Formalisms, Methods and Tools for the Large-Scale Morphological Analysis of Architectural Heritage Shapes*

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Abstract

Historical architecture is probably one of the most appropriate areas for understanding the extent to which the cultural production of the different regions of a territory participates in the construction of a common identity. Owing to their distinct nature, as well as to their increasing diffusion, today digital technologies are opening up new opportunities for the cross-analysis of a large quantity of objects, far in space but close in their characteristics (typologies, styles, rules of composition, etc.). This opportunity could stimulate the creation of innovative scientific frameworks to improve the historical, artistic and technical study of the relationships between architectural shapes and social interactions in space and time. This question brings together the study of the semantic and geometrical natures of architectural shapes with the design and development of information systems capable of addressing experimental research on the variability of shapes. This paper presents the main lines of research that the MAP laboratory intends to conduct over the next five years on this issue.

Introduction

In recent years, various projects have been concerned with the development of methods, tools and technologies for the creation of shared digital libraries for cultural heritage (EPOCH [1], 3D-COFORM [2], 3D-ICONS [3], …). Despite significant technological advances in the development of new solutions for the digitization, processing and integration of heritage artifact data, very few experiences have focused on integrating these new technologies into innovative methodologies to promote high-impact research initiatives, particularly for the large-scale study of architectural heritage.
Historical architecture is probably one of the most appropriate areas for understanding the extent to which the cultural production of the different regions of a territory participates in the construction of a common identity. Owing to their distinct nature, as well as to their increasing diffusion, today digital technologies are opening up new opportunities for the cross-analysis of a large quantity of artifacts far in space but close in their characteristics (typologies, styles, rules of composition, etc.). This opportunity could stimulate the creation of innovative scientific frameworks to improve the historical, artistic and technical study of the relationships between architectural shapes and social interactions in space and time.

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This question brings together the study of the semantic and geometrical natures of architectural shapes with the design and development of information systems capable of addressing experimental research on the variability of shapes. This paper presents the main lines of research that the MAP [4] laboratory intends to conduct over the next five years on this issue.

State of the art

Over the past decade, interest in emerging technologies has inspired a large number of digital documentation projects that have demonstrated the potential of digital representation of heritage artifacts at different levels [Levoy et al. 2000; Gruen, Remondino, Zhang. 2004; El-Hakim et al. 2008]. In particular, the use of 3D digitization technologies, as part of cultural heritage documentation programs, has led to the emergence of a new generation of graphic media, useful for multiple purposes: archaeological analysis, monitoring of degradation phenomena, dissemination and representation of historical knowledge, and so on. The creation of digital representations of heritage artifacts requires methods and tools capable of digitally acquiring and reproducing the finest visual and geometric characteristics.
Reality-based 3D reconstruction is now considered the field of technological research based on the use of sensors [Vosselman, Maas 2010; Remondino, El-Hakim 2006]. Thanks to advances in photogrammetry and computer vision, the past five years have been characterized by an impressive growth of image-based geometric modeling approaches capable of automatically reconstructing 3D point clouds and dense meshes starting from a set of non-oriented photographs [Vergauwen, Van Gool 2006; Vu et al. 2009; Pierrot-Deseilligny, Clery 2009]. These solutions, based on flexible methodologies for camera calibration and orientation, facilitate the production of 3D representations by non-experts (with no knowledge of photogrammetric acquisition methods and using common digital cameras). Our contribution in this field concerns the harmonization of morphological reading methods [De Luca 2009; De Luca 2011] in specialized acquisition and processing protocols [Pierrot-Deseilligny, De Luca, Remondino 2012] for the realization of geometrically precise digital surveys according to the requirements of architectural heritage documentation practices.
However, beyond the generation of detailed, colored 3D models, the creation of an intelligible geometric representation of architectural shapes is a much more complex problem. Research that has focused on this issue is generally based on the study of shape grammars [Havemann et al. 2004; Mueller et al. 2006]. Our main contribution in this field regards the definition of a generic formalism for the semantic-geometrical description of classical architectural elements [De Luca, Véron, Florenzano 2007]. This formalism can be used to generate libraries of parametric architectural models (such as bases, balusters, columns, etc.) as well as to measure the difference between theoretical models (taken from treatises on historical architecture) and real objects.
But the study of the morphological nature of architectural heritage shapes opens a broader question: reasoning about the shape of an object frequently implies reasoning on the identification of similarity metrics to be used for the purposes of comparison, interpretation and classification. Measuring the similarity between various digital objects has been an active research area for several years, starting from the development of computer vision analysis techniques up to the more recent approaches for 3D model analysis using algorithmic geometry. These methods now provide good results for multimedia object indexing applications [Tangelder, Veltkamp 2008], and their application in the cultural heritage domain [Biasotti et al. 2015]. This emerging field, however, opens the door to much more interesting issues for linking the analysis and classification of large collections of shapes to the broader area of large-scale spatial analysis.
Indeed, besides geometric representations, a large amount of heterogeneous data is generally collected, organized and analyzed for the study of historical architecture. The data are mostly drawn from different disciplines (architecture, archaeology, history, conservation science, etc.) and are based on various media (iconography, maps, manuscripts, etc.). Beyond the digital representation of architectural geometry (which now permits the management of quantitative data), the structuring of qualitative descriptions is a

