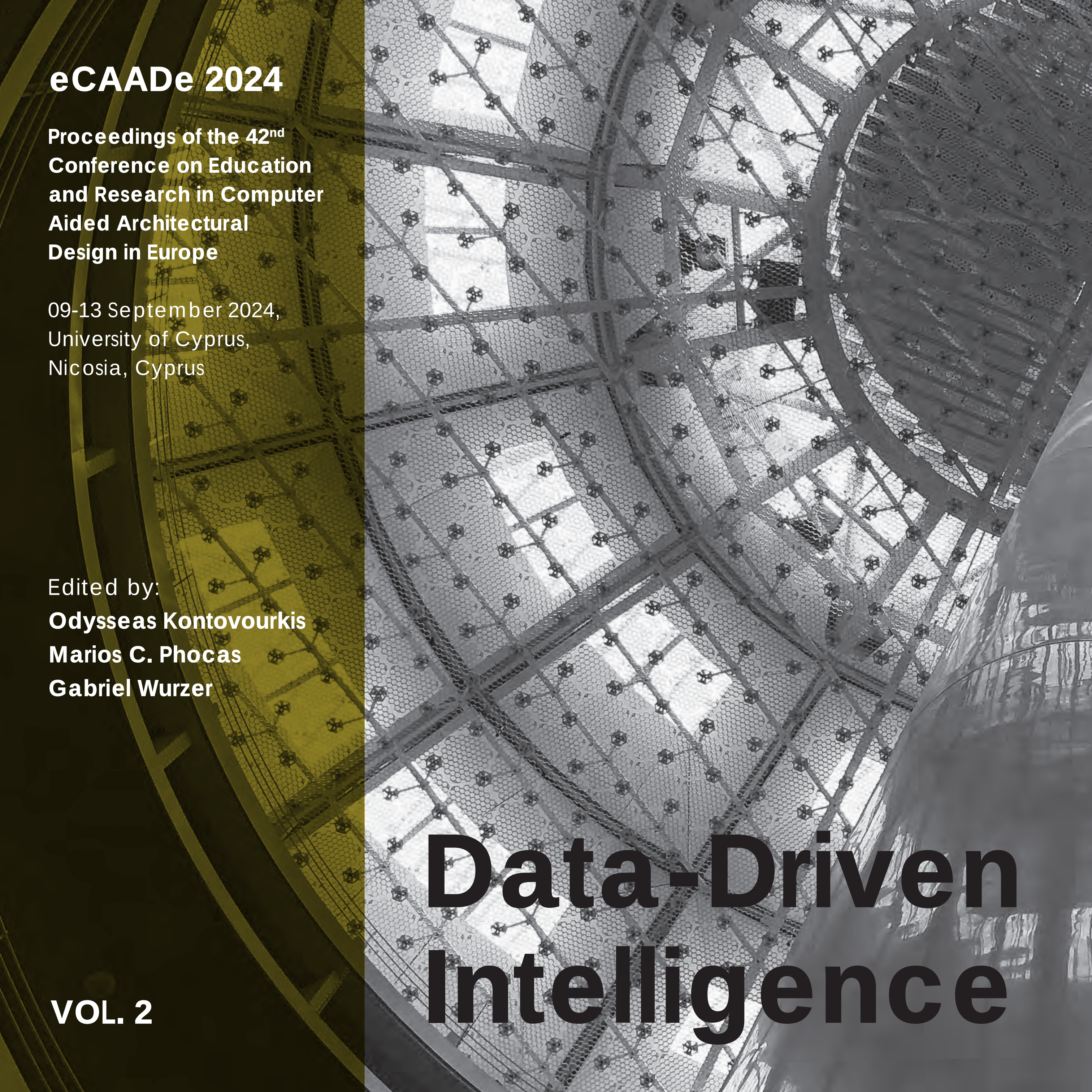

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Marios C. Phocas
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An Ontology-Driven Approach for Geometry Segmentation and Interpretation in Architectural Heritage/archaeology

