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Digital Three-Dimensional Modeling of Heritage by Frequency-Modulated Laser Radar: the case of Donatello's "David"

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Abstract

In this paper the application of a novel CW FM Laser radar is demonstrated through the acquisition of a three dimensional model of the world famous "David" by Donatello. The steps of the acquisition procedure and the related technical solutions are reported. The scientific focus was centered on the processing pipeline simplification due to this new acquisition methodology. Detailed results are presented, demonstrating how the use of this new generation of sensors allows the digitalization of artwork, made of materials that are normally very difficult to acquire, and to improve the overall level of modeling accuracy.

Categories and Subject Descriptors (according to ACM CCS): I.4.1 [Image Processing and Computer Vision]: Scanning

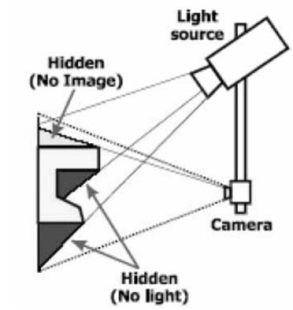
1. Introduction

The technologies for Cultural Heritage conservation and study have recently been greatly improved by three-dimensional acquisition and modeling techniques. A variety of Laser scanning systems, based on both optical triangulation [Rio94] [Rio84] [TH90] or time-of-flight measurement [HK92] [Dix98], capable of producing digital three-dimensional images of complex structures with high resolution and accuracy, have been developed. The application of such technologies to Cultural Heritage for 3D digital acquisition of sculptures, architectural and archaeological structures has been experimented on in several laboratories throughout the world with results of extraordinary interest.
Many statues, basreliefs and ancient objects have been modeled in the last few years [GBT*02], facing the various problems involved in the modeling of complex shapes [BBC*98] [BRM*02], that may at times, reach up to several meters in height [LRG*00]. The digitization of such extended surfaces with range cameras capable of acquiring only a small fraction of them at a time forced too much strain in the field of range data processing. The procedures for aligning range maps, for example, were first developed with robotics and vision [BM92] [CM92] [SL95], but through the application in the field of Cultural Heritage have been significantly refined [BR00] [Pul99] [RL01]. Editing the huge meshes generated by the merging stage is another complicated issue for the unavoidable holes due to limitations in data capturing, and specific automatic filling procedures have been studied [DMGL02], such as the problem of navigating into a mesh that may contain several millions of polygons without the need of costly high-end workstations [BCS01] [CMRS03] [RL00]. The wide field of computer graphics has also been very involved in the problem of texture mapping for Cultural Heritage models in order to give the highest degree of reality [BMR01].
In spite of these and other relevant outcomes, many aspects related to the data acquisition and processing, opened by new technologies are still the object of research. In particular the need to automatically align several hundreds of range maps involves both the risk of obtaining a model with metric distortions [GOC*01] and a huge processing overhead. This means exponential growth in the modeling time, with a heavy impact on the modeling costs that may discourage the mass application of these techniques to Cultural Heritage conservation.
Another practical problem that is more or less common to any active range sensing technique is the difficulty of imaging a noncooperating surface, such as shiny metals or very dark materials, that tend to dramatically reduce the amount

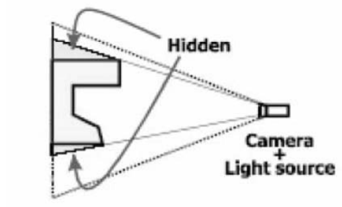
of light returned to the range sensor that performs the 3D measurement, involving a growth in measurement uncertainty or, sometimes, the impossibility of getting any measurement at all.
In order to face this problem effectively, a new commercial sensor has been experimented, based on CW frequency modulation of a laser source. In the next sections we will deal with current technologies based on two main principles: triangulation and time delay, explaining the main difference between the current sensors and the new one, and describing its application to the 3D modeling of a particularly difficult statue: the bronze "David" by Donatello, considered one of the most spectacular examples of Donatello's art.

