Photogrammetry for Medieval Archaeology

A Way to Represent and Analyse Stratigraphy

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***Abstract*—The paper presents an interdisciplinary project which is a work in progress towards a 3D Geographical Information System (GIS) dedicated to Cultural Heritage with a specific focus application on the Castle of Shawbak, also known as the "Crac de Montréal", one of the best preserved rural medieval settlements in the entire Middle East. The Shawbak archaeological project is a specific and integrated project between medieval archaeological research and computer vision done thanks to a long cooperation between University of Florence and CNRS. Focusing mainly on stratigraphical analysis of upstanding structures we provide archaeologists a two-step pipeline. First a survey process using photogrammetry, both in a traditional way and using the most advanced technique for obtained dense map and then a tool for statistical analysis. The photogrammetric survey is driven by an archaeological knowledge which is formalized by ontologies as a link between all the archaeological concepts which are surveyed.**

The archaeological knowledge studied is now limited to stratigraphy of upstanding structure using a stone by stone survey as well as a 3D reprojection of archaeologist design made on photographs. The 3D GIS is the last step of this chain and aims the automatic production of 3D models through archaeological database queries: these 3D models are in fact a graphical image of the database and at the same time the interface through which the user is able to modify it and produce different kind of analyzing.

All these developments are written in Java within ARPENTEUR framework.

Keywords- Medieval Archaeology, Stratigraphy, Upstanding structures, Photogrammetry, Computer vision, Dense Map, GIS, Principal Component Analysis, Clustering, Ontology.

I. Introduction

The archaeological research of the Castle of Shawbak, (Figure 1) also known as "Crac de Montréal", (see Figure 1) one of the best preserved medieval rural settlements in the entire Middle East [1, 2] has been chosen to develop a new documentation system. The site is a long period settlement, stratigraphically complex both in deep stratigraphy and in upstanding structures stratigraphy. Because its features, in accordance with the methodology of Light Archaeology [3] and also in accordance with the University of Florence research in Petra Valley [2], the Shawbak stratigraphic analysis began by upstanding structures [4].

Why? This choice allows to collect many archaeological data in relatively short time and it is also possible to compare in a large territory many building phases of different period to better know a history of an entire region (in this case the Crusader-Ayyubid Transjordan). Only later the archaeologists have decided to open some excavation areas to better understand the dynamic of settlement.

Figure 1. The Shawbak castle.

The stratigraphic analysis of upstanding structures produces a very large amount of data both graphical and stratigraphic. For the first one the common method to collect and to record them on the site is the survey.

The survey is achieved in different ways, often it is two-dimensional. Its goal is to define the area, the perimeter and the volume of all the recognized USM (standing for *Unità Stratigrafica Muraria* – similar to the stratigraphic unit for digging archaeology). Every USM is a building homogeneous action which is representative of different building moments. In other words to identify and record the different USM in upstanding structures allows archaeologists to define a relative chronology of the building by the relative position of every USM.

Figure 2. Documents produced by archaeologist: USM visualization.

II. A SURVEY DEDICATED TO ARCHAEOLOGY

Archaeological excavations are always irreversibly destructive, so it is important to accompany them with detailed documentation reflecting the accumulated knowledge of the excavation site. But not only the excavation needs an accurate documentation, also the upstanding structures research [5]. This documentation is usually iconographic and textual. Graphical representations of archaeological upstanding structures such as drawings, sketches, watercolors, photographs, topography, and photogrammetry are indispensable for such documentation and are an intrinsic part of an archaeological survey (see for example Figure 2). However, as pointed out by Olivier Buchsenschutz in the introduction to the symposium Images and archaeological surveys, in Arles, France, in 2007 [6], even a very precise drawing only retains certain observations that support a demonstration, just as a speech retains only some arguments, but this choice is not usually explicit. This somewhat lays the foundation of this work: a survey is both a metrics document and an interpretation by archaeologist.

The survey is a very important component of this documentation and its importance is largely due to the fact that the concepts employed by archaeologists during an excavation or interpretation are closely related to space/time. The structure of the study is based on the concept of stratigraphic units. Inherited from geology and then formalized for archaeology by E.-C. Harris [7], stratigraphic units are linked by geometric, topological and temporal relationships. They are fundamental for the interpretation of the archaeological research.