Cassia De Lian Cui [1], Stefano Cursi[2], Davide Simeone[3], Antonio Fioravanti[4], Edoardo Curr¨[5]
[1,4,5]Sapienza University of Rome [2] ISPC ï National Research Council
[3]University of Brescia
[1,4,5]{cassiadelian.cui|antonio.fioravanti| edoardo.curra}@uniroma1.it
[2]stefano.cursi@ispc.cnr.it [3] davide.simeone@unibs.it

Digital information systems are widely used for heritage documentation and management activities. The creation of 3D models based on different survey techniques, like photogrammetry and laser scanning, allows a fast collection of the studied assets in the form of geometry dimensions and point clouds. However, the raw geometric information and the mesh/solid converted data need to be associated with semantic annotation, defined as external and formalized knowledge of the architectural artifact.
This paper proposes a workflow using Semantic Web-related technologies to support point cloud segmentation activity of archaeological artifacts. The suggested approach is based on analyzing and integrating different layers of information through three main phases: the digital acquisition phase, the geometry creation phase, and the semantic enrichment phase. The defined framework is then applied to the archaeological case study of Tivoli to highlight how the workflow can significantly improve the quality and effectiveness of data segmentation in the existing heritage documentation processes by providing a solid basis for the generation of detailed and semantically enriched geometric information models. Finally, the creation of this system prototype will give overall support to aid the interpretations and value recognition of heritage sites thanks to the capability of representing and managing the categories (in Aristotleôs sense) and the uniqueness of concepts applied to this peculiar and paradigmatic case study.

Keywords: *Built heritage, Semantic annotation, Ontologies, Knowledge-based system.*

INTRODUCTION

Geometric-informative digital modeling of built heritage represents a rapidly evolving frontier. This process begins with an accurate survey of the artifact through advanced methodologies, 3D laser scanning, or photogrammetry techniques that allow the acquisition of a vast amount of point cloud data. Before the information modeling phase, a pre-processing step is required, which involves cleaning, correcting, and aligning the scans to form a single coherent model, removing extraneous elements, and reducing noise that could compromise the quality of the following segmentation step. Indeed, point cloud segmentation is the heart of the procedure since, through automatic, manual, or hybrid methods, it allows the identification of point data sets that form lines, surfaces, or volumes distinguishable by geometric and/or textural characteristics. This step goes hand in hand with classifying and interpreting the identified geometric elements by associating each with a constructive element of the building. This phase allows a deeper understanding of the artifact, thanks to the attribution of additional information to the classified elements, that goes beyond the simple geometric-spatial dimension, ascribing a precise meaning that reflects the function of the element and its context within the entire structure.

The adoption of ontology-based methodologies for the segmentation and semantic classification of point clouds is becoming progressively more influential in the context of built heritage documentation activity. Such methodologies seek to address and resolve the restrictions associated with traditional processes using formal knowledge schemas (Croce et al., 2020). The use of ontologies in this field enables more precise categorization and annotation of objects within point clouds, providing a platform for sharing consistently and integrating standardized information. This methodological evolution enriches the process of documenting architectural heritage and opens new study fields for the preservation, analysis, and digital management of historic buildings.

This paper proposes an ontology-driven segmentation process for complex heritage sites, where each phase of the digitalization activity is represented through entities of existing ontologies integrated with new classes and relations. The aim is to record and separate semantic annotations from their geometrical representations through a precise and shared vocabulary to represent data interpretability and information reliability in a machine-readable way. The purpose is to overcome the limits shown in the existing processes, where the ontology reasoner only assists from the input perspective rather than in the misclassification and interpretation steps. Moreover, there is always an univocal correspondence between geometries and semantic meanings, which clashes with the peculiarity of heritage assets. The proposed workflow is then applied in a unique archaeological site where changes, inconsistencies, and uncertainties represent one of the challenges for the complex semantics formalization, and finally, the system is tested through a sample query.