2. Triangulation and time delay based techniques

The most common systems for creating a digitized 3D image of an object within a limited range (about one meter) are based on optical triangulation [GOC*01] [SCR00] [SCR99]. Such systems are the most accurate, allowing a measurement uncertainty lower than one tenth of a millimeter. As uncertainty depends directly on the square of the distance between the camera and the object, a high precision is achieved by suitably limiting this distance, and thus the illuminated area. Therefore, the acquisition of relatively large objects, as in the case of a statue of human size, requires a large number of partial views or "range maps", taken all around the object, that then have to be integrated in order to represent the whole surface. The issue of possible alignment errors was addressed by the authors in conjunction with the National Research Council Canada (NRCC), that proposed a possible approach based on the integration of photogrammetry and 3D scanning [GBCA03], and experimented it in the acquisition of the wooden statue the "Maddalena" by Donatello [GBA04]. A further relevant difficulty is represented by the complex surfaces that hide other surfaces when imaged with a triangulation-based range sensor. Hence, only those points simultaneously lit by the source and "seen" by the camera can be measured (figure 1a). Since high-resolution is obtained by limiting the field of view, a complete 3D model requires acquisition and merging of a very large number of range maps (even several hundreds). Their alignment in a unique reference system is generally achieved by a special algorithm indicated as "Iterative Closest Point" (ICP), which is based on the minimization of the mean square deviation between overlapped portions of different range maps.
Range map acquisition, and most of all their alignment can be very time consuming. Thus, the high resolution 3D imaging of a statue can be very costly, leading to prevention of wide-spread use of the technique. Moreover, in spite of the great accuracy of each single range map, the alignment process introduces unavoidable errors, whose propagation can cause deviations of the final model with respect to the original dimensions [BRM*02]. Optical scanning technology can be integrated with digital photogrammetry to overcome this lack of accuracy according to a procedure demonstrated by the authors [GBCA03].



a)



b)

Figure 1: *Shadow effects for 3D scanner based on: a)triangulation b)time delay.*

The major attention of 3D triangulation-based techniques has been directed towards digital modeling of relatively small objects. The acquisition of architectural artwork is practically impossible using high resolution triangulation-based scanners, because of the great dimensions involved and of the distance of the scanner to object. Architectural Heritage is usually acquired by laser scanners based on the measurement of light pulses Time Of Flight (TOF), as they operate from distances of ten up to thousands of meters, and can acquire millions of points in relatively short times, allowing the digitalization of large surfaces.
Commercial TOF systems have been available since the early 90's, and offer range-measuring uncertainty from 0.5 to 2 cm. Scanning of the laser impinging over the inspected surface is basically implemented by a precise angular positioning device moved by a step-motor. By measuring the TOF needed by a laser pulse going from the range camera to the surface and back again to the instrument, an evaluation of the camera-surface distance is performed. This data, together with the angles determining the laser orientation, allow the evaluation of the three spatial coordinates of any scanned point. However, in order to scan the whole surface of the structure to be digitized by TOF laser scanners, a number of acquisitions taken from different standpoints are needed, and their alignment requires sophisticated processing techniques. Another important feature of TOF laser scanners is encountered when considering the unfavourable situ-

ation represented in fig.1a for a triangulation-based scanner. The situation occurring when using most TOF laser radars is represented in fig. 1b. The two-axis gimbals steer the Laser through 360 degrees azimuth and 90 degree elevation. Standard vertical orientation provides 90 degree elevation range. Horizontal orientation permits above and below measurements over a full spherical range. In this way all those surfaces that would have been hidden for a triangulation sensor, can be properly acquired and modeled.
A common problem to both types of Laser scanner is reflectivity of materials. Reflectivity can be too high, as in the case of glossy metal, or too low, as in dark aged bronze. The first inconvenience can be sometimes overcome by dusting the material with special powder in order to make its reflection more diffusive. No solution exists, however, for dark bronze artwork, as a nearly black object absorbs most of the light waves, and the reflected portion is not sufficient for accurate imaging. Moreover the metallic nature of the material gives a non-diffusive behavior to the surface that typically introduces an additional uncertainty to the measured 3D coordinates.

3. A novel technique: laser radar

The new 3D sensor experimented in this paper for Cultural Heritage modeling, which allows the above limitation to be overcome, is a Laser radar, referred to as LR200, manufactured by Metric Vision Inc., VA, U.S.A., and distributed by Leica Geosystems AG, Switzerland.
The equipment is a TOF range camera, operating on a completely different principle from pulse propagation, originally developed for microwave radars, and referred to as coherent Frequency-Modulated Continuous-wave (FM CW) radar [CLA94]. In coherent FM laser radar, the frequency of the laser is linearly modulated, either directly in the case of diode lasers, or by employing an acoustic-optical modulator in the case of gas lasers, with either a triangle or a sawtooth wave (fig. 2). This type of modulation is commonly referred to as a "chirp". The instantaneous frequency can be expressed as a function of time as:

$$f(t) = f_0 + \alpha t \tag{1}$$

where f0 is the minimum frequency of the laser and

$$\alpha = \frac{\Delta f}{\Delta t} \tag{2}$$

is the slope of the modulation, sweeping a bandwidth Δf in a time Δt.
The modulated beam is focused at the target, where it is scattered and collected by the receiver optics after round trip transit time τ. The distance to the target, R, is calculated using the relationship

$$\tau = \frac{2R}{c} \tag{3}$$

where c is the speed of light.
The way to find the distance is explained in fig.2 where both

