3D Digital Terrestrial Model Creation Using Image Assisted Total Station and Rapid Prototyping Technology

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Abstract

This paper presents the integrate procedure for the documentation and fabrication of the 3D Digital Terrestrial Model (DTM) of inaccessible and rough surfaces. The proposed procedure combines the use of modern Image Assisted Total Stations (IATS) with Rapid Prototyping (RP) Technology. The determination of the measurement accuracy, as well as, the a-priori estimation of σ_o of the surface creation is achieved by using the Monte Carlo technique and the least square method. Also, basic concepts and principles of RP technologies are presented. The application of the procedure was realized at the difficult and inhospitable area of the central crater "Stefanos" on Nisyros Island's Volcano, Greece. The a-priori calculation of the minimum essential scanning step, as well as, the testing use of two IATSs is included. Additionally, the elaboration and the special algorithms used for the actual RP fabrication of the crater's tangible model are illustrated. Finally a scholastic check of the model's reliability is applied.

Key words: Digital terrestrial model (DTM), Image assisted total stations (IATS), scanning, Rapid Prototyping(RP), Volcano of Nisyros

1. Introduction

Today the evolution of technology in surveying presents the new born Image Assisted Total Station (IATS). These instruments firstly enable the so called intelligent tacheometry (Scherer and Lerma 2009). IATSs are already used in specific applications such as remote monitoring methods instead of laser scanners or terrestrial aperture radar. The main reason is that they enable high accuracy (down to mm range) in all three coordinates directions even without targeting (Reiterer et al 2008).

On the other hand emerging from the field of Mechanical Engineering, a range of innovative, highly automated technologies (SLA, SLS, FDM, LOM, 3DP), have been introduced and evolved during the last two decades, recognized and described under the generic term Rapid Prototyping (RP) Technologies, also referred to as Additive Manufacturing, Freeform Fabrication, Layered Manufacturing, or even simply 3D Printing (Pham and Dimov 2001; Li Yan et al 2009). They utilize digital 3D geometrical data (originating from several different sources, such as CAD systems, 3D Scanners, Coordinate Measuring Machines, CT and MR tomography) for the additive fabrication of physical objects in successive layers. Prior to RP fabrication, the 3D data are properly prepared in computer software environments as 3D Solid CAD Models and then transferred to RP Machines via specific computer file formats (e.g. STL, VRML), (Kumar 1997; Fischer et al 2005), that fully describe the solid's boundary surface as an ordered triangulated mesh and assist for the appropriate for RP algorithmic layer preparation (slicing procedure).

The presented work aims to a total survey and digital documentation and representation of inaccessible and rough surfaces. Furthermore, the ability to fabricate actual tangible Rapid Prototyping models for them, based on the actual measured data, after appropriate processing via dedicated software has been investigated and is illustrated.

2. Comparison between Image Assisted Total Stations and Terrestrial Laser Scanners

IATSs perform all the common functions as simplified total stations. Also are equipped with at least one CCD camera. In some cases they incorporate two CCD cameras a wide angle (WA) camera attached at the top of their telescope and an internal camera for capturing detailed images. Therefore they have extra ability of scanning similar to those of Terrestrial Laser Scanners (TLS). That is why they are often called "light" scanners. IATSs are more convenient and easy to use. These instruments introduce a revolution in geoapplications, as they easily provide accurate data and complete models of the scanned objects, comparable to the ones obtained by TLS. For this reason the use of IATSs in some applications seems to be advantageous against the TLS.

TLSs are widely used for 3D modeling of buildings, constructions etc. Most of them are very expensive and difficult to carry out to the field, due to their increased total weight (including batteries) and also to the need for a computer at the site. Additionally TLSs measure a mass of dense points for every second of use (reaches 1million points/sec) instead of the IATSs, which measure a single point for each observation (Hai H. 2008). So the collected by TLSs data files are enormous. The lighter TLS models, which are more accurately and convenient (FARO Focus3D, 2013) limit the range of their measurements to some meter's decades (10m-40m). This is prohibitive for many applications.

The comparison between TLSs and IATSs shows significant advantages for the latter such as smaller volume and carrying weight, absence of large external batteries and no need for a laptop computer for their operation.