To do this two families of objects have to be surveyed: first, the artifact that we seek to position in space and of which we have a good a priori knowledge (in our case the atomic element is the ashlar block) and second, the area that we need to study,often represented as a digital terrain model (DTM) or more generally by a 3D surface. Throughout this work we deal with these two aspects, artifacts and unstructured surface, by addressing two different approaches; one using a priori knowledge through measurements and the second based solely on geometry.

The first approach, based on the a priori knowledge that we have about the measured artifact, uses our knowledge of the object to compute its size and position in space. This method can also reduce the time required for measurements.

The second approach, used to survey land for example but also the main structure of the castle, uses automatic tools coming from photogrammetry to compute a dense cloud of 3D points.

Finally, a very important point is the link between geometry and knowledge; a model, 3D or 2D, representing a site is a relevant interface to access the data known about the site. 3D representations of a site provide important added value to archaeologists who are then able to study a three-dimensional overall picture.

Moreover, it should be noted that, by archaeological research nature, archaeological data are incomplete, heterogeneous, discontinuous and subject to possible updates and revisions to each field season campaign. The documentation system, linked to archaeological data, must be able to manage these constraints.

III. KNOWLEDGE BASE PHOTOGRAMMETRY

A. The photogrammetric campaign

Several photogrammetric campaigns have been accomplished in Shawbak since 2003 allowing the production of several graphic outputs representing archaeological features and constructions. These campaigns are composed of photographic sets acquired with calibrated digital cameras both in convergent and parallel coverage with the survey of control point by Total station and DGPS. These control points are used to reference the photogrammetric models in a common geodetic system.

Until now, among the most common outputs achieved in this process are orthophotos, low-resolution 3d models and vector graphic drawings representing constructive features.

All these data collected since almost 10 years are stored in a database and can be used with the latest photogrammetric tools available now. We can use and compute models using more than 3000 oriented photographs georeferenced on the site.

B. Surveying aslhar blocs

Once all the photographs are oriented the I-MAGE process (Image processing and Measure Assisted by GEometrical primitive), developed in 2001, is used to support the user during the measuring process in photogrammetric surveys. Users can make a 3D measurement using one single photograph, without altering precision of the result. This method was already published in CIPA congress[8]; it allows the user to concentrate on the archaeological aspects of the survey with less attention to the photogrammetric one.

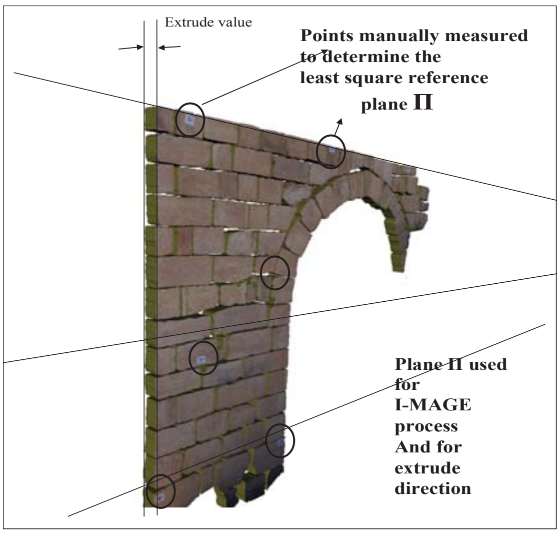

Figure 3. Ashlars' blocks using a plane as an approximation to the exterior face of the wall [1].

We use this approach also to produce 3D models of building blocks (i.e. ashlars) based on the only observable face.

The morphology of each ashlar's block is expressed as a polyhedron with two parallel sides, or faces. In most of the cases, only one side is visible, sometimes two, rarely three. The survey process can inform about the dimensions of one face, then the entire polyhedron is computed accordingly to the architectural entity's morphology (extrude vector) and the data (depth, shape, etc.) provided by the archaeologist.

