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# Semantic Structuring and 3D Modeling of Masonry Structure

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**Abstract**

*Studies of architectural heritage require tight control over spatial data. It is an prerequisite for the representation, analysis, conservation and structural restoration of architectural heritage. As regards the morphology of architectural works, the challenge is to move from 3D survey raw data to semantic 3D models. The objective of our project is to develop and experiment a process for the treatment of point clouds in order to create a computational model dedicated to mechanic behavior analysis. Thus, the modeling and semantic structuring is achieved through a knowledge-based approach. Semantic dimension and topological constraints are identified and explicated through the creation of a knowledge model of masonry works. This knowledge is used to implement a set of tools for the reverse engineering of digitized masonry structures.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Digitizing and scanning—I.3.5 [Computational Geometry and Object Modeling]: Geometric algorithms, languages, and systems—

## 1. Introduction

Architectural heritage studies draw on a large volumes and variety of data such as point cloud, scientific imaging, mappings of degradation, photographs, historical archives, analysis documents, coring, etc. To overcome the difficulty of collecting, comparing, analyzing and validating the various data required prior to restoration, the MONUMENTUM project aims at defining a prototype information processing workflow including spatial analysis of surfaces, geometric models of masonry structures, heterogeneous documentary sources, etc. The article focuses on one of several successive issues raised by the project: the geometric reconstruction of the raw data. This experiment aims at moving from the raw 3D surveying to a semantically-structured 3D model. The creation of such model is an absolute precondition to address the next issue of the project: the analysis of structure behavior [BDM13]. Following this introduction, Section 2 examines literature in geometric reconstruction applied to architecture. Section 3 describes our method. In Section 4, the masonry structures knowledge model for the modeling and semantic structuring is presented. Section 5 focuses on the first experiments in reverse engineering which can be defined as the architectural surface reconstruction of masonry structure. Future prospects of this work in progress and some concluding remarks are made in Section 6.

## 2. Geometric reconstruction solutions for built heritage

In the field of digital heritage, the modeling and semantic structuring are post-treatments applied to the raw 3D surveying to decompose architectural objects in several parts for expressing temporal state, material, mechanical behavior, etc. Many methods can be considered to model semantic contents from the raw data. The level of detail, the geometric complexity of the studied object or the quality of the data are some criteria that may be used to determine which reverse engineering processes should be used [BTS*14]. Recently a number of tools intended for professionals have been developed to process raw 3D data of in order to generate geometries of architectural heritage based on parametric models. They are accurate mathematical models that replaced approximate meshed representations. Leica CloudWorx, Imaginit Scan to BIM or Kubit VirtuSurv are some of these standalone software but new functionality have also been introduced in existing architecture software to read and process point-cloud files. Many projects rely on Autodesk Revit to perform reality-based modeling. It was originally developed for CAD, but is increasingly used in the reverse engineering field [QMC*15, GM13, BB15, Bre13, OBGB15, FFP13]. For example, Callisto Sari project carried out a 3D modeling based on point clouds from scanned data of the Palais d'Antin. The modeling was done with Revit and an unnamed plugin of the software. Another example is the GreenSpider project of TC Labs [GM13, Bre13]. This plugin allows the conversion of point clouds into input parameters for the native tools of the software. Its main drawback is the obligation to sample the points before importing them in Revit. It should be noted that a reverse engineering tool tightly integrated into Revit software was introduced in 2012 by Autodesk Labs. It provided datum, building and floor extraction but also automatic straight wall extraction for the creation of basic parametric Revit elements. Its current status is unknown. The previous example shows that the main factor limiting the use of exist-





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ing modeling software in the reverse engineering of architectural heritage comes from the inadequacy of their library of parametric models. Thus, in order to have relevant libraries of parametric models adapted to the multiplicity of heritage shapes, each project should implement its own library. Even if textual programming or scripting languages [CP09, SSUF10, HF04] were already used to create such libraries, they required a specific expertise before achieving the implementation of algorithms. In 2007, new parametric tools like Rhino's plugin Grasshopper have been introduced. The implementation of algorithms can be achieved through visual dataflow programming language thus decreasing the back and forth switching between the geometric shape and the algorithms. This in turn may allow heritage experts to focus their attention on the reverse design [MW10]. Previous experiments were accomplished with Grasshopper for the architectural features extraction of architectural assets such as regulating lines, which are used to control the proportion and placement of elements in proportioning systems [F.D12]. Notable experiments of modeling based on the use of regulating lines include the military architecture features modeling such as bastioned fortification [JCH13] and civil architecture features such as classical orders [CP09, dLVF06] or gothic windows tracery [HF04, Tak13].

