HIGH DENSITY DIGITAL FORM FOR CULTURAL HERITAGE: SYNTHETIC MODELING AND REVERSE ENGINEERING OF THE FOUR HORSES OF THE BASILICA OF SAN MARCO IN VENICE.

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ABSTRACT:

This research would like to illustrate an experimental work carried out in the filed of Cultural Heritage, finalized to determine a complete object shape at very high resolution. The aim was to go beyond initial dichotomy present between two main necessities: on one hand side a definition of a most accurate model of the study item, and on the other a granted possibility to control, over the time, the form and shape variations that surfaces could undertake for various reasons.
In the field of Cultural Heritage, it has been seen how a digital model, created from a precise data obtained with terrestrial laser scanner techniques, allow a continuous and accurate definition on an architectural scale. However, if a scale factor increases and a geometrical definition is required, for little objects or sculptures, application possibilities decrease considerably. A literature known case is David of Michelangelo, carried out by a Stanford University as a project of Digital Michelangelo (Levoy, 2000), as well as other projects done with purely experimental technologies, suitable for prototypes and with a pretty defined limits of use.
This research combines various experiences developed in different fields and modified for a domain of Cultural Heritage, in order to obtain, from a fusion of specific skills, a right methodology to approach study cases of a complex form.
The aim of experimental applications has been a validation of affirmations previously expressed: during a test phase a 3D digital survey was made of a portion of a sculpture of four horses situated inside of a Museum of St. Marks Basilica.

1. INTRODUCTION

1.1 The four horses of Venice

Figure 1: The four Venice Horses.

A beautiful bronze, gold – coated, sculpture arrived to Venice with a rich war plunder stolen by Venetians, under doge Enrico Dondolo, after a conquer of Costantinopoli after a IV Crusade in 1204, together with other goods of inestimable value. A placement of a four horse sculptures on the Basilica's facade probably took place during dogeate of Raineri Zeno (1253-1268), considering the fact that a mosaic decorating "a lunette" on the St. Alpio's portal, that is dated at approximately 1265, represents the sculpture already arisen to the location that it later maintains for centuries (Cecchi, 2003).
In December of 1797, for the first time after five centuries, following a Napoleon wish, four horses abandon the St. Mark's front and they are transferred to Paris. The sculpture, that is predestined to adorn a coronation of a triumphal arch of Carrousel, undergoes various additions. After the fall of Napoleon, Antonio Canova is put in charge of retrieval and transfer to Italy of all stolen goods. On 13 of December of 1815, under Francisco I of Austria the new lord of Venice, the four horses sculpture is repositioned on the front of St. Mark's. The precious statue, a unique example arriving from ancient times, has suffered considerable damages so before it had been repositioned it was taken to Arsenal for a restoration. Some other operations were necessary over the years so the statue was taken down twice from the arch of St. Mark and finally it found it's safe shelter during the last two World Wars. In 1960s horses were subordinated to a the Central Institute of Restoration for numerous analysis to be done. Those analysis confirmed a very bad conditions of the statue but were also very useful for the historical and morphological information of a horse statue. It appears to be an essential need to conserve the original statue at the Basilica's museum while the copies of horses were made to be placed on the exterior arch (AA.VV. 1999, Scienza [..]).
During the last restoration no elements were found that would help in dating the statue. Some uncertainties are still present

and, as a unique case in the ancient art history, the date of their creation oscillate within the IV century. B.C. and the IV century A.C
Anyhow, some observations as the use of fused mercury, the form of the eyes of the horses, manes and ears, a complex shape of dowels used for reparation before gold – coating, would suggest that the statue is datable at time of Roman Empire, at the period of Settimio Severo, at a school of Greek – oriental artists, followers and keepers of a great Hellenic tradition. The method of the production of the four horses sculpture is a confirmation of this theory: they have been made by blending of pieces (the head, the body, the legs, the tail) in a so called "indirect method". A metal alloy is made almost completely of copper and it requires a much higher fusion temperature that pure bronze: it's a very rare, if not a unique, case until now discovered for statues of these dimensions and finalized for a double gold – coating ("leaf method" and "mercury method"), a technique used mainly in the middle ages of Roman Empire. The excessive shimmering effect was smoothened by the artist by creating a dense engraving in the areas mostly exposed to light (AA.VV. 1977, I Cavalli di San Marco [..]).

