From High Precision Color 3D Scanning of Cultural Artifacts to its Secure Delivery Over the WEB: A Continuum of Technology for the Preservation and Delivery of Cultural Heritage

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ABSTRACT: The delivery of cultural heritage using web-accessible formats has been a limited success. The amount of information that can be displayed using standard web technologies remains limited to a disjointed set of text, images, short movie clips, Quick Time VR, and more recently, small 3D worlds and models represented in VRML format. What is really needed is a new technology that will be able to deliver heritage content into a more compelling storytelling form that is as rich as cinema but without its limitations of linear narrative and its inability to interact with its content. This paper presents some solutions to those issues by considering the continuum of technology necessary to deal with the creation, management, and delivery of cultural heritage content.

1 INTRODUCTION

Recent years have seen explosive growth in three-dimensional content. The 3D web content market is predicted to be one of the fastest growing global cultural markets over the next five years with a compound annual growth rate projected at 32 percent through 2007 (Box UK). An expected one million sites will utilize 3D content, accessed through an estimated half a billion 3D-enabled web browsers. This far exceeds any other growth area in the New Media sector.

The delivery of cultural heritage using web-accessible formats has been a limited success. The amount of information that can be displayed using standard web technologies remains limited to a disjointed set of text, images, short movie clips, Quick Time VR, and more recently, 3D worlds and models represented in VRML format. What is really needed is a new technology that will be able to deliver heritage content into a more compelling storytelling form that is as rich as cinema but without its limitations of linear narrative and its inability to interact with its content.

The goals of our research are threefold. First, we are in the process of developing software environments that will help historians and curators to create more compelling stories, emphasizing on key issues laden in complex historical events. Second, we are exploring new ways to collect, access and interpret the material needed for such stories, both for storytelling itself and also for others to access and interpret the stories to make their own tales. Third, we are exploring and testing new technologies to deliver online 3D environments and to develop the necessary technical infrastructure that makes it possible over high-speed networks to get access to this information in a secure way.

In this project, we are exploring the following issues that are critical to the mass delivery of 3D content:

- Development of a truly portable, high-resolution, and robust color 3D digitizing station;
- Development of specialized 3D authoring tools for curators and historians capable of integrating scanned color 3D model of artifacts, buildings, video clip, hypertext, and virtual actors;

- Development of secure client/server technology that can deliver interactive complex 3D worlds on low-end machines using compressed image-based technology such as SGI's VizServer;
- Development of large rendering servers capable of producing high quality images for each participant from 3D virtual model securely located at the server site;
- Development of a high bandwidth, low latency network capable of delivering the rendered images to the end user;
- Evaluation of various system parameters such as compression rate, network bandwidth and latencies and rendering quality on the quality of experience for the end user.

All of these technologies exist as separate components. It takes significant technical effort and skill to deploy them in context. An important objective of this project is to demonstrate mew ways of combining such technologies so that they can be effectively used for collecting, accessing and interpreting cultural heritage online. One can see in Figure 1 a block diagram of the system under construction.

In Section 2, we will describe how high-dimensional resolution (50 micron) and color resolution models can be created using a combination of off-the-shelf equipment. In Section 3, we will describe the current infrastructure capable of creating and managing large repository of cultural information. We will then describe a prototype system allowing curator and historian to tell stories about this cultural heritage. In Section 4, we will describe the current activities in the delivery of this content. We will describe a new architecture for web delivery that is adaptable to the network capabilities and guaranty the secure delivering of large content to a large public.

2 DEVELOPMENT OF A PORTABLE 3D AND COLOR DIGITIZING STATION

For cultural heritage applications, systems that are capable of digitizing artifacts rapidly and safely are still under investigation in many laboratories and cultural institutions around the world. An excellent review of the current state-of-the-art of these digitizing systems can be found in Blais (2004). The problems with digitizing cultural artifacts are that their shapes and material properties are usually very complex making the digitizing process very difficult. Some of the problems associated to the digitizing of these artifacts include:

- Objects have a wide dynamic range of surface reflectivity ranging from specular, to transparent, to truly dark matt surface;
- Objects have occlusions and cavities;
- Objects have large variations of surface roughness ranging from fine detail structures to rough chisel marks;
- Objects are not only rigid but also soft and articulated;
- Objects have imported information not only in the visible spectrum.