Computing an extrusion vector can be easy in the case where the architectural entity's morphology is obvious; during a wall survey for example an extrusion vector can be computed by a least square adjustment of a plane around the survey zone. This is the plane used by I-MAGE. In this case where the entity's geometrical properties are simple, the extrusion vector is calculated before the survey phase and the block is extruded directly from the measured points (Figure 3). In the case of the survey of an arch the extrusion should be radial and needs the geometrical features of the entity (intrados, radius, axis) and is therefore processed afterwards.

This approach for measuring blocks was already published in a ISPRS congress [9] and has been combined with the I-MAGE process in order to obtain an integrated tool.

C. Stratigraphic unit

According to the research fields of the entire group, we decide to concentrate our efforts to document the upstanding buildings. Starting from the most important concept of the stratigraphical archaeology, the stratigraphic unit, we try to document directly on the survey the main characters of each of them. From the publication of the first edition of E. Harris's book *Principles of archaeological stratigraphy* (1979) many archaeologists follow the idea that all archaeological sites, to a greater or lesser degree, are stratified and for this reason it is necessary to know the main principles of the archaeological stratigraphy to obtain all the possible information.

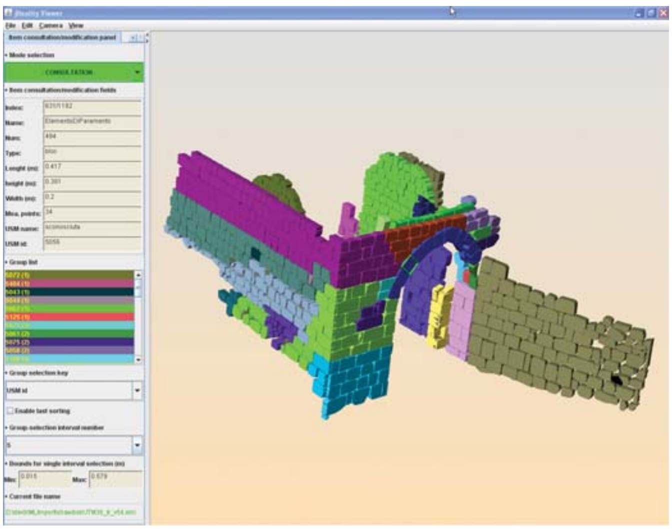

Figure 4. Ashlar bloc visualization with a random color according to the USM [10].

But what is a stratigraphic unit and why it is so important? First of all, forms of stratigraphic unit are the result of natural or human action of deposition or erosion (i.e. in the last case of construction or destruction). Concerning the stratigraphy of upstanding structures, to sum up for the purpose of this paper, stratigraphic unit is the result of an human action of construction. Its position on the entire wall and the physical and stratigraphical relationships with the others stratigraphic units are necessary to detect the relative chronological sequence of the entire building (and, comparing all the structures, the relative chronological sequence of the site). The characteristics that distinguish each stratigraphic unit of upstanding building are principally the lithology of stone, the dimension of the ashlar, the tools used to shape the ashlar, the kind and the quantity (or also the absence) of the mortar. Of course it is extremely relevant to note the physical relationships between the different stratigraphic units (see Figure 4 and Figure 5). So we need to survey all the dimensional and technological data and also, of course, to survey the position of all the stratigraphic units.

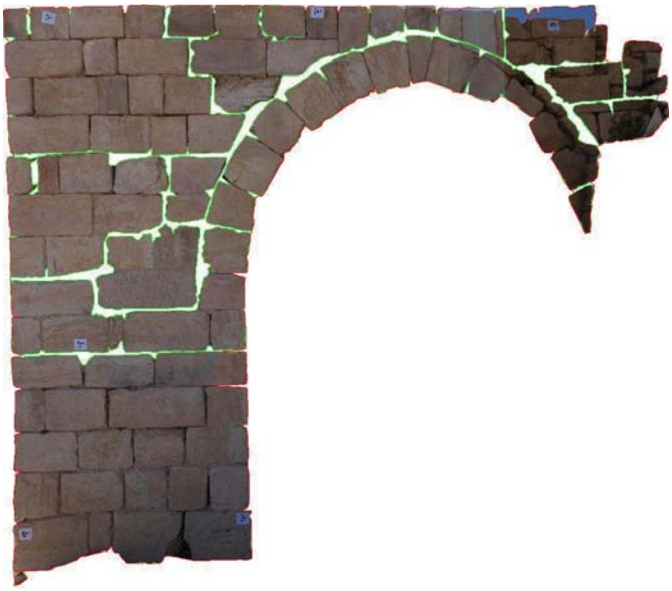

Figure 5. Orthophoto generation with texture and USM frontier.