## 3. Reverse engineering and architecture

In the field of architecture, reverse engineering refers to the modeling and semantic structuring of the raw data for the creation of a 3D model whose topological features are based on architectural constraints. Edge corrections, triangle insertion, polygon editing, holes filling, non-manifold parts fixing, etc. are achieved by using parametric models. Our reverse engineering method is model-driven: it is based on architectural knowledge, topological constraints and perform instantiation of parametric models from a libraries of parametric architectural models [VSS14]. Thus, the method for the reverse engineering of arches and vaults (Figure 1A) relies on reference works, including stereotomy treatises or architecture dictionaries that allows us to make explicit architectural constraints of more than two hundred masonry structures. These constraints are mainly extracted from the geometric design rules of masonry structures. The knowledge modeling highlights the existence of geometric design rules for the creation of arches and vaults. The architectural features extraction for arches and vaults modeling (Figure 1B) relies on a library of parametric models of arches and features extraction programs. Both the models and the programs are defined and implemented thanks to the specific knowledge of masonry structure design rules. Thus, the reconstruction of simpler geometric features of architectural structures in a point cloud can be realized and then associated to advanced vaults and arches modeling processes (Figure 1C). The semantic enhancement of the recovered geometry, consisting of intradoses of arches and vaults is achieved through the use of architecture software. Thanks to native libraries of parametric architecture items and powerful editors for imported geometries, it is possible to convert geometric features (the intrados surfaces) into architectural items (the vaults or arches).

## 4. Knowledge model for masonry structures

At the heart of the geometric reconstruction and semantic structuring is a knowledge model based on reference works such as dictionaries or stereotomy treatises. They are essential to model the vocabulary (every terms describing the components of the domain) and the grammar (every design rules fixing the constraints between components) of masonry structures. Thus, nearly 200 concepts are identified. They are shared among practitioners and there is a general consensus on their definitions. This controlled vocabulary is mainly based on the reference work Jean-Marie Pérouse de Montclos [SP10], the first researcher recruited in France to identify, investigate, publicize the heritage of cultural, historical or scientific importance. Despite a revised and expanded edition of its book Architecture, méthode et vocabulaire, the "articulation of notions" [dM11] can still be improved. A first improvement is the creation of a taxonomy that was designed to highlight parent-child relationships as well as semantic and geometric relationships of the identified concepts. Architectural structures can be described as the composition of geometric primitives [dLVF15]. For example, architectural arches are build based on a single or several consecutive geometrical curves like conic sections, polyline, catenary, etc. On the other hand, the main surface of a vault is the intrados: the inner surface of an arch or a vault. Like any geometric surfaces, the intrados of a vault can be described as the path, also known as a directrix, of a moving line, called a generatrix. Any architectural arches can be used as a generatrix for the 3D modeling of barrel, groin, rib vaults and cupolas. Thus, to create a 3D barrel vault, a generatrix is swept along a curve or a portion of curve such as line segment, ellipse, polyline, helix, etc. A cupola can be modeled by sweeping a generatrix along a circle (a cupola) or a polygon (cloister vault and other polygonal cupolas. Groin vaults and rib vaults are produced by sweeping a generatrix along each apothem of a polygon. The intersections of the swept surfaces are delimited by arises (for groin vaults) or ribs (for rib vaults). Other types of groin vaults and rib vaults includes double groins vaults and triple groins vaults subtypes which are composed of additional cells.

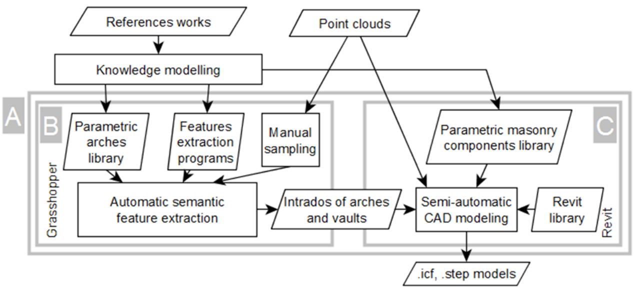


**Figure 1:** *Main steps of the reverse engineering method used for the model-ling of arches and vaults from captured data.*

## 5. Reverse engineering of arches and vaults

The reverse engineering of the arches and vault comprises two successive parts: the architectural features extraction modeling and the semi-automatic modeling experiments of arches and vaults. The first process aims at extracting architectural features from the raw data captured by photogrammetry or laser scanning. The second process seeks to use the resulting architectural information to automate the reconstruction of semantic models within a CAD software.