SEMANTIC SEGMENTATION AND ONTOLOGIES IN THE CULTURAL HERITAGE FIELD

In recent years, the advancement of surveying technologies and the increasing availability of 3D data have led to significant developments in point cloud segmentation, especially in the built heritage field (Zhao et al., 2023).

In this context, machine learning-based approaches, such as Deep Neural Networks (DNNs) and decision tree-based classification models, are among the most studied approaches for point cloud segmentation (Grilli et al., 2017; Zhang et al., 2023).

DNNs have been widely adopted for the semantic segmentation of point clouds due to their ability to extract complex features and relevant patterns from spatial data. Qi et al. (2017) introduced "PointNet" and "PointNet++," pioneering deep learning models that can directly process point clouds, providing a significant foundation for further research in the field of semantic segmentation of architectural assets. The use of decision trees is another practical approach for the classification and segmentation of point clouds (Breiman, 2001). These models, which construct multiple decision trees for data classification, have shown a remarkable ability to handle spatial data's variety and complexity. These algorithms can be trained on annotated datasets to identify and classify architectural elements automatically. However, their success depends heavily on the quality and representativeness of the training dataset.

Furthermore, some studies have explored the integration of DNNs and decision trees to improve segmentation accuracy further (Laptev and Buhmann, 2014). These hybrid approaches combine the powerful feature extraction capability of DNNs with the intuitive decision and effective segmentation provided by decision trees.

Despite demonstrated progress, segmentation of built heritage point clouds through machine learning still presents significant challenges, including the need for large labeled datasets for training, handling scattered or incomplete data, and semantic interpretation of identified segments. The experiences cited above highlight how the future works and challenges could focus on improving computational efficiency and integrating richer semantic information to facilitate specific applications in heritage preservation.

On the other hand, ontology-based approaches for point cloud segmentation focus on defining knowledge models that can describe the properties and relationships of architectural objects. These approaches aim to overcome the limitations of conventional methods by using formal knowledge structures that facilitate semantic interpretation and recognition of architectural elements. Significant examples in this field are the works of Zalamea et al. (2018) and Messaoudi et al. (2018), who developed an ontology for identifying and classifying architectural elements from point clouds of historic buildings. These approaches facilitate automated semantic segmentation, improving accuracy in architectural heritage preservation and restoration activities.

Some other studies have explored the integration of ontologies and machine learning techniques to improve the segmentation and classification of point clouds. For instance, Colucci et al. (2021) presented an approach combining ontologies with machine learning algorithms for automatically classifying architectural elements in 3D data, demonstrating how integrating formal knowledge can increase the effectiveness of recognition systems.

The application of ontologies in the segmentation and classification of point clouds reveals significant potential in accuracy and efficiency. However, the creation of detailed ontologies and their integration with vast datasets pose significant challenges. Context-specific ontologies and managing heterogeneous data require continuous work to adapt and optimize models.

The potentialities of ontology models in the formalization of concepts will continue to play a crucial role in the segmentation and semantic classification of point clouds, especially in complex heritage artifacts. Therefore, current research shows the need to develop more flexible and adaptable ontologies, integrate deep learning techniques, and explore new practical applications.

ONTOLOGY-BASED ANNOTATION FRAMEWORK FOR ARCHITECTURAL HERITAGE AND ARCHAEOLOGY

During the identification and interpretation process of an architectural element, from the survey data, it is possible to distinguish two levels of recognition: the geometrical and the semantic ones.

Geometric recognition focuses on shape, spatial arrangement, structure, and material aspects. At different scales, the identification of geometries from point clouds is traceable into multiple unitary entities. On the other hand, the semantic level associates meaning to the identified geometric entities through a specific interpretation activity. The connection with constructive components is the basis of the building system, a process that panders to the object-oriented logic applied in building information modeling.

The combination of these two levels in the historical context only sometimes adheres to the reality of the studied assets, and the majority of the existing tools force the uniqueness of the heritage artifacts under certain knowledge representation constraints. From the state of the art, the explored approaches are limited to identifying the most flexible and precise methodology for geometries management. However, they are still linked to a single meaning and semantic attribution, which restrains their applicability in the archaeological fields, where it is very challenging to determine a univocal definition and classification of certain elements.