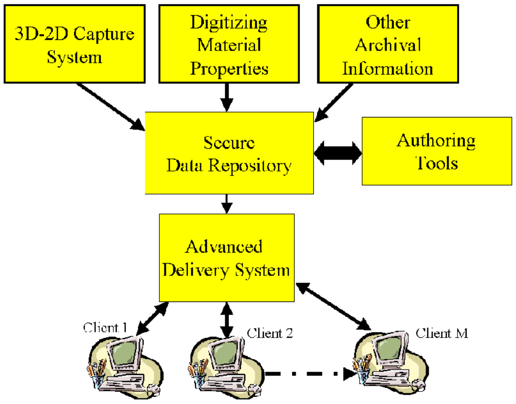


Figure 1: Block diagram of the system under development

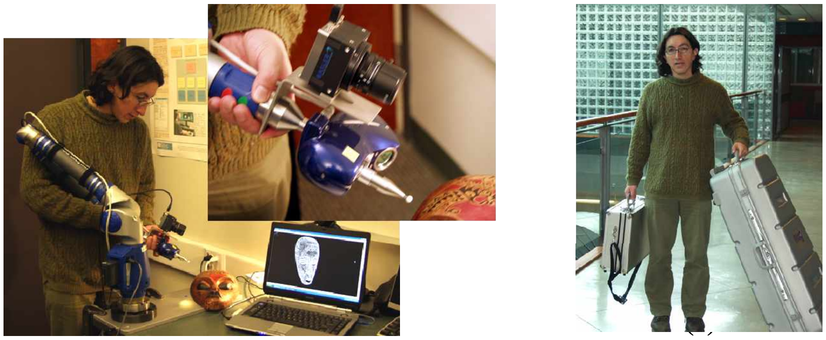
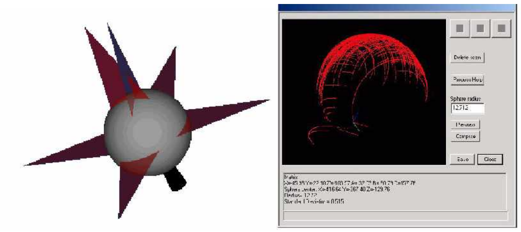


Figure2: (a) UofA color and shape digitizing station and (b) its carrying case.

In may projects, only a small fraction of the museum collections can be digitized because of the limitations of many 3D digitizers to deal with the very hard requirements of digitizing complex artifacts. Museum curators are frequently frustrated by those limitations constraining them to only digitize rigid objects like statues and jewelry that may have a limited importance for the story they need to tell. This is why in many instances museums have resorted to image-based rendering techniques (Debevec 2003) that show the apparent structure of an artifact without any need for the measurement of exact geometry. Image based methods require very little technology to create acceptable images for the creation of websites and catalogs and in many cases, this technology is sufficient, as illustrated by today's many virtual museum website.

The main drawback of image-based rendering is that the true shape of the object is not really known and if the purpose of the digitizing process is to create a permanent record that would allow in the future curators to reconstruct these artifacts if by accident, pollution, or wars they are destroyed partially or completely. Also, image-based rendering do not really allow for the dimensional monitoring of the artifacts a key element in preservation. From those requirements, we have designed a new digitizing station that tries to address some of those issues. One can see in Figure 2a a picture of the digitizing station developed during this project and in Figure 2b the carrying case used for transport. As one can see the digitizing station, can be easily transported by one person around the world allowing for digitizing artifacts where they reside at various cultural institutions.