1.2 The partner of the research

The operation phase of this project involved:

- Politecnico of Milan, DIIAR, Laboratory of Topography, Photogrammetry and GIS as project proponent, with coordination rule and the responsibility of the research program
- Procuratoria of St. Mark in Venice. It is responsible of the preservation and conservation of the San Mark Basilica and of the Marcian Horses too.
- Hexagon Metrology. A Swedish multinational company that orients its business mainly on measurements studies and, since 2005, includes societies such as Leica Geosystem and Metrology.It's exactly Leice Metrology the kindly take part to the project with the supplying the instrumentation and technical experience.

2. THE INSTRUMENTATION

2.1 Leica LTD840

Leica's LTD840 (Leica Laser Tracker) is the undisputed touchstone for aerospace portable CMM applications, with a wireless probing range of up to 15m. LTD840s high-end specifications translate into a probing measurement volume of up to 30m, enabling us to conduct demanding wireless probing of very large object with just one setup.
The LTD840's measurement range reaches a full 40m when used with a corner cube reflector. This laser tracker delivers the fastest measurement cycle in the industry for high point density (3000 points/second).
The laser tracker have the function to pinpoint the location of the object (X, Y, Z) from the basis of the Local Positioning Technology that will be the centre of the georeference system.
In this type of application is normally joined with T-Cam system.
We rely on state-of-the-art solutions such as the high-speed hand scanner Leica T-Scan and the armless and wireless Leica T-ProbeII* that work in tandem with the LTD840 Leica Laser Tracker.

2.1.1 T-Cam The T-Cam has the ability to acquire any rotation of a given object (i, j, k). T-Cam features include:

1. High-precision Vario Optic
2. Very homogenous orientation for the T-Probe and T-Scan and consistently accurate measurements
3. Precision quick release for reassembly without any compensation needed
4. High stability and extremely robust

Figure 2: Leica Laser Tracker and Leica T-Cam

2.1.2 T-Scan. Leica T-Scan is a high-speed hand scanner. The working distance is Min/Max 41-119mm and a scanning width (within working distance): 90mm ±25mm from the object. Set-up times are minimal, and there is no need for photogrammetric targets.

Figure 3: T-Scan

* We don't use this kind of instrumentation because not functional for our aim. We report for completeness some data relate to it. "The wireless Leica T-Probe enables ATT to measure aircraft tool and production parts at a much faster rate. Reducing the number of tracker relocations translates into a significant cost and time savings. An additional benefit is that the Leica T-Probe has the ability to measure or inspect points in deep pockets or recesses that could not be accessed in the past."

By projecting a laser beam point by point, the hand-held T-Scan uses flying dot scanning to scan any type of surface at a point rate of 7000 Hz and measures up to 7000 points per second. T-Scan features include a window for laser beam, including navigation laser to stay in measurement field.

1 Trigger for data acquisition
2 Infrared pulse antennas for rotation angle measurement
3 Eye safe laser class 2
4 Prism for the laser beam capture and the XYZ position measurement.

2.2 Detailed accuracy information*

The uncertainty specified below is achieved with Leica T-Scan using a point density setting of at least 0.35mm and a line spacing of at least 0.35mm under stable environmental conditions.

Measurement uncertainty of spatial length "UL" is the deviation between a measured length and its nominal value. This measurement uncertainty is specified as a function of the shortest distance between the Laser Tracker and the measured length. The length can be up to 6m and is perpendicular positioned to the laser beam. The centers of two fix-mounted spheres (sphere radius between 15mm and 20mm) at the end of the reference length are representing the nominal distance. The measured distance between the sphere centers is calculated using scan data of all four Leica T-Scan sides.