For these reasons, the main idea of this approach relies on the possibility of separating these two levels, semantics and geometry, to guarantee a more flexible knowledge model capable of handling a higher level of complexity during the built heritage digitalization process.

The first step of the ontology-based segmentation process regards the definition of the domains of interest and the overview of existing ontologies necessary to identify all the information required to fulfill the knowledge structure and representation of the proposed methodology.

The following framework has three main phases:

- Digital and manual acquisition phase, which is the preliminary activity performed to collect geometrical raw data
- Point cloud conversions to meshes or geometries phase through automatic or semiautomatic methods.
- Geometries to semantically enriched entities phase with tailored case-based knowledge structures.

As shown in Figure 1, within each chosen domain – digital and manual acquisition process, geometry, and architectural artifact – many published ontologies cover different areas and fields of application. Preliminary content analysis allows a better selection and evaluation of which entities are more suitable for this specific study field. The chosen entities are then customized and integrated with new classes and relations. An alignment action is performed when different ontologies and structures need to be linked and adapted.

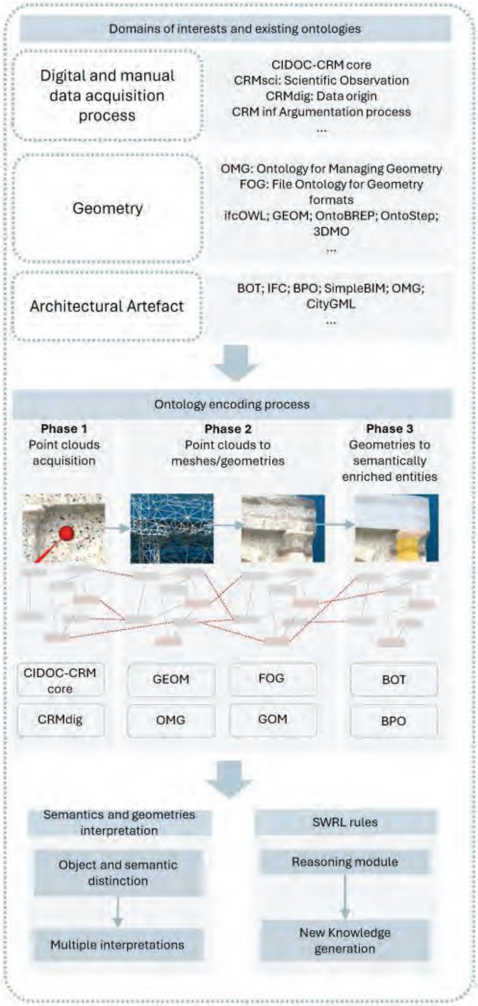

Figure 1
The proposed Ontology-driven semantic segmentation process.

This ontology construction process follows the one presented in the Linked Open Term (LOT) methodology (Poveda-Villalón et al., 2022), developed from the NeOn methodology (Suárez-Figueroa et al., 2015).

The three phases mentioned above are connected with new concepts and relations during the ontology encoding activity.

For the points acquisition phase, to document the data collection, we used the CIDOC-CRM (Doerr et al., 2020), a core ontology for cultural heritage representation, and the CRMdig, which is an ontology and RDF Schema to encode metadata about the steps and methods of production ("provenance") of digitization products and synthetic digital representations such as 2D, 3D or even animated models created by various technologies (Pitzalis et al., 2010).

For the geometric representation, we integrated the GEOM ontology dedicated to geometry descriptions with GOM (Wagner et al., 2019) (Geometry Metadata Ontology) that contains terminology to Coordinate Systems (CS), length units, and other metadata, with the OMG (Ontology for Managing Geometry) and FOG (File Ontology for Geometry formats) (Bonduel et al., 2019).

