Digital Flow in Stone Heritage Buildings

The Nasoni Keystone Experiment

Pedro de Azambuja Varela¹, Jose Pedro Sousa²
¹,² Faculty of Architecture, University of Porto + DFL/CEAU/FAUP
¹,² {pvarela|jsousa}@arq.up.pt

In a moment when digital technologies can interfere in every moment and task in the architectural production, architects are using them in many different ways. In architectural heritage, stone is a prevalent material and one can find some examples of architects exploring particular uses of computers when facing this kind of challenges. However, it seems that there is a lack of references trying to develop a transversal reading of the context, by offering a systematisation of those approaches. With this concern, this paper wants to describe and illustrate the way digital technologies can support architectural intervention in stone heritage buildings, bearing the specificity of this material, its constraints and opportunities. For each moment, specific computer-based technologies can be employed not only to perform those tasks, but also, to assure the flux of information through a digital continuum. This paper overviews those moments by discussing the technologies available and presenting some examples from existing reference practices. To test those concepts and arguments, this paper includes the description and illustration of an experiment carried out in the Laboratory by the authors, of a digital continuum process from surveying a stone building, to design and fabrication.

Keywords: Heritage, Fabrication, Stone, Literature review

INTRODUCTION
On the various approaches of intervention in architecture heritage, it is possible to identify three main design strategies: "repeating", "recovering" or "transforming". By "repeating", we address the cases where a faithful reproduction of the original is intended, be it for replacement, or for researching elsewhere. "Recovering" deals with the moments in which a part or totality of the subject has vanished and the purpose is to give back its original appearance. "Transforming" delves into local criteria by making a critical recovery not tied to the exact copying of the original subject.

The Charter on the Preservation of the Digital Cultural Heritage of UNESCO mandates digitalisation of heritage, as a means to preserve memory and ease possible reconstruction and restoration. A gap between computer technicians and archeologists/architects has been narrowing down due to the work of several efforts like RecorDIM by CIPA, i.e. the Inter-
national Committee of Architectural Photogrammetry formed by ICOMOS and ISPRS (International Society for Photogrammetry and Remote Sensing) [Georgopoulos 2014].

HERITAGE INTERVENTION REVIEW

Survey

Surveying is at the forefront of architectonic heritage interest. Flavio Biondo, one of the first modern archeologists, initiated a process in which other contemporary architects would go to Rome and survey by eyesight the ruins of Ancient Rome. This is the first contact with the build environment and, until the dawn of digital technology, measurements of relevant points were made by direct distancing on site, or by trigonometry. Although technology evolved towards accuracy and flexibility, digital tools brought additional benefits like quantity and speed.

3D laser scanning. One of the characteristics of heritage architecture morphology is the irregularity of surfaces due to erosion or partial collapse of building elements. This characteristic of super information is the ideal subject to a surveying system which has the ability to acquire a multitude of details about a surface. This solution first appeared in the 60’s, when laser scanning was beginning to be used for atmospheric cloud measurement. Soon it was also used in moon orbital flight for height mapping the surface of our natural satellite, paving the way for a more generalised use for metric surveying of static solid reality. Laser scanning has two main approaches: time-of-flight and triangulation. Time-of-flight scanning depends on measuring the time it takes from a pulse to be emitted until it is detected again by the scanner (emitter and receiver at same location), triangulation scanners measure the angles of a triangle with corners [emitter, target, receiver] with a known distance between the emitter and receiver. While triangulation scanning yields much more accurate results (0,0001mm vs 1mm), it falls short on the distance it can cover as it only provides accurate results in the range of a few meters [Blais 2003]. Architecture has its own scale and, most often, 1mm is the smallest relevant measure - this is one of the reasons time-of-flight scanners have been used extensively in surveying architecture.

Although very precise, laser scanners are very expensive ( >5000€ ), which is often incompatible with the low budget in which heritage missions (academic or independent) support themselves. While laser scanners are active systems, passive systems come a lot cheaper as these do not require any kind of specific hardware to emit radiation.