The system is composed of a FARO digitizing arm of 15 microns precision where a 4 mega pixels color digital camera and a laser scanner is attached to the end effecter to digitize respectively the color and the shape of the object. The digital color camera is a Basler A403KC capable of delivering 4 mega pixels at 48Hz. The sensor is a Bayer CMOS area scan at a resolution of 2352(H) X 1727(V) pixels. The Kéon scanner is a line scanner capable of digitizing 3500 pts/s at a tested precision of 50 microns. In addition to these sensors, a touch probe capable of a precision of 15 microns is also added to the system to deal with regions that cannot be digitized by the laser scanner. The digitizing process consists of painting the object with the arm and digitizing enough 3D points on the object surface to get a complete surface coverage. In order to integrate the color and 3D information a calibration procedure was developed. Since the Kréon range sensor is a range profiler the position of the arm at the beginning of each scan is determined by reading the high precision joint encoders where the position and orientation of the end effecter is determined in real time. The vector $p_a(t)$ and $o_a(t)$ represents the position and orientation of the end effecter at time *t*. The transformation between the end effecter and the central coordinate system located at the base of the arm is represented by a quaternion matrix $M_a(t)$ and is continuously updated by the arm hardware. The calibration of the arm relating joint encoder readings to the actual position of the end effecter is performed in factory at very high precision (15 microns). Since the range sensor is not located at the end effecter an estimate of the transformation matrix M_r between the range data in sensor coordinate system and the end effecter is necessary: this process is called positioning. Each profile measured by the range sensor $p_r(t)$ is positioned in the central coordinate system as expressed by:



(a) (b)

Figure 3: Positioning process: (a) six scanning views and (b) fitted sphere as displayed in Polygonia (Kréon) digitizing environment.

$$p_c(t) = M_a(t) M_r p_r(t)\,. \tag{1}$$

The estimate of M_r is computed by scanning a high precision steel ball of 12.5 mm in radius from six viewpoints as illustrated in Figure 3a. The goal of the positioning procedure is to compute the value of the matrix M_r that minimizes the error between the scanned profiles and a model of the sphere using a mean square error method. If the process is successful, the residual of the fitting error should be in the order of 60 microns corresponding to the final precision of the combination of the arm precision and the range sensor precision. One can see in Figure 3b an illustration of the positioning result after sphere fitting.

2.1 *Registration of the Color and the Range*

In addition to determining the position of the range sensor one must also determine how a point in 3D space falls into the color camera allowing us to compute its color or its texture coordinate. A point $\check{p}(t) = [X(t), Y(t), Z(t), 1]^T$ in the central coordinate system will be imaged by the color sensor if we know at all time the position of the camera and its perspective transform: external and internal camera parameters. The transformation of a point in the central coordinate system to a position $\check{v}(t) = [u_o(t), v_o(t), 1]^T$ in image coordinate system is expressed by:

$$\begin{bmatrix} u_o(t) \\ v_o(t) \\ 1 \end{bmatrix} \approx \begin{bmatrix} f_u & s & c_u \\ 0 & f_v & c_v \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} M_c M_a(t) \begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \\ 1 \end{bmatrix} \tag{2}$$

The matrix M_c is the correction between the position of the arm end effecter and the optical center of the camera. The parameters $f_u = \dfrac{f}{p_u}$ and $f_v = \dfrac{f}{p_v}$ are the normalized focal length of the camera. The parameters p_u and p_v are the width and height of the pixels and the parameters c_u and c_v are the coordinates of the principal point. The parameter s represents the skew factor due to non-rectangular pixels $s = (\tan\alpha) f_v$. The parameter α is the skew angle between the optical axes. If the intrinsic and extrinsic calibration parameters of a camera can be completely estimated at all time one could compute for any measured point its corresponding color. Equation 2 can be simplified to:

$$v(t) \approx P_c M_c M_a(t) p(t) \tag{3}$$

where the $3 * 4$ matrix P_c is the camera projection matrix.

Even though the pinhole camera model is a good first order approximation, it is not sufficient to do high precision work since it is only valid for paraxial rays. Non-paraxial rays require a more complex model to describe their behavior. Because of limitation in lens, one must model higher order effects such as lens distortions. These distortions include: chromatic aberrations, astigmatism, and radial distortions to name a few. In well-built lens, chromatic and astigmatic aberrations are compensated and can be in general considered negligible. The only dominant terms are usually the radial distortions. To correct the effects of radial distortion the centre of distortion (in most cases the principal point) must be estimated first. It is then used by a radial transformation function that re-map pixels rays into its first order equivalent. The following equations express the relationship between a distorted point at coordinates $(u_0, \quad v_0)$ and its undistorted location at coordinates $(u, \quad v)$:

