Active Optical 3D Imaging for Heritage Applications

Guy Godin, J.-Angelo Beraldin, John Taylor, Luc Cournoyer, Marc Rioux, Sabry El-Hakim, Réjean Baribeau, François Blais, Pierre Boulanger, Jacques Domey, Michel Picard
National Research Council of Canada

High-resolution 3D imaging and modeling is an important application in the heritage field. We describe several demonstration projects conducted in collaboration with museums and conservation agencies.

Recently, sensors and algorithms for 3D imaging and modeling of real objects have received significant attention in the computer vision and graphics research fields. The capacity to create, display, and manipulate a high-resolution 3D digital representation of an existing object's shape and appearance can play a significant role in the area of heritage, comprising museum collections and archaeological objects and sites.

The Visual Information Technology Group of the National Research Council of Canada (NRC) has designed and tested several 3D laser imaging systems and processing algorithms dedicated to the high-resolution modeling of complex objects and environments. While we also targeted areas as diverse as manufacturing, space robotics, and anthropometry, it became evident from the outset that heritage conservation and documentation would provide a major thrust for our research.[1] Heritage applications, especially those aimed at analytical tasks, pose high requirements on the data quality and the processing and visualization of the results (see the "Related Projects" sidebar). By their nature, museum collections provide a wide gamut of sizes, complexity, materials, and tasks for 3D imaging.

To gain a better understanding of the numerous issues in using the technology for heritage documentation, we initiated several pilot projects. Each one let us test and improve different aspects of its application to museum objects in the lab and at remote sites. We conducted these projects in collaboration with Canadian and international partners from museums and heritage organizations. Such collaborations provided invaluable first-hand experience and feedback in assessing the usefulness and relevance of the technology as well as a real-world context to identify possible technological improvements and further research directions.

In this article, we provide an overview of the heritage applications of our 3D imaging and modeling capabilities through several of our demonstration projects. These projects cover typical museum collections such as paintings and ethnographic and archaeological objects as well as field recording of archaeological site features, architectural elements, and large sculptures. For each sample project, we outline the particular challenges and lessons learned from the perspective of 3D imaging and modeling as well as of the specific application.

Model acquisition and construction

A high-resolution 3D model contains a wealth of information available for analysis. We can interactively examine features that are extremely small or only visible from

Related Projects

Several projects target constructing dense 3D and appearance models of works of art or archaeological sites. We mention a few representative samples here. A group from IBM[1] used a combination of structured light 3D sensing and photometric stereo to model Michelangelo's *Florentine Pietà*. In a large-scale project initiated by Stanford University,[2] seven of Michelangelo's sculptures were modeled, as well as other artifacts including the parts of the *Forma Urbis Romae*. A European project called Esprit Archatour (EP9213)—see http://www.newcastle.research.ec.org/— digitized and modeled sculptures using active range sensing. The Italian National Research Council in Pisa, Italy, developed and demonstrated acquisition and processing systems dedicated to heritage.[3] A group from the University of Tokyo built shape and appearance models of the 15-meter bronze Great Buddha in Kamakura.[4] Another recent project[5] focused on Internet-transmittable 3D digital models of some architectural elements of the Roman Coliseum.

a distance, thus allowing the study of fine details such as tool marks or surface texture. We can apply computerized visual enhancement and analysis techniques to the digital model. We can also use the model as the basis for restoration or reconstruction work.

The construction of the models of real objects requires the ability to explicitly measure surface geometry (see the sidebar "Optical Geometric Measurement") and to transform all the acquired information into a convenient representation. Our approach is to acquire high-resolution geometric models of the surface from a set of laser range images. When available, we also include appearance measurements as the parameters of a reflectance function. The model representation we use is a triangular mesh, at a sampling resolution comparable

Optical Geometric Measurement

Attempts to capture shape by optical means date back to the early days of photography. In the 1860s, François Villème invented a process known as *photosculpture*,[1] which used a set of 24 cameras. Profiles of the subject to be reproduced were taken on photographic plates, projected onto a screen with a magic lantern, and then transferred to a piece of clay using a pantograph. Studios opened in Paris, London, and New York, and stayed in operation from 1863 to 1867, when it was realized that the photosculpture process wasn't more economical than the traditional sculpture technique. A professional sculptor was still required for finishing the pieces, and the photosculpture process required a substantial investment in cameras, projection and reproduction systems, and skilled labor.

It's only with the advent of computers that the goal of capturing shape by optical means has regained substantial interest, more than a century later. Interestingly, one of the applications initially targeted by one of the first manufacturers of commercial 3D sensors was also the automation of personal portrait sculptures (see http://www.cyberware.com/info/backgrounder.html).

The use of photographs, and now of digital cameras, for geometric measurement is well established in the photogrammetry and computer vision fields. Through a combination of multiple views and careful camera calibration, we can recover the position of features in the scene at high accuracy. Such techniques that operate under ambient illumination are called *passive*. However, they can't provide measurement on surface without detectable features of sufficient density and contrast. For critical measurement situations, high-contrast targets are added to the surface for easier identification and localization. However, in most heritage applications, affixing targets on the objects isn't an acceptable solution. Furthermore, natural features on the surface may not be appropriate for a sufficiently dense or accurate recovery of surface geometry.

Active techniques avoid these limitations by creating features on the surface by the controlled projection of light. Detailed reviews and comparison of active optical sensor technology are available elsewhere.[2,3] A range sensor provides surface geometry measurements in the form of a range image, which is an array of 3D point coordinates. The scanning and imaging configurations determine the sampling density.

Active optical sensors fall into two broad categories. Time-of-flight systems measure (directly or indirectly) the delay between emission and detection of light reflected by the surface. Triangulation systems project light in a known direction from a known position and measure the direction of light returning through a known observation position. Hence, since a triangle is completely defined by one side and two adjacent angles, we can compute the position of the illuminated point with regard to the system. Triangulation systems differ from one another by the nature of the controlled illumination (laser or incoherent light), its geometry (beam, sheet, or projected pattern), and the return angle's detection mode. Other degrees of freedom required for surface coverage with beams and sheets are provided by mechanical displacement of the system or of the object, or by scanning mirrors. In the short measurement range (about 0.2 to 2 m), almost all current lab prototypes and commercial systems are triangulation-based. At the other end of the spectrum, some time-of-flight systems can measure distances in the kilometer range.