much more important research issue, particularly because it confronts the problems of multidisciplinary interpretation. Numerous methodologies and technologies have been developed in recent years to improve the management of heterogeneous digital contents, relying mainly on formal structures (thesauruses, ontologies, etc.) capable of unambiguously describing implicit and explicit conceptual elements (and their interrelationships) [Doerr 2002] mobilized in the documentation of heritage artifacts. Some works have focused on methods for linking semantic tags (vocabulary terms and structured concepts) to 3D models [Havemann, Fellner 2008], or to a hierarchical description of architectural composition schemes [Manferdini et al. 2008]. In addition, the joint analysis of spatial and temporal data has acquired particular importance for the study of object transformations, the temporal distribution of categorized events, and the distribution of spatio-temporal data [Kapler, Wright 2005].
Our contributions in this area have focused on the design and development of 3D information systems for structuring heterogeneous data around the morphological description of architectural heritage buildings. By combining the semantic structuring of morphological descriptions with the interconnection of multiple representations, our approach [De Luca et al. 2013] has revealed the potential of semantically enriched 3D representation for several applications: the management of semantic geometric models in 2D/3D annotation frames [Stefani et al. 2013]; the spatialization of semantic annotations to describe the state of conservation [Stefani et al. 2014]; the representation of morphological transformations through dynamic geometric models [Stefani et al. 2009]; the clarification of the semantic relationship between the conceptual and physical dimensions of a heritage object [De Luca et al. 2013; Carboni, De Luca 2016].

Scientific and technological issues

In view of this panorama of apparently dispersed scientific and technological issues, the main objective of our research program for the years to come is to introduce means of rupture in order to study technical expertise and stylistic influences in the history of architecture by providing innovative tools and methods for the dimensional observation, morphological analysis and classification of architectural shapes within large-scale participatory research campaigns. As illustrated by the state of the art, this ambitious program integrates several potential advances related to the historical and computer sciences in an original interdisciplinary research framework. The three main open questions are listed here.
First, in historical architecture, shapes can be considered as an essential trend marker. Understanding the dependencies between these trends and their evolution over time requires rigorous analyses (based on cumulative approaches) of how shapes vary across territories and periods. Exploring such a complex variability of shapes requires a classification strategy to study similarities, models, and semantic and geometric exceptions. This includes the interconnection of two levels of description. At the class level, architectural shapes can have an invariable definition (a vocabulary term indicating their role in a global structure, for example: a column) generally codified by historical knowledge. At the instance level, shapes have complex characteristics (geometry, visual appearance, materials, …) that clearly distinguish them (for example: a column of an existing building, built at a particular place and time). A first challenge is illustrated by the need to establish a rigorous documentation and analysis framework for exploring the variability of architectural shapes belonging to the same architectural concept.
The growing diffusion of image-based, flexible and easy-to-use modeling tools makes it possible to envisage the opportunity to collaboratively build a large digital library of 3D architectural models based on acquisitions of real objects. But if the implementation of a participatory documentation strategy for the massive collection of digital representations of architectural shapes becomes a realistic goal from a technological point of view, the increasing mass of uninterpreted point clouds and 3D models today underlines an essential need to develop new methodologies to facilitate the processing, sorting and analysis of data in relation to issues of historical knowledge. Indeed, beyond the aspects of geometry processing, the analysis of shape semantics requires a thorough understanding and identification of relevant morphological descriptors capable of adding