Table 1: Comparison of the basic characteristics between typical IATS and TLS

Feature	IATS	TLS
Weight	6kg	10 to 18kg
Supplying	Embodied batteries	Heavy external batteries
Target Surface	Accessible and inaccessible	Accessible and inaccessible?? (due to spheres placing)
Ancillary rig	None	indispensable, placing of specific target spheres uniformly on the scanning surface
Coordinate system	Unique for every instrument's position	Arbitrary for every instrument's position
Field Laptop	No	Indispensable
Office PC	Conventional PC	Extra powerful PC
Data volume	10-50 MB	>>>>1GB
Cloud Unification rectification	Not needed	Needed
Procedure	3D model creation and coloring the surface	Point clouds orientation, rectification, 3D model creation and coloring the surface
Quality information	Yes, by pictures	Yes, by pictures
Accuracy	±5mm - ±10mm depends on the scanning distance	>±10mm depends on the scanning distance
Color	Yes	Yes
Resolution	3mm	~2mm
Scanning Speed	20 points/sec	~ 150000 -1000000 points/sec
Cost	About 30,000 euros	About 100.000 euros
Other use	All geodetic applications	No

The choice of an IATS is preferable, especially for particular DTM creation as declivities façade. At these areas emerge numerous of troubles such as accessibility difficulties, carrying the instrument and positioning the appropriate target spheres needed for the TLS. Also as time passes high accuracy requirements for long scanning distances are increased (Lambrou and Pantazis 2006).

Table 1 presents a comparison of basic characteristics and specifications between typical IATS and TLS.

3. Rapid Prototyping Technologies

RP Technologies were initially used by designers and engineers, during the Engineering Design Process, as an immediate extension of 3D Mechanical CAD software (such as CATIA, Pro-Engineer, Unigraphics, I-DEAS and others) to produce several prototype components required, in a fast, cost-effective, automated and highly accurate manner. With RP and relevant equipment, prototyping and model making can nowadays be accomplished within hours, compared to days or weeks of past times (Wang et al 1999; Jauhar et al 2012).

The ability of RP to fast deliver physical objects directly out of digital data, combined with IT supported technological innovations also introduced in areas other than Mechanical Engineering, such as Architecture, Civil Engineering, Medical Sciences, Art, Mathematics, Biology, Archaeology, Paleontology, as well as Survey Engineering with Geographic Information Systems (GIS), has led to noticeable widespread of RP utilization, (Dimitrov et al 2006), to ongoing investigation of effective RP application (Polydoras et al 2011) and to interdisciplinary approaches and applications, like the one presented in this paper.

Architects, Civil and Survey Engineers were among the first to incorporate computers and Computer Aided Design/Drafting (CAD) software. All of them often require having actual scale models of buildings, structures and landscapes/areas for visualization, documentation, studies and communication purposes. It is acknowledged that humans perceive and understand better 3D objects and scenes, compared to any 2D drawing or map, as they can easily estimate distances and understand height variations with the inherent 3D human stereoscopic vision, (Rase 2002). Nevertheless, such models for decades have been manually produced.

Virtual Reality (VR) representations could nowadays also serve for 3D visualizations, and have been in some use, (Burdea and Coiffet 2003), also providing some functions not possible with real models (response to the interaction of users, sectioning views, time lapsing, animation sequences). But VR normally requires large and expensive infrastructures, powerful computer clusters and can often prove inadequate when a large number of persons have to simultaneously investigate a 3D structure or scenery.

Provided GIS systems/data and a 3D CAD digital representation exist, by following a proper workflow, existing RP methods could successfully deliver quality tangible 3D objects of buildings, structures, terrain, areas or landscapes and thus well bridge the gap between virtual and real environments, in an automated faster, more accurate and cost-effective manner than manual models, or even VR attempts.

4. Case Study

This study focuses on the documentation of a Natural Heritage monument, namely the crater "Stefanos" of Nisyros' Volcano, in order to preserve it for the next generations through the centuries. For this purpose the combining use of IATS and RP technology is researched.

Nisyros' volcano is one of the active volcanoes in Greece. The crater "Stefanos" is the biggest of the four volcanic craters located on Nisyros' island caldera and is accessible to visit (Picture 1). It has an ellipsoid shape with a big semi-axis of 180m, a small semi-axis about 130m and a depth of 30m. Also the floor of the crater is almost flat.