IV. Dense map, 3D point cloud generation by photogrammetry

A. Dense map by photogrammetry: current avaiable tools

To model the environment by photogrammetry in an unsupervised way it is first necessary to automatically orient a set of unordered images. This orientation phase, which is crucial in photogrammetry, as computer vision, has seen in the past three years a great boom. The problem was first solved in the case of ordered series of photographs, for example, making a circle around an object and recently in the case of photographs unordered [11, 12]. Once all the photographs are oriented several methods are proposed for producing a dense cloud of 3D points to represent the photographed area.

Two major families of methods exist. Those that use solid models as the voxels [13, 14] are based on the discretization of space into cells and the goal is to discriminate between full and empty cells to define the boundary between them. The advantage of this method consists in usinglots of photographs taken from arbitrary viewpoints. In contrast the delicacy of the final model depends on the resolution of the voxel grid which can be RAM consuming. On the other hand methods using meshes could adapt their resolution to better reconstruct the details of the scene [15].

Since 2007 IGN (*Institut Géographique National*, in France) has decided to publish in open source the APERO MICMAC software, dedicated to the automatic orientation of an unordered set of photographs and the calculation of the automatic mapping on a set of photographs oriented. (http://www.micmac.ign.fr) [16].

Also the work of Furukawa and Ponce on the dense map generation [17] have resulted in open source publications. We use this work for several months and some examples are presented in this paper.

These developments were coupled with a software bundle adjustment of operating on an unordered set of photographs are based on an implementation of SIFT on GPU due to Changchang Wu, University of Washington (http://cs.unc.edu/ccwu/siftgpu) and implantation of developments PhotoTourism [17, 18]. The bundle adjustment used is based on the Sparse Bundle Adjustment of Lourakis [19].

B. Surveying with could of point

Figure 6. Shawbak, dense cloud of 3D points using a large set of oriented photographs.

As we are working since a long time on this site we have a huge set of oriented photographs and it was possible to use part of them in order to generate a dense cloud of 3D point (see Figure 6) with the method proposed by Furukawa [13].

This approach, which seems to be highly accurate and quite exhaustive, is, at the first level, really poor from the semantic point of view. Of course we can manage a huge quantity of 3D points but we lose all the knowledge carried out by the original photogrammetric survey.

The main problem is how to combine from one side the high quantity of information, (3D points, color information for each point) and on the other side the indispensable archaeological knowledge.

We develop a hybrid approach, based on both photogrammetry and 3D visualization in order to use the data usually produced by archaeologist. Even in a 3D context archaeologist uses mainly 2D documents such as photos or orthophoto and USM are designed onto these documents (see Figure 2 and Figure 7).

For using directly the 2D documents produced by archaeologist we have developed a "surface picking" in order to select 3D points visible in the designed polygon. Of course a threshold allows defining a far clipping plane in order to make a 3D selection.

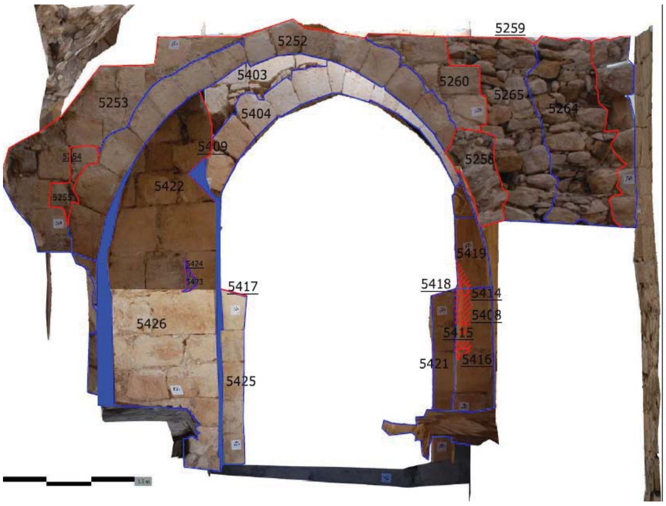

Figure 7. A 2D document annotated by archaeologists.