intelligibility values to complex (and not eloquent) masses of geometric representations. This question raises a second challenge represented by the need to devise a new generation of tools for analysts (historians, archaeologists, architects, etc.) capable of automating heavy geometric and visual correlations.
As several historical research efforts have demonstrated, architectural vocabulary is probably the most appropriate analytical tool to accompany the interpretative reading of structural compositions as well as stylistic grammars. But even if each sub-community in the history of architecture (including the area of archaeology) has done important work in defining thesauruses specialized in particular periods or geographical areas, terminology still maintains many ambiguities, especially with regard to the study of transnational trends on a large scale and over long periods. Similar shapes may have different names in different languages, but minor morphological differences. The present level of geometric and visual details provided by 3D digitization, as well as the potential of their comparative analysis and semantic correlation, opens new, unexplored classification issues, to be studied at the intersection between terminology, morphology and representation of knowledge. As a result, the third challenge is to provide new metrics for the analysis of shapes capable of increasing our ability to discover similarities, models and exceptions in large-scale surveys.
These three issues recover the dispersed, scientifically significant tools, methods and models of several disciplines. Their integration into transversal approaches is certainly the distinctive characteristic of our program, which is at the crossroads of trends that shape the contemporary technology landscape and, more broadly, the digital humanities.
First of all, the democratization and diffusion of means of digitization, now even integrable within shared computing platforms–cloud computing–which makes it possible to concretely envisage procedures for participatory semantic survey and annotation on a very large scale.
Secondly, the recent evolution of approaches for analysis and visual recognition, stimulated by impressive advances in computer vision and deep learning in the analysis and correlation of large masses of data, here could play a role in renewing methodologies of shape analysis and classification (art history, archaeology, conservation, …) through the identification of new models of morphological signature combining geometric, visual and semantic descriptors.
Finally, the process of harmonization currently underway in the field of cultural heritage information systems, in particular as regards the construction of domain ontologies, which now makes it possible to gather together heterogeneous, dispersed information while moving the center of gravity of approaches to documentation from a description focused on the "heritage object" to a more exhaustive description of the "plurality of viewpoints" (scientists, experts, professionals, curators, administrators, …), which, day after day, enriches the collective understanding and the transmission of the memory of these objects. This latter aspect is also an unprecedented opportunity to explore, through the analysis and correlation of masses of annotations and semantic links, the mechanisms through which communities (and even societies) construct the heritage value of these objects.
By considering our scientific contribution to the human and social sciences with the design and development of digital technologies, and not the contrary, our goal is to introduce a new generation of (generalizable) formalisms, (reproducible) methods, and (reusable) tools combining algorithmic geometry and historical knowledge for the massive and large-scale morphological analysis of shapes.

A collaborative semantic acquisition and enrichment framework

First of all, we intend to introduce (and disseminate) a rational contribution for resolving the current problem of information overload. The increasing mass of uninterpreted 3D data calls for the development of innovative acquisition-processing protocols to help analyze and sort data by spatialized semantic annotation. An innovative protocol [Manuel et al. 2014], which links the on-site acquisition of images (and their semantic annotation) to remote geometric processing (based on cloud technologies), introduces new possibilities for exploiting photo-modeling in order to obtain a comparative and collaborative analysis of large collections of shapes. This is the 'aïoli'

[5] platform, which our laboratory has recently developed and made available to the first beta users within the framework of scientific partnerships.
Therefore, on the basis of this result, we will concentrate on defining a methodology (and on developing a set of operational IT tools) to digitize masses of architectural shapes for the purposes of morphological analysis and classification using crowdsourcing (participatory collection) strategies. The preliminary analysis of the collections of selected shapes, combined with documentary research, will also gather together important sources for the development of semantic annotation methods (vocabulary terms, existing ontologies) and for the association of morphological signatures with spatio-temporal markers. We intend to carry out this work through the establishment of cooperative agreements with consortia that have already undertaken major inventory work within international networks (European Science Foundation (EFS) PALATIUM [6], Mapping Gothic France [7], Centro Internazionale di Studi Andrea Palladio [8], …).