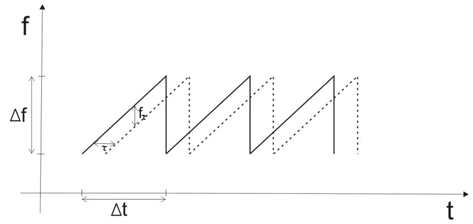


Figure 2: *Functioning principle of a CW FM radar.*

chirp signals, transmitted and received, are shown. The continuous line represents the transmitted signal, whereas the dashed line represents the received one that is equal to the previous but delayed by a τ time. It can be easily shown that by mixing the two chirp radar signals delayed by a τ time, the transmitted one and that received from a target at distance R, a waveform of fixed frequency results as:

$$f_\alpha = \alpha\tau \tag{4}$$

It is directly proportional to the distance R, thus the target range is detected by frequency analysis, according to

$$R = \frac{c f_\alpha}{2\alpha} \tag{5}$$

To obtain this result the coherent detection of FM Laser Radar is necessary. Laser beams can be characterized by both spatial and temporal coherence. For FM radar, temporal coherence is important, and is related to the finite bandwidth of the laser source. Temporal coherence specifies the time interval over which one can reasonably predict the phase of the light wave at a given point in space. This is essential to the concept of optical mixing. Therefore, in FM lasers, a portion of the transmitted beam is split from the incident light wave and forms the local oscillator, that is then mixed with the returned energy. Coherent light waves, when combined correctly on an optical detector, produce a beat frequency equal to the difference in the optical frequency (and hence phase) of the incident waves. As in electronic mixers, a sum frequency is also produced, but not detected since optical detectors cannot respond to signals in the optical range of approximately 10^{15} Hz. As in CW radar, the resulting FM signal at microwave frequencies, can be mixed with the original chirp giving as a result a signal whose frequency is proportional to the source-to-surface distance, according to 5.
FM lasers are largely immune to ambient lighting conditions and changes in surface reflectivity. Due to the fact that laser radars rely solely on beat frequency, in order to calculate range, it is less dependent upon signal amplitude than the other techniques. This enables the FM coherent system to make reliable measurements with as little as one picowatt of returned laser energy. This corresponds to a nine order-of-magnitude dynamic range of sensitivity.
In early FM devices, the accuracy of range measurement was limited by the linearity of the frequency modulation over the

counting interval. For example, if the target is one meter distant, a linearity of one part per thousand is necessary to ensure 1 mm accuracy. Advanced techniques employed in the MetricVision Laser Radars enable a high degree of linearity. In addition, these techniques can detect and compensate for real time variances from linearity. This enables range measurement with a hundred micrometer precision.
The heart of the Laser Radar is a broadband frequency modulated infrared laser (100GHz modulation), which provides a robust and eye-safe signal. The upsweep and downsweep comparison provides simultaneous range and velocity data for measurements. The single wide-aperture optical path maximizes signal strength and stability. Extensive signal processing extracts interference frequencies which are directly proportional to distance.
The Leica sensor also works on non-visible wavelengths (1550 nm). This point, together with an amazing SNR ratio increases compared to a conventional TOF scanner, and due to the frequency modulation approach, obtainment of a good response on materials apparently very dark in the visible spectrum is also possible.
Another critical point is the focusing volume depth, that in any triangulation based system ranges from 10-20 cm for fringe projection systems based on white incoherent light, to more than half a meter for laser line systems. In general TOF based systems do not take into account the laser spot size variations at distances very different from the focusing range because for uses on buildings and large structures it is supposed that ultra-high resolutions are useless. The Leica laser radar is instead built for applications such as industrial metrology, where the possible resolution can be much higher (e.g. far below 1mm), so that the laser spot size is taken under control through a dynamic focusing optical system. The drawback of this sophisticated focusing is represented by the time needed for getting each measured point. In the most precise modality only 20 points per second are measured. On the other hand this feature solves the problem of automatically acquiring (i.e. with no human control) extended surfaces involving large distance ranges between the range camera and the measurement points. The system can be programmed for acquisition through its control software and left unsupervised while it runs (e.g. at night). A peculiar aspect of this laser scanner is the way it re-orients all the data into the same reference system during the acquisition stage, thus eliminating the need for range map alignment, which is typically required in any modeling project. A redundant set of references, represented by steel spherical targets, called "tooling balls", are placed on the scene and fixed in place with custom metallic rings that hold the balls in a specific position. The ring can be glued onto suitable parts of the scene without touching any delicate spots that are to be digitized. At the first camera location the position of each tooling ball is determined by measuring the direction of maximum laser reflectivity on the ball. Adding the distance information and the "a priori" knowledge of the ball diameter, a very accurate estimation of the 3D coordinates of each reference target is performed. For the following camera locations the same targets are measured again in order to determine the rototranslation transformation respect to the first one. Once the new camera location is set-up, each point is measured and automatically reoriented in the main reference system, eliminating the need for a time-consuming iterative reorientation and of the related data redundancy; (30-40% of range maps superposition would be needed). This feature speeds up extraordinarily the 3D model generation. Last point to be noticed is the noticeable growth of accuracy compared to a model generated by automatically aligning range maps through Iterative Closest Point (ICP) algorithms. Previous experiences [GBT*02] demonstrate that error propagation with unconstrained ICP can lead to substantial errors. In the present project no software alignment is used and the model accuracy coincides with the extremely high laser scanner accuracy.

