The initiative began in April 2001 in Lund, when representatives from member states met and discussed the issues related to the digitisation of cultural heritage. The results of the meeting were the *Lund Principles* and the *Lund Action Plan* for the implementation of these principles with which the member states of the European Union committed themselves to increase their collaboration to strengthen the digital

diffusion of European cultural heritage, and to realize a common European platform of standards and guidelines, in order to facilitate the creation of digital cultural content and the construction of interoperable cultural portals offering easy access for all.

The *National Representatives Group (NRG)* was established during the Belgian presidency in 2001 as the "guardians of the Lund Principles", following the promising results of the Lund meeting with the objective to create trans-European coordination mechanisms and infrastructure to support the digitization of cultural and scientific content. The role of the NRG has been strengthened through the Charter of Parma, a strategic document presented during the Italian presidency that redefines the basic mission of the initiative.

Among the most important outcomes are two projects: MINERVA Plus, which opens up the network to the new accession countries of the European Union, as well as Russia and Israel; and MICHAEL, born out of the work that was carried out by the MINERVA working groups. MICHAEL has the objective of creating a trans-European cultural heritage portal.

The MINERVA project, in the European framework outlined, supports the activities of the NRG with the objective of accomplishing the Lund Action Plan. It was started thanks to the close collaboration between the Commission and member states with the goal of facilitating the creation of a common European vision in the definition of actions and programmes in the domain of accessibility and exploitation of cultural heritage through the web.

Thanks to the involvement of national governments, MINERVA coordinated corresponding national programs, and established contacts with other European countries, international organizations, associations, networks and projects involved in the digitization sector.

The network's activities are undertaken in the framework of the eEurope Action Plan, whose general goals have been acknowledged in the cultural heritage domain through the principles established in Lund.

Therefore, MINERVA operates on two levels, political and technical. The political level guarantees a close collaboration among member states through high-level institutions, the ministries of culture, that have responsibility of the cultural heritage, and between these and the European Commission.

Moreover, in this perspective MINERVA intends to give visibility to national initiatives:

- selecting, promoting and exchanging good practices
- adopting common standards and moving towards a European platform of guidelines and recommendations.

The second project, MICHAEL, intended to provide easy multilingual access online to the catalogues of digitised cultural resources of France, Italy and the United Kingdom, with the possibility of subsequently extending participation to all the countries involved.

The project will establish an international online service, which will allow its users to search, browse and examine multiple national cultural portals from a single point of access.

The end user will use the MICHAEL service to find and explore European cultural heritage material, which can be accessed over the Internet. This material may include learning resources, catalogue information or the description of physical collections; however, the majority of this material will be digitised cultural heritage assets such as images, 3D models and meta-data descriptions of archaeological sites, buildings, paintings, sculpture etc.

The projects and initiatives mentioned above show clearly that cooperation on an European level is very important and beneficial for the digitization of the existing cultural heritage. This is also emphasized by the fact that a number of important meetings and events focusing on this issue such as the ones listed below have taken place during the course of the ViHAP3D project.

7th - 8th April 2003 - Athens: Conference on "Culture, copyright and information society"

26th - 27th - 28th June 2003 - Corfu: NRG meeting and "Digitization of Cultural Content", two day workshop which launched the idea of cooperation among the main cultural networks at European level in order to avoid fragmentation of the efforts and achieve a tangible European added value.

16th -17th October 2003 - Florence: International conference on "The future of digital memory and cultural heritage", a working group consisting of experts in the field was proposed to identify the state of the art and plan the developments needed to implement the resolution principles. This group is led by the ER-PANET and MINERVA projects. Other projects or networks of excellence are key actors, such as DELOS, PRESTOSPACE, DIGICULT FORUM.

23rd - 24th October 2003 - Naples: The seminar "Territorial information systems for the conservation, preservation and management of Cultural Heritage"

29th - 30th October 2003 - Rome: International Workshop "Digitisation: what to do and how to do it" and meeting of the European Cultural Networks in the sphere of technologies applied to Cultural Heritage

19th November 2003 - Parma: The NRG meeting during which the Charter of Parma was discussed and approved as the strategic document outlining future strategies, highlighting progress, and fostering the sustainability of the group. The idea of defining a common European area for research launched by the Greek presidency was realized during the Italian presidency by the creation of a cluster of the European networks and projects that met for the first time on 30th October 2003 in Rome.

20th - 21st November 2003 - Parma: International conference on "Quality for cultural Web sites", one of the main cultural events organised during the Italian presidency of the Council of the Ministers of the European Union

28th June 2004 - Dublin Castle: The NRG meeting presented a draft of the convention on the value of cultural heritage for society, together with the international conference on digitization "Access all areas: serving the user"

15th September 2004 - The Hague: NRG meeting and conference on long term preservation of digital memory "Strategies for a European area of cultural resources"

2.2 Scientific and Technical Challenges

As described in the background section (Chapter 2.1), traditional image-based documentation of cultural heritage artifacts can now be complemented by more advanced digitization techniques. The main focus of the ViHAP3D project was to introduce computer graphics based techniques that digitize both, the shape (geometry) and appearance (color plus reflection properties) of an object to the cultural heritage community and to provide the necessary tools to acquire, process, and display such object models. Some of the additional benefits of these approaches are the ability to view the object models from arbitrary viewpoints and in arbitrary environments (including various illumination settings) and the preservation of the objects' appearance which contributes substantially to the perceived realism of the models. This section gives an overview over the scientific and technical challenges encountered in the course of the ViHAP3D project.

2.2.1 3D Scanning

3D scanning emerged as the main approach for the production of high-quality digital models of real objects or scenes. The adoption of 3D scanning technology, rather than a standard CAD-based modeling solution, is justified by the need of producing accurate samplings of the real object of interest, rather than a user-driven interpretation of what the shape should be (or should look like). In 3D applications the direction is therefore to replace the standard modeling approach with a (semi-)automatic sampling approach.

3D scanning should therefore be some sort of "photographic" approach to gather 3D models of real objects. This does not mean that 3D scanning will be the unique technique to obtain 3D models; there are a lot of cases where a good model obtained with standard CAD-based modeling instruments is more adequate to the selected application (as an example, consider some interactive visualization or VR systems where we need a synthetic and schematic representation of the scene).

The main advantages of 3D scanning are: the quality of the representation obtained, where quality is meant as accuracy of the representation (shape + surface attributes) with respect to the original; the manpower cost required to produce the model (that, as

we will see in the following, is now lower than the production costs of CAD models. On the other hand, the high quality of the shape representation is often coupled with a considerable complexity (due to high resolution sampling) of the model produced. There are many fields where an high accuracy is a must (industrial inspection, medical applications, rapid prototyping and reproduction, etc). Cultural Heritage (CH) is obviously a perfect example of such a domain: accurate models are needed to build up digital archives, to visually present the work of art to experienced users and finally to support interesting computer-aided applications concerning the restoration of CH.

As we will see in the following, producing a good quality model with 3D scanning technology is a complex task. In contrast with standard photography, scanning is not just gathering "images" with some sort of strange device, but a more complicated procedure where a series of post-processing filters have to be used on the raw data to produce a complete model. The situation at the beginning of the ViHAP3D was still rather pioneering, because the status of commercial instruments (hardware and software) was rather poor with respect to both surface attributes acquisition (e.g. color) and software support for the post-processing of the raw data. Producing high quality models was very complex, due to the substantial manpower needed (many weeks required for the production of a good quality shape model) and the very scarce capabilities in surface attributes acquisition (scanning of apparent color, illumination-dependent, was the only possible acquisition supported by existing tools). The main objectives have been therefore:

- to increase the capability of the scanning device in terms of surface attribute acquisition (BRDF sampling) → *shape + reflection attributes*
- to improve the ease-of-use of the processing tools and to reduce the time required to complete an acquisition → *increased automation*
- reduce processing resources required (space and time) to make the management of very complex scanning projects possible on low-cost, PC-based architectures → *manage complex tasks*

To clarify the status of the technology at the beginning of the project and to clarify which are the major results forecasted (and obtained), we have to describe in more detail which are the phases and tasks of a standard 3D scanning session, that we call scanning pipeline.

2.2.2 The Scanning Pipeline

The atomic task performed by a scanning device is to acquire a so-called *range map*. The range map produced by a 3D scanning device corresponds to the digital image produced by any photo camera in digital photography.

By definition, a range map contains a sampling of the object's region seen by the scanning device (the region seen by the scanner depends on the physical and optical

characteristics of the instrument used²). It encodes the distance from the scanner location to the points sampled on the surface. From these distances, known the laser emitter and sampling geometry, XYZ coordinates are easily reconstructed by the devices and returned to the user. Some scanning devices acquire also an RGB map, aligned with the range data (i.e. for each 3D point sampled on the object surface, we also get an associated RGB color value).

As it happens in standard photography, many different shots with the scanner are needed to get a complete coverage of the surface of a complex object, and these range maps shall be partially overlapping (a partial overlap of adjacent range maps is needed by the alignment phase, see below).

The classical pipeline of consecutive actions that characterizes a 3D scanning session is rather complex (see 2.1), involving many different operations:

- *Acquisition planning*: decide the set of range maps to be taken in order to provide a complete acquisition of the surface of the object (i.e. decide how many range maps are needed and the view specification of each of them);
- *Scanning* the artifact, and acquiring a set of range maps;
- Range maps *alignment* (also called *registration*): all the range maps have to be aligned to lie in the same space (see Figure). By definition, range map geometry is relative to the current sensor location and has to be transformed into a unique reference space, such that the sections of the range maps that correspond to the same surface zone will be geometrically overlapping. A pair-wise registration process (repeated on all pairs of adjacent and overlapping range maps) has to be run to build a complete registration of all the meshes, and this last alignment is enforced by a subsequent global registration phase run on all the maps in order to move everything in a unique reference system. Alignment can be manual, semi-automatic or completely automatic. When it is not performed in an automatic manner, alignment is usually the most time-consuming phase of a scanning session.
- Range maps *fusion* (or *merging*): build a single, non redundant mesh out of the many, partially overlapping range maps. Once all the range maps have been aligned together in a common reference space, a new triangulated surface is reconstructed. Many scanning systems use a volumetric approach: the 3D bounding box containing the object is divided into small cells. For each of these cells a small piece of surface is reconstructed from the available data (i.e. from the sections of range maps that intersect that cell). The final output surface is the union of all surface parcels reconstructed in all cells. Obviously, the smaller the cell size, the more accurate is the reconstructed surface, and the higher is its complexity (measured in number of triangular faces).

²In the case of the Konica Minolta VI910 scanner, the extension of the region sampled in a single range map is in the range of 20×16 cm up to 80×60 cm.

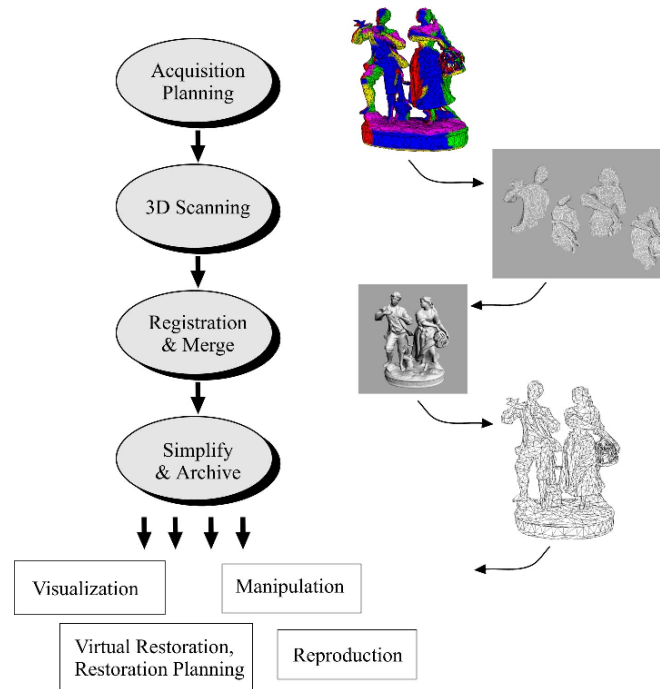


Figure 2.1: *The 3D scanning pipeline*

- *Mesh editing*: improves (if possible) the quality of the reconstructed mesh by filling small holes, removing small spurious unconnected components, applying smoothing filters, etc.
- *Mesh simplification*: reduces the huge complexity of the model obtained, by removing mesh vertices in a controlled manner (see Figure 2.3). The result of the integration of a large number of scans can be composed by millions of triangles. Obviously, processing, rendering, transmission or archival of these meshes are not simple tasks. Mesh simplification allows reducing the complexity of the triangle mesh to any size specified by the user. Current simplification methods allow to preserve the quality of the representation in a very accurate manner.
- *Texture mapping*: associate the available color information to the triangle mesh. This entails projection of the texture maps on the 3D mesh, reconstruction of an optimal parameterization of the mesh to these images and reconstruction of a new texture map from the selective union of all the acquired texture maps.
- Finally, *mesh conversion* and *archival*: export data to the representation scheme used by the application of interest.

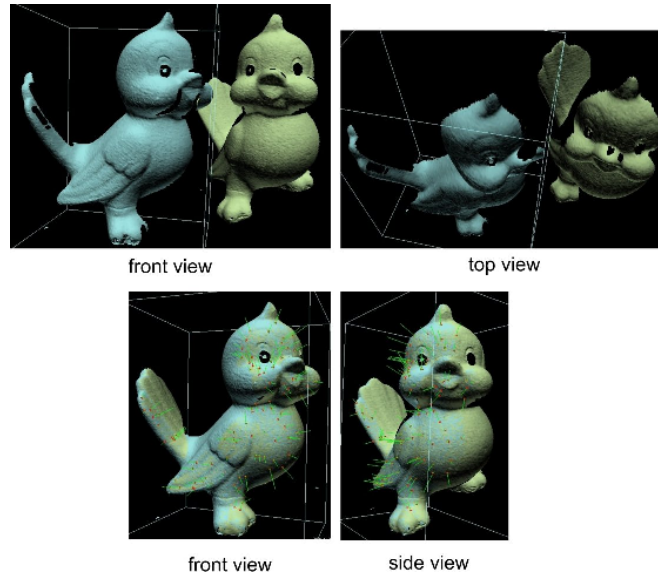


Figure 2.2: Range map alignment: two range maps, before (above) and after alignment (below).

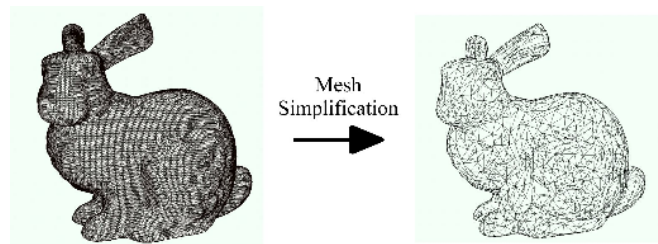


Figure 2.3: Surface simplification (reduction of the number of triangles by preserving as far as possible the accuracy in the representation of the shape)

2.2.3 Appearance Acquisition

Many traditional object digitization approaches approximate an object's appearance by a standard diffuse texture (so called *texture mapping*). Each surface location is thereby assigned a color value. This texture mapping step corresponds to pasting an image of the object taken under diffuse illumination onto the acquired object geometry.

Capturing the *appearance* of an object goes one step beyond this by digitizing the way light is reflected off an object's surface for all incoming and outgoing light directions and for all surface locations. The resulting data can then be used to also model effects such as specular or glossy highlights or colors changing with viewing angles.

Unfortunately, capturing the complete reflectance information of an object requires to view each surface point from all possible directions on the hemisphere and under all possible illumination conditions (yielding in total a six-dimensional function). Even

with automatic acquisition equipment (e.g., robotic capture systems) the cost and effort for acquisition is too high. But even if acquisition would be possible, storing and handling such huge amounts of data is not practical.

The main challenge for the appearance acquisition part of the ViHAP3D project was therefore to capture the appearance faithfully with moderate effort and – if possible – with a setup that is both affordable for and usable by a typical user from the cultural heritage community.

2.2.4 Virtual Heritage Tools

The ViHAP3D project allows new research in the fields of computer graphics and virtual reality, to develop new image acceleration techniques and new 3D stereoscopic vision systems. It focuses on the creation of efficient low cost, easy-to-use and high quality software systems and virtual reality systems, all oriented towards a new way to present Cultural Heritage data.

Virtual Museum Builder is an authoring tool that manages the on-the-fly setup of virtual museums. Given a set of (possibly) distributed 3D models, the tool allows for the arrangement of the digital artworks in a virtual space. The Virtual Museum Builder supports the definition of "virtual guides" in order to plan the visit through the different rooms of the museum according to the user's preferences. Links to further resources about a specific object (web sites, multimedia presentations, textual descriptions) can be attached to both the virtual objects and virtual spaces.

Virtual Museum Browser is an interactive navigation tool for exploring the digital contents created by the builder. The use of VR hardware such as tracking systems and data gloves, together with intuitive interaction mechanisms enables even untrained users to freely move around any object, view it from any direction or even bring different objects together for an easy visual comparison. Users can choose between free navigation and guide-assisted navigation for the different rooms.

The system has been designed to operate on different platforms ranging from low-end systems (PC with monitor) to high-end virtual reality systems, head-mounted displays and projections-based stereoscopic systems such as CAVEs. The use of multiresolution models, level of detail techniques and the new features of state of the art PC graphics boards enables the inspection of large collections even in low-end systems.

The UPC research involved in this project has produced several important publications during this period:

- Computing Maximal Tiles and Application to Impostor-Based Simplification, presented in the Eurographics 2004 and published in the Computer Graphics Forum Vol. 23 (3), 2004 which proposes an efficient algorithm to compute the largest planar region approximating a 3D object.
- MiniVR: a portable virtual reality system, published in the Computers & Graphics, Volume 28 which describes a new virtual reality system designed to be small

enough to be totally portable. It is a semi-immersive interaction system based on a movable stereoscopic projection screen with a tracking system to capture the movement of the screen with respect to the virtual model. The system can be used for cooperative inspection of very complex computer-aided design environments, allowing very simple interaction among users and designers at distant locations.

- **Way-Finder: Guided Tours Through Complex Walkthrough Models**, presented in the Eurographics 2004 and published in the Computer Graphics Forum Vol. 23 (3), 2004. The paper presents a characterization of suitable properties for camera paths and discusses an efficient algorithm for computing these paths with little or no user intervention.
- **Approximation of a variable density cloud of points by shrinking a discrete membrane**. This paper describes a method to obtain a closed surface that approximates a general 3D data point set with non-uniform density. Aside from the positions of the initial data points, no other information is used (as for example the topological relations amongst the points or the surface normal at the data points). The reconstructed surface does not exactly interpolate the initial data points, but approximates them with a bounded maximum distance. The method allows reconstructing closed surfaces with genus ≥ 1 and closed surfaces with disconnected shells.

2.3 Partners Involved

The project took advantage of the constant participation of cultural heritage end users, provided through SBAAS, a government institution responsible for preservation and restoration of cultural heritage.

Further users had been available through CNR, a research group participating in 3D acquisition projects and with links to national cultural institutions. The end users had been involved in specification and assessment of the project, and will ensure user acceptance of the project's results.

Furthermore, the consortium combined MPI's skills in interactive 3D graphics and reconstruction from photographs with those of UPC in VR technology, large model visualization, and post-processing. The four research/government organizations mentioned so far are complemented by two IT companies: Konica Minolta, specialized in high quality color 3D laser scanning technology and the generation of accurate 3D models, and gedas, a large IT company with strong experience in large database management and CAx (CAD, CAM, CAED) and VR solutions.

Together, the consortium reached a critical mass that enabled it to push the digital 3D content creation and exploitation to a new level. The project resulted in cutting-edge technology and guidelines for both acquisition and visual presentation of high quality 3D digital models. These guidelines, in the form of technical recommendations,

had been presented to the cultural heritage community and will hopefully be the base of possible future standardized procedures in the field.

2.3.1 MPI Informatik

An important characteristic of the work done at the MPI Informatik is the development of new algorithms, taking into account the opportunities and perspectives of modern graphics hardware, alongside a seamless consideration of the whole processing chain from data acquisition, via modeling (creation of a digital scene description) to image synthesis (creation of views from the description of a scene).

The estimation of the bi-directional reflectance distribution function (BRDF) of a 3D object requires reflectance measurements under numerous viewing and lighting directions.