Measurement uncertainty of sphere radius "UR" is the deviation between a measured sphere radius and its nominal value.

The measurement uncertainty of the sphere surface "US" is defined as the 2-sigma value of all deviation from the best-fit sphere that is calculated with all measured points. This specification assumes a reference sphere with a radius between 10mm and 50mm. These measurement uncertainties are specified as a function of the distance between the Laser Tracker and the sphere. Data of all four Leica T-Scan sides is utilized for the calculation of the sphere radius and the sphere surface.

Measurement uncertainty of plane surface "UP" is defined as the 2-sigma value of all deviation from the best-fit plane that is calculated with all measured points. Data from all four Leica T-Scan sides is utilized for the calculation of the plane surface.

Measurement uncertainty of spatial length:

UL = ± 60µm for <8.5m
UL = ± 7µm/m for >8.5m

Measurement uncertainty of sphere radius (2 Sigma):

UR = ± 50µm for <8.5m
UR = ± 7µm/m for >8.5m
US = ± 95µm + 1.5µm/m

Measurement uncertainty of plane surface (2 Sigma):

UP = ± 95µm + 3µm/m

2.3 How the scanner works

As explained before, the instrumentation is composed by two parts. One is the laser tracker the other one is optionally T-Probe** or T-Scan. The Laser Tracker is composed by two parts: the interferometer and by the T-Cam. The concept of the system measurement mode is relative simple to explain.

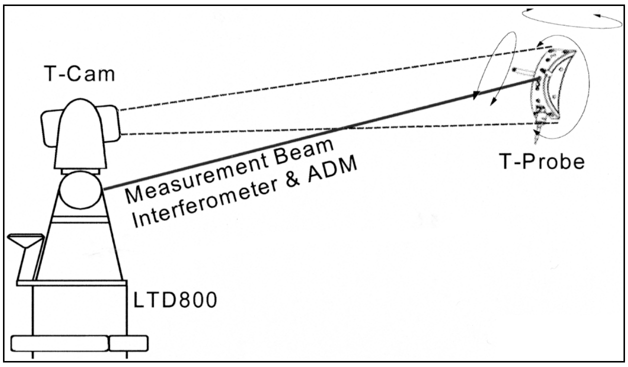

Figure 4: Scheme of the system measurement mode.

The interferometer measure the position of the T-Scan with a laser ray "captured" by the prisms that are positioned on every sides of the hand scanner. The T-Cam is a camera that follow the movement of the scanner and calculate the rotation angle of this instrument "reading" the "spatial orientation" of the Infrared Pulse Antennas that are also positioned on all the side of the scanner. In this way in every moment of the acquisition the position X, Y, Z (referred to the centre of the interferometer) is know besides the rotation angles. In this way all the points of every scan are georeferenced in the same coordinates system. It's obvious that the hand scanner must have full scope between itself and the interferometer to let the two instrumentation to be connected each other. In case that the laser ray disconnected from the instrumentation or that there is some obstruction between T-cam and laser the scan stop automatically preventing undesirable unregistered scans.

This scanner is normally used in mechanical and in particular in aerospatial application thanks to its great reliability and accuracy. We choose to test this scanner also in cultural heritage application because is very manageable and have very low noise.

The test wanted to proof what level of detail could we obtain. The global geometry of the horse head could be reached with many scanner and also with photogrammetry but where was some very tiny detail to model that we can reach only with structured light sensor or few some other scanners. The final decision springs from the location and the nature of the object: the statue is circa 2,5 meter high and the interesting head was the highest part of the single horse. Besides the four horse are very close each other and was impossible to build a scaffold to carry the scanner during the acquisition. In this situation the choice of a hand scanner was the optimal one.

Other constraint that is common with fast every cultural heritage cases is that no target couldn't be attached on the object. This kind of scanner doesn't need target to register every "scan images". Eventually block of scans that are different origin can be aligned in post processing elaboration with other methodologies.