Finally, for the architectural artifact, we considered the BOT (Building Topology Ontology) (Rasmussen et al., 2020), which is a minimal ontology for describing the core topological concepts of a building.

FROM UNSTRUCTURED POINT CLOUDS TO STRUCTURED KNOWLEDGE AND INTERPRETATION

The ontology encoding activity starts by representing the various steps in the digitalization process through ontology web language (OWL). It is then implemented in the Protégé. ontology editor.

The concepts represented in the first schema (Figure 2) focus on the CRMdig: Digitalization_Process entity, which is a subclass of the CRMdig: D7_Digital Machine_Event, and it is performed to create a digital object through specific devices, procedures, and techniques.

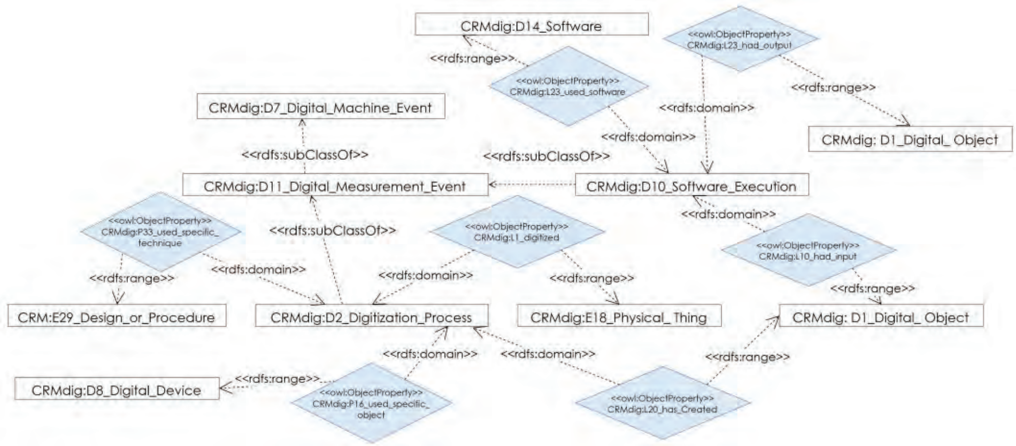

Figure 2
Ontology representation for Phase 1 -Digital Acquisition

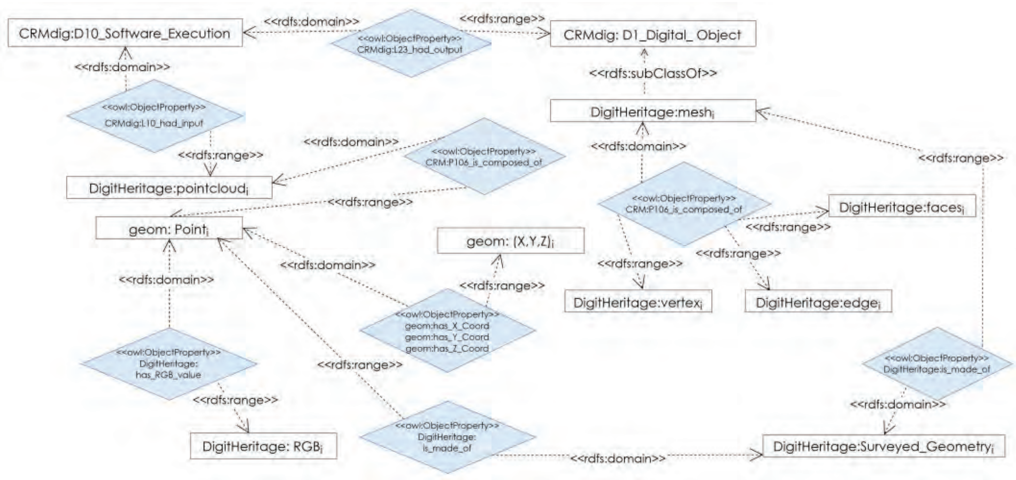

Figure 3
Ontology representation for Phase 2 – Point clouds to meshes or geometries

The digitalization of a physical object is an iterative process, and it needs more than one software execution through specific inputs and outputs based on the different input datasets (photogrammetry, laser scanning). This step is repeated until we obtain the point cloud model.