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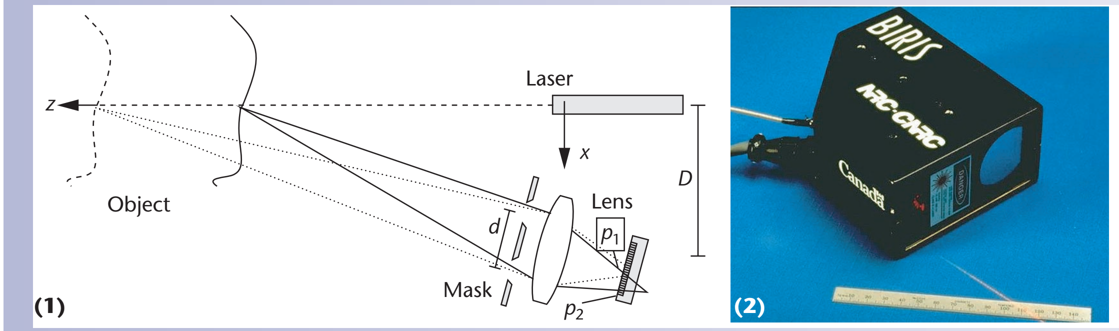
NRC 3D Sensor Technology

Our group at the National Research Council of Canada has designed and built many sensor prototypes, each targeting a different class of applications or operational conditions. While all of them are triangulation-based, they exploit two basic optical configurations.

The Biris class of sensors (see Figure A) was originally developed to work in difficult environments where reliability, robustness, and ease of maintenance are as important as accuracy. It combines plane-of-light triangulation with a dual aperture mask inserted in the detection system. This technique, when combined with advanced signal-processing algorithms, yields a high tolerance to ambient illumination, especially sunlight. Because an entire profile is acquired at once, one additional degree of freedom is required for imaging, usually provided by mechanical rotation or translation of the sensor head.

Another class of sensors developed at NRC uses the autosynchronized spot-scanning principle.[1] This configuration differs from the usual spot triangulation in that the directions of projection of the laser beam and the detection system's optical axis are rotated synchronously, through a double-sided mirror (see Figure B1). This means that the instantaneous field of view of the position detector follows the spot as it scans the scene. The lens' focal length is therefore related only to the desired depth of field or measurement range and not to the total lateral field of view. Implementing this triangulation technique yields a considerable reduction in the optical head size compared to the conventional triangulation method. Additionally, optical synchronization achieves an improvement in ambient light immunity due to a small instantaneous field of view. Speckle noise is also reduced through spatial filtering. This configuration alleviates the usual compromise between field of view, resolution, and shadow effects.

We've implemented several prototype sensors using the autosynchronized configuration, with different trade-offs between resolution, depth of field, and sampling speed. One important variant of this system adds the capacity for color reflectance estimation to the geometric measurement. A polychromatic laser beam (here, a three-wavelength RGB laser) is used for illumination. On the scene, the laser light appears white (see Figure B2). At the collection side, the same linear position sensor used for range measurement receives each wavelength after separation using a collinear dispersive optical element close to the collecting lens. This particular technique provides the key benefit that the geometric and color measurements are performed simultaneously and in perfect geometric registration on the surface. This avoids the issues of parallax and errors in calibration and registration encountered when obtaining color from auxiliary cameras. Furthermore, lasers provide well-defined

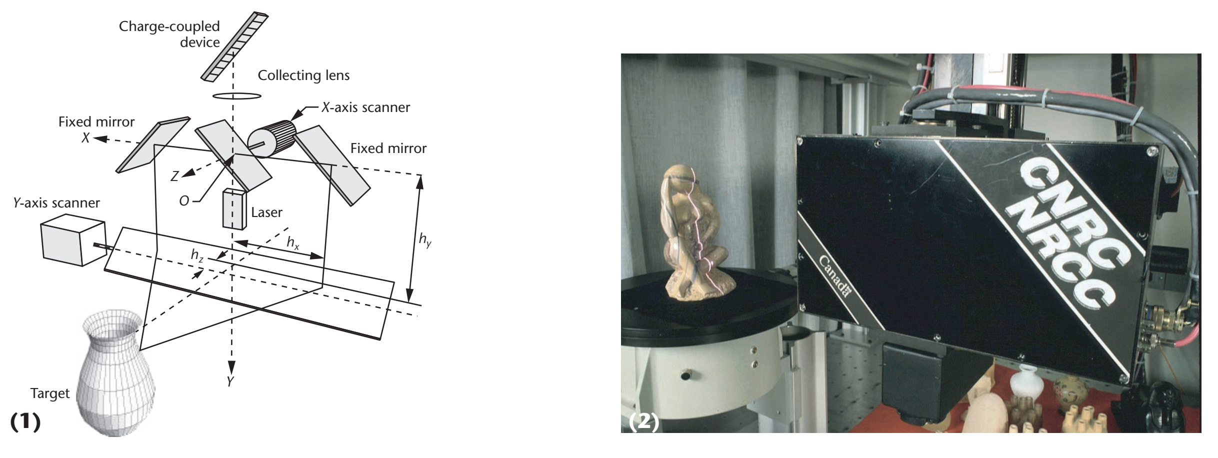


A **Biris sensor. (1) The optical principle combines triangulation with a double aperture mask to improve the robustness of the laser line detection. (2) The head is compact and rugged.**

to the original geometric data, with a color-per-vertex description of a diffuse reflectance model. This generic representation embeds all the information gathered by the sensing process. We can then perform analytical tasks on the model (or in some cases on the original data). This model also fits directly with current polygon-based rendering hardware. We can derive other representations for display purposes from the high-resolution model, including texture-mapped compressed models or point-based rendering. However, the high-resolution mesh remains as the archival-quality digital recording or 3D digital reference model of the object or scene.

Laser range sensing provides an explicit measurement of the surface geometry, in the form of an array (or image) of 3D surface measurements. Our research on 3D sensors has always been influenced by the requirements of heritage documentation. One thrust is toward maximizing the resolution and accuracy of the geometric measurements, coupled with the ability to estimate surface reflection using a polychromatic laser (see the sidebar "NRC 3D Sensor Technology"). Our work also targets portable, rugged, and rapidly deployable systems.

In heritage applications, a single range image often suffices to perform a task, such as detecting and monitoring cracks or documenting tool marks on specific areas of a work. However, most objects and environ-



B **Autosynchronized scanning configuration. (1) A dual mirror configuration. (2) A high-resolution sensor using a polychromatic laser for color measurement.**

and fixed wavelengths as opposed to the spectral distribution of incoherent light, which is often difficult to control. The sensor projects a single beam, which means that it only illuminates one spot on the surface at one time, thus reducing the impact of interreflections that occur in full image illumination or even sheet-of-light projection.