### 5.1. Architectural features extraction

Based on the previous knowledge model, a library of parametric objects containing architectural models is implemented in Grasshopper visual programming editor. This 3D modeling software can be used create complex 3D parametric scenes in a short time span while also "efficiently explore alternative forms without having to manually build each different version of the design model for each scenario" [Jan10]. Thus only geometric knowledge is required to specify the sequences of relationships and operations that automate the construction of geometries. Our previous research in reverse engineering of architectural items have demonstrated the benefits of this prototyping tool to evaluate reverse engineering methods [JCH13]. A library of parametric generatrix models containing more than twenty arches was implemented. The three parameters for arches includes the base plane of the arch, its width (also called span) and in some case, its height (also called rise). Thus a wide spectrum of arches and vaults can be created together with the parametric directrix models. On the other hand, the design rules are transcribed in topological constraints and features extraction algorithms. The following experiment uses the point cloud of a groin vault from the nave of the cathedral of Nancy in France. As described above, this type of vault is the result of the 3D sweep of a generatrix along each apothem of a directrix: a square in the present case. For the reverse engineering approach, the point cloud has to be analyzed to extract the input values for the parameters of the generatrix: base plane, rise and height. Once recovered, the parametric model of the vault can be automatically adjusted. The current method requires the user to sample the imported data to the point cloud occupying the volume of a single vault or arch (Figure 2a). These samples are then used as input parameters in the reverse engineering process. The next step is the computing of an oriented bounding box (Figure 2b). The vertical surfaces of this box approximate the base planes of the generatrix arches. However, points cloud artifacts are still present in the point clouds (sampling density, noise, outliers, misalignment and missing data) and they can have a major impact on the process [BTS*14]. The next operation selects sets of points belonging to vertical boxes distributed along the vertical axe (Figure 2c). The approximate base planes obtained from the bounding box give us lines close to the directrices of the vaults (as depicted by the arrow lines in figure 2d). These lines are used to sort two sets of points - one for each directrix. These points are already sorted according to the vertical boxes, thus creating subsets of points in horizontal and vertical planes. It is then possible to fit circles through the sorted subset of points (Figure 2e). The centers of these circles make it possible to calculate the springings (e.i., the planes where an arch or vault rises from a support) of each of the four generatrix arches as well as the two directrices involved in the creation of the vault. Once the springings extracted, perpendicular planes are calculated. It is therefore the base planes of the arch (Figure 2f). Hence the values of the three parameters for the modeling of the parametric generatrix implemented in the library are recovered. Every arch available in the library of parametric models is instantiated (Figure 2g) with these values. The point cloud is projected onto the instances according to the shortest distance. The generatrices are sorted according to their average distance to the point cloud: the sum of the distances between the original and the projected points allows the identification of the arch type and its characteristics (Figure 3g). Based on these arches and the directrices, the arrises are recovered and the intrados of the vault can be modeled (Figure 2h).

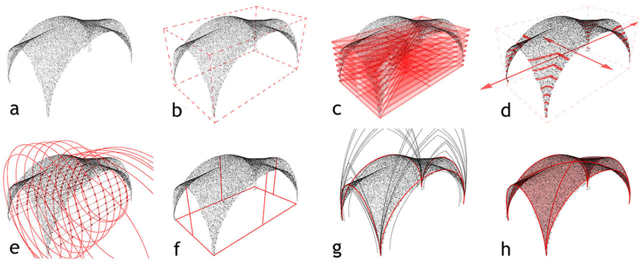


**Figure 2:** *Main steps in the reverse engineering process of a groin vault.*

### 5.2. Evaluation of the extracted intradoses accuracy

Several sets of intradoses of groin and barrel vaults were extracted from point clouds. The evaluation process is performed using the point clouds as reference. The first set of intradoses are the barrel vaults from the nave and the chapels of the church of La Brigue. The average distance of the nave intradoses present deviation of 1cm while the deviation is less than one centimeter for the vaults of the chapels of the same church. The results for the groin vaults of the cathedral are closed to those of the data sets acquired by laser scanning: less than 10cm which is less than the standard deviation (SD) of the nave barrel vaults of the church. The poor results of the vaults reconstruction of the churches of Verdun and Mons came from the specificities of the vaults whose keystones are higher than their arches.