Digital photogrammetry. On a single scan, an active system acquires the polar coordinates of a point in space; a passive system relies on two or more digital photographs to infer the relative locations of points relative to themselves. This kind of system relies in color information from the surfaces being scanned which, being sufficiently heterogeneous, provides a point cloud dense enough for accurate reconstructions under 1mm per 10m, given good quality photographs [Fabio Remondino 2011]. Digital photogrammetry relies in photographs for reconstruction of information about the subject. Using different photographs' diverging parallax to infer three-dimensionality is recently known as SfM (Structure from Motion), and takes essentially four automatic routines: photo matching, 3D positioning, dense cloud building and mesh creation. Photo matching is the process of pairing images by finding similar features across them. Once these features are identified, a parallax relation is calculated between each pair of points which get entwined in a 3D coordinate. Each of these 3D coordinates is part of the "sparse cloud", an initial representation of the 3D object with coloured matching points in a 3D environment. This point cloud is also useful for a quick visual analysis of the accuracy of the photo matching and position procedure. The next step uses the positions of the cameras to intersect rays (with origin in the camera and passing through matched photo pixels) in space which origin in the camera origin and point towards each of the pixels of the image, creating more spatial information; this is why the cloud density is directly proportional to the photos reso-
This process is by far the most processor intensive, and it may take from a few minutes to a few hours, depending on the quantity of photos used and point cloud density specified. This dense cloud is a collection of XYZ coordinates, but it may also contain RGB color associated with each point. When the point cloud is used to create a continuous triangulated surface (mesh), the RGB values may be used to colorize the mesh, but it is also possible to map the original photographs on the mesh surface, by using the projection vectors pertaining to the photos whose camera has an angle the closest possible to the surface normal, obtaining a textured mesh model of the scanned object.

From data to semantics. Efforts towards automation and precision are one of the key endeavours that lie in the crossing between architectural heritage and digital tools. Photogrammetry finds in the digital tools power a perfect environment for development, but industry usage is not always the target of research. ARPENTEUR is an architecture oriented photogrammetry software which was developed mainly for education and research purposes. Two of its key features are its simplicity of use and web based nature. Photogrammetry traditionally only provides coordinates of points in space. In order to enrich this possibility in the architectural environment, Drap et al. implemented a system to recreate surfaces based on points, with the assumption of a few archetric morphologic primitives such as the plane, the cylinder, cone or sphere. Knowing before hand what kind of geometry describes the surface that is being surveyed is compulsory to this system, which allows the user to model three dimensionally on top of the photograph.

An interesting problem was researched by the authors [Drap et al. 2008] when surveying the ruins of a romanesque church in Aleyrac, built with a clean stereotomy composed of fine cut stone ashlar. Instead of just surveying the visible surface of the architecture monument, it was set the purpose to model each constructive component individually; each occluded surface would have to be modelled to complete a closed polyhedron which represents the stone block. For this task, the strategy was set upon having the edges of each visible face of the block extruded along a vector until a certain depth. For planar walls, for example, this vector was inferred from the least square optimised normal on the neighbouring area. In the case of an arch, a specific algorithm was written so that the specific case of a cylindrical surface with horizontal axis was detected giving it the semantics of an arch; in this case the vectors emanated from the closest point in the cylinder axis.

Design

The work of the architect focuses in its greatest extent on designing, this is the moment in which decisions take place. With the data gathered from the survey, the architect plays a key role in making choices, and digital tools may help in taking specific paths. On a first moment we will look into a system of making such decisions in heritage intervention, and another example where an active role was taken in getting the right morphology of a stone monument.

Critical reconstruction. A virtual reconstruction is the 3D model of a lost or damaged object. It provides useful tools to archeologists and restorers for choosing strategies on intervene on heritage; conserve a faithful record on excavation sites, divulge culture in museums or media, help on reconstructing lost or damaged parts (or a whole) and choose between different options on restoring.