Furthermore there is another feature what leads our choice to Leica T-Scan and this is that this kind of instrumentation can work in every light condition. In particular the "automatic intensity adjustment" is the characteristic that is more interesting in this case. The scanner is able to calibrate itself during the scanning adapting itself to different kind of surfaces. shiny or mat and dark or bright. This is a very important features if you want to scan an object that present different kind of surfaces without having many noises or scanning error due to

* This data are taken directly from Leica products specification.(See References)

** From this moment I will speak only about T-Scan that is object of our test.

the different response of the laser to different colour and material.
In our case of test the horse head is made of bronze (mat) with a gold cover that was scraped away (See Figure 5). These scratches are circa 1,5 / 2 mm wide (that's why the request of high resolution scan) and create a very "confused discontinuity" among shiny and mat material that can create erroneous point acquisition.

Figure 5. Some particular of the horse head with the scratches what we want to modelling.

3. DATA ACQUISITION AND ELABORATION

3.1 The acquisition

For the acquisition including every operation of transportation, assembling of the instrument and calibration procedure we need one and half day.
We collect the data from two scan workspaces: one for the right side of the horse's face one for the left one (See Figure 64). For every scan we let an adequate common zone to let the following registration of the two parts.

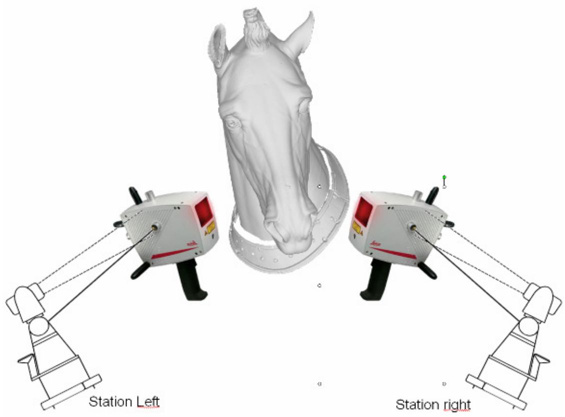

Figure 6: Scheme of the acquisition.

Table 1: Some numerical data of the acquisition.

	Left side	Right Side	Union
Scans Number	223	203	623
Original Points Number	4824325	8171867	12979182
N° points after first reduction*	3619233	4434726	9874155

* The first reduction is the reduction of the overlap

Figure 7: It's possible to see a moment of the scan. The red dot on the side of the hand scanner means that the laser ray hooks up the instruments and that the scan can be done!

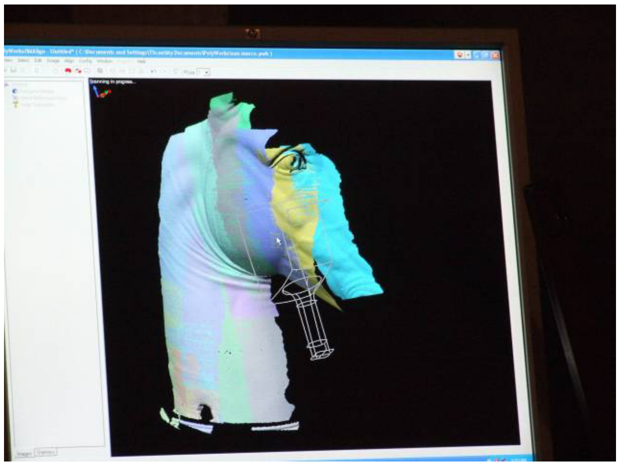

Figure 8: Simultaneously to the scan it's possible to see and control the work from a workstation. In this way the operator is able to see holes or bad covered areas. Every scan (as you can see in the pictures) is printed on the screen with a different colour. From the control pane the operator is able to set the resolution of the scan. Naturally only the resolution on the scan-line can be set. The resolution between two lines depend form the scan speed or by the scan repetition on the same zone. From the control panel it's so possible to control also the "line density".