Our polychromatic laser range sensor uses a combination of lasers at different wavelengths as the illuminant in triangulation range sensing. It also measures the energy reflected toward the sensor in each component wavelength. This quantity is a function of the absolute power of the illuminating laser, the distance between the sensor and the surface, the orientation of the imaged surface element relative to the camera, and the intrinsic reflectance properties at that point on the surface. We obtain the position and orientation of an imaged surface element from the range data, and we monitor the power of the incident laser. Because optical triangulation relies on controlling the angles of incidence and measuring the direction of reflected light, the remaining unknown element in the image formation process is the reflectance function. Under certain conditions, we can compute the parameters of a dichromatic model, composed of the sum of a diffuse and a specular component.[2] Often, we only use the diffuse component because the specular part is more difficult to estimate and is usually significantly observed on only a subset of the surface given a finite set of observations.

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ments require acquiring more than one range image to achieve sufficient coverage of the surface of interest. The necessary number of images will depend on the object's shape and the amount of self-occlusion—the presence of obstacles to sensor placement—and the object's size if it exceeds the sensor's field of view. Another benefit of merging different views is that the integration process itself filters the unavoidable noise present in the original data, given that no biases exist in the data.

Over the years, researchers at NRC, InnovMetric Software, and the Canadian Conservation Institute have jointly developed, tested, and refined a 3D modeling methodology for constructing models from a set of range images.[2] This approach is implemented in InnovMetric's Polyworks software suite (see http://www.innovmetric.com). We built the models shown in this article using this technology, except for the reflectance-modeling component.

Recording collections

The NRC is collaborating with museum and conservation agencies for evaluating the applicability of its 3D imaging and modeling technology. We've digitized more than 100 objects from a dozen museums and cultural organizations in our lab, as a way of assessing and improving the sensors and algorithms. We encountered a wide variety of materials, shapes, and scales. This research also helped us establish procedures for artifact digitization that would be satisfactory to the museum community. As a typical example, Figure 1 (next page) shows the Nisga'a Woodpecker-shaped rattle that's part of the collection of the Canadian Museum of Civilization (catalog number CMC VII-C-9).

We digitized and modeled the painted wood surface with our high-resolution color range sensor. It took a set of 30 range images to cover the rattle's surface, including the numerous concavities. We first produced a high-resolution model of 1.3 million triangles. The resolution in depth of the data is about 0.01 mm. The model in Figure 1 is compressed to 300,000 triangular faces, at a resolution of about 0.05 mm. For interactive visualization

1 Nisga'a Rattle: shaded view and color renderings of a high-resolution model.

2 Shape and color model of the *Tylosaurus* sp. *Mosasaur* fossil.

purposes, we also produced models at a lower resolution with a texture map.

One advantage of the polychromatic laser illumination technique is that the wavelengths are stable and known from the fundamental properties of lasers. Therefore, estimating reflectance models from these measurements is repeatable over time, so we can use this method for measuring changes over time in spectral response at these specific wavelengths. We can also measure changes in the shape of artifacts due to deterioration or following conservation treatment by comparing models acquired at different times. The 3D and color digital model becomes a permanent record of the object's condition at a given time.

Another important role of high-resolution recording is to provide remote access to collections for scholarly studies. Such applications raise the question, How many details should be measured? The answer depends on the artifact's complexity and on the type of information needed for a particular study. Researchers want a model that embeds at least as many details as are normally seen with the unaided eye.

We recently worked with paleontologists to try to provide some answers for fossil analysis.[3] This field requires the rapid dissemination of important fossil discoveries. Instead of sending the original or a physical replica, high-resolution digital models of a specimen can be shared for study and classification. But the adequacy of such model as a substitute had to be assessed. As part of this experiment, we generated a digital model of a fossilized *basisphenoid-basioccipital* from a juvenile *Tylosaurus* sp. *Mosasaur* using the high-resolution color sensor (see Figure 2). The overall length of the fossil is 113 mm. We assembled the model from scans at a sampling resolution of 0.1 mm, resulting in a mesh of about 3 million triangles. One of the conclusions is that digital models can potentially replace the physical specimen, depending on the level of detail needed. On the model, nerve and blood vessel pathways present on the fossil surface were clearly visible—such features provide important information for researchers. Other areas of the fossil, such as the basal tuber, required a higher scanning resolution of 0.05 mm.

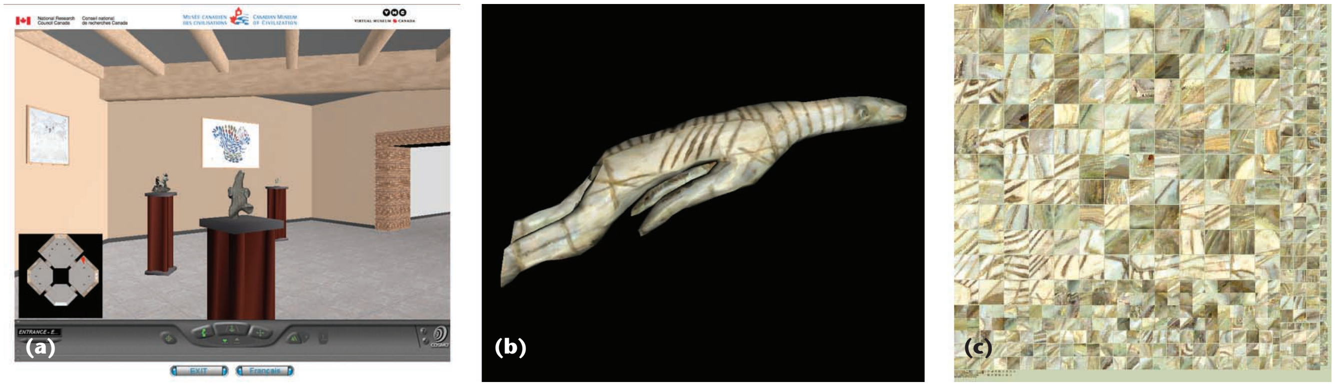
Interactive exhibit on the Web

The concept of virtual access to museum collections predates the Web, but the wide availability of powerful consumer-grade 3D graphic PCs and large bandwidth connections to the home has only increased interest in this application. While the main motivation for high-accuracy modeling remains documentation, conservation, and analysis, interactive visualization provides an additional immediate use for the data.