On the restoration of the Zalongon monument [Georgopoulos 2014], the conservation team needed to replace blocks of stone from the 1950’s sculpture, which had been deteriorated by harsh weather and frosting. A digital surface model of the existing situation was constructed with 3D laser scanning technology in order to prepare for the restoration project [Valanis et al. 2009]. The team used Rhino to complete the missing parts of the sculpture, but it was decided to use a semi-manual process. The relevant parts of the sculpture were printed in a 1:5 scale, and a sculptor completed the missing parts in a traditional fashion. Then, the physical result was digitized.
again with a structured light scanner so that further calculations and visualisations could enable masonry experts restore the sculpture. 

Many methods of getting information about a monument are concurrent (written documents, graphic depictions, surveying measurements, orthophotos, point clouds, archeologic assumptions, ...) and to negotiate these different sources of information in order to virtually reconstruct the monument, we can use different scales [Georgopoulos 2014]. The accuracy is a quantitative scale that measures the fine granularity of information, or the ratio of difference between the real and the represented. Reliability is a guiding vector on how much an information should weight on the final conclusion (for example, an old poem might have useful informations about a building, but it may also be very subjective; on the other hand, a specialised archeologist's opinion is much more prone to match the original object). These two scales combined result in one global factor called likelihood.

These factors were used when creating a virtual model for the ruined church of the monastery of San Prudencio in La Rioja, Spain [Gkintzou et al. 2012] or the Middle Stoa in Athens, Greece [Kontogianni et al. 2013]. The modelling was done in such a way that different parts with different levels of likelihood were given a specific meta information which was then mapped to the level of transparency of the virtual model, making the most likely parts opaque, in a gradation to transparency associated with smaller likelihood levels.

The Great Buddha of Bamiyan. The Great Buddha of Bamiyan, destroyed in 2001, was the subject of a research project within the Institute of Geodesy and Photogrammetry of the ETHZ in 2002 [Grün, Fabio Remondino, and Zhang 2002]. The purpose of the research was the construction of a digital 3D model which could be used to foster a possible reconstruction of the lost statue. An immediate purpose was set on 3D printing a physical model at 1:200 scale. As there was no three dimensional survey data prior to the destruction, the team had to rely on photographs of the statue to infer its three dimensionality. The photos used were taken with a metric camera, which means that it is specially tailored to provide distortion free captures [Adams 1981]. With three photos (these photos are analog, and were scanned into 16930 x 12700 bitmaps - 215MP resolution), the team used its own algorithm to calculate the positions of the camera in each of the photos and create the 178000 point cloud which was used to mesh the model.

This mesh obtained from the the three photographs proved accurate but incomplete, as the folds in the robe of the Buddha were not noticeable in the point cloud. As such, manual digital measurements were carried in the textured mesh, creating horizontal contours which yielded ca. 28000 points to the scanned point cloud. Depending on the case, there are situations in which some kind of manual reconstructing is needed; this manual labour is in fact semi-manual, as the 3D references for reconstructing are already very accurate and were obtained automatically. Besides reconstructing, adjusting a digital mesh might be a necessary task depending on the purpose, as discussed further down. Although the ETHZ team in 2002 did have to re-source into manual work for reconstructing parts of the statue, it is remarkable that with only three photos most of the job was done. This was only possible due to the high quality of the photos, which were taken by Prof. Kostka, a researcher with much experience in the area. However, an experience was made with amateur photographs from the internet, but the authors state that "the results extracted from the Internet images serve only scientific purposes" [Grun 2002].