Phase 2 regards the point cloud conversion into meshes or directly in recognized geometries.

During this phase, it is possible to identify point aggregations based on positions and color values. Depending on the different workflows, it might be converted into a number of meshes (DigitHeritage: mesh$_i$) composed of vertex, edges, and faces. The gathering of those triangles results in one or more geometries (DigitHeritage: Surveyed_Geometry$_i$). Figure 3 represents this step with the integration of new entities and relations named DigitHeritage.

The third and last phase concerns the semantic annotation activity, which can be performed manually, automatically, or both ways. Apart from the types of annotations, the overall aim is to make a classification based on domain and expert knowledge and, in any case, to combine this workflow with the output of the existing semantic segmentation processes. As represented in Figure 4, the point clouds are the input components for the DigitHeritage:Semantic: Segmentation, which has as output the Segmented_Geometries that is a DigitHeritage: Surveyed_Geometry$_i$ and it composes the bot: element entity but still maintains an autonomous formalization representation. The choice to use lightweight ontologies such as BOT is to build flexible and reusable representations at different scales, which are applicable in multiple case studies.

Finally, all the information necessary to perform the interpretation and identification processes is represented by two new classes: Direct_Analysis and Indirect_Analysis. In this way, the whole process, from raw data collection and acquisition to knowledge interpretation, is represented at a logical level of connections. This procedure allows the enrichment and development of the knowledge base over time, where the entities are updated according to new investigation activities carried out or new data collected from different knowledge sources. This ontology-driven semantic segmentation approach can be applied independently from the various technological tools.

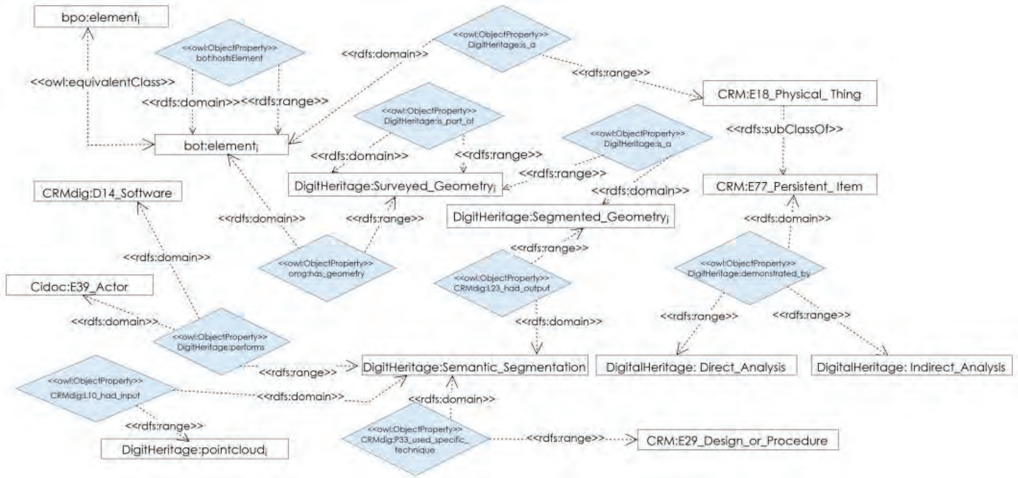

Figure 4
Ontology representation for Phase 3 – From geometries to semantically enriched entities

MULTIPLE ARCHAEOLOGIES: THE CASE OF THE SANCUTARY OF HERCULES AND SEGRÈ PAPERMILL

The proposed methodology has been applied to a specific area of the case study: the Sanctuary of Hercules and the former Segrè Papermill in Tivoli. This unique site history has seen multiple stratifications from Roman times. It was built between the 2nd and 1st centuries B.C., and the construction was born with religious, political, and commercial functions.