The Canadian Museum of Civilization produced the online *Inuit3D* exhibit[4] in 2000. It was part of the Virtual Museum of Canada (see http://www.virtualmuseum.ca/), a larger scale national effort to promote remote access to museum collections from all across the country through digital technologies. The *Inuit3D* exhibit features 12 digitized Inuit and Palaeo-Eskimo sculptures from the museum's collection, dating from 700 BC to the 20th century. The exhibit has three virtual exhibit rooms (Palaeo-Eskimo, Inuit History, and Inuit Art) containing 3D textured models, images, video clips, and text panels. The rooms and the objects are all represented using Virtual Reality Modeling Language (VRML).

Preparing an exhibit for remote access implies a number of compromises. In particular, designers must estimate the level of technology available to the typical end users in terms of display capacity, network bandwidth, tolerance to download times, and software configuration skills. An important factor in a virtual exhibit is to preserve an acceptable level of fidelity of models to the actual objects, even at the expense of longer download times. We prepared various model sizes for the *Inuit 3D* objects in collaboration with the museum staff. The museum curators opted to use the geometrically coarser models with the larger texture map models. Figure 3 shows a view of the virtual exhibit hall and the model of one of the Palaeo-Eskimo carvings.

The original high-resolution model is transformed



3 *Inuit3D* virtual exhibit. (a) Entrance to the Inuit Art hall. (b) VRML model of *Flying Bear*. (c) A tessellated 512 × 512 pixel texture map of the compressed bear model.

4 Palaeolithic figurines. (a) The *Armless Lady* scanned with the color laser system. (b) and (c) Renderings of the shape and color model. (d) A shaded view of the geometry enhances surface details.

into a texture-mapped compressed model using an algorithm that reprojects the color of the removed vertices onto the coarser mesh.[5] The user specificies a distance tolerance for the compressed model along with the dimension of the texture image. One of the main challenges in such a method is to tessellate the rectangular texture map efficiently, given a set of triangles of varying proportions and size, while preserving as much of the color information as possible and avoiding discontinuities between adjacent model triangles.

The virtual-within-the-walls museum

The *Inuit3D* exhibit wasn't our first venture into modeling a collection of objects for public display. In 1995, the Canadian Museum of Civilization approached us for an exhibit of palaeolithic figurines. The digital shape and color models would fulfill a dual purpose: to create a digital record of the collection and give visitors a closer and enhanced examination of the figurines.

Between 1883 and 1895, Louis Alexandre Jullien discovered 15 palaeolithic figurines at the Balzi Rossi site located at the French–Italian border, the largest series ever found in one location in Western Europe. Seven of the figurines, estimated to be 25,000 years old, were displayed in an exhibit called *Mothers of Time*. Two are sculpted in bone or ivory and the other five in different minerals, ranging in size from 23 to 72 mm. The figurines were displayed flat in a glass case. Thus, only one side was visible. Although magnifying glasses were available to the visitors, the small details, such as the tool marks and incisions, were difficult to discern.

Prior to the exhibit, the seven figurines were brought to our lab for imaging and modeling. We used the color laser autosynchronized sensor to acquire the data. The task presented several challenges because of the figurines' small size, fragility, and deteriorated surface condition (especially the ivory pieces). Figure 4 shows one of the ivory figurines, called the *Armless Lady*. A photograph of the original (67 mm in height) during scanning appears in Figure 4a. Figures 4b and 4c show renderings of the 3D color model. One of the visual enhancements that proved useful for visitors was a shaded rendering of the surface without the measured color (see Figure 4d). This representation enhances many of the surface shape's small details. During the exhibit, we coupled a 3D graphic workstation to a large rear-projection screen configured to operate in monoscopic or stereoscopic viewing mode using active shutter glasses. Visitors could examine the figurines by manipulating a track ball and changing display modes. The display reverted to a predetermined animated sequence when unused for a given time.

This project was significant at several levels. It pushed the limits of the prototype color sensor and modeling algorithms available at that time. It also served as a first public test case for establishing the technology's relevance and usefulness. Finally, it illustrated the potential of virtualized models of museum objects not as substitutes, but as complements and enhancements to traditional exhibits within the museum walls.

Modeling in the field

Many of our projects with museum partners were completed in the lab, using our highest resolution system. Curatorial staff transported the artifacts from the galleries or the vaults to the lab. However, it's often impossible, impractical, or undesirable to bring artifacts to a central lab. Hence, another of our research goals was to develop the ability to operate in the field with systems that we could easily transport and deploy and with tools that would let us acquire and analyze the data rapidly.

Digitizing objects and sites in the field entails a number of technical requirements. The system must be compact and rugged for easy transportation and rapid setup. It must also be robust for environmental conditions such as extreme temperatures and humidity or exposure to dust, sand, and salt. By design, the optical sensor must be immune to ambient light conditions, especially the sun. In the field, we can expect a limited or quirky power supply. Additionally, site work imposes several logistical difficulties such as restricted access to areas of interest, limited free space to position the sensor, and limited time to perform the measurements (often divided around constraints such as visiting hours). Nontechnical issues such as security of the equipment, personnel, and works of art being measured (including liability during scanning) also require attention. Other on-site scanning projects, such as those done by IBM and Stanford, faced similar challenges.[2,3]

When working outside the lab, we must worry not only about hardware failure but also about the possibility of progressive and unnoticed degradations in performance, caused for example, by equipment damage or changing environmental conditions. Hence, in addition to robust sensor design, regular on-site validation of sensor performance becomes an essential task, especially under fluctuating conditions. Methods and tools to monitor and test the system's calibration must be available and used systematically.

Perhaps the key difference between lab and site work is that when we work on site, there's rarely a second chance to come back and redo or complete the work. Therefore, a team's ability to plan an on-site job becomes crucial. Apart from breaking down the time allocated to specific steps in a project, we resorted to several operational methodologies to speed up the work. When building models from multiple views, one successful approach is to build at least a crude version of the model that registers the available data, as the data are acquired. On site, a person can be dedicated to this task, working in parallel with those in charge of the acquisition and providing immediate feedback. This procedure satisfies two objectives: to verify that adequate surface coverage has been achieved and to check the system calibration because the quality of the interimage registration will often be an early indicator of distortion in the geometric data.

We show here two examples of site work that illustrate different sensor technologies and uses of the data. One is concerned with the modeling of a sculpture by Giovanni Pisano, and the other with the documentation of archaeological sites.

Sculptures

In 1997, in collaboration with the University of Padua, the *Madonna col Bambino* by Giovanni Pisano (1305) was digitized using the Biris camera described in the sidebar "NRC 3D Sensor Technology." This 1.29-m marble sculpture is located inside the Cappella degli Scrovegni (Chapel of the Scrovegni) in Padua.[6] The primary goal was to build a complete 3D record of the sculpture and to prepare an archival-quality 3D digital model. We recorded a set of 62 overlapping images from a set of viewpoints chosen to cover the entire sculpture. We merged the views into a complete model of the object (see Figure 5). This model has been used as a conservation record to document the sculpture's condition and to prepare accurate scale replicas. Furthermore, the digital model allows views of the work in much more details than on the site, where access to the chapel and the sculpture itself is limited.