The crater "Stefanos" as well as the whole site of the volcano site has been researched for years ago. Remarkable studies had been carried out by the Institute of Geology & Mineral Exploration, by the University of Athens (Space Applications Unit in Geosciences, Laboratory of Geophysics) and by independent researching teams (Lagios et al 2005), (Lagios et al 2007), (Vassilopoulou et al 2002). An interesting research by the title "Orthophoto generation using IKONOS imagery and high-resolution DEM: a case study on volcanic hazard monitoring of Nisyros Island (Greece)" (Lagios et al 2005) had been aimed to the orthorectification of a 1-m resolution pan-sharpened IKONOS Geo image of Nisyros island. The aim of these elaborations is the systematic monitoring and registration of geological, geophysical and geometrical alterations of the volcano site, for the creation of a Geospatial warning system (http://www.geowarn.ethz.ch/).

Over against the aforementioned studies, the goal of this research is the creation of the detailed tangible three-dimensional model of the crater's surface and to print it even in 1:500 scale. The attainable accuracy of the model should permit the monitoring of the crater's alterations as time passes and also be analogous to the roughness and the complicacy of the surface. Namely about ±10cm seemed to be sufficient.

As the environment at the crater's area is really inhospitable, the attempt of the documentation introduces numerous difficulties. It is really difficult to reach the bottom of the crater carrying heavy equipment and also to remain there for long time. Temperatures reach 35 to 40 degrees Celsius during the season that the documentation took place (June 2011), while vapors of sulphuric gas are continuously gushed out from the earth's hurt, making the stay nearly insufferable. Thus the use of IATS seemed to be the best solution for this task. The area of the declivity to be scanned was about 25000 square meters, while the crater's floor surface is about 50000 square meters.

Picture 1. The Crater "Stefanos" of the volcano

4.1 A-priori Scanning Analysis

It has been proved that the a-priori estimation of the minimum essential scanning step, when using an IATS is feasible by using a special statistical technique (Pantazis and Nikolitsas 2011).

The Monte Carlo technique is used combining with the least square method (Rubinstein 1981;JCGM 101:2008 2008), for calculating both the uncertainty of the coordinates of the measured points and the standard error of the adaptation of a surface to these points.

Utilizing as input data the measurement uncertainty of angles and distances provided by the IATS and the scanning distance, about 10000 simulations of the coordinates'(x, y, z) calculation are carried out leading to the reliable estimation of σ_x, σ_y, σ_z (Alkhatib et al 2009).

Then, providing the coordinates' uncertainty and the scanning distance as input data, the standard error of the adaptation of a concrete geometrical surface to the measured points can be determined.

Consequently by using the above calculated standard error the minimum essential scanning step (s) for confidence level 95% can be calculated by the equation

$$s = s_0 \cdot z_{95\%} \tag{1}$$

Figure 1 presents the aforementioned procedure. It's obvious that a smaller scanning step has no reason, as it would lie close to the procedure's uncertainty namely under the threshold of the adaptation noise.

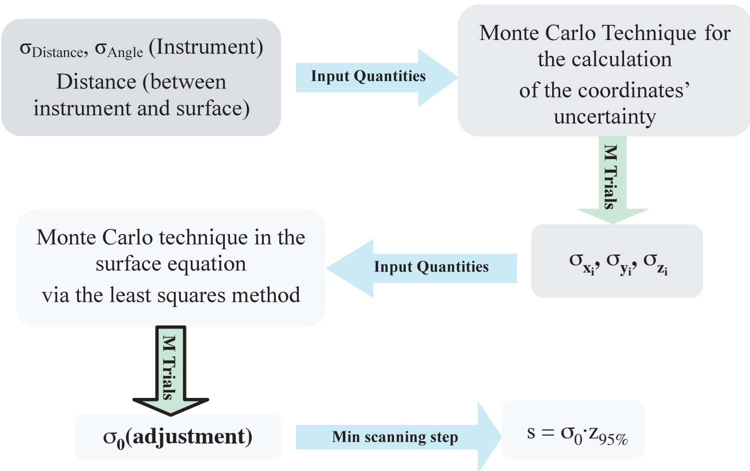


Figure 1: The minimum scanning step calculation

Additionally the approximate number n of the points to be scanned may be estimated by the equation:

$$n = \frac{\text{Area } (m^2)}{s^2(m^2)} \tag{2}$$

Considering that the scanning step is the same both for the horizontal and vertical direction. Thereby the appropriate time needed for the scanning can be approximated, as the nominal scanning speed for each IATS is known by the specifications.