2.3.2 UPC

The Computer Graphics Group is within the Software Department of the UPC (Universitat Politècnica de Catalunya). The group also participates in the Institute of Robotics and Informatics (IRI) and belongs to the Virtual Reality Centre of Barcelona (UPC-Gedas). Several software packages for geometric modeling and computer-aided geometric design and for navigation in virtual environments have been developed.

2.3.3 CNR

CNR, a research group participating in 3D acquisition projects and with links to national cultural institutions. The Visual computing Lab has been active on visualization and computer graphics since 1984. The main research contributions of CNR-ISTI consisted in advancing the technology for automatic acquisition of the geometry and pictorial detail of 3D objects or architectural scenes.

2.3.4 gedas

gedas is an information technology service provider offering consulting and highly advanced solutions on a global basis and aimed at optimizing our clients' business processes. The gedas Group is a Berlin-based IT subsidiary of the Volkswagen Group and has experience in the information technology market that spans some 20 years.

2.3.5 Konica Minolta

Konica Minolta 3D is specialized in high quality color 3D laser scanning technology and the generation of accurate 3D models. Konica Minolta's latest 3D laser scanning systems were used to generate accurate 3D models of cultural exhibits.

2.3.6 SBAAAS

SBAAAS, a government institution responsible for preservation and restoration of cultural heritage provided constant participation of cultural heritage end users.

Chapter 3

Approach

The ViHAP 3D project wanted to take advantage of the continuous participation of cultural heritage end-users, involving them in the specification and assessment of the project, thus ensuring acceptance of the project's results. But, inside the Cultural Heritage community, we also wanted to test the satisfaction of specific targets: digital content experts, content providers, schools, restorers and final end users – that is, museum visitors.

Moreover, since the project was supposed to provide a product, together with the involvement of end-users, the necessity of organizing an iterative development cycle was considered an obvious must.

In order to

- guarantee satisfaction of requirements and a real usability of the expected pipeline,
- offer user-friendliness of interface,
- increase the products capacity of satisfying the expressed requirements,
- assure the software reliability,
- reduce corrective improvements actions due to a non-validated or misunderstood interpretation of requirements,

The consortium operated as follows:

Each end-user offered a free description of his/her requirements through interviews conducted on the basis of a questionnaire accepted by all partners. The Initial User Requirements Report, as an organized interpretation and synthesis of the information resulting from interviews, was produced: according to it an Initial Functional Specifications Report was supplied and development of the first release in compliance with the corresponding specifications started. On the basis of the evaluations gathered from users, major and minor improvements were adopted and the tools submitted again to users' evaluation till a good level of satisfaction was reached.

The evaluation was done by both external expert end-users and developers. As a part of the assessment plan, external end-users were asked to create 3D scans of various artifacts, using the integrated scanner prototype. They were also asked to work on the resulting models, using the project tools to present them in virtually reconstructed environment. At the end of this activity, end-users were asked to provide an evaluation report, including requests and shopping lists.

As for restorers and museum visitors, to test the usability of the projects results, two case studies were prepared.

As for restorers, since they have peculiar needs, coming from the necessity of planning and documenting their activity on the artwork, an experimental multiple acquisition of the same sculpture (the so called *Minerva di Arezzo*) was done, in different stages of the restorations, and peculiar tools were released to grant restorers expectations and needs.

As for the general public – the very final end-user of the project’s products – a demo kiosk was built inside a real museum, using the projects tools (The funerary monument of the Emperor Henry VII, by Tino di Camaino, in the Opera Primaziale Pisana Museum in Pisa). Even in this case, an *in itinere* evaluation was performed, submitting the application to a panel chosen to be representative of the average composition of museum visitors; afterwards, individual real visitors’ satisfaction, as far as the usability, realism and usefulness of the virtual presentation was concerned, had been monitored through a professional survey.

Finally, the same 3D digital models had been proposed to a public of scholars inside one of the greatest Library and Photo Gallery of Italy, the *Kunsthistorisches Institut* in Florence.

We like to underline that high and middle schools together with Museum Educational Departments and Libraries, as the institutions in prime position to deliver the kind of unique learning resources needed at all educational levels were also closely involved as project end users. Fully aware of the European Commission interest in the educational market (considered as a key-market for Digital Cultural Heritage) and deeply convinced of the great improvement that an intelligent use of I.T. would offer to the teaching of art history, we hoped that the project might thus assume the function of establishing a cross-sector partnership between museums and libraries and schools - a cooperative framework, possibly a protected environment to be shared.

3.1 Scientific and Technical Objectives

The main objectives of the ViHAP3D project were preserving, presenting, accessing and promoting cultural heritage by means of interactive, high-quality 3D graphics.

In order to be conceived as a reliable medium, the technology for managing 3D digital models must satisfy several basic constraints: acquisition devices should be accurate, cheap and fast, and the resulting models should be visually convincing; the digital data must be usable even on low-cost platforms and finally, new classes of pre-

sensation paradigms are required in order to take full advantage of the communication potential of 3D representations. ViHAP3D addressed these issues by specifically facing the following three problem categories:

- 3D scanning for the acquisition of accurate and visually rich 3D models
- post-processing, data representation, and efficient rendering for the detailed interactive display and inspection of such models even on low cost platforms
- virtual heritage tools for the presentation and navigation in high-quality digital model collections.

The work was structured in seven work packages which center around three areas:

- The work on 3D scanning (WP3) provided a complete, integrated high accuracy scanning system for small and medium-scale objects. The system supports acquisition of 3D shapes, and at the same time captures and reconstructs surface attributes, such as texture and spatially varying reflection characteristics.
- The work on post-processing, data representation, and efficient rendering (WP4) exploited mesh processing techniques, multi-resolution surfaces and surface attributes (texture, reflection) in combination with hardware-accelerated rendering.
- The work on the development of virtual heritage tools (WP5) developed a set of virtual presentation tools for the presentation of cultural heritage model collections that can be used with off-the-shelf computer and graphics components.

In addition to that, there were work packages on the functional specification of the tools that were designed, and the definition of the requirements (WP2), the assessment of acquisition and presentation (WP6) and the information dissemination and take-up of the results (WP7)

3.2 Work Plan

The following section briefly introduces the general idea and methodology of the work plan, followed by a list of all workpackage, a detailed description of each workpackage, and a chronological list of deliverables.

3.2.1 General Description

The project focused on the implementation of an interactive computerised environment for the acquisition and virtual presentation of 3D Cultural Heritage objects. The technical activities were structured in three categories: *3D scanning* deals with the acquisition of 3D geometry and of surface appearance. *Post-Processing, Data Representation and Efficient Rendering* provides algorithms for optimizing the data representation

and rendering this data efficiently on low-cost PC hardware. Finally, *Virtual Heritage Tools* integrates these algorithms into advanced virtual reality (VR) applications that can be used to present the digital heritage created by the ViHAP3D 3D scanning system (or acquired from existing digital collections).

End-User Involvement: The implication of final end-users in this project is highly critical, although difficult to set-up because of the broad range of potential end-users. Involving directly a representative subset of end-users would have been very hard, increasing the cost of coordination and management. The proposers have preferred to involve a single major end-user (with connections to leading national and international cultural heritage institutions), with the main mission of choosing a set of representative end-users which played an important role in the definition of requirements and functional specification of the tools that were designed. The same partner also coordinated the diffusion of the projects outcomes, and has set up a Special Interest User Group (SIUG) from the beginning of the project. The ViHAP3D consortium enabled this SIUG to follow, and contribute to, the project activity thanks to an e-forum, a mailing list, an attractive and interactive website and workshops organized by the project.

Standardization: Conformance to standards was a constant concern. The consortium was perfectly aware of the international and de-facto standards (VRML, OpenGL, JPEG, MPEG, XML, etc.), which were related to its daily activities. The consortium also contributed to future standards by providing guidelines about the acquisition and real-time visualization of 3D data, with special concern for the needs of the Cultural Heritage field.

System description: The ViHAP3D project provided a complete pipeline of integrated hardware/software tools for the acquisition, processing, and reproduction of 3D cultural/artistic objects. These tools are described in detail in the following sections.

3.2.2 Workpackage List

WP No	Workpackage title	Lead contractor	Deliverable No.
WP1	Project Management	MPI	D1.1 – D1.6
WP2	Functional Specification	gedas	D2.1 – D2.4
WP3	3D Scanning	MPI	D3.1 – D3.5
WP4	Post-Processing, Data Representation, Efficient Rendering	CNR	D4.1 – D4.6
WP5	Virtual Heritage Tools	UPC	D5.1 – D5.2
WP6	Assessment of Acquisition and Presentation	SBAAAS	D6.0 – D6.6
WP7	Information Dissemination and Take-up of Results	gedas	D7.1 – D7.2

3.2.3 Workpackage Objectives and Milestones

In the following we briefly describe the *objectives* for each of the seven workpackages, the *tasks* that were carried out in order to meet the workpackage objective, and the associated *milestones* that were achieved during the course of the project.

Workpackage 1: Project Management

To implement all the management structures and project management reporting. Technical and financial management and reporting will be co-ordinated by the MPII.

Task 1.1: Project and Workpackage Management: The goal of this task was to ensure timely performance and successful achievement of the project. The activities related to project management included: project control and coordination, conflict resolution and risk management; progress and financial monitoring, resolution of contractual and payment issues; scheduling; technical coordination. The result of this task is this final report providing an overview of the achievements and experiences gained from the project.

Task 1.2: Project Office and Reporting to EC: The goal was to ensure smooth running of the project by providing an efficient structure for day-to-day operations and support for project co-ordination and technical management. Activities included: Meeting organisation; reporting; review organisation; deliverable approval; internal information exchange; workplan maintenance and follow-up; resolution of logistic problems. The result of this effort are the different Status/progress reports.

Milestones:

No.	Description	Month
M1.1	Project management structure setup completed	2

Workpackage 2: Functional Specification

In order to define the ViHAP3D system we took into account end-users, market, technology, and standards requirements. The consortium worked in close collaboration with a pool of users selected by partners SBAAAS and gedas, to define specifications and user needs that were taken into account all along the project. However, the main workload of this work package was concentrated on the first six months.

Task 2.1: User Requirements Definition: To identify the user acceptance conditions and user needs, and refine these requirement specification during the development process, a market/usability analysis was first performed at the beginning of the project. This analysis proved to be an important reference in defining the product specifications. The active involvement of end-users provided the grounding for the correct system requirement definition. The report took related projects and existing products identified during the market analysis into account.

Task 2.2: State of the Art Study: To give us an overview and a comparative evaluation of the current enabling technologies which could be adopted to fulfill the project goals, recent results achieved by both academic and industrial R&D activities were evaluated and compared in the framework of the specific features and constraints of the system. Moreover, great attention was paid to the market during the whole project, as well as to international standards and emerging technologies.

Task 2.3: System Specification and Design Refinement: Based on the requirements specification resulting from Task 2.1, we designed and specified exactly the most important system hardware and software system components.

Milestones:

No.	Description	Month
M2.1	Initial user requirements available	4
M2.2	State-of-the art report available	6
M2.3	Initial specification available	6
M2.4	specification update available	17
M2.5	specification update available	24

Workpackage 3: 3D Scanning

The objective of Workpackage 3 was to design a scanner that is able to accurately capture 3D object shape, correct color, and reflection properties. Another important goal was to design a software tool for assisting the user in the set up of the scanning process and for planning the set of poses required.

Task 3.1: Initial Scanner Prototype: The ViHAP3D project partners designed an accurate 3D scanning system that is capable of capturing 3D geometry and color images. The device was integrated with software which lowers the required amount of pre- and post-processing of the data gathered. During development, our focus was also on the speed of the complete acquisition process and on the usability for non-IT-expert users.

Task 3.2: Appearance Acquisition: We designed algorithms and hardware setups (controlled lighting etc.) that allow us to capture photometrically complex appearance attributes of objects (e.g. textures and spatially varying reflectance properties).

Task 3.3: Acquisition Planning: We designed and implemented a software tool to guide and assist the user in a complex acquisition session. The system supports the iterative selection of an optimal set of poses, ensuring complete coverage of the object surface. If possible, taking the appearance (Task 3.2) into account.

Task 3.4: Integration into Scanner Prototype: For this task, we integrated more sophisticated approaches (like those resulting from Tasks 3.2 and 3.3) into the scanner prototype. This integration could ultimately result in a device that captures 3D shape and surface reflection properties of an object at the press of a button. We reported on different possible hardware setups and the conflicts that arise from an integration.

Milestones:

No.	Description	Month
M3.1	Scanner design and prototype available.	10
M3.2	Appearance acquisition methodology available.	16
M3.3	Acquisition planning methodology available.	16
M3.4	Integration methodology available.	24

Workpackage 4: Post-Processing, Data Representation, Efficient Rendering

The goal of Workpackage 4 was to develop tools that transform the raw data produced by 3D scanners into optimized and application-oriented representations. These should integrate geometry and appearance and run smoothly in distributed environments. The Milestones of this Workpackage demanded an initial release, and a second release after the assessment by the users.

Task 4.1: Post-Processing Tools: The ViHAP3D project designed and implemented algorithms for a less manual labor-intensive and more accurate range map registration, a more space-efficient surface merge, which should also produce smoother and less fragmented digital representations of surfaces. Using these new algorithms, we designed a tool supporting the automatic processing of the scanned data turning it into a high quality triangular mesh with associated appearance data.

Task 4.2: Data Representation: Triangle-based data simplification and multiresolution techniques were designed to support progressive data transmission and efficient visualization. Geometry and surface attributes data were integrated and processed together.

Task 4.3: Hardware-Accelerated Rendering: In order to achieve interactive viewing of high-quality 3D models with surface reflection properties, we developed hardware-accelerated algorithms for rendering, thus exploiting the features available in modern graphics boards. The new algorithms allow for an interactive display of the models with correct appearance even on low-cost graphics hardware in standard PCs. The algorithms and software fragments were integrated in the software the resulted from the work on Tasks 5.1, 5.2, and 5.3.

Milestones:

No.	Description	Month
M4.1	Technical design of the post-processing tools	16
M4.2	first release of post processing tools available (for assessment)	18
M4.3	first release of representation tools available (for assessment)	18
M4.4	rendering algorithms available	10

Workpackage 5: Virtual Heritage Tools

In this Workpackage, we designed and implemented tools for the remote, virtual presentation and navigation of 3D virtual collections as well as of single objects of art. The tools were designed to be easy to use and intuitive, and to operate on both low-cost personal computing equipments and on sophisticated virtual reality installations like caves or head-mounted displays. gedas contributed to the tools in this work package with their expertise on database management. The tools developed also underwent an assessment phase by end users, followed by second release.

Task 5.1: Virtual Museum Builder: The Virtual Museum Builder is in essence an authoring tool that will manage the set up of a virtual museum. The system supports the arrangement of a set of 3D models in a virtual museum, which in turn can be a digital model of a real architectural (or natural) environment, or a synthetic exposition space. One major part of this task was the implementation of a distributed database for 3D models, taking into account such things as multiresolution representation (see Task 4.2).

Task 5.2: Virtual Museum Browser: We developed a 3D browser specifically oriented to the management of the user navigation in a complex virtual museum, providing easy and three-dimensional navigation and interaction metaphors (the user is able to freely move around within the museum), and very efficient and accurate rendering. The browser has been implemented using standard libraries (e.g. OpenGL) and will extensively use the features of current state-of-the-art PC graphics boards. Easy interaction and navigation were always in our focus.

Task 5.3: Virtual Inspector: The Virtual Inspector is a tool for the interactive presentation of a single artefact, supporting advanced and specialized features for inspection or analysis of the 3D data. It allows easy and flexible interaction with the 3D model. The Virtual Inspector also has the capability of displaying the surface reflection properties and can integrate different kinds of additional information (e.g. Websites, Sounds, Video) into the presentation.

Milestones:

No.	Description	Month
M5.1	first tools release available for assessment	18
M5.2	second tools release available for assessment	30

Workpackage 6: Assessment of Acquisition and Presentation

The objective of Workpackage 6 was to test the ViHAP3D system releases on real cases by end-users and to test user acceptance. The users provided valuable feedback for the refinement of our system designs. The assessment has been done for both types of end-users for the project: content creators and museum visitors, and for both types the assessment has been planned and executed separately.

Task 6.1: Special Interest User Group (SIUG): ViHAP3D has set up and maintained a special interest user group (SIUG) that allowed us communication with a larger number of international virtual heritage end-users. We set up an electronic forum (e.g. web site, mailing list, and similar means) for distributing news and requests to a large number of end-users. This forum was used for discussions among the users and developers, for distributing assessment and specification material, and for gathering information such as the user requirements reports.

Task 6.2: Scanning System Assessment: We planned and executed a complete demonstration project with virtual heritage content providers. Some carefully selected end-users from the heritage community worked together with the developers, and both sides did a scanning system assessment by carefully reporting their experience during the project.

Task 6.3: Virtual Heritage Tools Assessment: The "virtual museum builder" (Task 5.1) has been made available to SBAAAS, who built a demonstration kiosk in the *Opera del Duomo Museum* in Pisa, Italy. The digital collection of the *Arrigo VII Funerary Complex* has been set up inside this kiosk and the visitors were able to experience some artefacts in both reality and a virtual world at the same site. The visitors were also asked to assess the usability, realism, and utility of the virtual presentation. Validation and assessment was performed based on that feedback. In the same museum another application evaluated by the users. This application consisted in modelling (for some of the real objects acquired and physically present in the museum) a virtual environment representing the original use of the object or its location.

Milestones:

No.	Description	Month
M6.0	Special interest user group forum available	3
M6.1	Scanning system assessment plan available	18
M6.2	Heritage tools assessment plan available	18
M6.3	Results from scanning system assessment available	30
M6.4	Results from presentation tools assessment available	30

Workpackage 7: Information Dissemination and Take-up of Results

The goal of Workpackage 7 was to prepare the future exploitation of the project results and to disseminate them as widely as possible.

Task 7.1: Dissemination: The ViHAP3D project successfully disseminated its progress and its results by organizing and performing presentations, by setting up a web site, by setting up a demo kiosk, and by other dissemination actions at the national and international level (including TV broadcasts, newsletters, appearance at cultural heritage workshops).

Task 7.2: Exploitation: The project partners worked out a plan for the future exploitation including a consolidated business plan providing evidence for the viability and the self-sustainability of the products developed in the ViHAP3D project.

Milestones:

No.	Description	Month
M7.1	Web Site available.	4
M7.2	Dissemination Plan released.	5
M7.3	For confidentiality reasons limited dissemination starts.	12
M7.4	Public dissemination starts (conferences, public demonstrations).	24
M7.5	Public dissemination activity is maximal.	30
M7.6	The system is ready to reach the market, commercialization is about to start.	36

3.3 Deliverables

Table 3.1 lists all deliverables, sorted by delivery date. There was a total of 36 deliverables for ViHAP3D.

3.4 User Requirements

3.4.1 Selection criteria

Since the involvement of end-users was perceived as an action essential for the project, a wide group of potential end-users as well as a chosen panel of representative final and intermediate end-users were made up.