Fabrication

Intervention in heritage is many times approached as a reconstruction project, a way to rebuild a memory in a mimetic way. Today the methods employed in construction are hardly the same as they were in many heritage related projects original construction. Digital fabrication, by using CNC machinery, is able to recreate architectonic morphologies with a high degree of accuracy and logistically feasible.
Saint John the Divine. The Cathedral of Saint John the Divine, in New York City, USA, had its construction begun in 1892, a bold project to rival the relatively recently built catholic Saint Patricks Cathedral. Begun as a neo-byzantine design, it soon evolved into a neo-gothic structure, one of the largest cathedrals ever built. The Great World Wars, among other factors, contributed to the constant delaying of works, making it into a still active construction site. In the 1980's, Cathedral Stoneworks [1], a privately held company, started working in the cathedral, contributing with carved stone to replace damaged parts of the building or new additions towards the objective of its completion. The usage of computer controlled machines to fulfil these tasks was pioneering, introducing much faster times of fabrication allowing for a greater access to carved stone as a construction material. The process used involved structured-light 3D scanning previously laboured call models into the computer. After scaling the model to the final size, the cutting profiles would be sent directly to the machines; these included a 3.5m block saw for large block roughing, a four-axis profiling saw for finer roughing and a six-axis router for sculpting details. Hand labouring by specialised masons finished the pieces before they were sent to the construction site.

Sagrada Familia. Another on-going construction of a large scale temple is the Basílica i Temple Expiatori de la Sagrada Família in Barcelona, Spain. This church was started in the end of the 19th century as a neo-gothic design, but soon after Gaudi was commissioned to take over the project, the style gradually changed to the characteristic art nouveau of intricate geometry of the catalan architect [Burry 1993]. In the 1980's Mark Burry gets involved in the works. The difficulty surrounding the erection of the temple has two faces: on one side stone carving is a fading technique, increasing the cost and making the finalisation a seemingly farther vision; on the other side, Gaudi's unique genius made the understanding of the project and its solution quite puzzling, a fact much aggravated by the loss of the majority of paper plans and models with the panish Civil war. Burry brings new mathematics to the construction site and, with the help of the computer, makes solid breakthroughs in finding the design of various sections of the temple. Burry uses the computer to calculate solutions that fit Gaudi's geometries with the help of genetic algorithms, as well as using CAD to make accurate descriptions of the geometries that make the final design. Having the design in computer language is one of the steps to make use of digital fabrication. Large blocks of stone were cut and modelled using CNC controlled circular saws, being able to create a smooth finish. This was not the final solution in many occasions, though. The complex geometry was recreated in the stone block with a small surface offset, so that workers could work on the stone piece by hand giving it a fine rough finish, imprinting the unique touch that human hand has.

THE NASONI KEYSTONE EXPERIMENT

Follow the analysis of the case studies presented, we document an experiment in which the stone materiality of an architecture heritage building is subject to the various phases presented here in a digital continuum [Figure 1], from scanning to virtual rebuilding and digital fabrication of a part of a building in a natural scale. This experiment will sum up and validate the notions presented here, synthesising some of the digital opportunities and approaches in the architectural intervention in stone heritage buildings.
Nasoni and granite
Nicolau Nasoni was a 18th century architect who created a sub-style of the Baroque which, to certain extent, became associated with the northern region of Portugal. Nasoni was originally Italian and brought the intricate baroque aesthetics to Porto; however, instead of finding the smooth stone he was used to (Florentine *pietra serena* or Maltese limestone), he faced Porto’s granite, a hard and large granule rock, as main raw material for construction. This is observed as the main reason for a particular way of designing baroque decorations with large protruding elements and embossed elements with large radiuses, as a way to circumvent the inability of granite to hold small detailed motifs [Smith 1966].

One of Nasoni’s main creations was the Episcopal Palace of Porto [Figure 2], which is plastered and painted in white, but with door and windows frames in granite. The main door is topped with an arch, which has a decorated keystone; this particular block of granite was selected as a test model for hypothetic replacement.