This extraordinary monument has had interrupted agricultural and industrial uses over time. The latest reuse was settled in the 20th century. The Segrè papermill brought a comprehensive industrialization process to the area and it was dismissed in the 1970s.

The ontology-driven approach started from a geometrical digital and non digital survey to gather raw data. This process was performed in a small area of the northern porticus through lidar scan to test the validity of the workflow.

The area was chosen for the multiple stratification over the centuries and for the high complexity in the semantic segmentation process, since many elements were part of multiple structures with specific function and context and nowadays are included in other building components, and/or partially or totally lost.

The documentation activity was performed through data collection from different sources and data acquisitions, after that the acquired scans were processed and cleaned in Cloudcompare. Along this process, the defined ontology is instantiated to document how all these raw data have been acquired and processed.

In this case, we are going to focus only on the last phase related to the semantic segmentation process and on the relationship between the segmented geometries, the acquired geometries and the building elements.

Semantic segmentation and queries

The Semantic annotation activity started by converting the DigitHeritage: PointCloud1 into specific geometries such as semicylinder, arch, or parallelepiped; these are all part of the DigitHeritage: Surveyed_Geometry1.

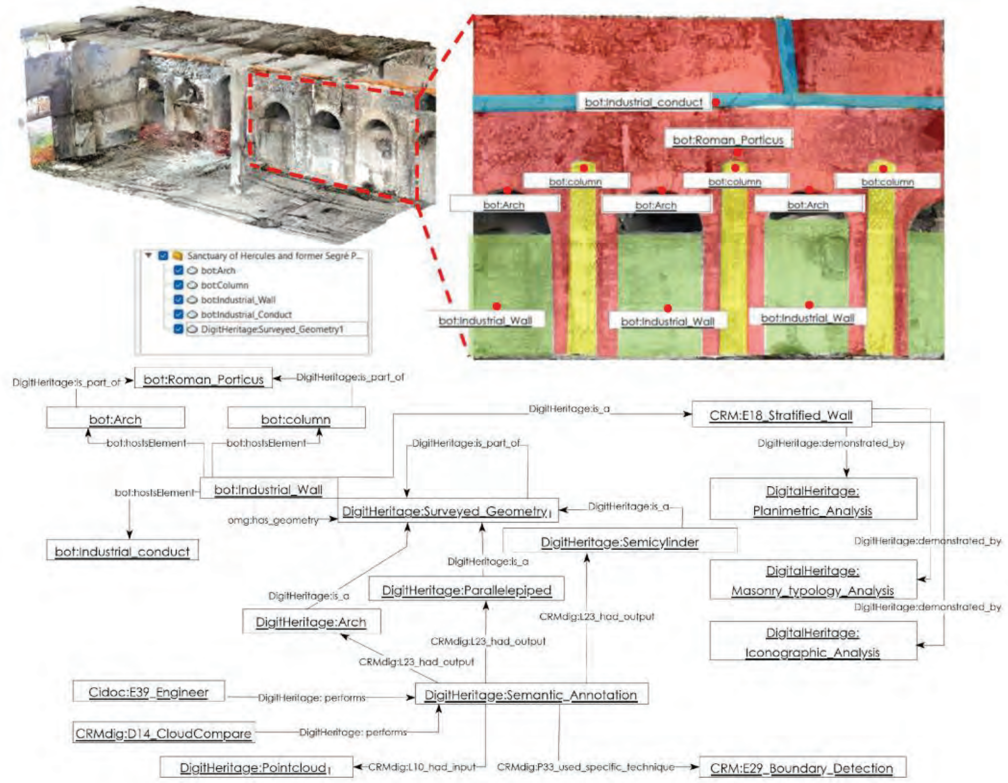

Figure 5
Semantic annotation on a portion of point cloud of the case study: the Sanctuary of Hercules and former Segrè Papermill

The Surveyed geometry is part of a broader geometry that composes a CRMe18_Stratified_Wall. The latest reuse was related to the papermill production process. Specifically, this room was used for paper storage, and therefore, the bot: Industrial_Wall and the bot: Industrial_Conduct host the Roman Porticus made of the bot: Arch and bot: Column.