4. Modeling of Donatello's "David"

The work presented here describes the results of a three-dimensional acquisition project concerning the "David", a bronze statue made by Donatello in 1440 for the Medici family. This masterpiece, which represents with overwhelming reality, a sensual adolescent body, followed another "David", made in marble more than twenty years before for the Florence Cathedral. The project was an important step in a program of digitizing all the statues by Donatello, conducted by the University of Florence in conjunction with the NRCC. The first step was the 3D acquisition of the wooden statue of the "Maddalena", performed using a triangulation-based structured light scanner [GBCA03].
The acquisition of the "David", however, was characterized by a number of difficult factors. The first and most evident is the very dark surface of the aged bronze that gives off an extremely low reflectivity (fig. 3). In any non-contact active 3D sensor the light is the "probing agent", and the response to white or laser light is a key element for an accurate and precise surface measurement. Therefore a nearly black object that absorbs most of the light waves is difficult to measure. Moreover the metallic nature of the material gives a non-diffusive behavior to the surface that typically adds an additional uncertainty to the measured 3D coordinates.
Another important point is camera positioning. Surface complexity and mechanical constrains in moving the range sensor around a statue, generally involve shadows, which create incomplete range maps. As previously mentioned, this complexity is enhanced with a triangulation sensor because every point on the surface has to be simultaneously framed by the camera and lying in the light beam trajectory. This is why some portions of the "David" would not have been acquired with such a sensor.
For all the above reasons, tests of the "David" acquisition using triangulation-based laser and structured light sensors gave very poor results. The introduction of the coherent FM Laser radar opened new prospects. As the instrument had

Figure 3: *David's workspace.*

never been used for Cultural Heritage modeling till that moment, Leica's European Headquarters willingly consented to our proposal of experimenting the new technique for acquisition of the "David", and provided us with the instrumentation and all the necessary cooperation.

The scenario of the acquisition experiment is shown in fig. 3. The laser radar, positioned on a support, is seen on the right. The acquisition plan was arranged in two different stages. In the first stage, a massive acquisition was performed, trying to minimize possible lack of data. The scanner was programmed to acquire 1 points/mm for imaging smooth surfaces like the body, whereas 2 points/mm were acquired for complex surfaces, like the face and helmet as well as the head of Goliath, which is situated under David's foot. Five points of view were selected around the statue, in order to cover most of the sculpture surface. The overall statue was automatically scanned from each point of view by suitably programming the scanning sequence and leaving the system to run with no human intervention. Although the acquisition time was relatively long due to the 50 pts/sec acquisition speed, a great advantage was drawn by the fact that, once programmed, acquisition proceeds automatically, thus allowing continuous running also at night. This is a completely different procedure from the tedious activity of covering the statue surface by using hundreds of overlapping range maps, as required by the triangulation-based systems.

The instrument is equipped with its own tripod, stable enough to avoid influence of possible mechanical oscillation over the measured values. During the acquisition the points were passed to the PC in charge of controlling the Laser Radar to a secondary PC, linked to the first one through an Ethernet connection. The latter was devoted to point triangulation and model building.