3.2 The elaboration procedure

The elaboration procedure is conducted with Polyworks of InnovMetric Software because the scanner still interfaces with this software and because every elaboration steps can be followed and set with a lot of parameter. In this way it's possible to follow all the process being conscious of the accuracy or the precision degree of the model and to render the process less automatic and out of control procedures.

3.2.1 Filtering. This step can be eluded for the absence of noise. Only a visual exploration of the discrete model was necessary to erase few gross error due to scan operation mistakes.

3.2.2 Scan alignment. The first operation was to align every scans. both for the left and for the right part. At the end the two parts of the horse head was registered together and another scan alignment applied to better fit all the scan together. To rise a good result we set the max distance* step by step beginning from 0.01 mm until 1 mm and the convergence parameter was set to 0.000004 that is the $\left(\frac{\sigma}{25}\right)^2$ where σ represents the standard deviation of the 3D digitizer in model units (mm). This guarantees that the accuracy of the final alignment will be at least 25 times better than the standard deviation of the 3D imaging device. We choose a σ of the instrument as circa 50μm.

3.2.3 Overlap reduction. to reduce the number of points of the whole model the overlap between every scan was reduced.

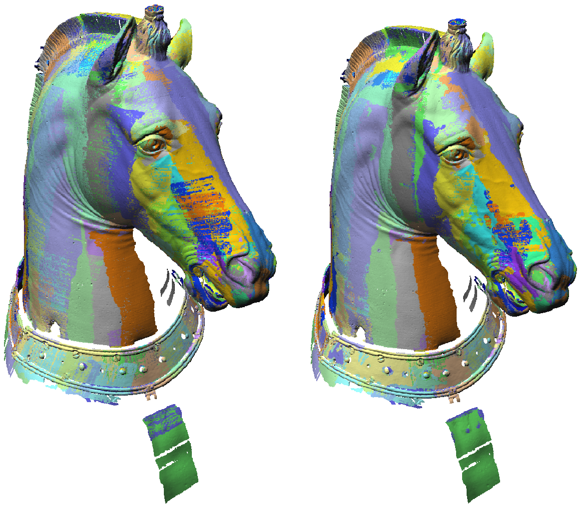

Figure 9: In the left image the aligned model. In the right one the same model after overlap reduction.

3.2.4 Mesh generation. The mesh generation process was the most difficult step. To preserve the quality of the scan it was not possible to good decimate the model. The mesh process take in this way a lot of time in particular to find the right mesh parameter set. We use a surface sampling step of 0.5mm, a max distance between two points image of 1mm and a standard deviation parameter as the sigma of the instruments equal to 0.05mm. no smoothing was applied to the model. The final mash have circa 8,6 million of triangle and take circa 6 hour to complete all the process.

4. CONCLUSION

To expose and to show the results of this project for the definition of the Digital form of the “Marcian Quadriga” means to give a starting point of their knowledge, to pay the attention on their conservation and at the same time to deepen they state of health.

But not only. The used acquisition methodologies can make usable to the national and international community the visualization, and the consultation of the Marcian Horses in the digital way.