The selected users were chosen in order to satisfy the following specifications:

- to be representative of every segment of the Cultural Heritage community potentially interested in ViHAP3D objectives and expected products (i.e., Museums, University Departments of Art History and Pedagogy, Libraries, Institutes for

Deliv. No.	Deliverable Name	Lead Part.	Date (Mon)
D6.0	Setup of Special Interest User Group	SBAAAS	3
D2.1	Initial User Requirements Report	SBAAAS	4
D7.1	Dissemination Plan	gedas	5
D1.1	Status/Progress Reports	MPI	6
D1.7	Project Presentation	MPI	6
D2.2	State-of-the-art Report	UPC	6
D2.3	Initial Specification	gedas	6
D3.1	Initial scanner prototype + design report	Konica Minolta	10
D4.6	Hw-accel. appearance rendering	MPI	10
D1.2	Status/Progress Reports	MPI	12
D3.2	Appearance acquisition algorithm	MPI	16
D3.3	acquisition planning algorithm	MPI	16
D4.1	Post-processing design report	CNR	16
D5.1a	First release of builder+browser tools	UPC	16
D5.1b	First release of inspector tool	CNR	16
D2.4	Specification Update report	gedas	17
D1.3	Status/Progress Reports	MPI	18
D4.4	First release of representation tools	UPC	18
D4.2	First release of post-processing tools	CNR	18
D6.1	Assessment plan for scanning system	SBAAAS	18
D6.4	Assessment plan for heritage tools	SBAAAS	18
D1.4	Status/Progress Report	MPI	24
D2.5	Specification Update report	gedas	24
D3.4	Integration/conflict report	Konica Minolta	24
D3.5	Integrated prototype demonstration	Konica Minolta	24
D6.3	Scanning demo results (web site)	SBAAAS	24
D5.2a	Second release of builder+browser tools	UPC	28
D5.2b	Second release of inspector tool	CNR	28
D4.3	Second release of post-processing tools	CNR	30
D4.5	Second release of representation tools	UPC	30
D7.2	Exploitation Plan	gedas	30
D1.5	Status/Progress Report	MPI	30
D6.6	Heritage tools demo / Demo Kiosk	SBAAAS	32
D6.2	Scanning system assessment report	SBAAAS	34
D6.5	Virtual heritage tools assessment report	SBAAAS	34
D1.6	Final Report	MPI	36

Table 3.1: All deliverables of the ViHAP3D project sorted by delivery month.

conservation and cataloguing, Research Institutes for high and middle school, Research Institutes for I.T. and Cultural Heritage, Auction Houses, Museum designers content creators, digital content providers, public and private collection and monument owners and managers);

- to be entitled to evaluate and eventually validate the project achievements in terms of both technological quality and usefulness for a better understanding and a valid interpretation of the artworks whose virtual models are offered;
- to be able of ensuring the largest diffusion of the project philosophy and methodologies;
- to be able to help the consortium to get in touch with the largest community of potential final end-users.

Conservators and curators, teachers and researches were contacted in order to present the ViHAP3D project, to evaluate their familiarity with 3D models and their feelings towards this technology.

The aim was to gather the end-users ideas about what the 3D scanner and related software should do, if and what for the project expected system could be useful, if and why one or more of the involved sectors and related solutions appear more useful than others. Moreover, we needed to know if the expected functionality's of the project were considered as sufficient to end-users objectives, and if not, which other features would they desire and for which use.

Confronted with the project's expected tools, Museum end-users still not acquainted with I.T. appeared in the main interested in, when not fascinated by, the potential variety of uses this new technology disclosed to them. Only a few museum operatives were still reluctant to rely on too sophisticated devices. In any case, nobody has denied access to his/her collection for scanning purposes within the scope of ViHAP3D project – provided no charge would result for the museum. However, a very few already have (or have started building up) a digital collection and almost none had a clear plan on how to use it and for whom.

3.4.2 General needs and requirements about the 3D Model

Museum curators as well as scholars, researchers and teachers have been particularly impressed by the possibility of inspecting a visually rich 3D model, inasmuch as it would consent the exploration of technical details in the surface treatment on art-works which are physically not available. Consequently scanning accuracy as well as acquisition of color and pictorial information (and its integration with the 3D model) is considered as mandatory. In other words, the sharpest fidelity to the original is requested in terms of geometry, surface, color and reflection characteristics. Being allowed to rotate the sculpture and inspect it from every point of view is also considered very important. Everybody recognizes the usefulness of such 3D model for educational purposes, in

a classroom as well as inside a library. For its effective diffusion, however, the possibility of using a low-cost platform is considered as mandatory, since the purchase of expensive hardware would be impossible for schools or even for libraries. Were these conditions to be fulfilled, everybody agrees on foreseeing a massive use of 3D models in substitution of the current one of slides and photographs.

As far as a 3D acquisition campaign is concerned, it is interesting to notice that none of the interviewed medium-size museums was planning it – or even dreaming of it.

Auction Houses may also be users of the 3Dscanning: but, since their interest would consist in allowing potential clients to inspect sculptures and three-dimensional objects for sale, a widely available network access would have to be granted.

Still struggling to transform traditional catalogue archives, based on paper forms and black and white photographs, into an Information System, National Agencies and Museums consider the 3D reproduction as a very distant perspective. For instance, both the National Italian Institutes for cataloguing and Restorations are very concerned about the necessity of clear statements as to the quality of the virtual images produced and, before adopting a massive usage of this type of reproduction, consider the agreement on standards as strictly mandatory. That is precisely why they are so interested in ViHAP3D declared ambition to provide guidelines that can be presented as technical recommendations and possibly become the basis for standardized procedures. Once a standard is defined, everybody agrees on considering 3D digital models as the ideal solution for a permanent archive.

3.4.3 3D Model's and restoration activity

The conservation field is the one where 3D digital models are more requested. They are expected to help keeping under control potential deterioration of surfaces (even of painted panels, where the movement of different layers has to be checked); recording the look of an artwork before and after transportation in order to detect every transformation or damage; planning restoration procedures; documenting every step of the restoration process. It is also considered as mandatory that the 3D digital models can be manipulated to simulate different solutions of assemblage of the artwork; that given areas can be evidenced; that to every single area attributes may be linked, describing its nature and/or the restoration activity performed on that portion of surface). These descriptions may come in different multimedia formats.

3.4.4 Visualization and communication in schools and museums

Production of results at different resolutions, interoperability with a third party software, easy and light storage of models are mandatory for museum designers who were in any case more than interested in having a virtual builder to roughly explore the set-

ting up of 3D models inside a box-case or in a room. They underline the necessity of exporting the 3D models in more sophisticated Builders while passing from first attempts to the executive project, and would not be interested in too strictly proprietary software. Similar requirements come from Museum curators interested in planning or evaluating a new museum organization and therefore in need of a virtual realization to test its effectiveness.

Virtual Heritage tools are considered quite interesting by Museum Curators and Digital Content Providers to reinforce real exhibitions with virtual models of sculptures or art-objects which are excluded from loan, to keep available for visitors a sculpture during its restoration (and also allowing them to follow the restoration in progress), or while it is temporarily out on loan, to allow a direct comparison between sculptures of debated attribution.

To virtually reassemble sets of sculptures now apart, to propose to the public and/or to a class a sculpture in its original location and condition are seen as promising possibilities, full of educational content, by Schools and Museum Educational Departments.

Specifically teachers think that 3D models can play a relevant role for educational purposes, and can be considered as a consistent teaching tool to learn the history of art. 3D models allow to inspect a sculpture better than a photography can do, or can allow to visualize, for example, all the changes or phases of a work of art over times, as well as past arrangements not still existing. But they might also be seen as a powerful help to attract children attention even before a proper art teaching would start.

Such an educational use of 3D models is quite innovative and can be very attractive but it would have a minor impact on school-people if not coming inside a model educational plan, produced in strong cooperation by teachers, art historians and IT experts.

Besides foreseeing an intensive use of Virtual Guided Tours as preparatory to the visit to the real Museum, teachers are also interested in having a sort of simplified Virtual Builder to be able to propose to their classes the reconstruction of an historical situation as a part of a cognitive process. For instance, a given number of 3D models could be virtually put back inside a simplified virtual reconstruction of their original location by students themselves after a guided research conducted on places and documents. More generally speaking, pedagogies request the availability of the "guided tour" single components, to be proposed to students in different stages of the knowledge process: only at the end of the process they would be asked to assemble the components.

Virtual builders could also be used in museographers' courses to reconstruct destroyed collections and to design new displays; it could also be helpful in the reconstruction of parks and gardens of historical interest from which statues or fountains have been removed; after reconstructing the park design, sculptures could be installed in their original setting.

It is important to notice that this kind of usage is always considered much more interesting than the mere setting-up of artworks in fanciful virtual setting, that doesn't look as an efficient instrument either to help research or an educational activity. That's

why it is also considered as essential that models can be connected to a database conveying multimedia, information about the reproduced artworks.

3.4.5 Disposition to investment

While great institutions, mainly the national centers for conservation, put high quality over any other consideration, the majority of museums, as well as schools, consider as mandatory not only the models' quality but also their global cost. Actually, since the budget of Cultural Institution is small (e.g., purchase of expensive hardware would be impossible for them), the possibility of acquiring 3D models in a fast way and to visualize them on low-cost platform is confirmed as an element of primary importance.

3.5 Evaluation of Results

3.5.1 The evaluation process

The evaluation was carried out in two different steps:

- during development, to test the tools while still in an incomplete stage, by the project partners;
- after the first and second release of the software, functionalities and performances of the tools had been used by external users, in order to give useful feedback for further enhancements

To give a correct and comprehensive evaluation for the tools, tests had been carried out trying to cover the widest possible choices in terms of

- type of user: museum/university, Graphic research lab, Cultural Heritage operator, industrial
- application: documentation, restoration, virtual museums
- data type: architectural, statues, small objects, different materials

Finally two test cases were prepared by the project partners and separately evaluated: the so called *Minerva di Arezzo* (an application devised to support restoration activity) and *The funerary monument of the Emperor Henry VII*, a demokiosk to be installed in the Opera Primaziale Pisana Museum in Pisa (see Section 4.8.2 for details).

3.5.2 Expert end users' evaluation

In order to have external users to evaluate the tools, CNR coordinated the selection of the assessment partners (multiple research groups in Europe, USA and rest of the world), provided them with support (instructions on how to use the scanning tools help in solving problems encountered, bug fixing, etc).

The selection was carried out aiming to round up a good selection of users, each one involved in projects related to 3D scanning or 3D model manipulation; trying to cover different data typologies, usages and methodologies.

The evaluation was that the ViHAP3D tools are at least at the same level but most of the times superior to commercial tools currently available. One of the most common observation is, in fact, that ViHAP3D tools are able to manage more data (and more efficiently) with respect to their commercial counterparts.

Very good comments have also been made regarding the ease of use of the various tools.

As for the scanning system (both the hardware devices and the related software), the users sent us very positive comments on the following features/characteristics:

- scanning sampling density: the possibility to use different sampling densities, to adapt the system to different operative condition, such as artworks' different materials, shape, decoration, etc.
- accuracy of the measure, which is the difference between the measured and the real point of location
- the capability of the system to produce both geometry (a range map) and color data (a RGB image)
- speed of the system, which is given by the time required to take a single measure (i.e. to produce a single range map)
- easy calibration: the absence of calibration phase increase the ease of use of the system and the overall duration of a scanning session
- weight and size of scanning device: it is quite easy to move around the system during the acquisition, especially over scaffoldings.

As for post-processing and mesh-management tools (i.e. the software tools needed to convert a large set of sampled range maps plus some associated color texture images into a single, continuous and accurate surface model) "MeshAlign" has been described as "simple to use" and "intuitive", despite the numerous implemented capabilities. Particularly appreciated was the possibility to visually inspect each single mesh-to-mesh arc of the alignment, finding problems at first glance.

Generally, the following general characteristics have been also highly appreciated:

- ease of use: reduced user assistance

- accuracy of the output produced
- speed
- low cost, since the systems works on inexpensive computing platforms (PC + game-oriented low-cost 3D graphic boards).

Moreover, especially from pure academic users, it was observed that since ViHAP3D tools are based on algorithms published by consortium partners on scientific papers (and therefore accepted by the scientific community), there are additional guarantee on the correctness of the implemented functions. Conversely, commercial software is usually a "black box", users have no data to understanding how do they function internally and to infer limitations or potential inaccuracies.

Maybe, the most important message emerged from the reports is that some improvements in the written manuals and in the online help system could help users to infer more easily the tools features and right way to use. In many cases, in fact, many of the problems encountered were caused by a misunderstanding of some tool functionalities and suggestions on how to improve the tools pointed out features already implemented but poorly documented on manuals and on the on-line help.

3.5.3 Measuring satisfaction of Museum visitors

A first version of the case-study (the Arrigo VII Mausoleum inside the Cathedral of Pisa) planned during the second year of the project, was finalized on September 2004: a complex application, including a video and a 3D multimedia was presented to visitors in a kiosk installed in one of the exposition rooms of the Museo dell'Opera del Duomo in Pisa. (see Section 4.8.2 for details).

Coherently to the project scheme, a scientific observation of final users reaction, aimed to come to an objective evaluation of the project's tools acceptance, had to start.

Since May 2004 a research team (Megaride, a leader firm in this field, born as a spin-off of the University of Naples) was charged with this task and the strategy to be followed was individuated. We agreed that the evaluation had to focus on the project tools, but would have also taken in consideration the information frame (i.e. the HTML pages through which some historical information was given). First the application would be analyzed out of context, by a panel of visitors-like people and only afterwards as a communication experiment inside a specific museum: moreover, in order to come to understand if the application encountered their needs, the museum and its visitors had also to be analyzed through a proper survey, based on a questionnaire, and on the analyses of the usage sessions.

As the whole process of evaluation, the survey was aimed to the analysis of key features such as usability, defined as 'the rank a product can be used by a selected panel of users to achieve specific purposes with effectiveness, proficiency and fulfillment, within a particular use contest' (Standard ISO 9241-11 Ergonomic requirements for office work with visual display terminals - Guidance on usability).

So, throughout evaluation practice, we tried to decide whether the software complied the needs and expectations of a museum visitor; it was easy to understand and to use; it allowed the fulfillment of those very activities in a correct, fast and satisfying way; which further development could be foreseen to meet museum visitors needs.

The survey result

Both the percentage of visitors using the kiosk and the 3D models (more than the half of the total for the first one and 71,5% for the second one) and the video registrations testify the capacity to attract and maintain attention of this new way of presenting art works. Coherently, unanimous is the absolutely positive evaluation of the application as a whole - and especially of the Visual Inspector tool - from any point of view (usability, efficacy, utility)

More specifically, overall evaluations of 3D models were positive (86,5%); they were found very easy to use in the 97,4% of cases and their inspection useful in the 92,1%.

The usage of the whole application appeared comfortable to the 95% of visitors (easy to use: 68,7%; very easy to use: 26,3%).

The whole application was perceived as more useful than traditional documentation (84,4%): an indirect confirmation of visitors satisfaction came also from the declared interest in having at disposal inside the museum similar multimedia applications for other artworks and from the tendency to buy them, if put at disposal as DVD: (similar applications were requested by 85,6% of visitors and 20% of them declared an interest in buying the multimedia application.

A confirmation of the good usability of the application also came from the analyses of the registered usage sessions: none of the critical points emerged during the panel assessment was registered anymore.

The survey methodology

The evaluation of usability was based on a questionnaire, given to a random selected panel of visitors to fill in. In detail, it had been given out at the museum entrance, in a closed envelope labeled with a short presentation of the survey, to be opened only at the end of the visit. Once filled in, the visitor had to give the questionnaire back at the exit, to receive a little present as thanking for the time spent.

The questionnaire was distributed in-between the 29th of December 2004 and the 6th of February 2005 (29 December-10 January; 19-30 January): during that period around 2.500 visitors bought tickets to enter the Piazza dei Miracoli museums and monuments, 280 questionnaires were filled; 200 of them attested that visitors did make use of the kiosk.

The questionnaire result was integrated by the examination of some video registrations of users' interaction with the application: the focus was on the time of usage and

on navigation behavior. The analysis of digital recording has been performed by playing back "avi files" and using an ad hoc form, reporting trend lines for each session of use.

The sample was composed to the same extent by men (49,1%) and women (50,9%); as for the age, we have mainly adults from 25 to 59 years old (77,0%) with a meaningful presence of young people aged from 15 to 24 (15,8%); just a short percentage (7,2%) belongs to the senior class (60 years on).

As for nationality, Italians are slightly more numerous (66.2%) than Europeans (16.9 %) and extra-Europeans (16.9%).

Concerning their educational level, about the 45% of the visitors have a high school degree, while 36% of the visitors are graduated and 16% have an intermediate school degree.

According to the specific purposes of the survey, the sample was asked to express a self-evaluation of its own computer skill level: over 75% declared a high or intermediate familiarity in using a PC, while only 20% had a low one.

Coherently with Opera Museum size, about half of the sample declared to have visited the museum in less than a hour, from 1 to 2 hours (40%).

3.5.4 Restorers' evaluation

In the framework of collaboration already between the Archeology Restoration Center (Florence, Italy) and CNR, the ViHAP3D tools have been actively experimented, tested and assessed. Multiple complete acquisitions of the Minerva of Arezzo (a bronze statue) have been performed at different restoration stages. In the last acquisition, CNR acquired a high-resolution sampling of the shape of the entire statue and MPI sampled the reflection properties (BRDF) of the head section of the statue a preliminary assessment was thus started together with conservators and restorers. Restorers appreciated the accuracy of the 3D models. Suggestions for further improvement of the set of tools including the request for tools for the production of paper-based technical drawings coming from the 3D model - i.e. easy production of printed technical drawings-were accepted and implemented. First results were presented in a workshop held in Florence, on February 2005 and received a very positive feedback from the restoration experts during the Minerva workshop in Florence (February 2005).

3.5.5 Schools' evaluation

According to the school assessment strategy defined by the scientific committee gathered to evaluate the pedagogical efficacy of the project tools , complex educational programs -different for each level of schools-had to be organized.

Consequently, at the end of school year 2003-2004, SBAAS and IRRE Toscana (a research institution for pedagogical methodology, end user of the project) selected, among the ones involved in the first 3D educational programs, 20 teachers ranging

from primary to high schools, in order to cover all educational cycles, and asked them to use the kiosk content for their educational purpose.

The committee agreed that, in order to have a meaningful and valid test of the multimedia application's impact in terms of usability on young people, an objective observation of students' behavior, conducted during their first, naive, usage of the application, was needed. Furthermore, to evaluate the application efficacy, a short questionnaire was prepared and proposed to students immediately after the experience.

The 3D application was also evaluated in the frame of the European project ART-NET (started date the 15th of January 2004 and ending on the 14th of January 2006), specifically devoted to a comparative analyses of art reproduction in schools.

The product was judged extremely involving and stimulating and its educational value overcoming the exhausting combination of the historical-artistic themes, offering-through the access to 3D virtual models- a precious meeting point (of the infinite possibilities of narrative interference) between the artistic culture and the very recent environment of the new media.

The didactic objective was also considered to be pursued by means of close-ups - which the virtual reality technology allows - allowing a formal understanding - almost tactile - of the work, allowing the user to manipulate 3D models of the sculptures.

The involvement of the user/visitor was perceived as very successful thanks to the implementation of a 3D visualisation engine (the visual inspector) which allows the user to interact with the extremely detailed and philologically corrected three-dimensional models obtained from the 3D digitalisation of the elements of the original sculpture. The result is involving and extremely accessible.

Chapter 4

Results and Achievements

4.1 Functional Specification

The functional specification has outlined the relationship between the user's requirements and the merits of the specified ViHAP3D tools. It has been based on SBAAAS' *Initial User Requirements* survey and other contacts between the ViHAP3D consortium and potential end-users. These inputs have been detailed in the initial specification to better match the final user interest and profit of the latest hardware developments.

After the first write-down, in parallel to the update of the specification, a continuous assessment of available tools in the area of cultural heritage has been carried out. This has been aided by input from of the Special Interest User Group. This growing group of interested parties allowed the consortium to continuously improve the necessary features of the final product. It also enabled the ViHAP3D consortium to refine the system specification and develop the tools accordingly.

The functionality of the set of tools to be developed in the framework of ViHAP3D has been set up and is presented in Figure 4.1. The diagram shows the main features of each tool and offers a quick overview of the relationships between them.

4.2 3D Scanning

4.2.1 Easy3DScan Software

The objective of the Easy3DScan tool is to provide a front end to the Konica Minolta scanner, managing the acquisition process from the beginning to the end in the easiest way possible.