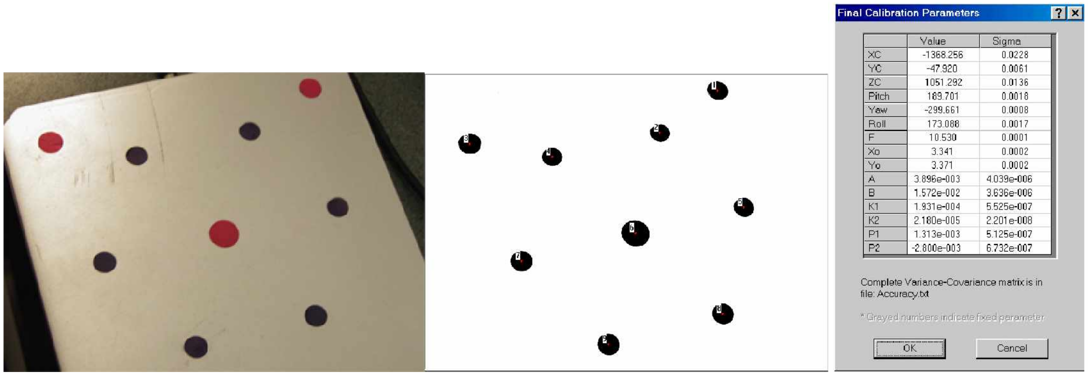
$$u = u_o + (u_o - c_x)(K_1 r^2 + K_2 r^4 + \ldots) \tag{4}$$

$$v = v_o + (v_o - c_y)(K_1 r^2 + K_2 r^4 + \ldots) \tag{5}$$

where K_1 and K_2 are the first and second parameters of the radial distortion and *r* is defined as $r = (u_o - c_u)^2 + (v_o - c_v)^2$. It is important to note that any modification to the focal length produces a change in the values of K_1 and K_2. In the current setup, the focal length of the lens is kept constant. In order to estimate the internal and external parameters of the camera system a calibration procedure was developed. The calibration procedure can be summarized as follows:

- Acquire the images of the patterns illustrate in Figure 4a with the camera from at least three viewpoints; the 3D center of each circular region is first determined using the touch probe of the arm where a circle is fitted to the points. The circle center is determined at a precision of ~15 microns.
- Extract from the images the target center in pixel coordinates by using an adaptive thresholding technique as illustrated in Figure 4b;
- Compute the camera parameters using a non-linear bundle adjustment algorithm.

A description of the camera calibration method used in this paper can be found in El Hakim (1996). In this paper, the authors present a complete two-step method for calibrating cameras. The first step is to find the epipolar transformation by either the Sturm's method or by the use of the fundamental matrix. Then the intrinsic parameters of the camera are found from the equation of the absolute conic and the Kruppa equations (Faugeras 1990). In order to do so, the algorithm starts by detecting the center of the targets illustrated in Figure 4b using a segmentation technique based on adaptive thresholding. Following this foreground/background segmentation the position of the target is determined at sub-pixel accuracy using a moment method (El Hakim (1996)), which is, known to be very accurate and robust. From the computed target positions in image space and their positions in 3D space, the targets are identified and the solution to the non-linear calibration matrix problem including aberration is computed using a very stable non-linear



	Value	Sigma
XC	-1368.256	0.0228
YC	-47.920	0.0061
ZC	1051.292	0.0136
Pitch	189.701	0.0018
Yaw	-299.661	0.0008
Roll	173.088	0.0017
F	10.530	0.0001
Xo	3.341	0.0002
Yo	3.371	0.0002
A	3.896e-003	4.039e-006
B	1.572e-002	3.636e-006
K1	1.931e-004	5.525e-007
K2	2.180e-005	2.201e-008
P1	1.313e-003	5.125e-007
P2	-2.800e-003	6.732e-007

Complete Variance-Covariance matrix is in file: Accuracy.txt

* Grayed numbers indicate fixed parameter

(a) (b) (c)

Figure 4: (a) Picture of the target assembly, (b) targets localization using Shape Capture, and (c) typical output of Shape Capture calibration program.

bundled adjustment algorithm. To make sure this procedure is accurate, we used a commercial photogrammetric package called *Shape Capture* (http://www.shapecapture.com).