A data preprocessing is done so that is not used the whole data set but only the 3D points of the data set that are in the polygonal region coming from the photograph and which can be projected onto in the space between the screen and the model. A selection of 3D points is done using a normal picking method with all the 2D points inside the polygon and we look for the screen's closest element that collides with the ray.

To achieve this, we project all the 3D points of the 3D object dataset on the screen and we test if they are inside the polygonal region. If they are, we include them into a second set. This is done in order to increase the speed of further processing.

Normal picking is performed for all the screen points that are inside the polygonal region. To achieve this, we trace a ray starting from the camera location and passing through the pixel of the screen inside the polygonal considered region.

A statistical approach is used to determine the best plane defined by the selected 3D points and this plane is used to discard far points and be sure selecting the points belonging to the studied USM.

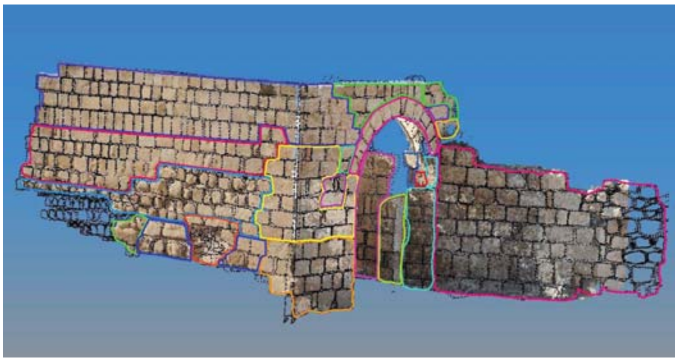

Figure 8. The 3D points cloud with both the ashlar blocs and USM designed.

The whole procedure enables the user to choose a polygonal region on a building wall and to obtain only the points measured on this structure. Figure 8 and Figure 9 show USM perimeters and 3D points present inside each of them.

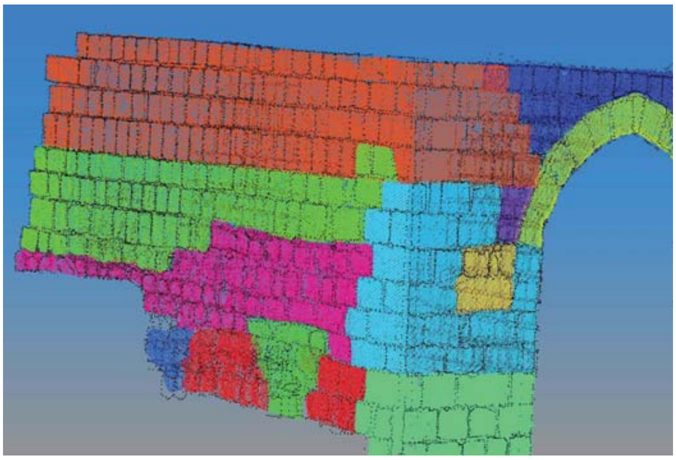

Figure 9. Once the 3D points are selected we change color according to the USM.

C. *Interface or "Negative stratigraphic unit"*

The most relevant acquisition of the Harris principles is the concept of interface. According to Harris "There are thus two main types of interface: those which are the surfaces of strata and those which are only surfaces, formed by the removal of existing stratification." In this essay we talk of the second ones, the interfaces formed by the removal of existing stratification.

These interfaces create their own surfaces and area, they have stratigraphic relationships with other units of stratification and their own boundary and surface contours, but they haven't a volume, they are not formed by ashlars and mortar because they are the only sign of an action of destruction (both natural and antropic), for example when the wall decays and falls down, when there are the traces of an earthquake or the traces of the human destruction (sometimes to rebuild other structures or different part of the same structure).