Normally, 3D scanning tools are difficult to use because they are basically multi-purpose tools, that are not only able to do the acquisition but also a set of mesh manipulations. In our case we are focusing on a narrower application, thus having the possibility to tailor the interface and algorithms to accomplish a single task automat-

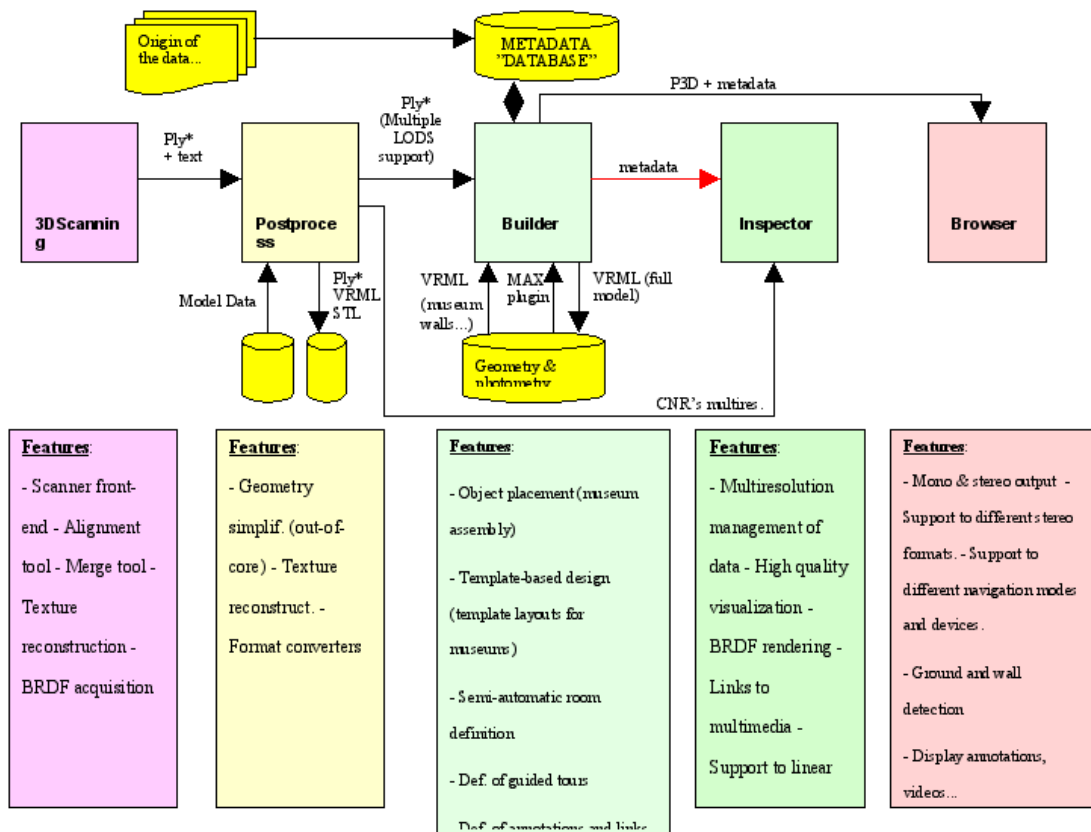


Figure 4.1: As the diagram shows, tools covering five functionalities has been developed and integrated in the scope of the project. These tools proof the validity of the approach. The coloured boxes present a fast view of the features of each tool or set of tools covering the five functionalities. These features are properly detailed in the refined System Specification Report.

ically. However, this focusing does not restrict the usage of the tool to small projects only, since it's possible to use Easy3DScan in the acquisition phase of a 3D scanning campaign (even a large one, as the Arrigo VII funerary complex) and then process all the data with the other ViHAP3D tools. In this way the ease of use of the tool helps speeding up the acquisition phase. Furthermore, the capability of Easy3DScan to do automatic alignment of circular scans can save a lot of time in the subsequent processing.

For the development of the tool, we had some important features in mind:

- simple user interface, making it very easy to learn
- short startup time: no initial calibration of the rotating platform is required
- the tool should perform (unattended and automatically) the following steps:

- alignment of the range maps
 - merge them into a single triangle mesh
 - simplify the mesh down to the required size
 - texture-map the color info (RGB images acquired by the scanner) to the mesh
- multiple output formats should be available (PLY, VRML, OBJ, STL, ASE) to cope with the users needs for further processing.

Development Methodology:

Easy3DScan is the first software that makes 3D scanning a completely automatic process.

To reach this goal, a motorized turntable driven by the PC is used together with a Konica Minolta Vivid 900/910 scanning system. In this way the object is moved automatically in front of the scanner, reaching a 360° coverage. To acquire the whole surface, several of these circular scans are performed with the scanner or the object in different positions. Easy3Dscan provides an alignment engine based on ICP algorithms with a simplified front end, that required minimal user intervention.

One unique characteristic of Easy3DScan is, that the turntable does not need to be calibrated in a pre-scanning phase, thanks to an automatic procedure that recovers the rotational axis of the turntable using the object movement measured through the scanner.

Merging of the individual scans and the simplification of the resulting mesh is done by the tool automatically. The user only has to select the merging resolution and the size of the final, simplified mesh.

Moreover, color information acquired by the scanner can be encoded in a high-quality texture map, which is mapped onto the final 3D mesh without any user intervention.

All the algorithms implemented in the software are the same as those used in the other ViHAP3D tools, modified only to require as little input from user as possible.

Capabilities and Results

Easy3DScan has been tested, like the other tools, from an early stage of development to extensive acquisition campaigns, gathering important information on how to improve the system.

The result of this is a powerful, but still lightweight, software that is able to perform all the steps necessary for the production of a high quality 3D model.

The most important feature of the tool is the possibility to build a complete model in just a few steps, without a precise knowledge of the underlying process.

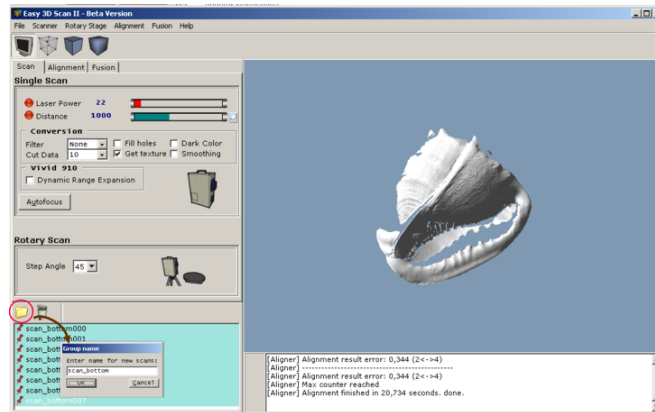


Figure 4.2: Scanning session: after the selection of a step angle, the range maps are acquired and automatically aligned; a file name has been assigned for this group (see the group name selection widget).

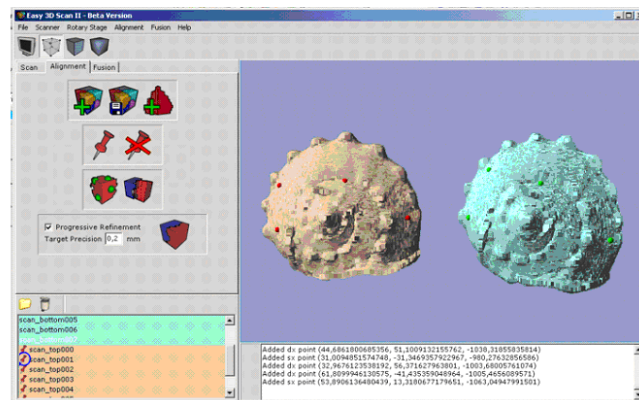


Figure 4.3: Easy3DScan in Alignment mode: two circular scans are roughly aligned using point-to-point correspondences, then a fine alignment is performed using an ICP algorithm.

This kind of automation and the integration of all steps in a single product does however limit the applicability of this solution. It would be impossible to grant the same level of flexibility and performance that is offered by the individual tools, each one configurable and optimized for a single task. Large acquisition projects, for objects of human size or bigger, are outside the scope of this particular tool. On the other hand, on small and medium objects, using Easy3DScan can provide a noticeable speedup of the process.

The primary audience for this kind of application, are users whose needs are focused on acquisition of many small-medium sized objects (a collection).

Thanks to a friendly user interface, the time needed to get acquainted to the software is very short, therefore enabling users to use the software productively after just a few hours of training.

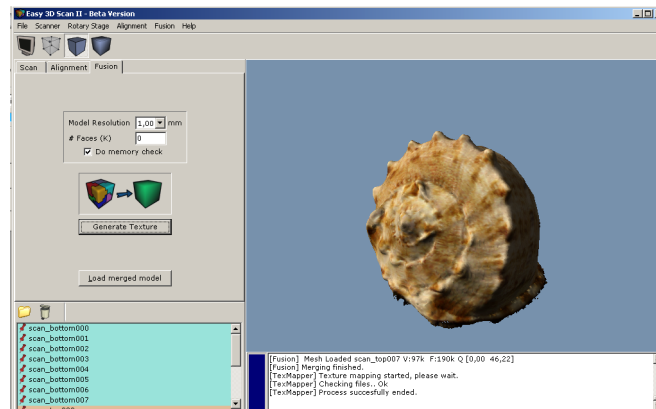


Figure 4.4: Fusion session: result of attaching the synthesized texture to a merged model.

4.3 Acquisition of Surface Properties

Real world objects, such as works of art, archeological artifacts and even common everyday objects, exhibit large variations in color due to the way light is reflected from their surfaces. A high quality digitization method must be capable of capturing these effects if the digital models generated from the real objects are to look realistic. We therefore developed an efficient method for acquiring high quality models of real world objects. The resulting digital models can be viewed under arbitrary viewing and lighting conditions. The efficient acquisition technique, small size, high quality, and versatility of the generated models make this technique well suited for large digital collections.

4.3.1 Introduction

Integrating 3D objects into digital documents is a challenging task for two reasons: A great deal of effort is required to create highly detailed 3D models and their inherent complexity makes storage, transmission, and interactive display difficult. Nevertheless, having highly detailed 3D representations of real world objects is a must for conserving cultural heritage artifacts in a virtual museum.

In this section, we focus on the acquisition of faithful, highly detailed representations of the reflection properties of real world objects through the use of an efficient, image-based technique. A more in-depth description of the techniques described below can be found in [Lensch01a, Lensch01b].

4.3.2 Describing Surface Attributes

The appearance of an object – its "look" – is determined by the properties of its surface such as the (diffuse) color. However, a single color value or even multiple color values

(in a texture) are not sufficient to fully describe a real world object. For example, the difference between a matte and a glossy surface cannot be expressed as a color value. Several metrics such as gloss or haze are used to describe individual appearance properties of an object. (See [Hunter87] for an overview.)

A more general measure is the bi-directional reflectance distribution function (BRDF) that describes how light is reflected at the surface of an object. More formally, a BRDF is a four-dimensional function that describes which portion of the light hitting a surface from an incident direction is reflected into an outgoing direction. The incident light is scattered at the surface and distributed in many directions (see Figure 4.5).

All of these metrics are useful for describing the surface of an ideal object made of a single homogeneous material. However, most objects encountered in the real world consist of several different materials. They are almost never perfect but instead show small imperfections like material variations, scratches, or accumulated dirt. This is especially true for works of art or archeological objects, which are of special interest for the ViHAP3D project. A very precise way to represent these details is to assign a different BRDF to each surface point that leads to a spatially varying BRDF. Without these details, objects tend to look artificial and unrealistic (see Figure 4.6).

4.3.3 Data Acquisition

For our measurements, we acquire the object's geometry with a *Konica Minolta VI-910* 3D laser range scanner. The resulting triangle mesh can be transformed into a level-of-detail representation for faster transmission. In the remainder of this section, we focus on the acquisition of surface attributes. A detailed overview over mesh acquisition and processing techniques can be found in Section 4.5.

Surface attributes are captured in a second step using an image-based technique. We capture all images using a professional-level digital camera after calibrating the camera's intrinsic parameters [Zhang99], in order to have a known relationship between pixels in an image and points in space. The BRDF measurements are performed in a lab covered with dark felt [Goesele00] to reduce the influence of the surroundings on the measurements as much as possible. A special light bulb of known brightness serves as point light source for the BRDF measurements.

Several views of each object are captured with different camera and light source positions. For each view, we acquire a series of photographs of the object lit by the point light source, with varying exposure time from which a high dynamic range image [Debevec97] is calculated. After calibrating with the known brightness of the lamp, each pixel of the high dynamic range images contains full range, floating point radiance samples. Furthermore, we take two images to recover the light source position relative to the camera and one image of the object's silhouette to register the 3D geometry model with the images [Lensch00]. In a production environment, the 3D scanner, camera, light source, and the test object could be combined into a single, calibrated gantry to speed up the acquisition process and to render the registration unnecessary.

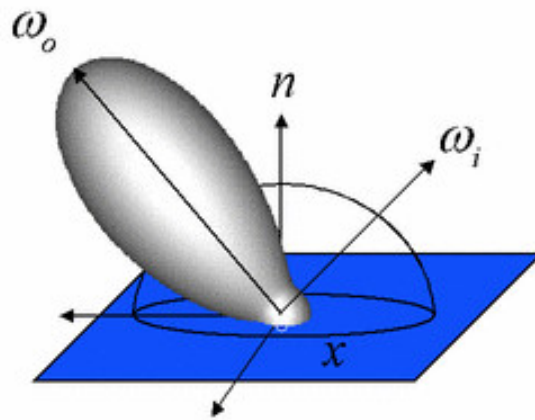


Figure 4.5: Illustration of a BRDF: Light is hitting the surface at point x from an incoming direction ω_i and is reflected into direction ω_o . All directions are given relative to the surface normal n . If ω_o is varied while ω_i is kept constant, the BRDF describes the amount of light reflected in direction of ω_o . Highlights are caused by the specular part of the BRDF where light is reflected mainly around the mirror direction. The small, spherical part corresponds to diffuse reflection where light is equally distributed in all directions.

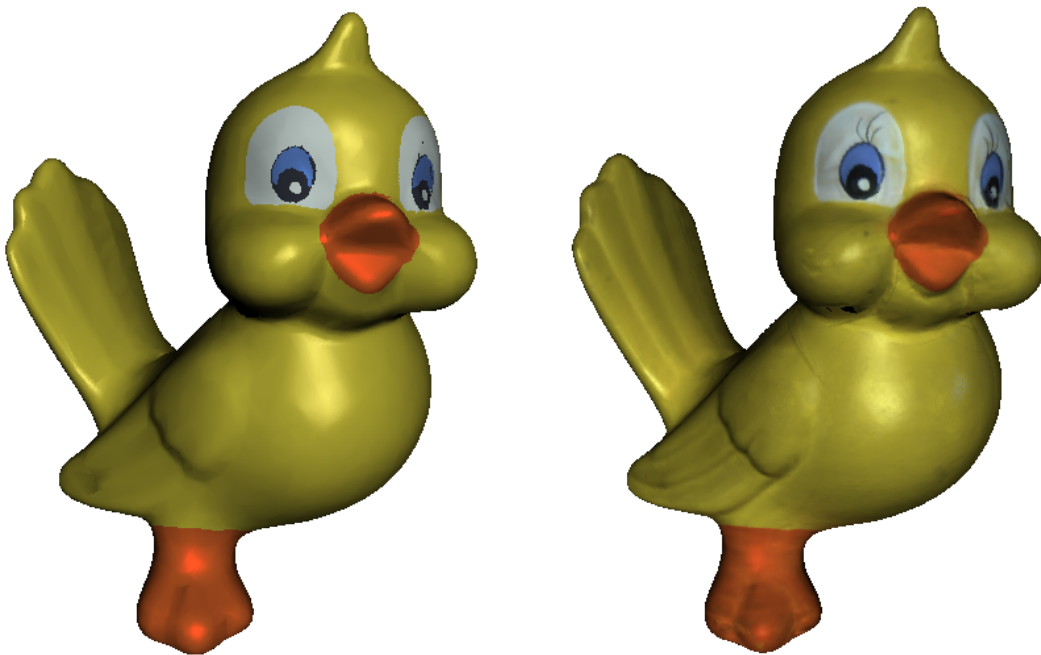


Figure 4.6: Comparison between an object rendered with five different BRDFs (one for each basic material) and a spatially varying BRDF. The added details help to make the object look more realistic.

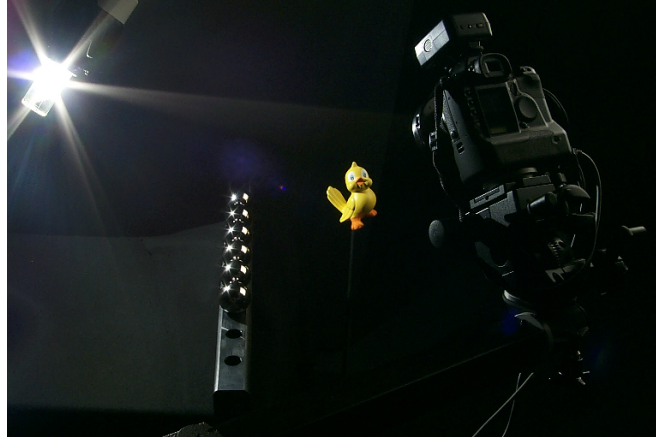


Figure 4.7: A view of the acquisition setup in the photo studio with light source, camera, calibration target for the light source position, and test object.

4.3.4 Data Preprocessing

In the acquisition phase, we collected several different types of data such as a polygonal mesh describing the geometry of the object and the reflectance samples from the images. After acquisition and registration of geometry and image data, it is necessary to merge and rearrange the data for further processing. For each point on the model's surface, we collect all available information in a data structure called a lumitexel. It contains the following information:

- the position of the surface point (its coordinates)
- the orientation of the surface at the surface point (represented by the surface normal)
- the photometric data for each of our input images in which the surface point was illuminated by the light source and visible from the camera's position. This data includes the direction to the light source and the camera as well as the amount of light that is reflected into the camera.

4.3.5 BRDF Generation

From the collected data we have to generate a BRDF for each surface point capturing its reflection properties. The process of BRDF generation, which can be broken down into BRDF fitting, clustering of lumitexels, and projection, is described in general below and in more detail in [Lensch01b].

Actually, a lumitexel can already be seen as a very sparsely sampled BRDF in a tabulated representation, typically with only four to ten entries. But instead of using the radiance samples captured in the lumitexel directly, we will represent the surface

appearance by a mathematical BRDF model whose parameters have to be estimated with respect to the error between a lumitexel and the BRDF.

This representation mainly has two advantages: first, only the parameters of the BRDF model have to be stored instead of a list of radiance samples; and secondly, a BRDF model is defined even for incident and outgoing directions that have not been acquired, providing smooth data extrapolation.

The number of radiance samples per lumitexels is too small to obtain faithful BRDF parameters from a single lumitexel. However, the parameters can be estimated accurately for a whole group or cluster of lumitexels, i.e. by increasing the number of samples. The given lumitexels are therefore partitioned into clusters so that each cluster corresponds to just one basic material of the object. The general idea of the clustering is to first fit a BRDF to an initial cluster consisting of all lumitexels. Then we generate two new BRDF models representing two new clusters. The lumitexels from the original cluster are then distributed according to their distance to the generated BRDFs into the new clusters. New BRDF models are then fitted to the two clusters which best approximate the lumitexels in the new clusters. To obtain a clear separation between the generated clusters, we repeat the steps of distributing the lumitexels and BRDF fitting until the clusters are stable.

As can be seen in Figure 4.6, above, the representation of an object by a collection of only a few clusters and corresponding BRDFs make the virtual object look artificial because real surfaces exhibit changes in the reflective properties, even within a single material. These changes cannot be represented by a single BRDF per cluster since all lumitexels within the cluster would be assigned the same BRDF parameters. To obtain truly spatially varying BRDFs, we had to find a specific BRDF for each lumitexel. See [Lensch01b] for a more detailed description of the projection process.

4.3.6 Results and Conclusions

We developed a method to generate high quality 3D models of objects including their reflection properties for each surface point. Compared to other methods that capture only the colors of an object (e.g., in a standard texture), the spatially varying reflection properties increase the realism to a great extent. Compared to other approaches that capture reflection properties such as surface light fields or reflectance fields [Wood00, Debevec00], this method requires only a small acquisition effort and leads to a very compact representation of the resulting 3D models, which can be viewed under arbitrary viewing and lighting conditions.

The following figures present some models acquired with our method. The model of the clay bird (see Figure 4.6) illustrates the importance of spatially varying reflection properties. The bronze bust in Figure 4.8 below shows another reconstructed object with very different reflection properties. The bronze look is very well captured.

Figure 4.9 compares an object rendered with an acquired BRDF and a photograph of the object. There are only a few differences in the highlights because an inadequate



Figure 4.8: *Model of a bronze bust. Note that it looks realistic even under modified lighting conditions.*

number of radiance samples were captured. Capturing more samples or images will increase the quality of the object model.