The calibration procedure of this package is known to procedure very accurate results that are in the order of one part in a million for 5 Mega pixels cameras. It implements the so-called standard photogrammetric calibration model, an industry standard in the field of metrology. One can see in Figure 4c a typical output of the program.

The positions matrix M_c is then estimated by solving the following minimization problem for all target centers:

$$\min_{M_c} \left\| P'(t) - M_c M_a(t) P(t) \right\| \tag{6}$$

where $P'(t)$ is the computed position of the target center estimated in the camera coordinate system by the photogrammetric software.

2.2 *Demosaicing*

One of the key elements for the measurement of color in heritage applications is the ability to calibrate color according to some known standards. A color image requires at least three colors sample at each pixel location to represent an estimate of the real color spectrum. In theory, a color camera should need three separate sensors to make these measurements. To reduce size and cost, many cameras today use a single 2D sensor with a color filter array placed in front of the sensor. The color filter array allows only one color to be measured at each pixel. This means that an estimate of the missing two color values at each pixel must be performed using a process known as demosaicking. The most common array is the Bayer color pattern shown in Figure 5. Green pixels are measured at a higher frequency because the peak sensitivity of the human visual system resides in the medium wavelengths, corresponding to the green portion of the spectrum. Because the pixels are not defined in the standard RGB format, an interpolation process must be used. One can find in Gunturk et al. (2005) an excellent review of various demosaicing techniques.

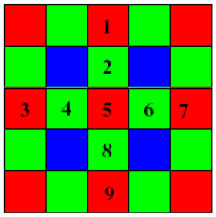


Figure 5: Bayer color pattern

In this paper, we have implemented a simple edge-directed interpolation algorithm as described in this paper. The algorithm consists of detecting a local edge, and to interpolate color only along the edge instead of across it. Edges are detected only horizontally or vertically, and the interpolation is used only on the green channel since it has more information. The algorithm is the following:

1. $\Delta H = | R3 - R7 |$ and $\Delta V = | R1 - R9 |$
2. if $(\Delta H > \Delta V)$ $G5 = (G2 + G8)/2$
3. else if $(\Delta V > \Delta H)$ $G5 = (G4 + G6)/2$
4. else $G5 = (G2 + G4 + G6 + G8)/4$

The situation for green interpolation of a blue pixel is analogous.

2.3 *Color Balance*

In addition to demosaicing, one needs also to color balance the image relative to some standards. A white balancing algorithm is composed of two main parts. For color balancing, the system analyzes the image and uses a statistical method to estimate the current ambient lighting conditions. Second, using this estimate, the system converts the acquired image into a format that is appropriate for the targeted rendering environment. For this purpose, we use the tri-stimulus color space XYZ as a reference (Wandell & Farell 1993). The process of color balancing and calibration consist of showing to the Bayer sensor a Mac Beth color chart illuminated by uniform lighting as illustrated in Figure 6. For each color sample, we know the value of the color in the standard XYZ color space. Mathematically the process of color calibration consist in computing the linear transformation, *L*, that maps the camera RGB values into the surface XYZ value relative to the standard reference defined by the Mac Beth color map. The Mac Beth color map is first segmented for foreground/background using an adaptive threshold technique. Then each colored sections is identified and labeled as a connected component. An average of the RGB values is computed from the Bayer pixels for each region. The RGB of each region are represented by a matrix S of size 3xN and the known corresponding XYZ values expressed by a matrix X of size 3xN. The process of color calibration consist on finding the linear transformation matrix L that minimize the following error metric:

$$\min_L \left\| LS - X \right\| \tag{7}$$

The matrix L that minimizes Equation 7 is obtained from computing the pseudo-inverse of S. As defined by:

$$L = XS^t (SS^t)^{-1} \tag{8}$$

As discussed in Wandell & Farell (1993) the quality of this linear transformation is determined by respecting its assumptions of constant illumination and the fact that the material should

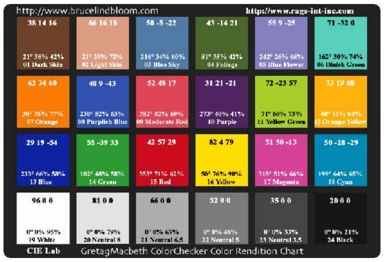


Figure 6: Mac Beth color calibration chart with corresponding XYZ values.