From site to digital model
The object to be scanned has a bounding box of ca. 850x860x630mm, and is ca. 6m above the ground. This creates some constraints in the 3D scanning. A hand held scanner is not suitable, as maximum distance for this kind of devices is 3m. A fixed scanner measuring time-of-flight would be suitable regarding the distance and detail needed (maximum of 1mm between points scanned), but logistics would hold the experiment; as such we found opportune to experiment digital photogrammetry.

A series of 24 photographs of 6.9 MP was shot with an Olympus TG--3 digital camera, in such a way that the exposed surface of the stone block would be acquired in the photos to greatest extent possible [Figure 3].

The software available to create 3D point clouds from photographs ranges from open source and free packages to commercial available ones; reading the results published [Barsantia, F. Remondino, and Visentin 2013] and by internal tests, it was decided to use Agisoft PhotoScan (Figure 4).
It did not take more than two tries to achieve good results; the most sensible step for the scan was the "Align Photos" routine, which guarantees that the subsequently produced dense cloud is accurate, whether it is more or less detailed.

A mesh was also produced, along with its texture. Although the texture is not strictly necessary when acquiring geometry for subsequent fabrication as color is not regarded as an output, it proved useful when adjusting the boundaries of the stone block.

The mesh was edited in Blender for fine fixing abnormal point interpolation and to remove unnecessary geometry, as the purpose was to fabricate only the stone block, and not the facade surface.

**Robotic programming**

This test purpose is to validate the reconstruction of a stone component of a surveyed heritage building. For practicality reasons, the material used was EPS, which shares one important feature with granite: isotropy and granularity; the greatest difference is, obviously, hardness and weight. The technology used for working the stock material is multi-axis milling, making material hardness not a relevant factor in the workflow proposed.

The machine used for the final model is a 9-axis robotic arm, a Kuka KR120 HA r2700; the exposed model surface (facade and intrado) would be milled and the remainder surfaces would be cut using a hotwire; a prototype would be 3D printed using a MakerBot Replicator 2X.

The exposed surface mesh (left in Figure 5) was imported into Rhino so that routines could be programmed for fabrication. The mesh was positioned so that the exposed surface is facing up; in relation to the real building, if we take the vertical as the Z axis, and the horizontal line in the facade as the X axis, it was rotated around the X axis so that the facade side had their average normals pointing to towards Z+.

The prototype model (1/10 scale) to be printed was created by making a closed surface out of the exposed surface, by solid extruding the outer contour to the lowest Z in the exposed surface. This extrusion is only an abstract representation of the real stone, as no information was surveyed regarding the geometry behind the facade surface; the same geometry was decided to be used for final model hotwire contour cutting.

The milling routine was programmed by creating an algorithm in Grasshopper visual programming environment. The main contour curves were obtained by intersecting parallel XZ planes (offset each a stepover value in mm) with the mesh. These loose curves were transformed into a continuous (multiple "S" shaped) 3D polyline (henceforth called milling path) to minimize the robot head travel time. To program the robot movements, a series of LIN commands (This type of command instructs the robot end effector to describe a straight line in space between two planes; the XYZ axis of the plane tells how the end effector should be aligned, and the XYZ coordinates position it in space) were used. For this purpose, the milling path was divided in points set apart a distance value in mm (distance is a variable in the algorithm), creating ca. 32800 points. To take advantage of the multiple axis of the robot, these points were not translated as origins of mere XY planes, but the normal orientation of the surface was taken into account. This allows for the mill to reach "undersides", that is, parts of the surface whose normal is pointing to -Z. The algorithm was changed so that the planes feeding LIN would have their Z aligned with normals, but the direct intrinsic direction caused the spindle to hit the artwork; the algorithm was changed so that it reflected a mean averaged of the normals in the area, creating much smoother changes in the mill direction and avoiding hits. Two different sets of com-
Fabrication

As a prototype, a 1/10 scaled model was printed in ABS plastic. This model provided for easier to grasp geometry features of the surface to be milled, specifically the difficult corners and occluded areas.