4.3.7 Application Areas

Apart from generating a more accurate and visually appealing representation of an object, the method described in this article has several desirable properties that open up new possibilities for digital collections of real world objects:

- The method requires only a small number of input images, speeding up the acquisition process. Although our current research prototype requires manual intervention during the acquisition process, a robot-controlled gantry could lead to an almost fully automatic system.
- The relatively small size of the resulting models is ideal for environments such as those digital libraries that have limited storage capacity or limited bandwidth.
- The high quality of the objects and the ability to view them under arbitrary viewing and lighting conditions make them useful for a wide range of applications in entertainment, edutainment, and scientific research. Virtual collections of art

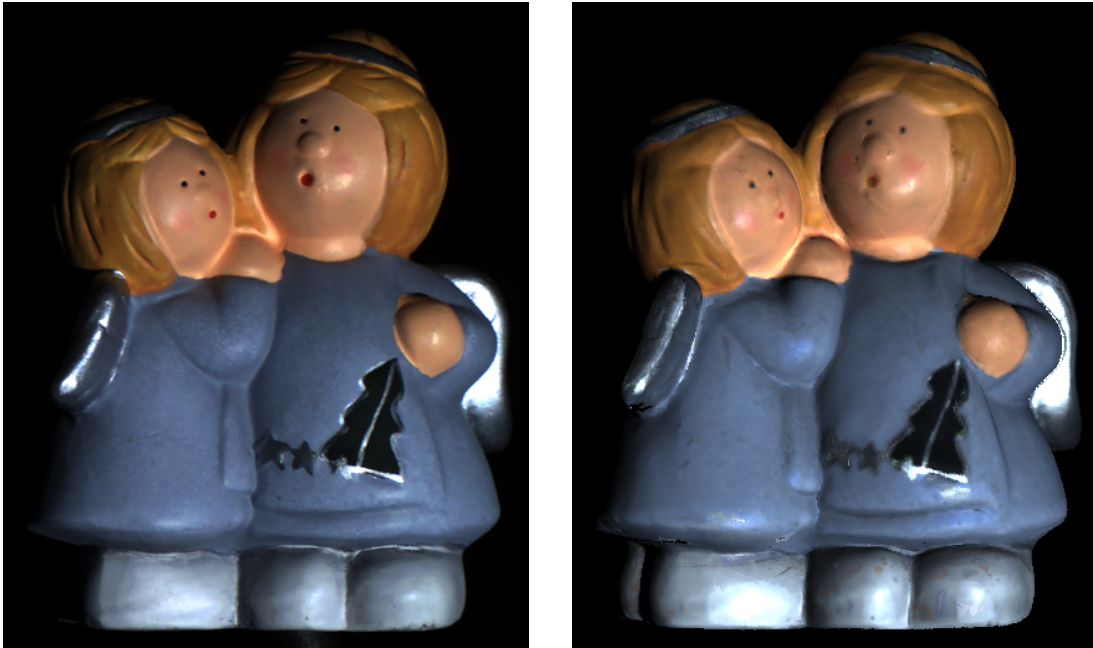


Figure 4.9: Comparison between a photograph (left) and a rendered image of our 3D model under similar lighting conditions.

works originally located at different sites all around the world can be built and presented on-site or (using simplified versions of the models) via the Internet.

4.4 Integrated Scanner Prototypes

During the course of the project, multiple integrated prototypes of 3D scanners have been presented. One of the prototypes featuring auto registration and color mapping functionalities was evaluated under real test conditions in conjunction with other consortium partners and external potential future users of the system. It was also demonstrated during the ViHAP3D Exhibition and Workshop “Real and Virtual World in Dialogue – 2000 Years of Ceramics in the Saar Region” in Saarbrücken (see Chapter 4.8.1). All visitors had the chance to try and to use all components of this improved (revised) prototype setup. Visitors and selected users have recognized this solution as an “easy to use” and “fast” system, which can be considered as a potential future solution for the cultural heritage communities acquisition demands. We have received very positive feedback and acceptance for this solution. All Objects which we have presented during the exhibition and other events were captured with the Improved Scanner Prototype set up.

We have also tested and presented the revised prototype at several sample acquisitions and at exhibitions such as:

- Acquisition of the surface reflection properties (BRDF) of the “Minerva Head”

(by MPI and CNR staff), done at the Restoration Laboratory of the Tuscan Archaeological Superintendence, Florence (Italy).

- Acquisition of the “Himmelsscheibe von Nebra” (MPI, Konica Minolta).
- Acquisition of several sculptures by E. Barlach in Güstrow (MPI).
- Acquisition of several statues of the Arrigo VII complex, at the Museum of the Cathedral of Pisa (Italy); multiple statues have been scanned, to allow the future digital reconstruction of the funerary monument of Arrigo VII (dismantled and partially dispersed in the 15th. century).
- Acquisition of two archaeological works for the Archaeological Museum of Cagliari (Italy).

The results of these acquisitions are described in detail in the ViHAP3D “Scanning Demo Results” report.

4.5 Software for Post-Processing, Data Representation, Efficient Rendering

4.5.1 Mesh Align

The aim of the Alignment Tool is to place a series of range maps in a common coordinate space. Each range map produced during 3D scanning belongs to a different coordinate system. To reconstruct the object, the first step is to bring all parts in the same reference space. The Alignment Tool gets individual range maps as input and, with human intervention, produces the alignment data necessary to merge the individual scans into a single model.

Characteristics of the Alignment Tool include:

- ICP fine alignment: efficient and precise alignment engine based on the Iterative Closest Point method (chosen because it’s fast, reliable and quite customizable).
- Graphical interface: to help the user interacting with the tool we provide an advanced graphical interface featuring:
 - a representation of the dataset in use
 - rapid access to all functions of the program
 - visualization of alignment errors
- Minimal human intervention: the tool provides automatic or semi-automatic algorithms for

- initial placement of the partial scans
 - choice of alignment parameters
 - mesh-to-mesh arc creation,
 - detection of alignment problems
- Scalability: the tool provides hierarchical multiresolution access to the data to increase interaction speed when working on very large input datasets.

Development Methodology

For the design of this tool, CNR started using its previous alignment tool (MeshAlign v.1) as a base. To build a system providing the functionality described in section 4.5, all input from the old system users and the extensive 3D scanning expertise of the CNR group has been taken into account to develop the interface and the internal organization of the new program.

Commercial software that includes alignment capabilities (e.g. INUS Technology's "RapidForm") has been also tested to compare the different approaches and their performances.

As described in detail in the State of the Art report (see ViHAP3D Deliverable D2.2), the registration is the most time consuming phase of the entire 3D scanning pipeline, due to the substantial user contribution required by current systems.

The initial placement is heavily user-assisted in most of the commercial and academic systems (interactive selection or manipulation of the range maps). Moreover, all actions have to be repeated for all overlapping range map pairs. This pairwise process can be considered as a graph problem where: given the nodes (i.e. the range maps), we have to select a subset of arcs such that every node is linked to other nodes if they have to be aligned together. If the set of range maps is composed by hundreds of elements (the scanning of a statue 2 meters tall generally requires from 200 up to 500 range maps, depending on the shape complexity of the statue), then the user has a very complex task to perform:

- for each range map, find which are the ones partially overlapping
- given this set of overlapping range maps, determine which one to consider in pair-wise alignment (either all of them or a subset);
- perform all the pair-wise initial alignments.

Apart from the interface (described in the following), one of the main improvements of the alignment system is the hierarchical management of the project. In a classical alignment approach, the user puts the range maps in place one by one, manually specifying the alignment between any possible pair of overlapping range maps.

A different approach, based on a jigsaw puzzle metaphor greatly reduces the processing time. The idea is to work in a hierarchical way, constructing small groups of well aligned range maps and using them as a single piece to build larger groups.

When working with this approach the user just has to place any single range map (or any group of already aligned range maps) in the correct position with respect to the others, without worrying about directly specifying all the alignment arcs between the various range maps. Once this new element is placed, the new MeshAlign v.2 tool is able to detect the adjacencies between the various range maps in a completely automatic manner, setting up the data structures needed for the alignment automatically.

A keen data organization and a spatial index are needed to implement the approach described above, making it possible to automatically detect the range map overlaps once an approximate alignment between two separate groups is known. Taking into account that the set of range maps that we have to manage can be really large, we implemented the data structures in a most scalable way (both in terms of space and time efficiency).

Tool Interface

As outlined in the previous paragraph, the user interface is very important since some functionalities of this tool are still mainly based on human intervention.

Therefore, it is necessary to show the object during the alignment with as much visual fidelity as possible, but without losing the interactive feedback to user input.

One has to consider that the standard data size that has to be managed (and rendered) by the system can easily overwhelm the current rendering capabilities of hardware accelerated graphics subsystems. The size of a single range map is usually around 400,000 triangular faces, and in a standard scanning project we have at least one hundred range maps, totaling 40 million triangles.

To maintain interactive response to all the mesh manipulation and rendering actions, a multiresolution engine has been provided in the new MeshAlign v.2 system. This engine automatically simplifies the range maps (simplification is run the first time a range map is included in a project in the background) and encodes the results in a multiresolution structure. The user is free to select the proper level of detail (LOD) at any time using a slider. Therefore it is very simple to display the range maps with the right tradeoff between precision and user interaction speed.

The alignment tool provides the standard rendering modes (wire frame, flat and smooth shaded). The system assigns colors to the different range maps, to make them more distinguishable in rendering.

The initial placement method has been also enhanced with respect to the previous system. Following the approach used by many commercial products, we introduced a new manual placement method based on the selection of three or four corresponding pairs of points on the two range maps that are to be aligned.

The user interface also allows management of the hierarchical project organization in a visual way. The sub-window in the bottom-left (with a layout similar to a hierar-

chical file-browser) displays the groups defined by the user during the alignment (first level items) and for each group, all the range maps assigned (second level items). For each range map some info on the range map (size, bounding box) and the list of alignment arcs created by the system is displayed. Finally, numeric data is visualized for each arc (e.g. the residual error associated to this arc after the alignment, a valuable information to the user to steer and improve the alignment).

Data Structures and Algorithms

Advanced data structures and algorithms can be found in three different parts of the tool.

- **Multiresolution management:** when a range map is loaded, it is automatically simplified and converted into a progressive mesh format. We use our proprietary simplification technology (described in the last section of this report). This enables the user to select different resolutions in an interactive manner during the entire project. It should also be noted that, even if a reduced model is used for visualization, the alignment algorithm in the final iterations always uses the high-resolution representation. Alignment quality is therefore not affected by the use of a multiresolution data representation.
- **Hierarchical project management:** in an alignment project, the task that consumes most user skill/effort is the organization of the range maps. The automatic arc selection tries to resolve this problem: once the user has placed a range map (or a group of range maps) in the correct position, all the overlapping range map pairs are automatically detected using an occupancy grid. All the needed alignment arcs are therefore created in an automatic manner.
- **ICP variations:** the standard Iterative Closest Point approach is used in the alignment core. The basic ICP algorithm has been slightly enhanced in order to be able to deal with "difficult" situations. The modifications are mostly related to the point and pair selection. The entire algorithm is controlled by various parameters: the tool determines the optimal settings for the project using some heuristics. The user can afterwards tune these values to improve the results.

Capabilities and Results

MeshAlign is a standalone tool with a user friendly interface, that is able to manage the alignment phase for very large acquisition projects.

The basic usage of the tool is learned quickly due to the intuitive approach to the alignment. An experienced user is then able to work on very large or problematic dataset thanks to the high level of configurability of the tool.

As the other tools, MeshAlign has been extensively used in all acquisition projects of ViHAP3D. Beside its usage on data produced by the Konica Minolta scanner, it

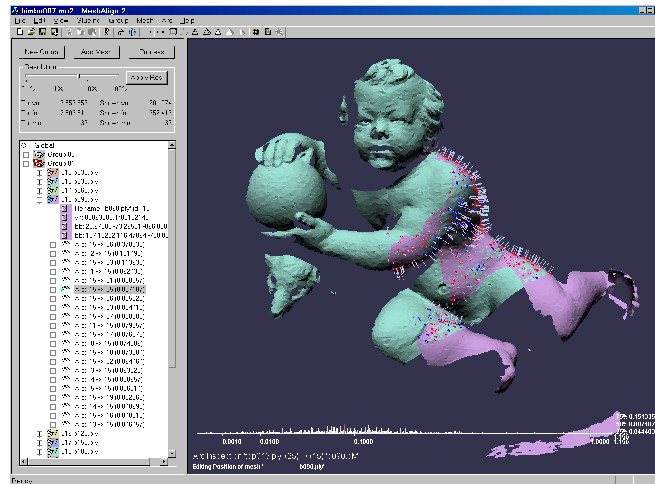


Figure 4.10: A screenshot of the MeshAlign tool: on left side it's possible to see the tree used for hierarchical range map management. On right, a single alignment arc between two range maps is graphically displayed, numerical information is also displayed

was also used to align range maps produced by other kinds of scanners. This includes Time-Of-Flight scanners, Structured Light, Photometric Stereo and Laser Triangulation scanners. The possibility to work with many different sources of data is a very important feature and clearly demonstrates the robustness of the implemented algorithms.

The incremental approach used by the tool (where the user performs the alignment like building a jigsaw puzzle, combining smaller pieces into larger chunks and then working directly with the resulting chunks), helps managing larger alignment projects, by dividing the process in smaller and easier steps (both for man and for machine).

The interface has been structured to help the user to keep everything under close control, many users contacted during the assessment that used the tool found that this awareness of the underlying process greatly helped in the alignment task, especially in larger projects.

4.5.2 Mesh Merge

The Mesh Merge Tool is used to produce a complete model by merging partial data files (range maps) from the 3D scanning phase that have been aligned with the Alignment Tool.

The merging step is implemented with an automatic process that can be controlled by setting just a few reconstruction parameters: the resolution, the smoothing factor and whether the automatic hole-filling feature should be enabled.

The Mesh Merge Tool has the following characteristics:

- Command line: since the whole merging process is performed without human

intervention, the tool does not require a graphical interface. Instead, program execution can be controlled with a script. The program stores data about its internal processing in a log file.

- Volumetric approach: in the literature, merging techniques are divided in volumetric and non volumetric. Both families have been used in academic as well as in commercial software. Volumetric methods, however use all the input data to determine the surface, thereby reducing the acquisition noise. They are quite efficient and customizable.
- Scalability for big projects: when working with very big projects, the merging tool should be able to work with datasets consisting of many GB of data. Moreover, to obtain models at high (sub-millimeter) resolution, the amount of memory required could easily exceed the machines capabilities. Therefore, we implemented a method to perform a split merging.
- Close hole / filtering engine: if necessary (and on user request), the tool should be able to perform some filtering operation on the model that is being generated during merging. This kind of operation can be, for example, closing of small holes due to lack of scanned data, noise filtering or generation of offset surfaces (needed for rapid prototyping applications).

Development Methodology

We decided to endorse a *volumetric method*: this family of algorithms have some interesting characteristics. They use of all range data, including redundant observations useful to reduce sensor noise and they are efficient in time and space and robust. Finally, these methods can be extended to support controlled hole-filling functionalities.

The base algorithm used in the tool is the *Marching Intersection (MI)* algorithm, derived from the well known *Marching Cubes (MC)* method. This algorithm has been designed to obtain good performance but with much smaller memory requirements compared to a standard implementation of a volumetric method based on "Marching Cube". The time and memory savings of MI come from the choice of keeping only the intersections of the range maps with the grid in memory, instead of storing a complete 3D distance field as the standard volumetric methods do.

Using MI, additional mesh processing can be performed when the model is still in its intersection-based representation, using a local distance field calculation. Afterwards, triangle mesh generation is done using a lookup table (analogously to the MC method).

A flexible tool should be able to manage sets of range maps taken with very small inter-sample distance (e.g. 0.25 mm) and representing objects that can have an extent of a few meters. Therefore, the use of a volumetric method can require the setup and initialization of a very large voxel grid: a typical statue, that is 2 meters tall, scanned at 0.25 mm requires a 8,000*2,400*2,400 voxel set when we want to reconstruct it at the

same resolution used in scanning. The space complexity of this voxel set is 360GB. Such a large data structure cannot be represented on a current low cost PC as it is. The construction and processing of this voxel set has to be implemented by working independently on partitions, to reduce the memory footprint to a manageable size.

The merging tool includes a split-merging feature, which allows to process a huge dataset by working on sub-sections of the data, loading each time only the range maps involved in the generation of that single section of the voxel set. The various parts of the final model are joined after the split merging process with a small time overhead.

Manipulation Tool "Mesh Simplification"

Aim of the Mesh Simplification Tool is to provide accurate, robust and time efficient simplification capabilities.

Simplification is a mandatory instrument when one has to manage the meshes produced with 3D scanning devices. The sampling resolution of current scanning instruments is up to 10 sampled 3D points per squared millimeter, producing surface meshes composed by 20M-100M faces is therefore common. Meshes of this size usually have to be reduced to a more manageable size in order to be used in real applications

The Merging Tool has the following characteristics:

- The simplification engine should reduce the mesh size in an accurate and progressive manner. One of the more successful approaches for the simplification of a triangulated surface is based on the iterative removal of a single element (vertex or edge): at each step the algorithm automatically selects and delete the element whose removal introduces the smallest error. The selection is very fast and at the same time the error estimation is very accurate.
- The simplification should be able to manage huge meshes (consisting of many millions of triangles) in an accurate manner. To obtain this functionality, out-of-core approaches have to be considered. The out-of-core simplification methods available in the literature sacrifice the accuracy of the results. Our goal is to maintain the high accuracy of the simplification engine based on edge collapse and quadric error, implementing it in an out-of-core fashion.

Development Methodology

The main characteristic of the simplification tool is the possibility to manage huge meshes on low cost architectures, producing very accurate results. This is possible using a hierarchical data representation approach and a clever data access strategy.

Since the out-of-core simplification requires a more complex data structure and a peculiar organization of the input data, it was decided to release two different tools:

- *PlyDeci* : this application supports the simplification of models that can be completely loaded in memory. It implements the basic simplification kernel and works with all the data loaded into core memory;

- *PlyMerge*, *OctBuild*, *Raw2Ind*, *OctDeci* : these tools are devoted to the out of core simplification for very large models.

PlyDeci is an implementation of the classical edge collapse simplification kernel, with the evaluation of the error introduced by any edge collapse action done according to the Quadric Error Metrics (QEM) method. It basically uses the approach of Garland-Heckbert (quadrics are saved and updated during the simplification of the currently loaded section of the mesh).

The second simplification tool, *OctDeci*, implements out-of-core simplification and adopts a hierarchical data representation scheme, called OEMM (Octree-based External Memory Mesh). This external memory structure is not just another space subdivision or data paging scheme. Memorable characteristics of our approach are:

- it supports a global indexed representation (built on any huge mesh given in input as a triangle soup);
- it allows any partial data load/update/write-back operation, by performing an automatic on the fly re-indexing of the loaded data portion: in this way, any loaded portion is represented in core memory with indexed lists containing only the loaded vertices and faces.

Data subdivision is performed using a standard octree-based regular split. Elements spanning adjacent cells are identified in the construction phase and consistent id's are assigned to the corresponding vertices in adjacent nodes (vertex indexing also satisfies the lexical order of the corresponding octree nodes). Finally, each border element is assigned to a single node of the octree. This allows data loading of any subset of the mesh, which is converted on the fly into a single, consistent mesh indexed on the local subset of vertices. The potential boundary elements contained in the interior of the loaded region can therefore be treated as any other element, while a tagging strategy (One outstanding characteristic of our approach) allows easy detection and management of the elements located on the boundary of the current region. This simplifies the design of the out-of-core memory geometric algorithms for which mesh simplification is a perfect example. Therefore, the underlying space decomposition is completely hidden (and managed by the data structure), and coding geometrical algorithms working on data partitions becomes easier.

Thanks to the freedom of accessing any small subset of the mesh consistently, we can easily implement different mesh processing algorithms on the OEMM data structure, such as for example mesh simplification. The bottleneck on either input and output data size is thus removed.

Simplification is performed on the OEMM by loading portions of the dataset (OEMM subtrees) and working locally on one portion at a time. For each loaded subtree, the OEMM management policy loads also all the adjacent leaves. This ensures that all the possible mesh edges contained in the loaded subtree are evaluated for a possible collapse. Therefore, at the end of the traversal the mesh is uniformly simplified



Figure 4.11: An example of good simplification. Even when the geometric complexity is greatly reduced, all the details are preserved. Left: 2.104.792 faces, Middle: 130.343 faces, Right: 19.936 faces

(while other hierarchical approaches are constrained to leave the inter-cell boundaries untouched).