For the crater's model the goal is to estimate, the optimum scanning step according to its specific figure. A close approximation is that the crater's shape could be described by a geometric shape surface. Considering that the closest geometric shape to the crater's surface is a part of a monochono hyperboloid (fig.2), and then equation (3) describes its mathematical type (Abbena et al 2006).

$$\frac{x_i^2}{a^2} + \frac{y_i^2}{b^2} - \frac{z_i^2}{c^2} = 1 \tag{3}$$

where,

a, b, c are the semi axes of a monochono hyperboloid solid surface

x_i, y_i, z_i are the coordinates of each measured point i on the surface

As equation 3 is not linear, the Taylor method is used and the following equation is formed:

$$\frac{-(2\cdot x_0^2-4\cdot x\cdot x_0+2\cdot x^2)}{a^3}\cdot\partial a+\frac{-(2\cdot y_0^2-4\cdot y\cdot y_0+2\cdot y^2)}{b^3}\cdot\partial b+\frac{(2\cdot z_0^2-4\cdot z\cdot z_0+2\cdot z^2)}{c^3}\cdot\partial c\cdot$$

$$+\frac{2\cdot x_0-2\cdot x}{a^2}\cdot\partial x_0+\frac{2\cdot y_0-2\cdot y}{b^2}\cdot\partial y_0+\frac{-(2\cdot z_0-2\cdot z)}{c^2}\cdot\partial z_0=0 \tag{4}$$

Figure 2. The monochono hyperboloid

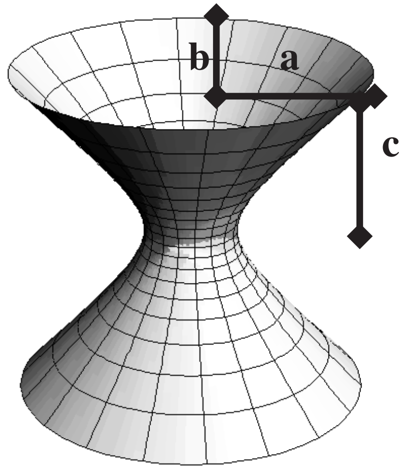
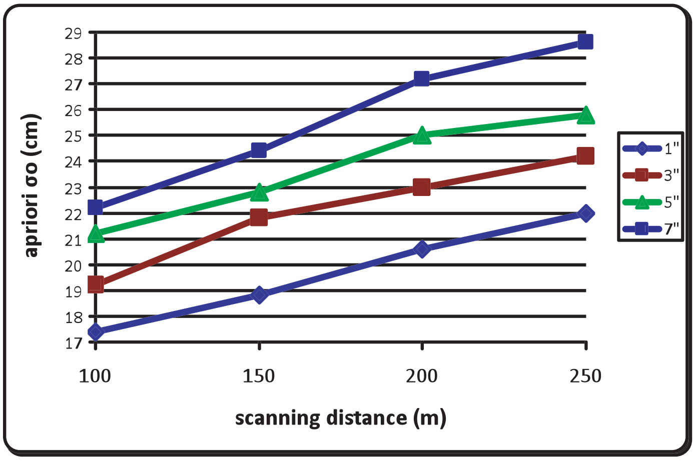


Figure 3: The a-priori standard error σ_o for the points'adaptation to a monochono hyperboloid, for confidence level 95%, for different IATSs accuracy.



By applying the least square method via the Monte Carlo technique on the equation (4), performing about 10000 adjustments, the a-priori σ_0 of the adaptation of the surface to the points to be measured is calculated for confidence level 95% (fig.3) (Gotsis 2012). According to the diagram as IATSs which will be used provide ±1″ angular accuracy, so σ_0 of the points adaptation to this surface is equal to ± 22cm. This defines the minimum essential scanning step that the concrete geometrical surface could be scanned. Under this threshold a smaller scanning step has no sense as underlie the noise of adaptation. However nothing better out of this σ_0 could be achieved as the crater's surface is a rather rough surface.

Apart from the above approximation the final decision, for the optimum scanning step should take into consideration the following parameters:

- The crater's surface is not a strict geometrical surface.
- The roughness of the actual surface and the aforementioned difficulties of the environment.
- The will to use two IATSs, in order to test them in harsh circumstances and to be able to compare each one with the other, as this would be a unique application.

Bearing in mind all the above analysis it was decided that the optimum scanning step is 1m with both IATSs. Thus the final model including all points will have almost the half scanning step, namely about 0.5m.