For the final model, a 500x400x330mm block of EPS was used, to be milled at 1/2 scale (right in Figure 5; Figure 6). A first pass was done with a roughing mill, protruding 160mm from the spindle head, and 20mm in diameter. The maximum plunging depth was minimised by taking full advantage of the multiple axis capability of the robot; this allowed for the roughing pass to be executed in a single in ca. 15 minutes.

The second pass (finishing) was routed using a 35x7.1mm mill. A total of 190 parallel passes of ca. 60 seconds in a continuous flow each was needed to finish the fabrication of the exposed surface.

Once the scanned surface of the stone block was milled, occluded surfaces were cut with a hotwire (Figure 7). The still cuboid block of EPS was positioned on top of a pedestal so that the vertical wire could encircle it in its totality. The hotwire was also used to section the excess volume in the base by manually controlling the robot in a horizontal movement.

The finishing mill left some traces of intersticial
unmilled material, as well as small connected debris; these were removed with a fine sandpaper. A view of the final result is given in Figure 8.

**CONCLUSION**

When dealing with heritage related architecture elements, time is an unavoidable concept. The time that passes since the object was built until we, today, acknowledge its importance, reflects on its weathering, but also in the difference of means of production and style. Restoration implies going back in time somehow, to reproduce or reference the style or materiality with which the object was made. Digital tools help in this task, allowing for practically automatic three-dimensional reproduction of built elements. However, once the digital model of the existing component is available in the computer, it can easily be changed, allowing for possible fixes or other type of improvements. The challenge is within the critic position one takes when approaching heritage; the possible erasing of weathering or choice of a similar material are some of the attitudes that make the architect responsible for the result of a conservation or restoration mission in a heritage architecture.

**ACKNOWLEDGMENTS**

The authors would like to thank all the Digital Fabrication Lab (DFL) team for the overall support to this experiment. This work was developed in the scope of the Research Project with the reference PTDC/ATP-AQI/5124/2012, funded by FEDER funds through the Operational Competitiveness Programme - COMPETE, and by national funds through the FCT - Foundation for the Science and Technology. It is also part of the PhD research with the reference SFRH/BD/93438/2013, supported by the FCT - Foundation for the Science and Technology.

**REFERENCES**


Barsantia, SG, Remondino, F and Visintini, D 2013, '3D Surveying and Modelling of Archaeological Sites; Some critical issues', *ISPRS Photogrammetry, Remote Sensing and Spatial Information Sciences*, 5, p. W1

Blais, F 2003 'Review of 20 years of range sensor development', *Electronic Imaging 2003*, pp. 62-76


Cignoni, P and Scopigno, R 2008, 'Sampled 3D models for CH applications: A viable and enabling new medium or just a technological exercise?', *Journal on Computing and Cultural Heritage (JOCCH)*, 1(1), p. 2

Drap, P, Grussenmeyer, P, Hartmann-virnich, A and Photogrammetric, AHv 2008, 'Photogrammetric stone-
by-stone survey and archeological knowledge: an application on the Romanesque Priory Church Notre-Dame d'Aleyrac To cite this version: VAST2000 Euroconference, 1, pp. 139-145


Karara, HM and Faig, W 1980, 'An expose on photographic data acquisition system in close-range photogrammetry [JJ]', International Archives of Photogrammetry, 23, pp. 402-418

Kontogianni, G, Georgopoulos, A, Saraga, N, Alexandraki, E and Tsogka, K 2013, '3D Virtual Reconstruction of the Middle Stoa in the Athens Ancient Agora', ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 1(1), pp. 125-131


Smith, RC 1966, Nicolau Nasoni: arquitecto do Porto, Livros Horizonte

Valanis, A, Tapinaki, S, Georgopoulos, A and Ioannidis, C 2009 'High resolution textured models for engineering applications', Proceedings of the XXII CIPA Symposium, Kyoto, Japan