Knowledge modeling driven by the correlation of morphological signatures

The information framework introduced by our approach of data collection and semantic enrichment merges the spatial, geometric and visual information contained in a mass of photo-models (point clouds and 3D surfaces, oriented photographs, dimensional parameters, textures, etc.) with a set of structured vocabulary terms within a domain ontology. This framework opens paths for exploration that could question the current semantic annotation and classification methods (today mainly based on qualitative attributes) by introducing relevant morphological parameters (calculated by correlation of geometric detail attributes), whose informational richness has not yet been explored in this area.
The inclusion of qualitative and quantitative attributes would make it possible to create an extensive and semantically structured library of digitized artifacts while isolating, structuring and directly illustrating architectural concepts within a terminological scaffolding. However, although the scientific literature on computer graphics has recently produced numerous works highlighting the potential for semantic annotation of 3D models, the application of geometric characteristics to the description of an architectural shape (especially when we observe heritage artifacts) requires an in-depth analysis of the relationship between the concepts of multiplicity and intelligibility. This question concerns two interconnected relationships: on the one hand, the relationship between a generic model (an architectural concept already described in historical literature) and a related collection of instances (real architectural objects), and on the other hand, the relationship between geometry (morphological characteristics) and semantics (prior knowledge). In continuity with our previous contributions on this subject [Lo Buglio, Lardinois, De Luca 2015; Pamart, Lo Buglio, De Luca 2015], one main expected result would be to introduce possibilities of annotation and correlation where semantics can be exploited in pre-processing stages (based on a priori knowledge, descending approach) and/or in the post-processing stages (extraction of similar morphological characteristics, ascending approach), by developing tools to assist analysis and human interpretation by automating very heavy geometrical comparisons.

A collaborative platform for large-scale historical research

Heritage artifacts are more often the result of temporal stratifications, modifications, additions and transformations. This aspect raises important problems concerning the annotation of shapes, since a good observation and interpretation approach must combine several overlapping semantic layers that relate to multiple states of the same object, including iconographic sources that attest to its transformations over time. Indeed, the implementation of the annotation/classification methods envisaged by this project requires a profound correlation of heterogeneous data that can be used to qualify architectural shapes. In an attempt to integrate (from a conceptual and methodological point of view), the phase of spatial data acquisition with that of their semantic structuring, the original idea of our approach concerns the desire to establish a relationship between heterogeneous data within a geometric-spatial dimension. This means that instead of using 'entity-relationship' links to anchor architectural shapes and associated information, geometric projection functions (formalization of spatial orientation parameters of iconographic sources) are used as a channel for disseminating relevant information (semantic attributes, spatio-temporal markers, morphological signatures) between all levels of representation (from architectural detail to territory). In addition, through our morphological analysis of shapes on the architectural level (as well as the level of architectonic detail), by observing the spatial and temporal distributions of these shapes on a geographic level, our approach aims to introduce multi-criteria and multi-level exploratory analysis mechanisms. The results of this phase of our work program will lead to the construction of an open platform, in continuity with our team's ongoing efforts to develop cloud technologies for large-scale participatory historical surveys.

Conclusions

By establishing a framework for rigorous documentation and analysis, based on innovative tools and methods aiding morphological analysis by the automation of heavy geometric correlations, our ambition is to introduce new 'shape-oriented' metrics for the study of architectural heritage. Our research program for the years to come does not follow the simple logic of deploying technological solutions for the digitization, processing and dissemination of cultural information, but it is organized around the identification of the true potential of development of digital technologies for the study of historical architecture. For this reason, our approach integrates, through a methodology of interdisciplinary work, the scientific advances related to the fields of historical sciences, knowledge engineering, computer vision and algorithmic geometry, aiming ultimately at the construction of a software and human infrastructure favoring the emergence of cumulative approaches to the study of built heritage.

Notes

[1] EPOCH Network of Excellence <www.epoch-net.org> (consulted on July 20, 2017).

[2] 3D-COFORM Project, Tools and expertise for 3D collection formation <www.3d-coform.eu> (consulted on July 20, 2017).

[3] 3D-ICONS Project, 3D Digitisation of Icons of European Architectural and Archaeological Heritage <www.3dicons-project.eu> (consulted on July 20, 2017).

[4] MAP, Models and Simulations for Architecture and Cultural Heritage. A CNRS (French National Center for Scientific Research) and MCC (French Ministry of Culture and Communication) joint research unit. For further information: <www.map.cnrs.fr> (consulted on July 20, 2017).

[5] aïoli – a 3D semantic annotation platform for the collaborative documentation of cultural heritage objects. A cloud platform developed within the MAP laboratory. For further information: <www.aioli.cloud> (consulted on July 20, 2017).

[6] European Science Foundation (EFS) PALATIUM <http://www.courtresidences.eu> (consulted on July 20, 2017).

[7] Mapping Gothic France <http://mappinggothic.org> (consulted on July 20, 2017).

[8] Centro Internazionale di Studi Andrea Palladio <http://www.palladiomuseum.org> (consulted on July 20, 2017).

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