So it is very important first of all to detect this kind of features and then to survey the position and the physical and stratigraphical relationships with the others stratigraphic units.

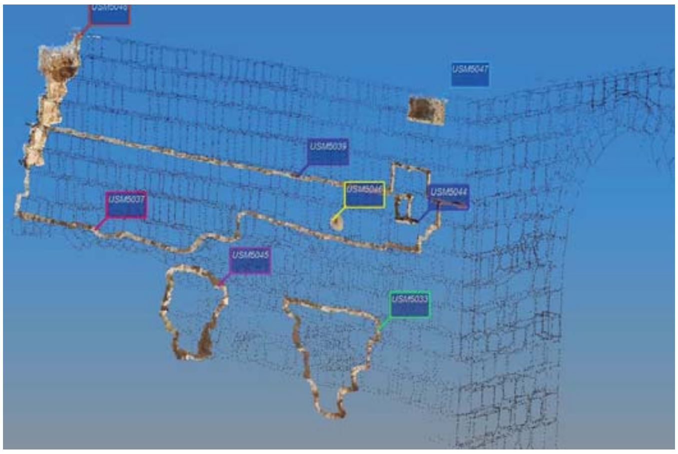

Figure 10. Negative USM, perimeter extracted in the dense cloud of point or, in certain case, the 3D points belonging to the surface.

Figure 10 shows negative USM represented by the set of 3D points extracted using the perimeters designed on the photographs by archaeologist. In some case perimeters are represented by a dense strip of 3D points in other case the dense cloud of 3D points represents a surface on the wall.

V. STATISTICAL ANALYSIS AND CLASSIFICATION

The objective aim of this analysis is to summarize the information contained in all the measures (variables) of each block wall. The practical interest of this study is to find a link between the measures on each block, and their corresponding USM. We first extract the most reliable features, and use them to automatically classify the next blocks. Principal Component Analysis (PCA) is widely used in data analysis. It generates new independent variables with a maximum variance. This last property will allow us to perform an unsupervised clustering.

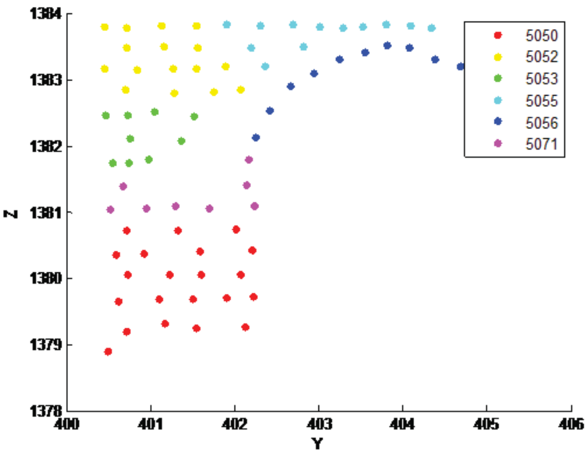

Figure 11. Clustering with human operator.

Figure 11 shows the block wall classification done by a human operator. Each color represents an USM, where each block is represented in the Y, Z plane.

The example contains 6 measures obtained on a sample of 78 block of the wall. These selected variables are:

- X1, the X position of the block wall
- X2, the Y position of the block wall
- X3, the Z position of the block wall
- X4, the Total Height
- X5, the Total Length
- X6, the Total Width

Figure 12 shows the eigenvalues of the correlation matrix. Here, we see that the first three components represent 92.4% of the variance, so the other can reasonably be neglected. Based on the first principal component, we can clearly see that the variability mainly comes from X1, X2 and X4 components. The second principal component is high when the blocks are wide and long (variables X5 and X6). The third principal component depends on the X3 and X4 variables.