The other tools (*PlyMerge*, *OctBuild*, *Raw2Ind*) are ancillary to *OctDeci*: they are used to convert the input data into the format required by *OctDeci* (a more detailed description is in the MeshSimplify User Manual, included in the Deliverable D4.5)

Actions and Results

The main acquisition campaigns performed during the ViHAP3D project were conducted on the basis of the criteria mentioned above. The list of the selected artworks includes:

- the Arrigo VII mausoleum complex (ISTI-CNR): the mausoleum has been dismantled long ago with only some of the original statues remaining. The aim is to virtually reconstruct the original setting of the funerary monument.
- the campaign at the Cagliari archeological museum (ISTI-CNR): The goal is to demonstrate the effectiveness of this kind of technology to Sardinia Superintendence.
- the acquisition of the apsidal facade and of some architectural elements of the Pisa Cathedral (ISTI-CNR). It took place in the framework of the ongoing restoration of the facade, to help planning the restoration and to monitor the resulting changes.
- the acquisition of wall inscriptions (graffiti) in the Lupanare house in Pompeii (ISTI-CNR Architecture Department, Ferrara University). The idea is to use 3D processing techniques to enhance graffiti readability.
- the acquisition of Parthenon sculptures, Athens: in collaboration with the University of Southern California (USC), in the framework of a very big acquisition campaign ongoing in Athens.

- The acquisition campaign at the Max-Planck-Institut für Informatik, Saarbrücken: 7 objects have been acquired, with originals coming from the following museums:
 - Villeroy & Boch Mettlach
 - the Fayencerie Sarreguemines
 - the Altertümersammlung
 - the Museum für Vorgeschichte, Halle and the Barlachsammlung Güstrow

The acquired models offer a wide range of technical typologies and problems and elicit proper technical solutions. The feedback of the end users of the system was very positive.

4.5.3 Manipulation Tool "Mesh Repair"

Objectives

The Mesh Repair Tool is an application that automatically repairs scanned models and produces coherent and closed mesh models of the artworks. After the mesh merge phase the scanned objects can contain holes in places that are unreachable by the scanner. The tool detects small and large holes and gaps, creates an acceptable geometry in the missing parts and generates a final closed model of the object. The Mesh Repair Tool is part of the post-processing tools.

Development Methodology

The repair tool uses a robust discrete algorithm that converts the initial mesh to an intermediate volumetric voxel model and fits a closed discrete membrane to the surface voxels. The final set of face-connected voxels can be considered as a one-voxel thick representation of the surface: it contains the initial unrepaired mesh while presenting the required closed topology. A final step uses a modification of the Marching Cubes algorithm which preserves the initial surface in the voxels that contain triangles of the initial mesh and generates a surface closing the gaps in the rest of the voxels. The algorithm has clear advantages over other possible alternatives. It is automatic, robust, and guarantees the final genus of the object. It can also be used in cases with large gaps and holes, where other existing algorithms based on measurements of the vertex sampling rate of the input mesh would fail. The volumetric and discrete approach ensures a guaranteed topology while preserving the initial geometry. These results cannot be reached by other existing state-of-the-art algorithms. The algorithms in this tool are part of one of the Ph.D. thesis (J. Esteve), developed under the project.

Results and achievements

The result is a set of methods that have been integrated in a repair tool for scanned objects. The methods have been published in a paper by J. Esteve, P. Brunet and A. Vinacua ("Approximation of a variable density cloud of points by shrinking a discrete membrane") and have been tested by repairing the set of sculptures of the Arrigo VII set.

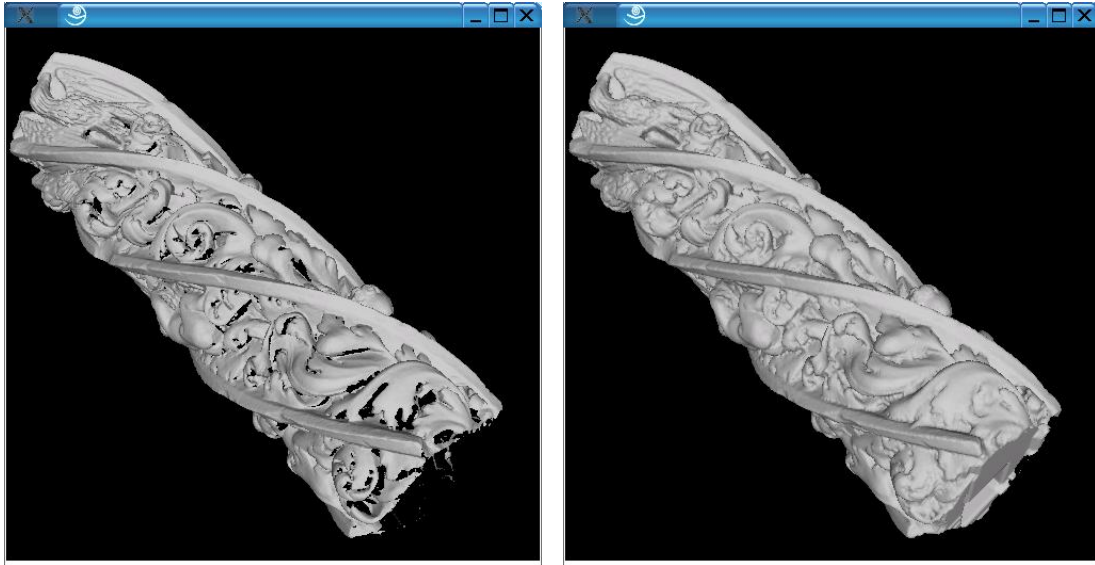


Figure 4.12: Left: Mesh produced by scanning an artifact. Regions that the scanner omitted appear as holes in the mesh. Right: The missing parts in the mesh have been filled in by the Mesh Repair tool.

Figure 4.12 shows the repair result on one of the Arrigo objects, the "colonna". Preliminary tests are confirming the usability of this tool as part of the ViHAP3D postprocessing tools.

4.6 Virtual Heritage Tools

4.6.1 Virtual Museum Builder

Objectives

The Virtual Builder is an authoring tool that allows the user to arrange the scanned digital artworks into virtual museums that will be explored later with the Virtual Browser.

A virtual museum consists of the following basic components:

- A Virtual Space, which is a collection of walls, floor, and other architectural elements that act as the environment to the artworks.

- A collection of Virtual Objects, i.e. virtual heritage objects that have been captured with the scanning tools mentioned previously.
- A collection of Virtual Guides, which offers the possibility to plan the visit through the different rooms of the museum according to the user's preferences and the desired degree of interaction.
- A collection of Multimedia Links providing additional contents about a specific object or museum room. This includes links to web sites, text, sound, still images and movies.

The Virtual Builder provides the user with a user-friendly graphical interface for creating virtual museums including all the above elements.

Results and Achievements

The Virtual Builder is an application that can be used for building new virtual museums. It has been designed taking into account the user requirements in the specification phase of the ViHAP3D project and the feedback from the evaluation of the first version. The final version of the tool is therefore well adapted to the users needs.

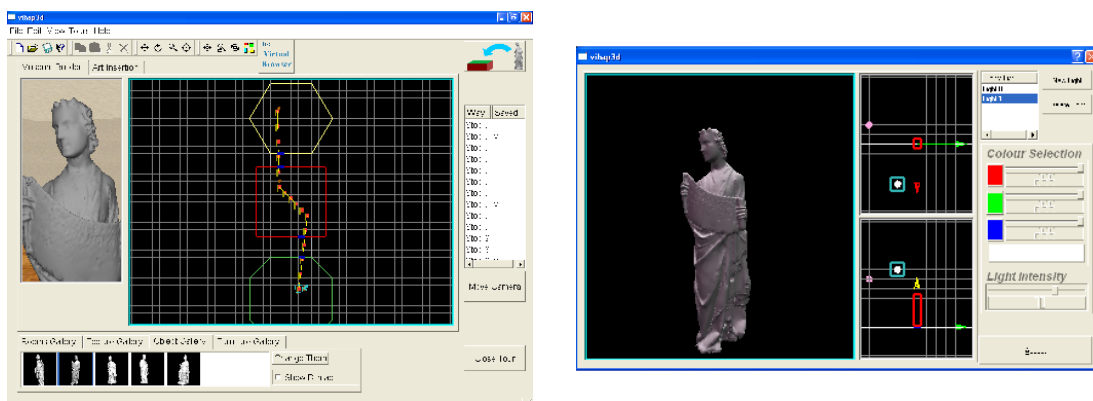


Figure 4.13: Screenshots of the Virtual Builder showing how paths through the museum are automatically created and how the lights illuminating a single object are defined.

The Virtual Builder can at first be used for building the virtual space from scratch by designing galleries of rooms and objects. It supplies tools for room placement and scaling, for linking rooms through corridors and for adding textures. It can also import existing CAD models (e.g. 3DStudio MAX).

The Builder can then place objects and appropriate lights in the rooms. It offers an easy-to-use object insertion functionality through a drag-and-drop GUI, object placement and scaling tools and resources for placing light sources around each art object. Image-based rendering acceleration is used to speed up the interaction. Guided tours

can be easily defined, and automatic tours with default lights can be generated. Any object can be linked to additional multimedia information, including text, pictures, movies, sounds and links to web pages. Multimedia information can also be attached to information points that can be interactively located in the museum rooms. The Virtual Builder includes a link to the Virtual Browser tool and to the Inspector tool through the Browser.

4.6.2 Virtual Museum Browser

Objectives

The Virtual Browser is an interactive navigation tool for exploring the virtual museums created by the Virtual Builder.

The Virtual Browser supports virtual reality hardware devices such as tracking systems and data gloves, and implicit interaction mechanisms that enable even untrained users to freely move around the museum, and explore its exhibited virtual objects from any viewpoint. Users should be able to choose between free navigation and guide-assisted navigation through the different virtual museum rooms.

The system must be designed to operate on different platforms ranging from low-end systems (PC with monitor) to high-end virtual reality systems (head-mounted displays and projection-based stereoscopic systems).

The use of multiresolution models, level-of-detail techniques and occlusion culling enables the inspection of large collections even on low-end systems.

Development Methodology

The VR Browser has been designed by taking into account several research results attained by the UPC team during the ViHAP3D project. The paper on "Mini VR, a portable VR System" (Computers & Graphics 2004) proposed a low-cost VR platform that integrates with the Browser tool. Some other research results include simplification techniques based on intermediate volumetric models: "Minimal Isosurfaces" or MiniMac (to be published in the CAD Journal 2005) and "Maximal Tiles for Extreme Simplification" (EG'04, Computer Graphics Forum Journal). We have also published research results on the automatic generation of museum tours, "Way Finder" (EG'04, Computer Graphics Forum Journal 2004). The basic methodology for the Browser design has been based on these and other research results. In consequence, this tool is well adapted to the user requirements and that it is based on the most recent published results. The main advantage of this specific tool over other existing browsers is the suitability for our application, its matching with the user requirements and the tight integration with the two other tools of the WP5 in the ViHAP3D project: the Virtual Builder and the Virtual Inspector.

Results and Achievements

The result is a VR Browser System that fulfils the user requirements and needs. The Browser tool uses optimized visualization algorithms and includes multiple navigation modes (inspection, fly, walk) through multiple interaction devices, and both free and assisted navigation (guided tours). It allows event-driven multimedia info and supports ground and wall collision detection. The output can be visualized in advanced VR systems and it has been tested on a VR, Workbench-like, immersive table, on a Power Wall, on a Cave and on Head-Mounted Displays. It has also been tested on the Mini VR, a VR portable system under Linux with orientation tracking. The Browser tool can receive the museum models from the Virtual Builder, and it can call the Virtual Inspector for close-up inspection of individual artworks.

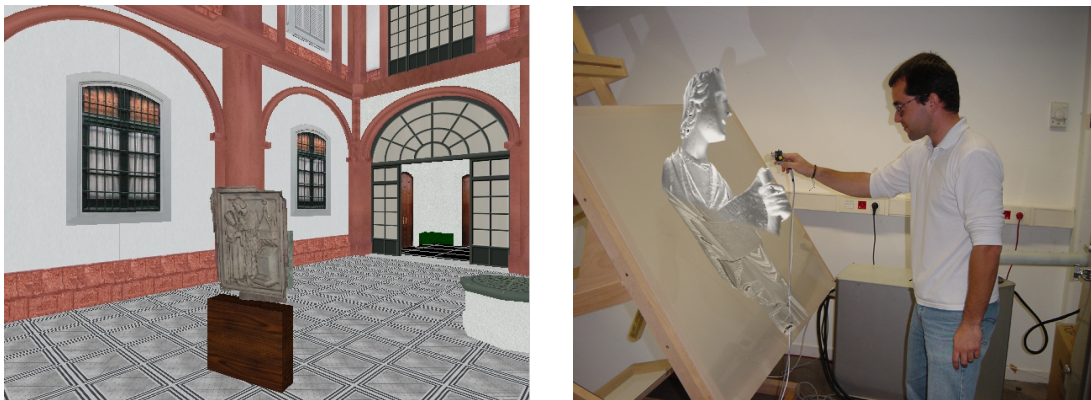


Figure 4.14: Left: *Walk through a virtual museum.* Right: *A virtual object is inspected at a so-called workbench, a display device that conveys a three-dimensional image.*

The Virtual Browser supports a Time-Menu that allows space-time navigation through different periods of time. The user can interactively change the time period, and the art works change their location accordingly. This navigation mode is useful for a fast understanding of the historical evolution of the sites.

4.6.3 Virtual Inspector

The technology for automatic shape reconstruction evolved rapidly in recent years, and a huge amount of data can be easily produced. The problem is now to find a way to manage and visualize the high complexity 3D data produced with 3D scanning devices on commodity computers.

The aim of *Virtual Inspector* is to allow naive users a detailed inspection of a large, complex 3D models at interactive frame rates on off-the-shelf PC's. It is mainly oriented to the visualization of single artworks (sculptures, pottery, etc.), and adopts a very intuitive point-and-click interface to guide the virtual manipulation and browsing of the digital replica.

The Virtual Inspector tool features:

- **Multiresolution:** to ensure interactive frame rate in visualization, the tool uses a multiresolution rendering algorithm to display each part of the object at the best resolution possible without losing the interactivity
- **BRDF rendering:** the tool performs a realistic surface shading by using the BRDF data acquired with the ViHAP3D Scanning Tools.
- **User interface validation:** since the tool is targeted toward non-experienced users, it provides a simple navigation method. The navigation has been tested with the participation of people with various degrees of computer graphics experience.
- **Hyperlink management:** the tool displays spatially located "anchors" to external multimedia resources and lets the user follow them to visualize additional multimedia data associated to the artefact.
- **Customisable interface appearance:** the tool can be used to display objects with different data associated (geometry only, geometry and BRDF, two or more 3D parts) and different metadata.
- **Preset views:** to help the user during artefact inspection, the visualization tool can use some pre-defined views framing important details or regions of the artefact. Those views are defined in the auxiliary artefact data.

Development Methodology

Interface

Using XML-based scripting, it is possible to reconfigure the appearance of the user interface: various *panels* containing the interface element (rendering, navigation, help, annotations) can be initialized and placed anywhere on the screen and sized as needed. This will allow the tool to be tailored to different types of artifacts and to different styles of presentation.

At startup, the Virtual Inspector application reads a given nsp file, containing the interface description in XML tags and configures itself according to the instructions specified there. XML has been chosen because of its well known advantages (availability of syntax aware parsers, human readability, extendibility etc.).

3D Model Management

Visualization efficiency is obtained by adopting a multiple level of detail representation. The best-fit level of detail is selected automatically (according to the current view frustum), visibility culling and a *ready-to-render* representation of the geometry further improve rendering efficiency.

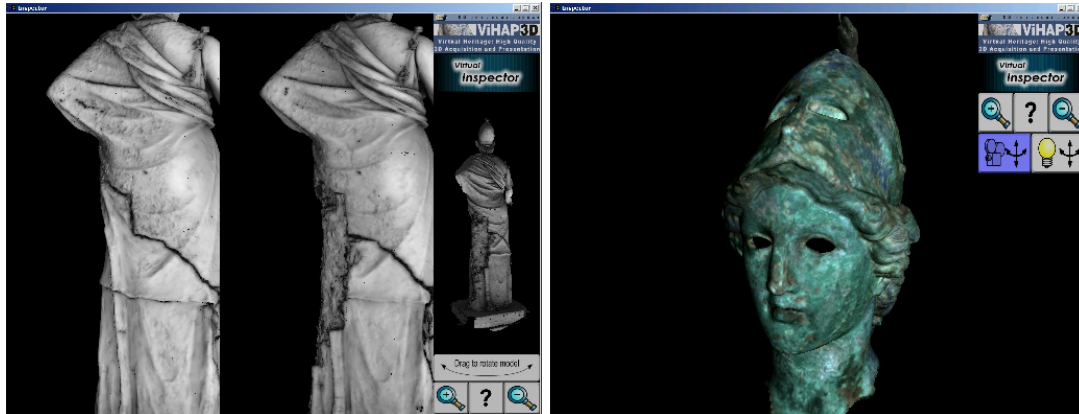


Figure 4.15: Interface example: Left: two models representing an object evolution displayed together with linked manipulators. Right: single object, with BRDF rendering.

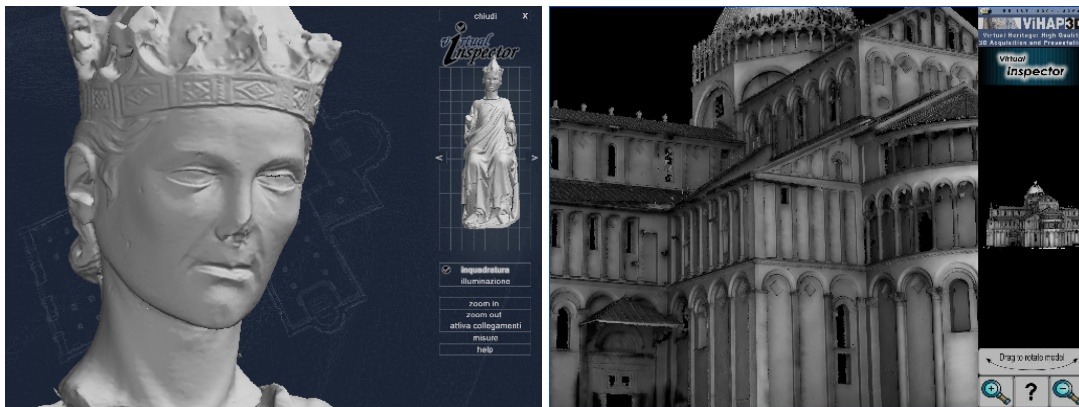


Figure 4.16: Interface example: Left: Arrigo VII kiosk, widget and interface customized by professional graphic designer. Right: single model from time of flight scanner, displayed with constrained manipulation (it's only possible to move around the building in a restricted area).

The multiresolution data structure is generated from a very high resolution 3D model using the CNR simplification algorithms (the same implemented in the simplification tools). The structure contains different levels of detail and is divided into sections. That way, different portions of the object can be accessed independently

A lot of different solutions have been proposed in the literature for the efficient visualization of large, complex digital 3D models. In the design of Virtual Inspector we considered, among the others, the following issues:

- Choosing the right resolution: Highly accurate models can be composed of a number of primitives much larger than the number of covered pixels. Rendering an appropriately simplified version of the model often introduces an image-space error lower than a single pixel. Therefore, Virtual Inspector will offer both

a plain, mono-resolution representation mode (i.e. data encoded by a standard 3D model file) and a more sophisticated multiresolution representation and rendering mode,

- **Culling unnecessary geometry:** Given a particular view and resolution, only the visible geometry should be rendered. The adoption of an internal representation that is based on a hierarchical data structures (octree) allows us to detect the sections of the model that are not contained in the current view frustum or are occluded.
- **Keeping in memory only the required data:** Digital models can be composed by tens or even hundreds of millions of triangles and could require several GB of memory. Only the currently viewed portion of the model should be loaded into main memory. Again, this goal is fulfilled by a keen out-of-core design of our octree-based representation.

Capabilities and Results

Virtual Inspector has been used throughout the project to present many of the objects acquired during the acquisition campaigns performed for testing or dissemination.

Those objects have not only been used as a showcase for experts (in the field of computer graphics or Cultural Heritage) but they have also been presented to a wider audience during different expositions:

- Ferrara Restauero
- Minerva Workshop
- MPI exposition
- Arrigo VII kiosk

The public presentation of this tool has always been a success, receiving good feedback from the people using the tool.

The configurability of the tool has been tested in numerous occasions, setting up different interface layouts to maximize presentation effectiveness for different kind of objects.