4.2 Scanning Implementation and Processing

Both IATSs Topcon IS and Trimble VX were used. Both provide angular measurement accuracy ±1arcsec in horizontal and vertical angles and ±5mm ± 2ppm (Trimble 2008,Topcon 2009) in the distance measurement on the scanning mode. They have adequate range to cover the crater surface from its center, namely about 200m. According to the afore mentioned analysis the expected uncertainty of the x, y, z coordinates of each measured point was calculated about ±2cm for confidence level 95%, which is really satisfying. It is pointed out that the aforementioned uncertainty may be worsening due to harsh environmental circumstances in the crater. The influence of the different materials of the rocks, the different color of the surface, the changes of the temperature and the vapors of sulphuric gas on the final achieved uncertainty can't be predicted.

Furthermore, according to their specifications, their scan speed is 20point/sec (Topcon 2009) and 15points/sec (Trimble 2008) respectively. This by the selected scanning step leads to about 30 minutes scanning time for each IATS.

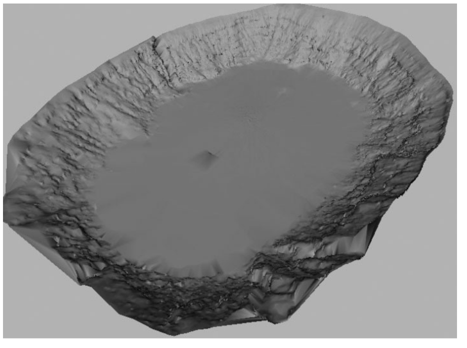
A local reference coordinate system was established including geodetic orientation to the North. Three station-points were selected; two of them placed at the bottom of the crater for the scanning realization and one station at the brink of the crater outside in the wider area. The choice of the stations was made mainly with the criterion of the best visual contact to the object.

The IS station measured 45.362 points in about one hour, while the VX station measured 49.585 points in about 4 hours, including some more sparse points on the floor of the crater. The IS proved to measure really faster, as it measures about equal number of points in just a quarter only of the time.

The initial data processing was carried out in two different software packages, one for each IATS, namely the Topcon's Image Master Software and the Trimble's Realworks. The goal was to process the point clouds, create the surface and color it based on real photographs of the terrain taken during the scanning.

Both software packages have similar functions, differing only in their approach for creating a triangular lattice, which in turn is the base for further surface creation. The Realworks software permits the creation of the triangular lattice through a projection of a geometric solid (plan, cylinder), or by using a projection through the central scanning point or by choosing free triangular lattice creation. In this case the procedure of free triangular lattice creation by triangulated polygon mesh is selected as the two other methods caused significant geometrical alteration on the created surface. Figure 4 presents the outcome of this processing, a prototype digital surface model derived by the total measurements from both IATSs.

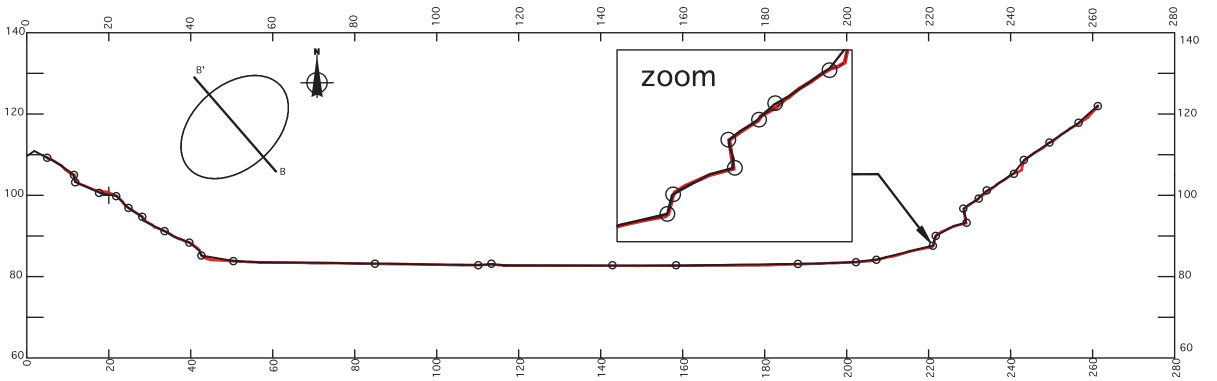
Figure 4: The prototype digital model of the crater's surface



Furthermore the reliability of the model was checked by the comparison of the two,almost perpenticular, main cross sections of the crater derived from the model to the Coresponding ones which are measured at the site. The sections were measured carefully point by point manualy, aiming throught the telescope of the VX which was placed at the crater's center point. About a hundred of points were captured and their coordinates were calculated in the same coordinate system. As the bearing of each section was calculated, the exact same sections were exracted from the 3D model. The differences between the hand–made and the coresponding digital–made cross section, varie from 2cm to 7cm. These assessed as satisfying, for such a rough and scraggy surface, where the points couldn't be marked. Figure 5 presents the comparison between the two versions of a section.