A team of three people acquired all the scans in a single day. The sculpture was digitized at a lateral sampling resolution of 0.5 mm and a depth resolution of about 0.15 mm. The prototype Biris sensor was mounted on a rotation platform fixed to a sturdy tripod. A notebook computer provided the visualization and processing tools. Compared to the prototype used on this project, the current generation of the Biris sensor yields a significantly improved resolution.

During our stay in Padova, we created other bronze bas-relief models by Donatello located in St. Anthony's Basilica. We also used the Biris system outdoors to model architectural and bas-relief elements of the facade at the Abbey of Pomposa, near Ferrara. Our work in Italy demonstrated the usefulness of a portable digital 3D imaging system in augmenting the current level of documentation for environments and objects located on remote sites with accurate and realistic 3D models. We focused our work on the data acquisition, calibration, and accuracy verification for rapid model building.

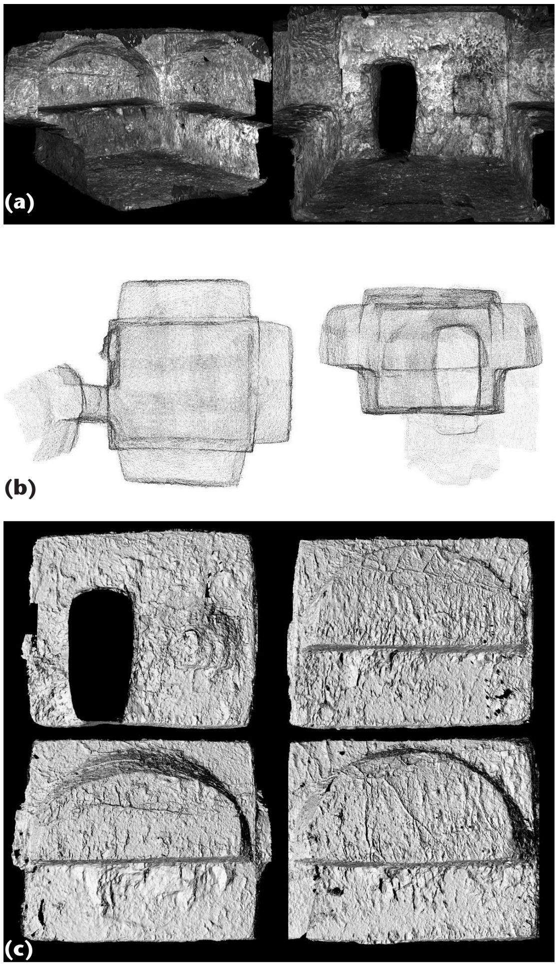
Archaeological sites

Archaeology offers numerous opportunities to use 3D imaging. However, the remote location of many archaeological sites imposes some of the most stringent operating conditions for equipment and people. In 1996, in collaboration with the Israel Antiquities Authority, we undertook a pilot project to demonstrate the recording of archaeological site features for conservation professionals. We used a portable version of the autosynchronized spot triangulation-imaging system. This configuration also has the advantage of operating over a large depth of field ranging from 0.5 m to 10 m, with varying resolution across the measurement volume. Thus, we can use it for high-resolution imaging of artifacts at a close range and for longer range (several meters) work on larger structures, with a lower sampling and depth resolution. This sensor system uses an infrared laser (820 nanometers) and doesn't record color information. The main objectives were to digitize the geometry of a variety of artifacts and sites using the same sensor, over the course of a few days at St. James' Tomb in Benè Hézir, the Holy Sepulchral Lintel at the Rockefeller Museum in Jerusalem, and several archaeological and architectural elements in Caesarea.

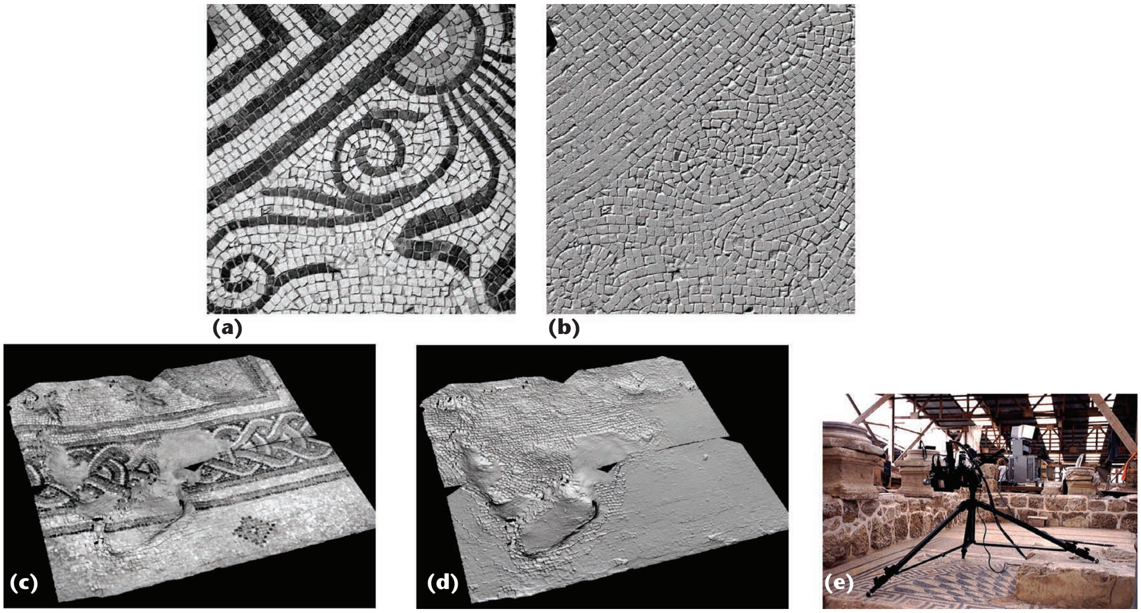
5 Imaging Giovanni Pisano's *Madonna*. (a) The Biris mobile system. (b) Subset of images forming the head. (c) The completed model.