When setting up the interactive kiosk, the layout and appearance of the tool was refined by a professional graphic designer, thus demonstrating the scripting flexibility and enhancing the usability.

The possibility to render BRDF data has proven to be a major requirement when the correct surface appearance of an object should be conveyed. Virtual Inspector is able to faithfully display this kind of data, as demonstrated in the various exhibitions organized.

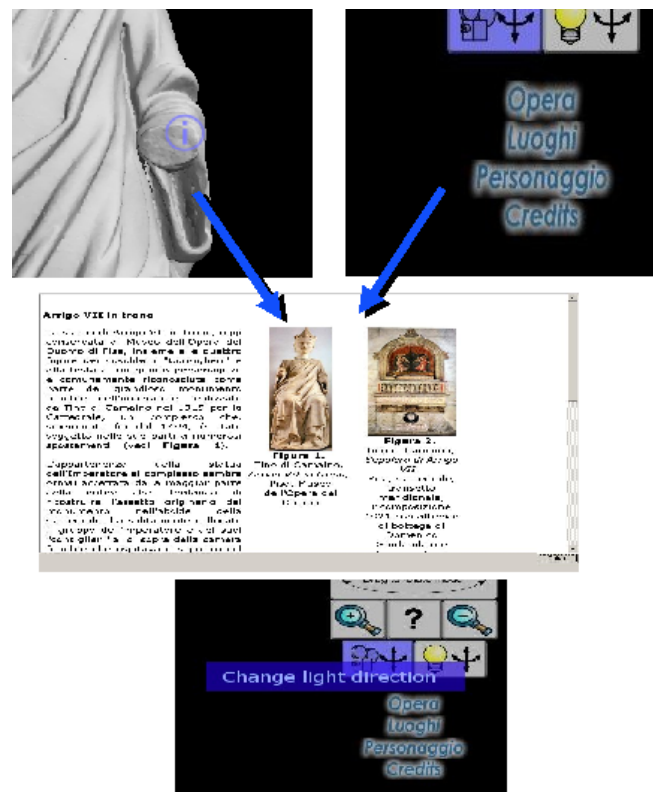


Figure 4.17: Another important point is that the tool can run on standard PC equipped with a 3D graphics card or even on a notebook, thereby lowering the cost of museum installations and giving schools and home users the possibility to use it without the need for costly upgrades.

4.7 Repository of 3D-Models

The data repository is a set of applications for organizing and accessing all information created within the the ViHAP3D in a structured way. It also aids the final users to know which objects, collections of objects, textures, etc the user has, and it is also useful to download more data from other users of the application via Internet. The use of the application involves the definition and use of xml files, which are stored with all the other files. This xml files are also used as metadata files and have all the information that can be consulted by the user.

This xml files are generated using an electronic form that force the user to introduce all the information in a fixed way. The form has some fields that are mandatory, and some other that are optional. Once this form is completed the application generates the xml file with all the information provided by the user. This application also creates some standard folders to leave there all the information related to the object (and collection of objects). If the user set ups properly, the application copy/move the information to these folders too. This application is not able to modify existing objects

or collection of objects, apart from adding objects to a collection, once an object is completed it can not be modified. If the user wants to modify an already created object he is forced to recreate it has a way to ensure the integrity of the information.

Once the xml file has been generated and the data files has been set, the user can run another application called TDR (TCP/IP Distributed Repository) that is able to read and understand all these xml files and share all these data files to some users trough Internet over a TCP/IP protocol. This application has a user/password (with AES Encryption) protection and user friendly interface for user configuration in order to administrate the users who access to the information. When the application starts up, the user is able to share these objects or collection of objects with other users, therefore the user is able to send all the required files by an object or a collection.

The application server provide folders for Mesh files, LOD files, Texture files, Sound files, Metadata files, and some other unknown types to leave some degree of freedom to the user. The user is able to know to in which category each one of the files of the user is shared.

Summing up, the main characteristics of the TDR are:

- Server management capabilities. Each server stores some information about it, as a short description, together with the necessary information for the connection and the allowed number of clients, in front of the server and network performance.
- User account management capabilities. Each user account stores some information about the user together with optional password and accessibility level.
- Files shared between users in front of the type of user (access level) AES
- Encryption of information sent by TCP/IP plus the user and password stored files
- More than one client per computer
- Just one server per computer in order to avoid socket concurrency politics.
- TDR remember the files shared in different executions.
- Hierarchical recursively sharing policies.
- Pre-visualization of XML and related files name, length and type before to download
- XML download level (download of independent files is not allowed in order to protect the consistency of the repository)
- Download resume capabilities in case of network crash.
- Download could be paused and continues later in front of the user interest

- Client could put files directly in server, under user/password validation
- Server real time information: Number of users, description of them and already shared files.

4.8 Dissemination and System Evaluation

According to research efforts commissioned by the European Commission, European cultural institutions are still scarcely aware of the potential benefits of applying information technology to Cultural Heritage. More specifically, as one can read in the final Report of the DIGICULT project, there is a gap between major institutions (where theoretical knowledge and practical applications are largely present) and the majority of small or medium museums, even those with highly significant or exceptional collections.

Actually, the ViHAP3D goal, to improve 3D digitizing and the virtual presentation technologies and to make them generally affordable by endorsing low cost platforms, has immediately encountered a strong interest in the Cultural Heritage community.

However, the relatively scarce familiarity with Information Technology found among museum operators and their tendency to delegate the setup of digital presentations to external companies, did not allow us to get a strong feedback from them in the first phases of the project.

As a matter of fact, reading the specifications report proved to be a hard task even for content creator end-users – and the specification report was obviously not given to final end users (i.e. museum visitors). It became therefore mandatory to create, as soon as possible, occasions and events where users could see the functionality of the ViHAP3D tools in live demonstrations . This process started with the Saarbrücken exhibition, culminated in the Pisa Kiosk, a 3D multimedia application put at disposal in a real museum, and had important intermediate phases with booths at conservation and communication fairs.

4.8.1 Exhibition 2003

A preliminary assessment of the current state of the ViHAP3D project outcomes – hardware and software – was obtained with the model exhibition "Real and Virtual Worlds in Dialogue - 2000 Years of Ceramics in the Saar Region" held in Saarbrücken. The exhibition did show-case all the technology developed in the framework of ViHAP3D.

The workshop organized at the end of the exhibition (October 7th, 2003) brought experts from museums, cultural heritage administration professionals and restorers together, thus creating an excellent opportunity for an assessment of the acquisition pipeline and the presentation of the acquired objects.

4.8.2 Pisa Kiosk

One of the main acquisition campaigns within ViHAP3D was performed on the tomb of Henry VII, a gigantic, complex and enigmatic artwork. The thirteen sculptures belonging to this imperial monument are now available as 3D models, with all the necessary historical and artistic information. Thanks to specific high-tech tools, both scholars and the general public can now assess the art historians' attempts to reconstruct this terrific mausoleum to its original position, the apse of the world famous Cathedral of Pisa

The Monument

Built in 1315, by determined Pisans and realized by Tino di Camaino, the tomb of the emperor Henry VII of Luxemburg was originally placed in the centre of the apse of the cathedral, directly beneath the mosaic representing Christ in Majesty on the apsidal vault. This forceful setting, chosen by the Ghibelline city as a sign of enduring loyalty to their emperor, did not last long however. The statues which made up the mausoleum (whose complex structure still remains a mystery) were scattered to various parts of the piazza. Only the statue of the recumbent emperor, on the sarcophagus, was returned to the left transept at the beginning of the 20th century, to the same position it occupied at the end of the 15th century.

The other pieces eventually identified as part of the complex have been in this museum since it was opened in 1986. They have now been joined by two angels removed from high up on the facade of the cathedral, where they had remained – unacknowledged – for centuries. Visitors can now judge the plausibility of the recent recognition of these sculptures as part of the imperial tomb and their attribution to Tino di Camaino. This interpretation is confirmed by the angel's scrolls with the eulogy of "Henricus septimus".

The Project

Nevertheless, a question mark remains over the original form and placement of the tomb. Virtual reality has proved to be a helpful tool for approaching this kind of problem. Thanks to three-dimensional digital models of all the statues as well as of the cathedral, we can now study the respective positions of the pieces and construct probable arrangements.

The ViHAP3D project has dedicated a specific experiment to this case. The first results have been collected in a video and in an interactive installation, where it is possible to see (at an extremely high level of detail), both the virtual sculptures accompanied by historical information, and the various reconstructed arrangements.

The kiosk experience was planned to exhibit all the results of the ViHAP3D project at the same time. Therefore, it was necessary to use all the scanning and processing tools to build accurate 3D models, the museum tools to create and present the models

to the visitors. The experience gathered throughout the project was needed to complete the kiosk setup in a satisfying and effective manner.

The Arrigo VII funerary complex was selected since it fulfilled various requirements:

- we were looking for a complex case study, consisting of multiple objects in order to allow us to monitor the improvement of the tools developed in the project over time, and to support the setup of virtual expositions.
- each single item is of a sufficiently large size and complexity of shape to be considered as a challenge for both scanning and visualization;
- the 3D representation is useful to provide a better comprehension and presentation of the artworks in the framework of a real museum exposition;
- the set of artworks are inter-related, a common "story" exists between them. This supports the development of virtual presentations that are not only encoding shape data but also artistic, historical and political knowledge.

4.8.3 Actions

The activities of the project can be divided in the following tasks:

- acquisition of 3D models of all the elements of the Arrigo's monument, using high-accuracy 3D scanning
- post-processing of the raw scanned data, to build up a complete model for each statue and to obtain optimized 3D representations (different levels of detail)
- to model the Pisa cathedral in its 14th century status, we acquired the current architecture with a scanning device and re-modeled the lost components with a CAD tool
- design and implementation of interactive systems to present the models and the associated multimedia data to the general public and to experts (to support study and analysis of the complex).

To produce a faithful representation of the monument, all of the statues and elements of the mausoleum have been acquired in digital format. In this project, the main problem was the size of the dataset to be processed: 15 different components, with a total of 3000 range maps. Processing of the scan set was performed with the suite of scanning tools (MeshAlign, MeshMerge, MeshSimplify), developed in the framework of the ViHAP3D project.

The design of the Arrigo VII installation has been done with the help of a professional graphic designer. Consequently, the layout of the application, all icons and

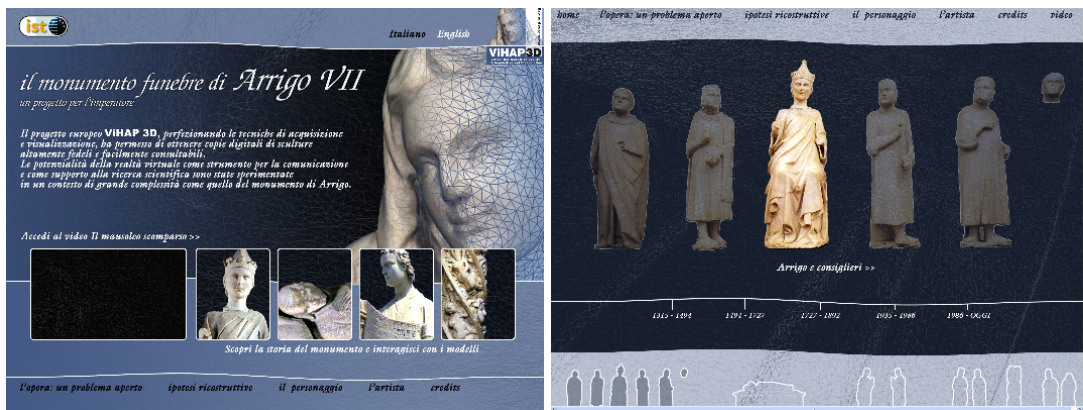


Figure 4.18: *The kiosk: The initial screen of the multimedia kiosk and one of the following sub-index pages. The image on the right shows the index page related to the "Arrigo VII enthroned" and his group of counsellors. The Virtual Inspector can be started by clicking on any of the icons of the statues.*

background graphics elements have been completely redesigned with respect to initial versions of the Virtual Inspector system. This has been done by simply specifying new images and their locations on the screen for all icons and elements of the GUI in the XML initialization file and did not require modification or recompilation of the Virtual Inspector program.

The Arrigo VII visual presentation in the museum has been designed with introductory HTML pages, both to present some general artistic/historic information on the Arrigo VII complex, and to provide links to activate the Virtual Inspector. These index pages also hold links to time-navigation pages, which present each subset of statues in their respective locations during their seven century life.

The Superintendence, ISTI-CNR and Opera del Duomo have also set up an experimental educational program concerning the Arrigo VII monument. Students have been taught the history of the Cathedral Square ("Piazza dei Miracoli"), combining traditional lessons with the use of different interactive media, such as CD-ROM, Internet, and 3D models of the main monuments. Afterwards, they have been engaged in a virtual journey around and inside the Arrigo VII's Mausoleum: this way, they have learned to read the artwork, to find and interpret documentary sources, to explore the digital models of the monument's elements, interacting with them and virtually constructing possible alternative disposition of the statues themselves.

4.8.4 Ferrara Restauero, 2003, 2004, 2005

ViHAP3D results and technologies have been presented and demonstrated at the Ferrara Restauero event. Ferrara Restauero is the most important event in the Cultural Heritage and Restoration field. It is held yearly in Ferrara (Italy) and attracts a very large number of visitors. CNR and SBAAS have been hosted by the Regione Toscana booth,

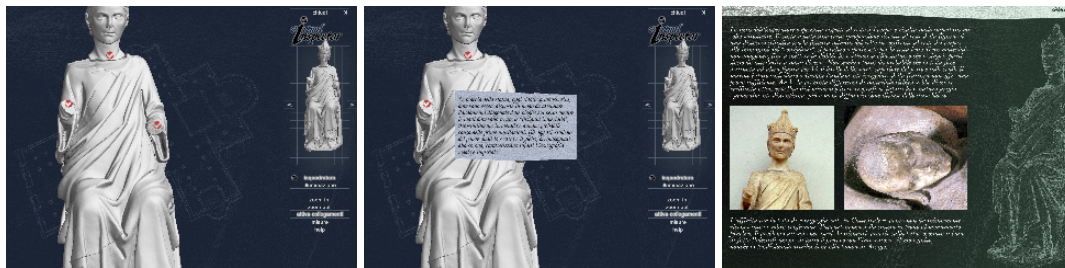


Figure 4.19: *Virtual Inspector: Left: the "Arrigo VII enthroned" statue rendered with active hot spots. Middle: A short popup panel, describing the missing hand, appears when the mouse passes over the hot spot. Right: an example of an HTML page activated by clicking the hot spot that is on the neck.*



Figure 4.20: *Exhibition visitors at the ViHAP3D demo kiosk. The kiosk is integrated into the exhibition of real statues and provides additional information and interaction possibilities.*

and have been responsible for the set up of a major section of this large stand (around 40 square meters of space dedicated to ViHAP3D). Some images of the stand are presented in Figure 4.21.

The participation to Ferrara Restauero allowed us to disseminate the project results to a very wide panorama of potential users, both at the national and international level.

Firmly convinced of the importance of the Ferrara event as a precious occasion for dissemination, a presentation of the project's final results was organized in the 2005 edition, even if it would have taken place after the formal conclusion of the project. The Arrigo application (the Pisa kiosk) was exhibited in one of the booths. A workshop dedicated to discuss and assess the project's result, under the title "Digital 3D models assessed by end-users: considerations around a case-study" was held.

The panel gathered different types of end-users (restorers, researchers, political



Figure 4.21: *ViHAP3D booth at the Restauro 2004 in Ferrara.*

and administrative decision makers) who discussed the project's result as presented by Claudio Montani (ISTI-CNR, Pisa) and by Clara Baracchini (Soprintendenza BAP-PSAD, Pisa). Among the participants were:

Giorgio Accardo, Istituto Centrale del Restauro, Roma; Marcello Balzani, Fac. of Architettura, Università di Ferrara; Antonio Cioffi, Accademia di Belle Arti di Brera, Milano; Martina Hansmann, Director of the photo galley of the Kunsthistorische Institut, Firenze; Antonia Pasqua Recchia, General Director for the Technological Innovation, Ministero per i Beni e le Attività Culturali, Roma; Ludovico Solima, Seconda Università degli Studi di Napoli

4.8.5 “Minerva di Arezzo” Workshop, 2005

The usage of the ViHAP3D technologies on the Minerva di Arezzo testbed (a bronze statue on restoration at the Restoration Center of the Archaeological Superintendence of Tuscany) has been presented and demonstrated at a dedicated workshop held on February 3, 2005 in Florence.

This workshop was organized to present the results of an assessment and dissemination activity run during the year 2003, and aimed at the acquisition of a complete 3D



Figure 4.22: *The “Minerva di Arezzo” Workshop 2005 in Florence. Left: The audience during the presentations. Right: Members of the ViHAP3D project presenting at the Workshop (left to right: R. Scopigno, P. Cignoni, M. Goesele).*

digital model of the Minerva of Arezzo (a bronze statue, property of the Archeological Museum of Firenze, currently under restoration), enriched by a sampling of the BRDF (surface reflection properties). The acquisition has been done jointly by CNR and MPI. The attendance was rather good (around 30 people), mostly restorers and art historians.

4.8.6 Florence, Kunsthistorisches Institut, 2005

The director of the institute, Dr. Gerhard Wolff, and the director of the photo gallery, Dr. Martina Hansmann, both end users of the project, discussed with SBAAS and CNR, the efficiency of the project tools after using the Arrigo application in their institute for some time. While their comments have been precious for the previous assessment, this occasion was as an important validation of the project tools as far as content creators and art history academics and researchers are concerned

4.9 Project Web Site

In order to disseminate the results and the current progress of the project, the ViHAP3D consortium launched the website <http://www.vihap3d.org> in 2002. Since then, the website has been updated regularly to inform about both upcoming and finished activities, such as the exhibition in 2003 and TV broadcasts reporting about ViHAP3D.

Information about all consortium partners, their respective role within the project and contact addresses can be found. The website also includes a collection of scanned objects for public use. Furthermore, to allow an easy exchange of data, there is a section on the website which is only accessible to consortium partners.

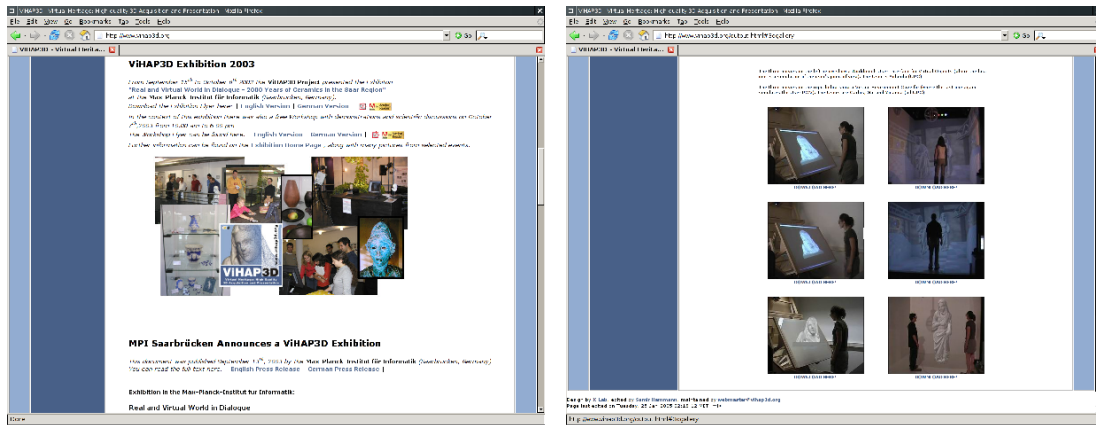


Figure 4.23: Website of the ViHAP3D project describing the project's results.