4.3 Mesh Improvement and Preparation for Rapid Prototyping

The direct interconnection of the points collected with the IATSs with triangular elements, given the circumferential and vertical distances



selected for scanning, resulted in a relatively un-natural aesthetic result for the crater's surface, resembling to a terraced surface.

Figure 5: The comparison between the two two versions of a section.

To further enhance the natural look of the crater's scan, before the actual RP construction of a model, it was - at this point - decided to incorporate some software tools mostly used in Reverse Engineering (RE) - Mechanical Engineering (ME) applications in relevant dedicated RE & ME software, namely Geomagic Studio. Algorithmic "spike removal" to eliminate sharp points and "surface smoothing" commands were used on the triangular mesh of the crater, to such an extent that its surface would not much deviate from the actual points collected and would still look macroscopically realistic, but noticeably smoother.

The result of the surfaces before and after their improvement can be seen in Figure 6.

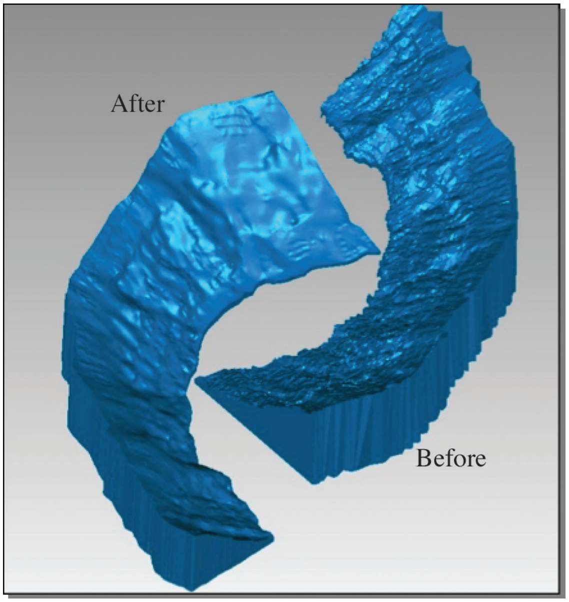


Figure 6: STL files prepared for Rapid Prototyping

A segment of the crater in both forms, of processed and unprocessed terrain surface, was decided to be RP reproduced for surface enhancement evaluation, before building a full crater model.

As stated above, RP requires a solid part, or else a closed-surface volume, to build an object. Up to this point, only triangulated meshes of an open surface of the crater were available. In order to end up with solid parts, another RP dedicated/STL manipulation software tool, Magics RP, was used. All surface models of the crater (the raw and enhanced segments, as well as the full one) were imported in this software and their upper – outer boundary was vertically extruded (Z-axis), at a distance below the craters lowest height, thus forming a solid. Further, by "cutting off" the digital models via a XY oriented plane, full solid models of the crater were achieved, resembling much like an athletic stadium. Proper triangle reduction in areas of redundant meshing, to later reduce processing times on the RP machine, was also performed before exporting the final solids of the crater into STL files for Rapid Prototyping.

For the actual fabrication of tangible RP models of the Nisyros' crater, a Helisys Laminated Object Manufacturing, model LOM1015 Rapid Prototyping Machine was used, hosted in the Rapid Prototyping and Tooling Laboratory of the School of Mechanical Engineering of NTUA. This LOM1015 machine utilizes 0.1mm thick sheet of paper in order to additively build parts, in layers processed with a CO_2 laser, with an achieved dimensional accuracy of approximately ±0.25mm.

Parts produced by a LOM machine look much like wooden objects, in a natural brownish shade, well suitable for the presented application.

In a first prototyping stage the two variations of a segment of the crater were built, scaled 1:1000, in order to aesthetically evaluate the result, prior to the full crater fabrication. A "raw" version with the terrain's surface exactly as exported by the Topcon's Image Master software (Picture 2a) and the same segment with the surface enhancements performed in the Geomagic Studio environment (Picture 2b). The two parts were simultaneously built in the LOM machine in about 14.5 hours, requiring another 2 hours for part separation and minor post-processing. By examining the objects obtained, it was verified that the software-enhanced crater surface-planned for full prototyping- indeed, looked more natural and realistic (Picture 2b).