Since the 1.60 m tall statue is located on a pedestal 1m high, the total height of the structure is 2.60 meters. It is generally necessary to move the camera above the object with most range cameras in order to acquire the data corresponding to the top. Since the scanner is rather heavy (70 kg), this could have been a big logistical problem. Luckily, thanks to a specific feature of the system, some of the acquisitions could be

Figure 4: *Use of the mirror to estimate points' coordinates of the cap.*

Figure 5: *Tooling balls used to align all the range maps.*

performed through a high accuracy front face mirror whose weight is more than 10 times lower, and that could be moved at the desired level leaving the main scanner on the ground (see Figure 4).

As outlined in the previous section, the need for range map alignment in the same reference system is drastically simplified by placing a set of reference tooling balls on the scene, as seen in figure 5.

These balls has been acquired through the mirror and then in direct way; knowing these coordinates it's possible calculate the angles of the mirror to align the acquisition "seen" through it. One crucial issue for generating a triangulated surface was the nature of the cloud of points produced by the measurement system. For its way of acquiring data with no constrains over the scanning area, the range map it generates is a so-called "unstructured cloud of points", basically made up of a list of triplets (x,y,z) that can be exported as a text file, with no clue of possible connections to each other. The data were therefore processed with the IMAlign module of the Polyworks software package, manufactured by Innovmetric (Canada). It has a specific function for triangulating unstructured clouds through the Delunay algorithm [LS80]. The user has to manually specify a reference orientation and, because of this, the software generate a partial mesh from a specific point cloud. This procedure was repeated for all the orientations were needed, in order to cover the whole surface.

After this phase, a study of which portions of the statue were missing was necessary. An accurate verification of the preliminary model was done in order to identify the better positions of the scanner for the second session to cover the missing parts as much as possible. The second stage included the acquisition of small surfaces from various points of view, and merging between the two stages was done with an ICP algorithm through IMAlign (Innovmetric). This second section of acquisition obtained in a further fase has been acquired by the obligated use of the software ICP since the tooling balls were removed. Then, an editing procedure was used in order to cover some of the holes. As no automatic procedures were used in order to keep the elaboration under control without modifying the shape of the statue, a long manual processing was involved (400 man hours).

As it is impossible to reproduce threedimensionality on paper, Figures 6 and 7 show some significant views of the David model. Fig. 8 is included to demostrate the unprecedented capability of obtaining arbitary sections of the statue volume, allowing extremely accurate measurements between arbitrarily selected pairs of points to be performed. This feature can open unprecedented prospects to quantitative studies of 3D artwork.

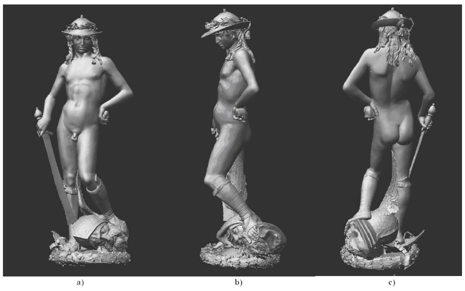


Figure 6: *Snapshots of the David's final model: a)front view, b)lateral view, c)rear view.*

Figure 7: *Snapshots of the head of the David's model: a)front view, b)lateral view.*

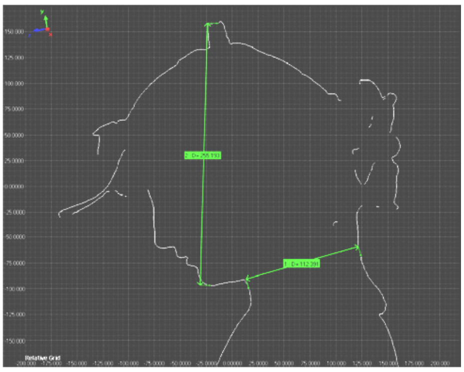


Figure 8: *Possible measurements through a section.*

5. Conclusions

In this paper, the acquisition of a high accuracy 3D digital model of a masterpiece by Donatello, the "David", kept at the Bargello Museum in Florence, Italy, has been described. Extraordinary good overall metric accuracy has been achieved thanks to the performance of the new Leica 3D sensor LR200. ICP alignment is not required by the acquisition procedure based on the new technology. With respect to previous projects the modeling time is reduced by one order of magnitude (editing excluded). Such modeling results open new interesting perspectives for making 3D modeling a routine tool even on sculptures with difficult materials and complex shapes.

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