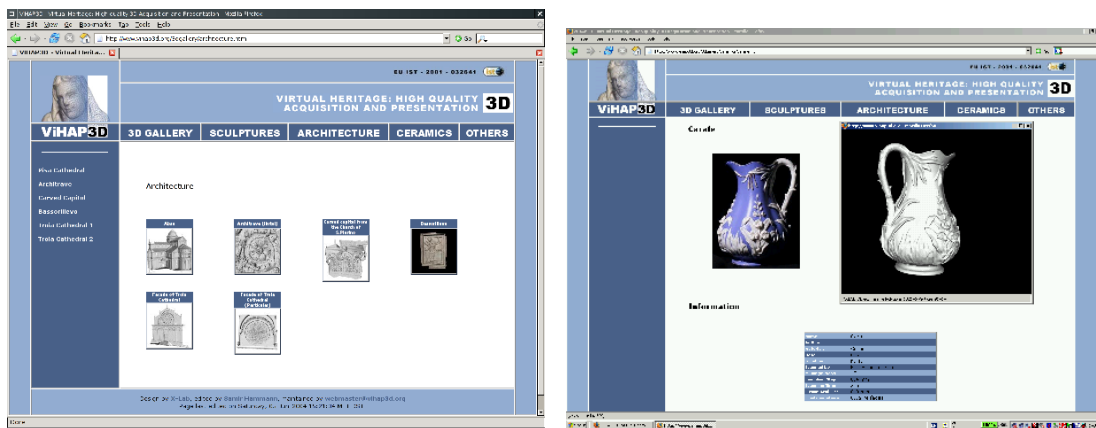


Figure 4.24: Object repository at the ViHAP3D project website.

4.10 Project Impact

The impact of the ViHAP3D project can be measured in various ways including impact on the scientific and cultural heritage community.

4.10.1 Scientific Impact

Several groundbreaking scientific results have been achieved within the ViHAP3D project. These are described in detail in Sections 4.2, 4.3, 4.5, 4.6, and 4.7. One of the highlights is the first system that is capable of capturing and presenting both geometry and surface reflection properties of real objects. Another key achievement is the integration of various new algorithms into the Easy3DScan software, that allows almost fully automatic acquisition of the 3D geometry. The project partners also developed a series of post-processing tools to prepare the acquired data for further use. The virtual heritage tools can be used to arrange the acquired objects in virtual museums

and to automatically create guided tours through the museum. They provide also a way to interactively render individual objects with very high quality on a variety of output devices.

A broad range of articles about many of these achievements has been published in high-profile conferences and journals including 6 publications at the ACM SIGGRAPH Conference (special issue of ACM Transactions on Graphics) and 5 publications at the annual Eurographics Conference (special issue of Computer Graphics Forum) in 2003 and 2004. A complete list of publications by the ViHAP3D project partners during the course of the project is included at the end of this document. The work on the ViHAP3D project contributed furthermore to 16 Masters theses and 7 Ph.D. theses – out of these 10 Masters theses and 3 PhD theses have already been completed.

Another indication for the scientific success is the fact that many of the ViHAP3D tools are used by the leading researchers in the computer graphics and cultural heritage area inside and outside Europe (see the list of current users in Section 4.10.3).

4.10.2 Impact on Cultural Heritage Community

As soon as we were able to present 3D Digital Models acquired with the project technologies, also explaining the relatively low cost of the operation, reactions became enthusiastic among all the people involved in every field of Cultural Heritage Management: the digital replicas' accuracy makes them invaluable in establishing virtual archives of the sculpture heritage, while the visualization systems' flexibility represents a powerful tool for exhibitions, scientific and historical analysis, restoration procedure planning and to frame reconstructive hypotheses of dismantled monuments.

The Italian Ministry for Cultural Heritage is planning to insert 3D digital models in the *culturaitalia* website currently under work; the Italian national Institute for Conservation will include the project's models in its archives and a number of regional, national and international projects are being prepared with the aim of building up digital 3D collections to be inspected by scholars with our tools and to become vehicles of efficient information for museum visitors.

4.10.3 Current System Users

Results will have high impact in the following sectors of productive and formative activities:

- Hardware opto-electronic devices (3D scanning)
- Software tools for the construction of digital models of complex, real 3D objects or works of art.
- Authoring systems and data browsers for the efficient management and presentation of 3D graphics on both distributed and local environments.

- Improved awareness of potentials of 3D virtual representation in cultural heritage fields.

Here follows a list of all the users contacted and involved in the tool assessment. In square brackets is indicated which software package they received (some users declared interest only for part of the ViHAP3D tools):

European Users

- *Dott. Francesco Gravina*, Regione Toscana, Direzione generale delle politiche formative e dei beni culturali, Florence, Italy.
- *Dott. Lorenzo Gonzo*, IRST - ITC, Microsystems Division, Trento, Italy.
- *Prof. Enrico Puppo, Prof. Alessandro Verri*, Dip. Computer Science, University of Genova, Italy.
- *Dott. Maurizio Forte*, ITABC - CNR, Rome, Italy.
- *Prof. Dieter Fellner*, Computer Graphics, Technical University Braunschweig, Germany.
- *Fabio Remondino*, Institute of Geodesy and Photogrammetry, Swiss Federal Institute of Technology, Switzerland.
- *Martina Hansmann*, Kunsthistorisches Institut in Florenz, Max-Planck-Institut, Florence, Italy/Germany.
- *Prof. Javier Finat*, Dpto de Algebra y Geometría, ETS Ingeniería Informática, University of Valladolid, Spain.
- *Juan Carlos Torres*, University of Granada, Spain.
- *em Rafael J. Segura Sanchez*, Dpto. Informatica, Universidad de Jaen, Escuela Politécnica Superior, Spain.
- *Hans Tangelder, Frank ter Haar*, Institute of Information and Computer Science, Utrecht University, The Netherlands.
- *Alexandre Ackermans*, INFORM4, Université Libre de Bruxelles, Belgium.
- *Bruno Mottin*, Centre de Recherche et de Restauration des Musees de France (C2RMF), Louvre, France.
- *Dr. Christian Sevcik*, GeoData IT GmbH, Austria.

Users outside Europe

- *Prof. Anselmo Lastra*, Dept. of Computer Science, Univ. of North Carolina at Chapel Hill.
- *Prof. Paul Debevec*, Institute Creative Technologies, Univ. of Southern California.
- *Prof. Holly Rushmeier*, Dept. of CS, Yale University.
- *Dr. Kevin Cain*, INSIGHT, The Institute for Study and Implementation of Graphical Heritage Techniques.
- *Prof. Ioannis Stamos*, Department of Computer Science, Hunter College and Graduate Center, City University of NY.
- *Dr.-Ing. Christian Frueh*, University of California, Berkeley, Video & Image Processing Lab.
- *Prof. Peter Allen*, Department of Computer Science, Columbia University, New York, USA.
- *Prof. Luiz Velho*, IMPA - Instituto de Matematica Pura e Aplicada, Rio de Janeiro, Brazil.
- *Christoph Held, Prof. Heinz Ruether*, School of Architecture and Planning, University of Cape Town, South Africa.

Chapter 5

Prospects for Exploitation

5.1 Market Structure

The project partners research and development focused on the base technology for capturing and realistically displaying complex 3D objects. This offers an amazing range of applications. In the project we used this technology for preserving, presenting, accessing, and promoting cultural heritage. More specific we focused on *Virtual Heritage* that can be either displayed on stand-alone computers “on site” or distributed to customers over the Internet. Hence, some examples of applications we have in mind are *Virtual Museums* (e.g., distributed as CD-ROM or DVD) or *Distance Learning* via Internet. Since we focused on high-quality measuring and display, this technology will enable unexperienced visual richness.

The ViHAP3D project designed tools for markets which are deeply concerned with cost and productivity issues (caused by limited funding and the often huge amount of objects to be digitized). To be successful in the Cultural Heritage market — as well as in many other market segments — a technology should not only provide superior quality but also needs fulfill these other constraints. The main goal of the ViHAP3D project was therefore to design a cheap, portable scanner adequate to low-budget institutions and applications.

The output of the ViHAP3D project is a new solution for the cultural heritage field including new and effective tools that will open several possibilities for using 3D capture and presentation technology. Our main customers such as museums and restoration institutes can use the products for their daily work as described in the previous chapters. Some parts of the system (especially the 3D scanning component) can however also be used for other applications which can be interesting from an economic point of view:

1. documentation and research
2. reconstruction of objects (3D output available via 3D printers, CNC milling machines, ...)

3. museum shop (selling 1:1 copies of important objects in the museum shop)
4. archiving objects as a 3D dataset (e.g., for future restoration)
5. deformation measurements of paintings and other 2D pieces of art
6. creation of optimal transport packaging (similar to a mold made from protective foam)
7. user assistance tool for restoration

Finally we have to remark that the results obtained in this project are not inherently limited to Cultural Heritage applications, but are of fundamental interest to all research and commercial application areas involving the acquisition and presentation of three-dimensional data. Some examples are:

- The *movie industry* is already using computer graphics to create visual experiences that were previously impossible. Our research will allow digitising real objects so they can be used together with other computer-generated scenes.
- The *video game industry* is also seeking to achieve photorealistic rendering quality. We will enable them to incorporate extremely realistic objects in their games.
- *Online shops* are usually only showing a simple picture of the offered products. It is conceivable that online shops will profit from the conducted research, as they can display their products as high-quality three-dimensional objects.
- The same is true for many other *web sites* that want to attract visitors (architecture, industry, etc.).
- Even *product design* can benefit from our technology. It will allow them to use measured materials and create photorealistic renderings of the designed objects.

5.2 Competitive Products and Services

The biggest advantage of the outcome of the ViHAP3D project over our competitors is that at the moment there is no “complete solution” existing in the market that covers the whole pipeline from acquisition to display. We have developed such a complete solution for the cultural heritage area which allows our customers to preserve, present, access, and promote cultural heritage by means of interactive high quality 3D graphics. This solution will be sold from “one hand” and was developed by leading research institutes in combination with two strong industrial partners. The active involvement of SBAAAS as an experienced and critical model customer gave us huge insights in customers needs and allowed us to develop our products close to the market. Additional input from expert users was provided via the Special User Interest Group

(SUIG) whose input is reflected in the User Requirement Report (Deliverable D2.1). The output of the ViHAP3D project is therefore a unique complete solution. As detailed above, it is however not limited to the cultural heritage area but can be easily extended and applied to several other relevant areas.

5.3 Exploitation Routes

There are two main ways to exploit the results of the ViHAP3D project: Combined exploitation by all partners together (e.g., when the complete solution described above is sold to customers) and exploitation by the individual partners.

5.3.1 ‘Combined Partner’ Exploitation

Main Exploitation activities have been done based on a market analysis. A marketing plan has been created that exploits the future commercialization of the complete solution (acquisition technology, post-processing tools, virtual heritage tools for display). Analysis of the market situation and the exploitation plan yielded two main lines of business which can be developed in order to exploit and commercialize the output: *solution sales* and *services*.

Solution Sales

This line of business consists of selling the ViHAP3D system as complete system to potential customers. The aim is to sell software licenses, and provide the necessary hardware including training and after sales support. Figure 5.1 gives an overview over the solution sales concept.

Services

This line of business consists of offering and selling *services* based on the ViHAP3D products. The aim is to offer and sell services such as a “3D scanning service” or a “virtual museum design service” (see Figure 5.2 for an overview over the service concept). Only the resulting data is then provided to the end users. This service is tailored to users which have a strong need for the ViHAP3D system but cannot afford the required investment into the tools and human resources. A second type of customers for this service are persons and institutions who want to use the ViHAP3D services only for a small number of objects for a relatively short amount of time. In this case, investment into a full solution cannot be justified.

ViHAP3D Exploitation and Marketing Tools

To present the output of the project to potential customers we have installed *ViHAP3D Demo Centers* at five locations (CNR in Pisa, MPI in Saarbrücken, KM in Hannover,

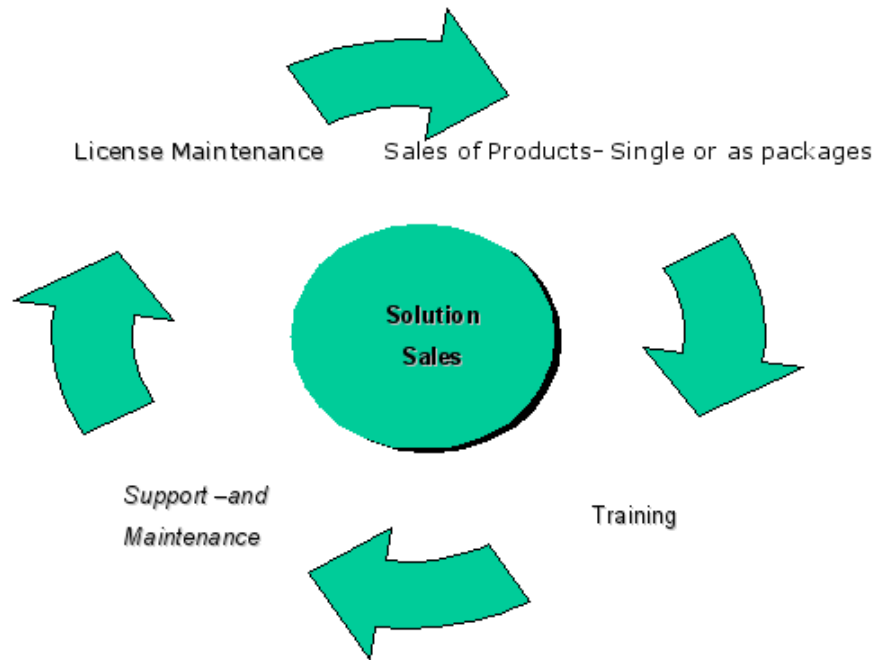


Figure 5.1: Overview over the solution sales concept.

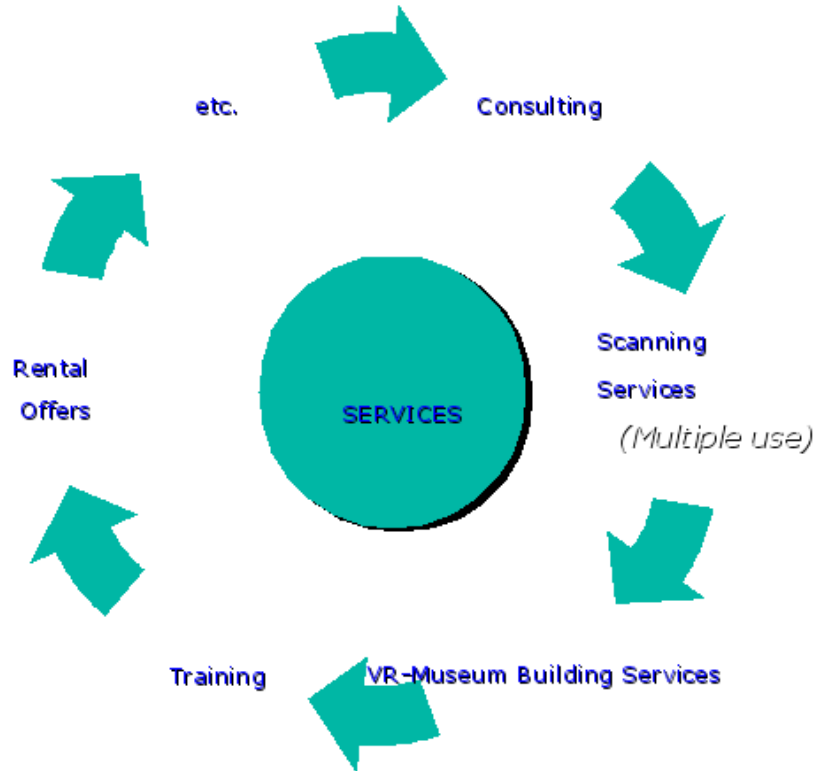


Figure 5.2: Overview over the service concept.

gedas in Barcelona, UPC in Barcelona). In addition, we performed several *Test Installations* at customers sites to further publicise our work.

The ViHAP3D products were also presented fully or in part at several exhibitions and fairs (e.g., in the booth at Restauro in Ferrara) and in talks and presentations at major conferences both in the cultural heritage area and the computer graphics area (see also the overview over dissemination in Chapter 4.8). Individual promotion and marketing activities have been performed with the help of standard marketing tools such as product flyers, CD-ROMs, . . . as well as via press releases and TV documentations.

5.3.2 ‘Individual Partner’ Exploitation

As reflected by the Work Plan (see Chapter ??), each of the research and industrial partners of the ViHAP3D project developed parts of the hardware and the software tools (often in collaboration with one or two other partners). The partners will continue to exploit their work individually, e.g., by basing further research on the current tools as described in Chapter 6.

Some ViHAP3D customers will only be interested in a portion of the project outcome and will therefore not be willing to buy the offered complete solution. The individual partners will therefore also market and sell their software and hardware tools and licenses to such customers.

Chapter 6

Perspectives for Further Research

The knowledge, technology, and expertise developed during the course of the ViHAP3D project can be exploited by selling products and services as detailed in the previous chapter. The project introduced also various scientific advances and breakthroughs documented e.g. by the scientific publications published by the project partners during the course of the project (see Appendix B). These yield excellent perspectives for further development e.g. through the generation of future RTD project proposals within the context of the EC-IST program. The following list shows some possibilities for further development based on the results of the ViHAP3D project:

Integration of 3D Data Captured with Different Devices

For complex scenes it is often required to employ several different 3D scanning devices to capture the full scene. A time-of-flight scanner could e.g. be used to capture the overall architecture of an outdoor scene whereas a laser triangulation system could be used to acquire architectural detail and decorations. The different properties of the sampling devices (e.g., sampling density, sampling noise) makes integrating the data into a single model difficult. Robust and (semi-)automatic algorithms could considerably speed up the integration process and improve the quality of the resulting models.

Texture Mapping and Texture Generation

Sample acquisition performed with the ViHAP3D post-processing tools showed that there is a need for improved tools to map photographic detail (images taken with a standard digital camera) automatically to the scanned models. This requires e.g. in the case of architectural scenes to manage a very large number of input photographs in order to create a very high resolution texture preserving all relevant details.

Extension to Different Material Classes

The current appearance acquisition system is targeted at opaque objects, i.e., objects that reflect the light at the point of incidence. More general object classes such as transparent objects (e.g., glass, transparent plastics) or translucent objects (e.g., marble, skin) require different approaches. Studies performed during the ViHAP3D project show some promising preliminary results for translucent objects and could be used as a basis for further development.

Likewise, current 3D scanning technology is often limited to opaque objects with close to diffuse reflection. As many common objects do not fall into this category, new 3D scanning technologies could be developed that either broaden the class of objects that could be acquired with general scanning technologies or that focus on specific types of objects such as highly specular objects.

Improved Simplification Algorithms

Further research in this area will be carried out by UPC and is focused in different fields: Watertight simplification algorithms based on the generation of Maximal Tiles. UPC has a doctoral researcher, A. Chica, doing his PhD thesis in these algorithms. This research is based on an already started work on extreme simplification.

Out-of-core data structures for interactive navigation in very complex scenes. This will be the PhD thesis of R. Trueba, another UPC researcher. The work integrates the use of triangle strips with octree-based data structure to handle huge geometric models at run time by using external memory management.

Appearance Preserving Simplification for very Complex Scenes. This might be a continuation of the already published Carlos Andujar PhD thesis results. This work was published in the ACM Transactions on Graphics and extended in the Mingle 2003. A further research is focused on improving the image quality of the simplified objects, using an automatic texture generation of the triangulated models.

Improvements in the Way-Finder Algorithm

Automatic path planning for visitors of virtual museums simplifies navigation and improves user experience. The existing algorithm will be extended to be able to avoid furniture in the cell and portal graph, and introduce new criteria for the computation of the path.

Portable VR Systems

New research will focus on creating new low cost VR systems and improving the already existing ones like the Portable System which has been designed during this project. These new VR systems can bring important results for museum applications in a near future.

Chapter 7

Conclusion

The ViHAP3D project has been successful in reaching its objective of preserving, presenting, accessing and promoting cultural heritage by means of interactive, high-quality 3D graphics. The project partners built a unique pipeline to acquire accurate and visually rich 3D models, to apply various post-processing steps to the models, and to present them to expert and laymen audiences using the virtual heritage tools. All parts of the system have been tested in real-life applications. Feedback from expert users from the cultural heritage community and the general audience collected at the museum kiosk, the Saarbücken exhibition, or during ViHAP3D's presence at conferences and fairs shows that there is a broad interest in the developed technologies and applications. Dissemination efforts such as project newsletters and the ViHAP3D web site ensured that people who have a professional interest in the project (cultural heritage sector, computer graphics sector) were in touch with the latest project results.

Finally, all goals and milestones that were defined in the planning of the project have been achieved and all deliverables have been produced in a timely fashion. In the course of the project there has been a fruitful collaboration between the scientific and industrial partners which also led to new ideas and directions for future research and collaboration within the project consortium.

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Appendix A

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<http://www.ViHAP3D.org>

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Appendix B

Selected Scientific Publications by the ViHAP3D Partners

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