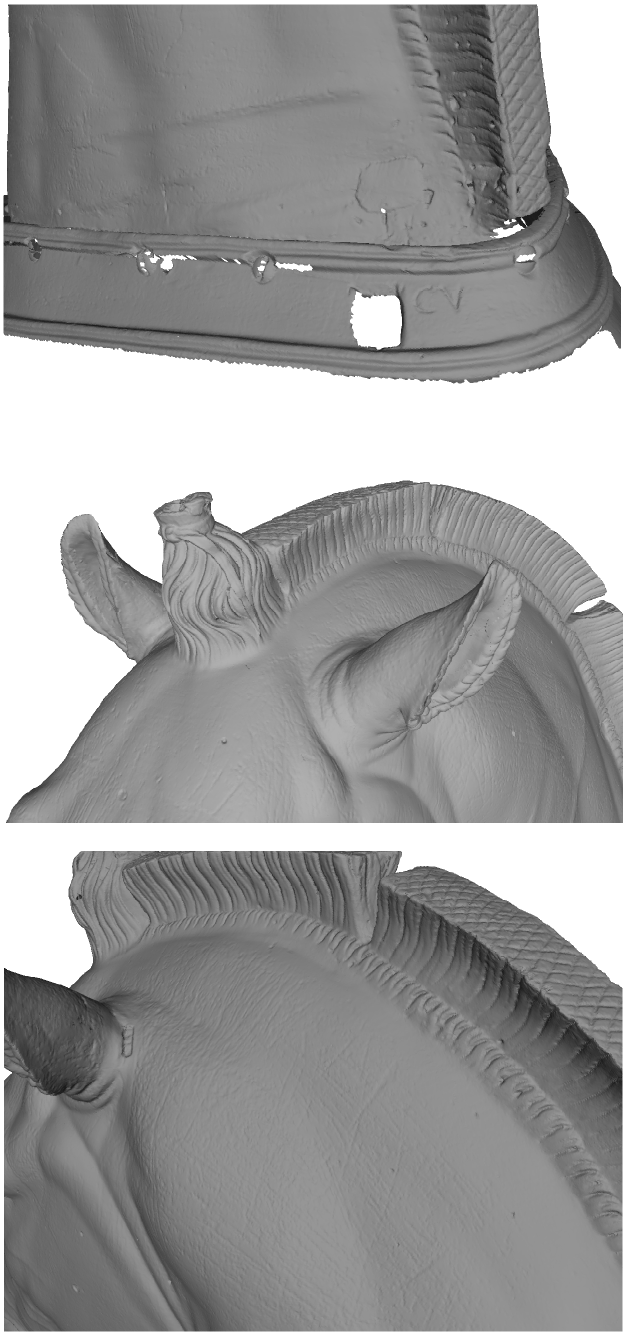

Figure 10: In these pictures is shown some close views of the raw mesh. No filtering, hole filling or other elaboration are applied after the mesh generation. It’s possible to distinguish the details that we want to model. The holes that you can see on the surface are real holes and only some little defect must be corrected in very complicated and no accessible places like the interior of the mouth and somewhere on the collar. In this upper photos is possible to see very clearly an incision on the collar (CV). On some foot and on the rear part of the neck are visible some roman number. The sense of this is unknown; somebody guess that these are number that can suggest the weight of the horse. (AA.VV. 1977, I Cavalli di San Marco).
On the other pages some general views of the global model.

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* This parameter defines a maximum acceptable distance between a 3D image point and another 3D image. If a 3D point is farther than this maximum distance from another image, the best alignment parameters between that point and the image are not computed. The Maximum distance parameter controls the robustness of the image alignment computations

5. REFERENCES

AA. VV., 1977. *I Cavalli di San Marco – Catalogo della mostra*. Procuratoria di San Marco, Venezia.

AA. VV., 1999. *Scienza e Tecnica del restauro della Basilica di San Marco*. Istituto Veneto di scienze letterature ed arti. La gongola, Padova, Vol. I e II.

Anderson S., Curless B., Davis J., Fulk D., Ginsberg J., Ginzton M., Levoy M., Koller D., Pereira L., Pulli K., Rusinkiewicz S., Shade J., 2000. The Digital Michelangelo Project: 3D scanning of large statues. *Proc. SIGGRAPH 2000.*

Cecchi R., 2003. La Basilica di San Marco. La costruzione bizantina del IX secolo. Permanenze e trasformazioni. Marsilio, Venezia.

Leica Metrology LTD 840. http://www.leica-geosystems.com/metrology/en/ndef/lgs_35316.htm (accessed 4 June 2007)

LaserTrackers Features and Benefits. http://www.leica-geosystems.com/metrology/en/products/laser_tracker/lgs_36108.htm (accessed 4 June 2007)