Eigen vector :

	F1	F2	F3	F4	F5	F6
X	0,541	0,287	0,087	0,342	-0,323	0,629
Y	-0,540	-0,290	-0,079	-0,342	-0,371	0,603
Z	-0,229	-0,352	0,776	0,471	-0,001	-0,006
totalHeight	-0,441	0,117	-0,517	0,724	-0,004	0,002
totalLength	-0,311	0,576	0,240	-0,109	0,617	0,347
totalWidth	-0,268	0,603	0,245	-0,088	-0,614	-0,346
Eigen values	2,625	2,080	0,838	0,453	0,003	0,000
Variability (%)	43,755	34,675	13,971	7,547	0,051	0,001
% sum	43,755	78,430	92,400	99,948	99,999	100,000

Figure 12. Main component on 6 variables.

There are several techniques to find links between variables, such as k-means, mixture models, logistic regression …
As we can see, the situation is unfavorable; first because the variables describing the system are numerous compared to the blocks in each class, secondly because the risk of multi-colinearity is great.
The accuracy of the estimator will be poor. To overcome these drawbacks, we first removed highly correlated variables (X1 and X2) and (X5 and X6), and finally used the remaining uncorrelated principal components.

Figure 13 shows the results obtained. To demonstrate the variability contained in these four variables, we will keep, as a first approximation, two dimensions:

- The first one associating the Y position of the block wall (X2) and the total height (X4)
- The second one opposing the Z position of the block wall (X3) to the total length (X5).

Eigen vector :

	F1	F2	F3	F4
Y	0,640	0,283	-0,238	0,674
Z	0,320	0,681	0,518	-0,406
totalHeight	0,606	-0,315	-0,425	-0,594
totalLength	0,348	-0,598	0,703	0,169
Eigen value	1,709	1,262	0,674	0,355
Variability (%)	42,724	31,561	16,847	8,868
% sum	42,724	74,285	91,132	100,000

Figure 13. Main component on 4 variables.

We used a hierarchical cluster analysis to build the unsupervised clusters. This technique is built on a successive point merging based on a proximity criterion. This kind of method requires two important things: - the dissimilarity measure between block walls; - the merging threshold (distance between classes). Many solutions exist to determine these two measures. In our application, we used Euclidean distance for inter-block distance, and the Ward method for the dissimilarity between classes. Here, we point out that despite the existence of methods for determining the optimal number of clusters, we chose a division into six clusters as suggested by our archaeologist partners.

Figure 14 shows the results using the 4 principal components obtained earlier. Globally the clusters correspond to human operator supervised decomposition (Figure 11). However, we note the preponderance of the Z variable for the classification. This explains the fact that the class corresponding to the arc has not been determined. Then, we changed the variables and chose the size parameters (X4, X5 and X6). We applied the same method with the same settings and got the result in Figure 15. Unlike the previous result, we could extract the arc, but the other blocks were not correctly classified. This result is very interesting because we can consider a nonlinear method to perform the classification.

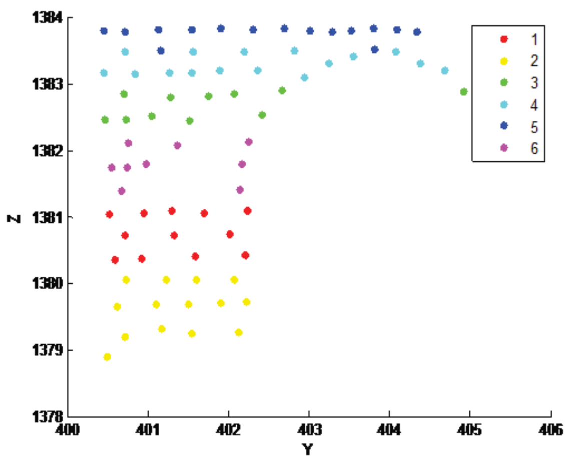

Figure 14. Clustering with 4 principal components.

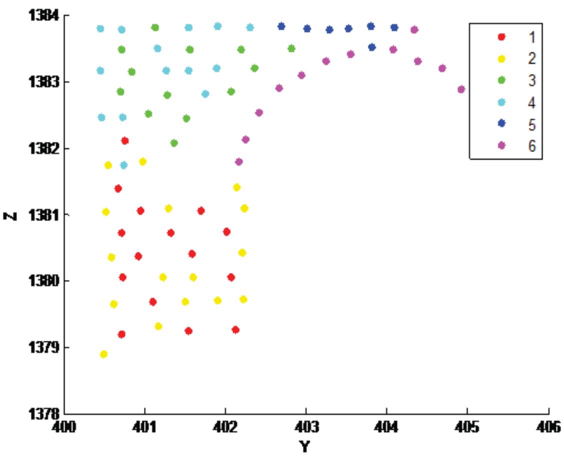

Figure 15. Clustering with 3 size parameters.