| Site | Shrine (La Brigue) | | Church (Verdun) | Cathedral (Nancy) | Church (Mons) |
|---|---|---|---|---|---|
| Structure | groin vault | | nave groin vault | | |
| Size (m) | 10x6x6 | 20x7x8 | 5x3x3 | 14x7x8 | 20x7x8 |
| Technic | Laser scanning | | | SfM | |
| Accuracy (cm) | 13.4 | | 4.3 | 18.18 | 21.2 |
| Mean (cm) | 1 | 30 | 33.5 | 12.4 | 20,3 |
| SD (cm) | 12 | 12.4 | 28.4 | 9.5 | 17,8 |

**Figure 3:** *Assessment of b-rep barrel vaults accuracy*

### 5.3. Semantic modeling of arches and vaults

Breps of intradoses are reconstructed but they are not yet semantic objects. In order to create models suitable for the modeling and behavior analysis as well as the analysis and decision aid, we use Revit software to reconstruct architectural models. Several tools and the existing parametric library of the software can be used to create enhanced 3D models. A workflow was established for the creation of vaults based on the intrados extracted from the initial point clouds. First, the resulting surfaces of the previous process are baked in Rhino environment before being exported in ACIS format. The import CAD tool of Revit is used to open the ACIS file. More specifically, the intrados is imported into an In-Place family of category Mass. This family type has the required tools for the creation of specific geometries, such as vaults and arches, not otherwise possible in predefined Revit system families. Only then is it possible to use the Roof by Face tool of the software to create a vault based on its intrados. Preliminary tests with the recovered groin vaults of the cathedral of Nancy show that the process failed. Revit is unable to compute the width of the roof at the arrises (the edges formed along the points where the barrel vaults intersect). For now, the groin vault intrados has to be divided as the product of the intersection of barrel vault intradoses in order for Revit to compute the roofs).

## 6. Conclusion and futures works

The MONUMENTUM project aims at developing an open and extensible software platform for the management of knowledge that enhances the comprehension and analysis of degradation phenomena affecting ancient buildings. Semantic structuring and 3D modeling of masonry structures is one of the issues of the project. Post-treatments are applied to surveys to create models for the analysis and diagnosis of the state of buildings [BDM13]. A knowledge model of masonry structures was developed in order to reconstruct intradoses and vaults. Experiments on several types of vaults and arches are very satisfactory. A prototype workflow is also initiated with the use of an architecture software capable of creating 3D models semantically richer. We can rely on the software library as well as a dedicated library that use the segmented arches and vault as input parameters. Further experiments must be conducted to improve the architectural features extraction for arches and vaults modeling. Other point cloud samples of arches and vaults are to be used in the process to ensure its robustness. But one of the medium-term objectives is to use the reverse engineering on input data not restricted to the point cloud of a single arch or vault. The process must be able to function even if the point cloud contains noise.

## References


[BB15] BAIK A., BOEHM K.: Building information modelling for historical building historic jeddah - saudi arabia. In *Proc. of the 2nd International Conference on Digital Heritage* (2015), vol. 2, pp. 125–128. doi:10.1109/DigitalHeritage.2015.7419468. 1

[BDM13] BAGNERIS M., DUBOIS F., MARTIN13 A.: Numerical analysis of historical masonry structures for stone degradation diagnosis: an application to the roman amphitheater of nimes. In *Proc. of the 1st International Conference on Digital Heritage* (2013), vol. 1, pp. 521–528. doi:10.1109/DigitalHeritage.2013.6743792. 1, 4

[Bre13] BREGIANNI A.: *BIM Development for Cultural Heritage Management*. National Technical University of Athens School of Rural and Surveying Engineering Lab of Photogrammetry and Politecnico di Milano School of Architecture B.E.S.T Department, 2013. 1