The *Arcosolia Room* of St. James' Tomb measures approximately 2 m × 2 m × 1.8 m in height. It's carved in rock and the interior surfaces are rough and irregular in shape. Architectural and archaeological sites that bear surfaces of this nature are difficult to record accurately with a high level of detail using conventional techniques such as traditional surveying, rectified photography, photogrammetry, and distance meters. The goal was to digitize the tomb's entire volume to prepare an archival record for conservation documentation. We recorded the tomb's interior with an average sampling resolution of 1 mm and a depth resolution of 0.3 mm. It required one half day of on-site recording time to acquire 65 images (512 × 512 points each) that cover the entrance tunnel, walls, floor, and ceiling. Subsequently, about four days were required off-site to finalize a series of 3D digital models at different resolutions. Although modeling the tomb's geometry was the project's main objective, we also mapped the intensity of light reflected in the laser infrared wavelength as a black-and-white texture to provide some sense of the appearance of the rock face for illustrative purposes.

We can render the resulting digital model in several ways to assist in the analysis and interpretation by experts. This flexibility of representation from a single source of information is one of the advantages of 3D imaging as a basic documentation system. Figure 6a shows renderings of the tomb's interior, with the intensity measured in the laser wavelength represented as a black-and-white image. Remember, these rendered representations are more than just substitutes for photographs. The actual 3D position of each point on the model's surface is available, thus allowing dimensional



6 Synthetic views of the *Arcosolia Room*: (a) cutaway views, (b) a complete envelope, and (c) an orthographic projection of the four walls.



7 Mosaics at Caesarea. The combination of (a) intensity and (b) shape information provide information for documenting the layout. (c) and (d) We can also record the floor's deformation. (e) The sensor at work.

measurements between points, displaying of profiles, area and volume estimation, and so on. Figure 6b shows the model's shape as a cloud of points, offering a global perspective of the cavity's entire shape as seen from an artificial point of view embedded in the rock. Alternate forms of representation can be obtained easily, such as a set of orthographically projected pseudophotographs on four sides (Figure 6c), where all perspective effects are removed to preserve proportions. Such a representation can't be achieved photographically. As in many of the examples discussed previously, applying a uniform reflection model to the geometric data enhances surface details. Finally, we also experimented with an immersive virtual reality display for full-scale interactive navigation and exploration of the tomb.

During the same trip, we used the same system on a different site and for a different type of application. Located on the Mediterranean coast, the archaeological site of Caesarea contains Roman and Byzantine mosaic flooring. With its small and irregular spaced tiles and patterns, mosaic flooring is often difficult and time consuming to accurately record using conventional techniques such as rectified photography. Using rectified images, we can obtain a scaled line drawing of the floor details, but it's correct only when all the tiles lie in the same plane.

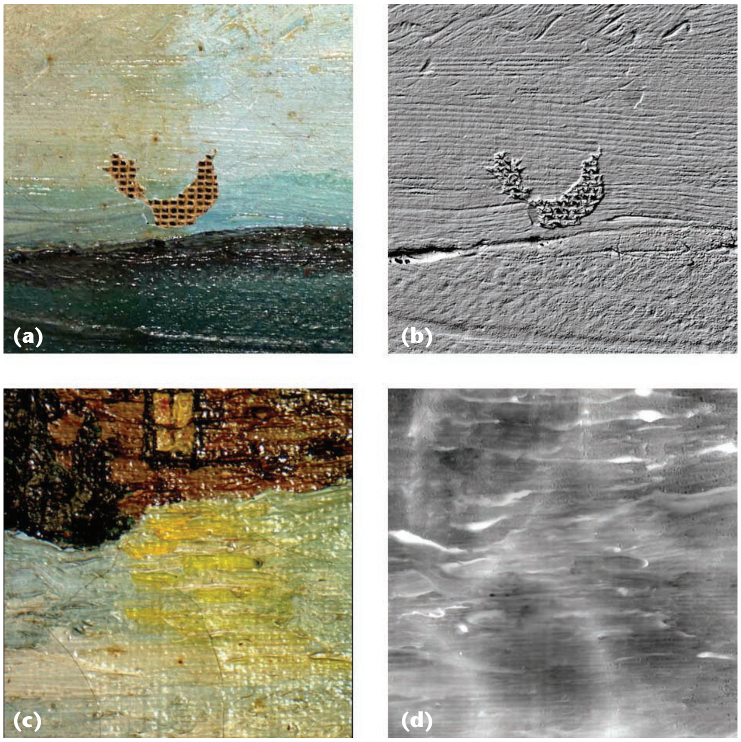
Three-dimensional information from the laser scans of a floor mosaic produce the same results with greater accuracy, in less time, and with the advantage that a metric representation is provided for the complete mosaic surface, not just the interstices as is usually the case. This 3D representation provides information on the tile conditions that aren't easily extracted from 2D photographs, even when using multiple views. Image-processing algorithms allow extraction of edges of well-defined pieces of mosaic. These algorithms can significantly reduce the production time of a 2D (vector) condition database of the floor mosaic for conservation applications. Furthermore, details of the individual tiles' geometry also become available for analysis. To demonstrate this application, we digitized a 0.25-square meter section of flooring at a sampling resolution of 0.5 mm and a depth resolution of 0.1 mm (see Figure 7).

Landscape of paintings

In the heritage field, 3D techniques have been applied mostly to sculptured objects. Yet, the seemingly flat world of paintings provides another application area for high-resolution 3D imaging. Art historians and conservators frequently use a variety of traditional scientific techniques to examine and study paintings. X-ray imaging is used to examine the internal structure, infrared photography reveals underdrawings, and ultraviolet fluorescence photography can distinguish original paint areas from later additions. High-resolution 3D imaging provides an additional layer of information to historians and curators. In scanning a painting, features of interest are typically digitized at a sampling resolution of 0.05 mm in the x and y directions. The z dimension (or brush stroke height) of each point is recorded at a resolution in the order of 0.01 mm.

For paintings with varnished surfaces, a unique feature of an optical technique is that the 3D image captured by the system originates from the surface of the paint layer—under the varnish, rather than from the varnish surface itself. This results in a detailed high-resolution recording of the surface relief or 3D structure of the paint layer from brush stroke details as well as crack pattern formations, paint losses, and other characteristics due to aging. Figure 8a is a detail of a 50-mm square section with a paint loss. The varnish has been removed from the right half (bright side) but remains on the left side (yellowed section). Figure 8b is a shaded monochrome range image of Figure 8a with the color or texture removed from the shape image. Viewers can examine the brushstroke features including the canvas imprint and paint loss in detail. In the 50-mm square section shown in Figure 8c, a small D-shaped *cupping* formation appears in the bottom half of this section. It's barely visible in this image or to the naked eye when viewing the painting itself, yet it conveys important conservation information. Paint cupping, or incipient cleavage of the paint layer from the canvas support, is the first indication of a crack formation, which leads to paint loss. Figure 8d displays a gray-level coded image, which highlights the D shape. A common visual technique used in studying the condition of painting surfaces is raking light, where actual light is projected on the canvas at a low incidence angle to accentuate the relief. Using the 3D surface data, this technique is easily emulated. It provides a familiar analysis tool to experts. The artificial nature of this lighting allows a display with or without cast shadows. In addition, the shading applied on the surface model without the measured color removes the perceptual interference between gradient effects in the pigment and the actual surface geometry.