VI. THE UNDERLYING KNOWLEDGE MODEL

Site survey such that Shawbak castle involves different domains (archaeology, architecture, photogrammetry, 3D vision, …) that are each focused of specific concepts. We can see these domains as views on the real site where concepts instances are representations of real material. For example, an ashlar block can be seen as a point cloud within the photogrammetric domain, as a textured mesh within 3D vision domain and as a set of documentations within archaeological domain.

Making a complete survey needs the use of a common formalism for representing knowledge and data coming from involved domains. The choice of ontological formalism is driven by formal and applicative reasons.

From a formal point of view, ontologies enable to represent knowledge by means of concepts and instances linked by relations. Such formalism can be seen as a graph where concepts and instances are nodes and relations are edges or as a logical formalism made of triplets *(subject, predicate, object)* where *subject* and *object* are concepts or instances and *predicates* are relations. The domain heterogeneity of our kind of survey can be represented with ontology by making representations of each domain in an independent way (domain ontology) and by completing the survey specific ontology with relations that link concepts of different domains (application ontology). This modular approach provide a modular ontology that can be easily updated and maintained as a modification of the knowledge representation of one domain dot not require to change the whole ontology.

On the other hand, there are many specifications and tools for dealing with ontologies. The W3C consortium has provided recommendations for representing (OWL) and querying (SPARQL) ontologies. These two recommendations have been implemented by various tools and libraries such as PROTÉGÉ (http://protege.stanford.edu/) for ontology creation and JENA (http://incubator.apache.org/jena/) for interfacing between OWL, SPARQL and JAVA framework.

VII. CONCLUSION AND FUTURE WORK

This project is due to a long cooperation between University of Florence, Italy and CNRS in Marseille (LSIS laboratory).

We are working on a documentation system dedicated to medieval archaeology which integrates three main components:

- A survey tool based on photogrammetry and computer vision, using traditional photogrammetry where an operator is able to design specific point with annotation belonging to a specific knowledge and also, with recent advance in photogrammetry and computer vision, which can produce huge quantity of 3D points with color information but, this time, without any semantic information. In this case we develop a bridge between the two approaches in order to add semantic data on the cloud of 3D points.
- A 3D and 2D visualization tool, which allows interactivity between the stored data (the data persistence is done with both XML formalism and relational database) and the user. This tool can manage geometry computed from photogrammetric data as well as dense 3D points cloud.
- A statistical analysis module which allows producing new knowledge on the measured artifact (clustering on ashlar bloc for example).

All these developments are using and underlying knowledge model formalized with ontology which allows to build links between the concepts managed by archaeologist as well as these used in survey techniques.

We are now working on several aspects of this project:

- Improving the module which transfers the semantic data from the manual photogrammetric process to the dense 3D point cloud. This is done by using the same original support to produce archaeological and 3D data: the photographs. Archaeologist can design USM and ashlar bloc onto oriented photographs.
- Improving and integrating the statistical computation module to increase correlation between ashlar blocs and other archaeological data.
- Finally, from the archeological point of view the units of stratification represent an archaeological aspect of time's cycle and this is the cause of their relevance. In fact the other important goal of the Harris's work [20] was the invention of the Harris matrix, the most convenient system to collect and place in a chronological order all the events that occur in a site. For this reason our next step will be to make possible to visualize on the survey also the stratigraphical relationships and the Harris matrix. But it is not enough because the Harris matrix don't permit to indicate the concept of the life span of the stratigraphic unit and this is a big problem, very evident for the upstanding structures stratigraphy [21]. So our most relevant future work will be the effort to indicate more relationships between the stratigraphic units, maybe following also the Allen's theory [22, 23], to better put in evidence all the life-phases of an archaeological structure.

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