(a) (b)

Figure 7: Color calibration of image texture: (a) before color calibration, and (b) after color calibration.

be perfectly diffusive. In our current implementation, we use a photographic quality Mac Beth target and compute the color before demosaicing to avoid the influence of color interpolation in the color balance process. One can see in Figure 7a the original image of an Indonesian mask and in Figure 7b the corrected colors using this technique.

2.4 *Model Integration and Coloring*

Once all sensing modalities are calibrated and registered, one can start the process of model building. In this process, we use Innovmetics toolkit called Polyworks to perform most of these operations. One can see in Figure 8a to 8d an illustration of the processing pipeline. The only difference for this application is that we rely on the mechanical registration to provide the registration between the views.

There are two ways to create models in this framework. The first one is to compute for each scanned data points its color by back-projecting the points onto the color camera and then to use Polyworks-processing pipeline to combine the scanned images and to create a model represented as color per vertex. One of the advantages of this approach is that the object can be manually moved during the scanning process allowing the operator to digitize regions that would be hard to reach using the scanning arm. The main disadvantage of this method is that one needs to digitize a large amount of 3D data points in order to get a good resolution on the texture.

The second mode of operation consists in creating a good geometric model first and then to color the model afterward by simply painting the texture onto the 3D model. One advantages of this process is that the geometry of the model can be reduced significantly and high-resolution textures can be acquired to represent the artifact at visual high-acuity. The main disadvantage of this method is that the model cannot be moved in front of the scanner or if it is a re-registration process must be first performed. After numerous considerations, the second mode of operation was considered the one capable of producing visually a better 3D texture model as illustrated in Figure 8d.

(a) (b) (c) (d)

Figure 8: (a) Color coded multi-views using mechanical registration, (b) merged views at full resolution (466435 triangles), (c) compressed version at 1.0 mm precision (11962 triangles), and (d) textured model (11962 triangles) using the texture illustrated in Figure 7b.

3 AUTORING TOOLS FOR THE MANAGEMENT AND CREATION OF LARGE HERITAGE DATABASE

Digital cultural content in the form of three-dimensional representations provides innovative tools and new ways for researchers, historians, anthropologists, archeologists, architects, environmental and urban planners and students to conceptualize, study and learn about historical events and cultural places. Three-dimensional representations afford learning beyond what images and print can provide by facilitating the exploration of temporal, spatial and causal relationships inherent in historical events and cultural stories. The objective of this work is to design a state-of-the-art 3D learning environment. The aim is to facilitate, through the exploration of virtual worlds, the creation of stories so that storytellers can create, refine and interrelate stories from several perspectives and so that story viewers can start, pause, replay and otherwise explore stories online. In order to do so we have integrated a series of commercial multimedia tools capable of creating advanced 3D multimedia environment that support storytelling. In many ways those tools are very similar to the one used by the game industry. These tools included modeling software such as Maya 5 for the creation of 3D environment housing the artifact digitized by the 3D sensors and to create virtual characters populating the virtual world. In addition to Maya, we also used VR Creator from Multigen to create and optimize 3D scene graph allowing us to combine 3D, 2D, sound, virtual lighting, and computer animation of virtual characters into a coherent multimedia experience. Even though some of those tools have a steep learning curve, we were able to demonstrate that they are at the reach of most social scientist. Using these tools, we were able to create compelling immersive world that were fun, interesting, and were able to convey a story. To help the creation of those 3D virtual environments, an integrated repository system for storing, accessing, delivering and interpreting stories was developed. One can see in Figure 9 a block diagram of the system developed during the project. Our objectives were to devise, implement, use and test a generic repository for visual material related to cultural disciplines such as architecture, art and heritage. Our design abstracts from the particular requirements of, for instance, slide collections, interpretive essays, museum exhibitions, lectures or student work-posting, and implements a set of common features based on the metaphor of a gallery. To achieve this aims a significant amount of heritage content had to be sourced and copyright cleared and then generated, scanned, digitized or modeled to form a rich array of 3D artifacts, peoples, buildings and landscapes. In order to deal with this large array of heterogeneous material a special type of database system had to be used. At the end, we decided to use Antarctica's Visual Net software. Visual Net makes shared information more accessible through visual interfaces, intuitively guiding people to results they can see. Unlike text-based search tools, Visual Net creates browsable maps to graphically display results and their relationships enabling people to navigate and find information more intuitively and efficiently. In this implementation, over 5000 cultural artifacts were cataloged and integrated in the database.