In preparation for the 1996 retrospective of the artist Corot, we collaborated with the Centre de Recherche et de Restauration des Musées de France (CRRMF, or Center for Research and Restoration of the Musuems of France). The CRRMF used a variety of techniques including x-ray, infrared, and ultraviolet to scientifically examine and interpret details of Corot paintings and was producing a CD-ROM with scientific data on 85 of his works from the Louvre.[7] They were interested in including an interactive example of Corot's fine brushstroke details on the CD. To do this, we scanned the Corot painting *Auvers, Street Descending* from the National Gallery of Canada in our lab (see Figure 9). The CRRMF then incorporated the data into an interactive display on the CD that lets viewers manipulate the position of an artificial light source and examine the details.



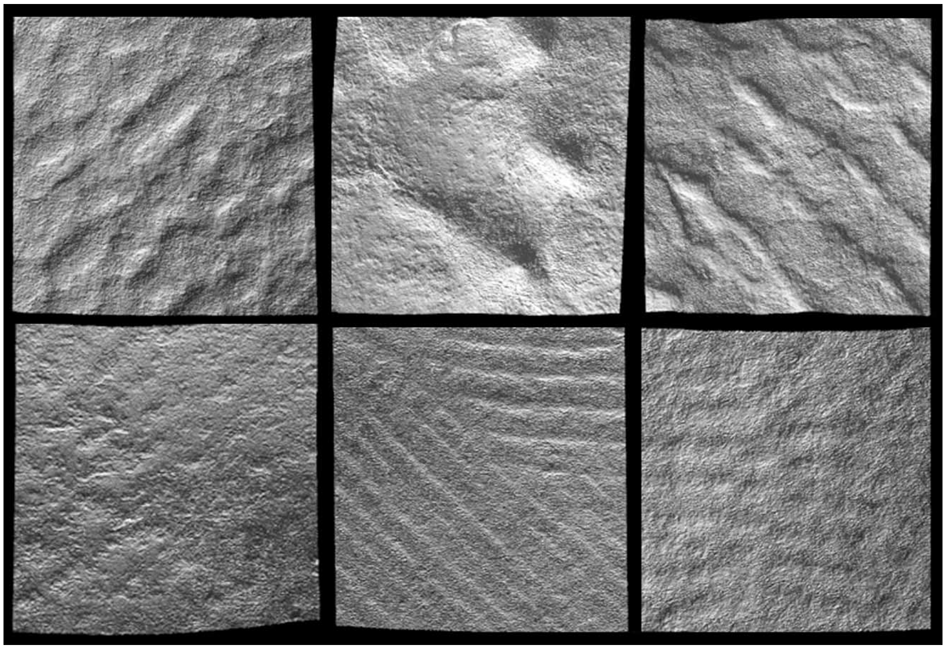
8 Image details of two 50-mm square sections of a painting. (a) Section with a paint loss. (b) Shaded monochrome range image of Figure 8a. (c) Small D-shaped fine crack or cupping formation. (d) Gray-level coded image of Figure 8c, including the D-shaped cupping.

9 Scanning the Corot painting, *Auvers, Street Descending* from the National Gallery of Canada.

Scanning marble

Working in the area of heritage often raises specific research issues. Such a case occurred through our involvement in the Digital Michelangelo project and our study of measurement on the surface of marble. In 1999, we were invited to deploy one of our sensors in Florence to complement Stanford's 3D laser scanning systems. Our role was to capture, in the course of a few days (and nights), the fine details of the tool marks in selected patches on seven different sculptures. The patches were chosen to represent a variety of types of tool marks, marble types, and surface polishing. They measured 50 mm × 50 mm and were sampled at a resolution of 0.05 mm, using our high-resolution system. In the lab, we normally mount the sensor on a translation system. For this project, we used a sturdy tripod and a rotation stage to displace the sensor head. We didn't use the color measurement capability in this portable configuration. Figure 10 (next page) shows renderings of some of the chisel marks.

Analysis of the data revealed an interesting phenomenon, which was also noted on the images acquired by Stanford with their custom plane-of-light system. The noise in the range measurement was significantly higher on marble than other materials. This effect was particularly noticeable on the smoother and more polished areas. For example, in chisel marks, while the bottom of the grooves were visibly rougher or dirtier than the top surface, the depth measurements from the range sensor were clearly noisier on the smoother top surface. Marble, while hard, is translucent: the laser illumination on the surface forms a glow exceeding 10 mm in diameter. In addition, marble has a heterogeneous granular structure at a scale comparable to the sampling density. Back in the lab, we performed a series of experiments to characterize the measurement behavior, using a flat clean sample of Carrara Statuario marble, the same type used by Michelangelo. We observed that, in addition to the



10 **Some of the chisel marks on Michelangelo's *Prisoner* sculptures in Florence, Italy.**

expected slight bias in the depth measurement caused by translucency, there was indeed an increase in the noise of range measurements. Furthermore, this increase was a function of the laser spot's size on the surface.[8] We're currently continuing research on the effect of various materials on sensor performance.

Conclusions

Through a number of pilot projects, we've demonstrated the feasibility and relevance of recording heritage objects and sites using laser range imaging. The number and variety of real-world test cases, a few of which we described here, let us assess and improve the technology and the working procedures. Our collaborators in the museums and cultural agencies were exposed to early results and provided us with precious feedback. The growing acceptance of this technology and feedback from practitioners and users will encourage and further guide developments in sensor systems as well as processing techniques that address specific requirements of object and site documentation.

Our future research directions continue to be driven by heritage applications in addition to other high requirement fields. We're working on enhancing our sensor systems, in terms of accuracy, speed, and robustness. We're also integrating range imaging with photogrammetric methods to exploit their complementarity. As shown in the case of marble measurement, there's still some studies to be done in understanding the behavior of sensors on various materials. And, appearance modeling from images continues to pose many challenges, especially if the goal is to provide a repeatable measurement for monitoring artifacts.