Therefore, in a second prototyping stage, the STL file of the enhanced version of the Nisyros' crater, scaled 1:2000 in respect to the actual, was also transferred to the LOM machine for fabrication.

In about 8 hours of actual build time and another 3 hours for part separation, part surface protection and finishing, a complete 1:2000 tangible scale model of the Nisyros crater was completed. It is illustrated in Picture 3.

5. Conclusions

(a)

(b)

Picture 2: 1:1000 scaled crater segment LOM prototypes

Picture 3: 1:2000 scaled model of the Nisyros' volcano central crater

In this paper the combined use of IATSs and RP Technologies is engaged for the creation of tangible 3D DTMs for specific applications. The integrate process of a-priori estimation of the scanning parameters (distance, scan step, time) is introduced.

A difficult task has been succeeded by exploiting the advantages of IATS, although accessibility and other kind of difficulties are occurred.

The a-priori theoretical scanning analysis and the specific spatial parameters of the studied surface leads to valuable results for the uncertainty of the final coordinates, as well as, to a convenient and justified decision regarding the selection of the optimum scanning step. The question of the optimum scanning step emerges as the main decision in every scanning implementation so the calculated minimum essential scanning step defines the threshold in order to select the optimum one. The Monte Carlo technique helps this estimation in respect to the shape of the surface to be scanned.

The resemblance of the actual surface of the crater to the geometrical surface of a monochono hyperboloid is satisfying and leads towards a min essential scanning step of 22cm. The actual 50cm scanning step succeeded, proved adequate for the crater's documentation.

The use of IATSs gives the possibility to realize this project in about 10 hours of field work shared in three days due to the environmental conditions. Also, 11 hours for building and post-processing the 1:2000 scale physical model of the crater were needed. Moreover, one to two days are typically enough for the elaboration of the original raw data in the appropriate software packages. Thus, an overall of 2 weeks for the complete workflow of data processing and exploitation was spent.

Scans performed with IS are considerably faster than the ones with VX. It is proved that both the used IATSs have reduced speed comparing to the nominal scanning speed referred by their manufacturers. The scanning speed was 12 points /sec speed (reduced by 40%) with IS and 4 points /sec (reduced by 75%) with VX. Probably the environmental conditions and the surface texture are liable for this result.

Thus the selected scanning step (1m) proved to be optimum. As the selection of a smaller one (e.g 50cm) would increase about four times the remaining time in the crater's bottom, which would be hard row to hoe. Both IATSs are appropriate for this work, but IS is preferable as it permits less time to be spent in the crater.

The first approximation of the model by the IATS' software is not as aesthetically satisfying as the second elaboration of the model obtained after processing with ME-oriented software Geomagic Studio and its available software tools for surface improvement. The accuracy and reliability of the model was succeeded by approximate ±5cm all over the surface.

The detailed 3D model of the crater "Stefanos" is a unique result focused on the limited area of the Nisyros' caldera in comparison to other projects, which had documented the whole caldera or Island. This total geometrical documentation of the crater could serve also to other research teams. For the long term preservation of the digital record of the crater, the digital model information (polygon mesh, STL) can either as STL file or converted as VRML file data to be exploited in digital libraries like the Geospatial warning system (http://www.geowarn.ethz.ch/) in order to be utilised for researching and tourist reasons as well.

Apart from that, the real object (RP prototype), which is documenting the current image of the crater could be used as a master pattern for reproduction of replicas.

More over the replication of the survey after some years will lead to reliable results for the crater's monitoring such as in similar researches (Pesci A. et al 2013).

The LOM RP technology utilized, successfully delivers a realistic tangible model of the crater, while the Geomagic Studio routines permit a natural smoothing of the surface that enhances the resemblance to the actual crater's terrain.

The LOM RP model of the full crater presented a very realistic result and close resemblance to the actual volcano, as can be justified by photographs and satellite images of the area.

Conclusively IATSs may deservingly be used instead of TLSs saving money and labour in specific detailed DTMs creation. Additionally it is proved that the combined use of 3D spatial data and RP technology, it can find interesting application in natural structures documentation and not just for the creation of mechanical products, in which had been utilized till today.

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