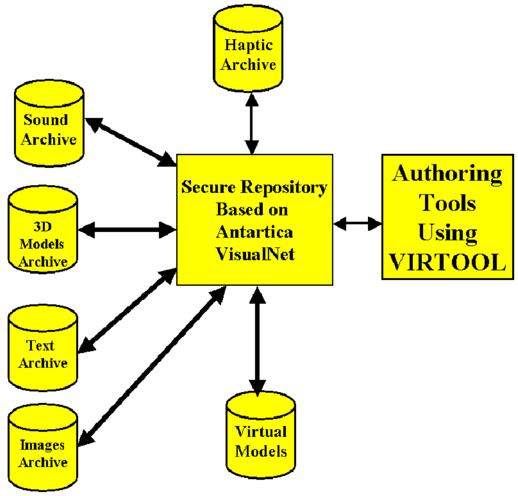


Figure 9: Block diagram of Data Repository System.

4 SECURE DELIVERY OF CULTURAL HERITAGE CONTENT OVER A BAND LIMITED NETWORK USING VISUAL AREA NETWORKING

As we have argued previously, access to heritage content is limited in many ways. A technical "solution" around such limitations is to model objects in a variety of ways and make models and their visualization accessible through online environments. Such a "solution" ignores very real issues in who should have access to complete descriptions of artifacts. Many artifacts are culturally sensitive and, clearly, should not be widely copied in a form sufficient for facsimiles to be readily manufactured. Good solutions can be found in image-based virtual reality and remote visualization via rendered images as supported by SGI VizServer technology. Both of these technologies support remote visualization on low-end computers. Both provide some assurances for the secure transmission of precious heritage data. We are currently developing a client/server technology that will expand SGI VizServer software to the realm of cultural heritage delivery. By adding watermarks and a few other security features, it will be now possible to deliver to low end-users high quality visualizations without the need to transmit sensitive information except images over the Internet. It also solves the problem of viewers using low-end machines, since most of the high-end rendering will be performed on large remote machines. One can see in Figure 10 a block diagram of the delivery system developed so far. A similar mode of delivery was recently proposed by Koller et al (2004) for the online delivery of the Michelangelo data set.

Our system is very similar except that it is based on the video compositor technology from SGI that combines video transmission and compression in hardware. One advantage of using this technology instead of using a dedicated render farm as in Koller et al. (2004) is that each server machine must have a copy of the 3D model to deliver the images to a client limiting its scalability. Our system use SGI advanced multi-pipes technology based on a shared memory infrastructure where only one copy of the 3D model is need to reside in core memory for the various rendering pipes. The power of the server can be increased at will by adding low cost rendering pipelines and there is no limit to the size of the database residing in memory. In addition, because of the centralized management of the rendering process, collaborative visualization is made easy.