No one can claim that a single technology can solve all problems and address all situations. Similarly, active range sensing can't be expected to be the only tool required for documenting artifacts and sites. Nevertheless, it will play a significant role as an input device from the real world to the virtual. For this field to contribute useful tools for heritage applications requires formalizing accumulated experience into systematic and accepted procedures for documenting an object or a site. Through continued research, validation, and refinement, we can expect that 3D imaging and modeling will become an essential tool in the preservation, restoration, and knowledge dissemination of the world's cultural heritage. ■

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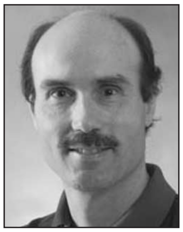
Guy Godin *is a senior research officer with the Visual Information Technology Group at the National Research Council of Canada. His research interests include 3D computer vision and image analysis, shape and appearance modeling, and interactive visualization. He has a B.Ing and M.Eng in electrical engineering from École Polytechnique de Montréal and McGill University, Montréal.*

J.-Angelo Beraldin *is a senior research officer at the National Research Council of Canada. His current research interests include sensor systems engineering and signal processing (hardware and software) for 3D vision systems. He has developed expertise in optoelectronic aspects of range sensors as well as in the calibration of them. He is active in the field of heritage in Italy for which he organized three workshops.*

John Taylor *is an imaging applications scientist at the Institute for Information Technology, National Research Council of Canada. He has worked for more than 30 years on the development of scientific applications for the analysis, examination, and study of works of art. Prior to joining NRC, he worked at the Canadian Conservation Institute and the National Gallery of Canada. He holds a BS and MS in chemistry from Michigan Technological University and is a fellow of the International Institute for Conservation.*



Luc Cournoyer *is a technical officer with the Visual Information Technology Group at the National Research Council of Canada. He has worked on the development of various laser range sensors, mainly on the optomechanical design and on various demonstration projects for several classes of applications. He has also developed software for sensor control and for data processing and manipulation. He graduated as a physics technologist from the Collège de La Pocatière, Quebec.*

Marc Rioux *is a principal research officer at the Institute for Information Technology, National Research Council of Canada. His research interests are in the development of 3D digitizing, modeling, and display for machine vision; optical dimensional inspection; and visual communication in the Visual Information Technology Group. He received a BS in engineering physics and an MS in physics, both from Laval University, Quebec City.*

Sabry El-Hakim *is a senior research officer at the National Research Council of Canada's Visual Information Technology Group, Institute of Information Technology. His research interests include image-based modeling, multisensor data integration, camera calibration, and virtual reality. He received his MSc and PhD in photogrammetry from the University of New Brunswick. He is the chairman of the International Society of Photogrammetry and Remote Sensing (ISPRS) working group on scene modeling and virtual reality and is the chairman of the SPIE series of conferences on videometrics.*

Réjean Baribeau *is a research officer at the National Research Council of Canada's Institute for National Measurement Standards, where he works in the field of color science applied to color imaging technology. Previously, he worked with NRC's Institute for Information Technology on the museum application of 3D laser scanning technology. He received a BSc, MSc, and PhD in physics, all from Laval University, Quebec City.*

2002
Editorial Calendar

January/February: Information Visualization
Computer-based information visualization has emerged as a distinct field centered around helping people explore or explain data by designing software that exploits the properties of the human visual system. New methodologies and techniques are critical for helping people keep pace with the torrents of data.

March/April: Image-Based Modeling, Rendering, and Lighting
Despite its recent arrival on the scene, the field of image-based modeling and rendering has already established itself as an important tool for a wide range of computer graphics applications. Image-based techniques use real-world digital photographs to synthesize novel imagery, letting us creatively explore and reinterpret realistic geometry, surface properties, and illumination.

May/June: Graphics in Advanced Computer-Aided Design
The use of computers in the design and manufacturing processes has come a long way from the first CAD systems in the automobile and aerospace industries, with the huge mainframes and enormously expensive displays. Current CAD systems exploit innovative uses of the new technologies that help to move ideas from concept to model to prototype to product.

July/August: Virtual Worlds, Real Sounds
We only need to close our eyes for a moment to experience the amazing variety of information that our ears provide, often more quickly and richly than any other sense. Using real sounds in virtual worlds involves parametric computation; synthesis; and rendering sound for VR, entertainment, and user interfaces.

September/October: Computer Graphics in Art History and Archaeology
Archaeologists can use computer graphics techniques to reconstruct and visualize archaeological data of a site that might otherwise be difficult to appreciate, with applications in analysis, teaching, and preservation. Similarly, art historians use computer graphics to analyze, study, and preserve great works of art, which may be too fragile or too valuable to touch or move.

November/December: Tracking
High-resolution tracking of user position and orientation (head, hand, feet, and so on) is increasingly a critical issue for virtual reality, augmented reality, modeling and simulation, and animation. Current tracking hardware is based on a variety of sensors including magnetic, optical, inertial, acoustic, and mechanical (as well as hybrid combinations).

IEEE Computer Graphics AND APPLICATIONS

__François Blais__ is a senior research officer with the National Research Council of Canada. His research and development work has led to the development of many range-sensing systems. His research interests cover various fields in digital and image processing, control, 3D, vision systems, and their applications. He obtained a BSc and MSc in electrical engineering from Laval University, Quebec City.

__Pierre Boulanger__ is an associate professor at the Department of Computing Science of the University of Alberta. He worked for 18 years at the National Research Council of Canada as a senior research officer where his primary research interests were in 3D computer vision, rapid product development, and virtualized reality systems. He has a BSc from Laval University, Quebec City, in engineering physics, an MSc in physics from the same university, and a PhD in electrical engineering from the University of Montreal.

__Jacques Domey__ is group leader of the Visual Information Technology Group at the Institute for Information Technology of the National Research Council of Canada. His research interests are in 3D imaging and applications. He received a BSc in engineering physics from École Polytechnique de Montréal and MSc from the Institute of Optics of the University of Rochester. He is also involved in licensing and technology transfer. He is a member of IEEE, SPIE, and Professional Engineers of Ontario.

__Michel Picard__ is a technical officer at the Institute for Information Technology, National Research Council of Canada. His projects include work on 3D imaging systems and 3D animations, especially virtualized environments. He has worked for Hymarc as an imaging technician, where he collaborated with the Canadian Museum of Civilization on multiple 3D projects. He has an Architectural Technology Diploma from La Cité Collégiale, Ottawa.

Readers may contact Guy Godin, Visual Information Technology Group, National Research Council of Canada, Bldg. M-50, 1200 Montreal Rd., Ottawa, Ontario, Canada K1A 0R6, email guy.godin@nrc.ca, http://www.vit.iit.nrc.ca.