[BTS*14] BERGER M., TAGLIASACCHI A., SEVERSKY L., ALLIEZ P., LEVIN J., SHARF C.: State of the art in surface reconstruction from point clouds. In *Eurographics 2014 - State of the Art Reports* (2014), vol. 1, pp. 161–185. doi:10.2312/egst.20141040. 1, 3

[CP09] CHEVRIER C., PERRIN J.: Generation of architectural parametric components. In *Proc. CAAD Futures Conference 09* (2009), pp. 105–118. 2

[dLVF06] DE LUCA L., VÉRON P., FLORENZANO M.: Reverse engineering of architectural buildings based on a hybrid modeling approach. In *Computers and Graphics* (2006), vol. 30, pp. 160–176. doi:10.1016/j.cag.2006.01.020. 2

[dLVF15] DE LUCA L., VÉRON P., FLORENZANO M.: Semantic-based modelling and representation of patrimony buildings. In *Proc. SVE Worksop towards Semantic Virtual Environments* (2015), pp. 1–11. 2

[dM11] DE MONCLOS J. P.: *Architecture : description et vocabulaire méthodiques*. Inventaire général du patrimoine culturel (France), 2011. 2

[F.D12] F.D.K. C.: *Architecture: Form, Space, and Order*. John Wiley and Sons, 2012. 2

[FFP13] FAI S., FILIPPI M., PALIAGA S.: Parametric modelling (bim) for the documentation of vernacular construction methods: a bim model for the commissariat building, ottawa, canada. In *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* (2013), pp. 115–120. doi:10.5194/isprsannals-II-5-W1-115-2013. 1

[GM13] GARAGNANI S., MANFERDINI A.: Parametric accuracy: Building information modeling process applied to the cultural heritage preservation. In *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (2013), pp. 87–92. doi:10.5194/isprsarchives-XL-5-W187-2013. 1

[HF04] HAVEMANN S., FELLNER D.: Generative parametric design of gothic window tracery. In *Proc. of the Shape Modeling International* (2004), p. 350 âĂŞ 353. doi:10.1109/SMI.2004.37. 2

[Jan10] JANSSEN P.: *Houdini Modelling 101*. 2010. 3

[JCH13] JACQUOT K., CHEVRIER C., HALIN G.: Reverse engineering of scale models using dataflow programming: Application to the fortification of plans-reliefs. In *Proc. of the 1st International Conference on Digital Heritage* (2013), vol. 1, pp. 63–69. doi:10.1109/DigitalHeritage.2013.6743714. 2, 3

[MW10] MALEKI M., WOODBURY R.: Programming in the model: contextualizing computer programming in cad models. In *Proc. of the 2010 Spring Simulation Multiconference* (2010), pp. 35–41. doi:10.1145/1878537.1878723. 2

[OBGB15] ORENI D., BRUMANA R., GEORGOPOULOS A., B.CUCA: Hbim for conservation and management of built heritage: Towards a library of vaults and wooden bean floors. In *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* (2015), pp. 215–221. doi:10.5194/isprsannals-II-5-W1-2152013. 1

[QMC*15] QUATTRINI R., MALINVERNI E., CLINI P., NESPECA R., ORLIETI E.: From tls to hbim. high quality semantically-aware 3d modeling of complex architecture. In *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (2015), pp. 367–374. doi:10.5194/isprsarchives-XL-5-W4-367-2015. 1

[SP10] SANDERS D., PREVO M.: *Common Data Value Standard and the AAT. Architectural Heritage: Inventory and Documentation Methods in Europe*. Council of Europe Press, 2010. 2

[SSUF10] SCHINKO C., STROBL M., ULLRICHT T., FELLNER D.: Modeling procedural knowledge: A generative modeler for cultural heritage. In *Proc. of EuroMed 2010* (2010), vol. 6436, pp. 153–165. doi:doi:10.1007/978-3-64216873-4_12. 2

[Tak13] TAKAYAMA J.: Computer-generated gothic tracery with a motif-oriented approach. In *Proc. of IASDR* (2013). 2

[VSS14] VOLK R., STENGEL J., SCHULTMANN F.: Building information modeling (bim) for existing buildings-literature review and future needs. In *Automation in Construction* (2014), vol. 38, pp. 109–127. doi:10.1016/j.autcon.2013.10.023. 2