5 CONCLUSION

In this paper, we demonstrate a framework that integrates the creation, management and delivery of cultural information. On the content creation side, we were able to develop with off-the-shelf equipment a true portable high-precision digitizing station that can capture at the same time shape and color. We had two design goals; one was to make sure that cultural institutions could easily copy this system without the need for expensive hardware development. Second, we made sure that the digitizing system was simple enough that it can be used by the average museum curator or by archeologist during their fieldwork. On the management and content creation side, we were able to show that VisualNet is an excellent database software for heritage applications. It was easy to classify and search the data even though its heterogeneous content. By using commercial modeling software such as Maya and VRCreator we were able to show that these tools can be used by historian and curators to tell compelling stories about the past. Unfortunately, all these programs are independent and are not really specialize for heritage content creation. In the next phase of this project, we will try to combine the functionality of these programs in an integrated environment more suited for historian and curators. Early testing of the delivery system using a modified version of SGI Vizserver demonstrates clearly that Visual Area Networking is a key element to the future deployment of on line delivery of 3D cultural content. This technology has tremendous cultural ramifications. This means that eventually everybody owning a low-end PC could be immersed in three-dimensional interactive environments as a means of learning, working and playing. It also guaranty that cultural institutions can now deliver securely 3D information to a large public, a key issue that in the past stopped the deployment of such systems. In addition, by centralizing the production of images, cultural institutions can guaranty to end user high quality content and images on various display devices such Pocket PC to large screens in VR theaters located in museums.

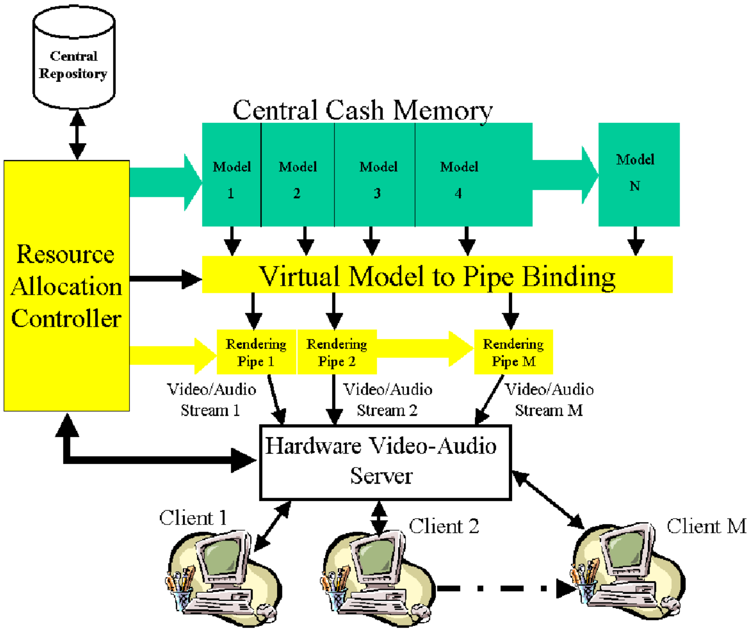


Figure 10: Block diagram of the delivery system.

REFERENCES

Blais, F. 2004. Review of 20 Years of Range Sensor Development. *Journal of Electronic Imaging*, 13(1): pp. 231-240.

Debevec, P. 2003. Image-Based Techniques for Digitizing Environments and Artifacts. *Proc. of the 4th International Conference on 3-D Digital Imaging and Modeling (3DIM'03)*, Banff, Alberta, October, pp. 234-242

El-Hakim, S. F., Beraldin, J.-A., Godin, G., and Boulanger, P.. 1996. Two 3-D Sensors for Environment Modeling and Virtual Reality: Calibration and Multi-view Registration. *International Archives of Photogrammetry and Remote Sensing*, Volume 31, Part B5, Commission V. Vienna, Austria. July 9-19, pp. 140-146.

Faugeras, O.D. & S.J. Maybank, 1990 "Motion from point matches: multiplicity of solutions". The International Journal of Computer Vision, 4 (3): pp. 225-246.

Gunturk B.K., Glotzbach J., Altunbasak Y., Schafer R.W., and Mersereau R.M.,. 2005. Demosaicking: Color filter array interpolation in single chip digital cameras. *IEEE Signal Processing Magazine (Special Issue on Color Image Processing)*, in press.

Wandell B.A. & Farrell J.E. 1993. Water into Wine: Converting Scanner RGB to Tristimulus XYZ. Proceedings of SPIE Vol. 1909, pp. 92-100.

Koller D., Turitzin M., Levoy M., Tarini M., Croccia G., Cignoni P., and Scopigno R.

2004. Protected Interactive 3D Graphics Via Remote Rendering. ACM Trans. Graph. 23(3): pp. 695-703.