All the information related to the attribution of meanings to the building elements was finally demonstrated through direct analysis: DigitHeritage: Masonry_typology_Analysis and indirect analysis: DigitHeritage: Planimetric_Analysis and DigitalHeritage: Iconographic_Analysis (Figure 5).

Once the instantiation process has been completed, the last step regards the validation of the framework by querying the ontological structure to check the consistency of the knowledge formalization.

Based on the ontological schema, some simple queries in SPARQL were performed to generate new knowledge from existing information. Here below, two of them are represented.

The first one selects all instances of the DigitHeritage:Segmented_Geometry and any rdfs:label or rdfs:comment and optionally selects any related instances connected by any relationship that is not an rdf:type.

```
PREFIX DigitHeritage:
<http://www.semanticweb.org/DIgitHeritage/#DigitHer
itage:>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-
syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-
schema#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>

SELECT ?instance ?label ?comment ?relatedInstance ?
relatedInstanceLabel
WHERE {
  ?instance a DigitHeritage:Segmented_Geometry .
  OPTIONAL { ?instance rdfs:label ?label . }
  OPTIONAL { ?instance rdfs:comment ?comment . }
  OPTIONAL {
    ?instance ?relationship ?relatedInstance .
    ?relatedInstance a owl:NamedIndividual .
    OPTIONAL { ?relatedInstance
rdfs:label ?relatedInstanceLabel . }
    FILTER (?relationship != rdf:type)
  }
}
```

While the second one helps to retrieve all Segmented_Geometry instances and their related Surveyed_Geometry by the is_part_of property, as well as the Physical_Thing they are a type of through the is_a property.

```
PREFIX bpo:
<http://www.semanticweb.org/DIgitHeritage/#bpo:>
PREFIX CRMdig:
<http://www.semanticweb.org/DIgitHeritage/#CRMdig:>
PREFIX Cidoc:
<http://www.semanticweb.org/DIgitHeritage/#Cidoc:>
PREFIX DigitHeritage:
<http://www.semanticweb.org/DIgitHeritage/#DigitHer
itage:>
PREFIX DigitalHeritage:
<http://www.semanticweb.org/DIgitHeritage/#DigitalH
eritage:>
PREFIX CRM:
<http://www.semanticweb.org/DIgitHeritage/#CRM:>
PREFIX omg:
<http://www.semanticweb.org/DIgitHeritage/omg:>

SELECT ?segmentedGeometry ?surveyedGeometry ?physic
alThing
WHERE {
  ?segmentedGeometry a
DigitHeritage:Segmented_Geometry .
  OPTIONAL {
    ?surveyedGeometry
DigitHeritage:is_part_of ?segmentedGeometry .
  }
  OPTIONAL {
    ?segmentedGeometry
DigitHeritage:is_a ?physicalThing .
  }
}
```

The constant update of the ontology schema and the incremental work on the ontology population activity will help construct more complex queries with larger amount of data.

CONCLUSIONS

The main objective of this work was to develop an ontology-driven segmentation process for complex heritage sites.

This process consists of the knowledge formalization of three main steps: digital and manual data acquisition, conversion of point clouds into meshes or geometries, and the semantic enrichment of the defined entities.

Furthermore, the overall workflow enables classification based on domain-specific knowledge by combining manual, automated, or hybrid methodologies for the annotation activity and distinction between semantic annotations and geometric representations.

Indeed, the proposed methodology allows a representation of the existing artifact that is not constrained to the rigid one-to-one correspondence between geometries and semantic meanings. The application to the case study demonstrates how the data interpretation activity in a complex heritage site is not always a straightforward process, and thanks to the ontological model, it is possible to represent changes, inconsistencies, and uncertainties as integral aspects of complex semantics formalization in a meaningful way.

Although the structure was implemented and tested through simple queries, more investigation and work is necessary to understand how ontology reasoning could make the result more precise and efficacious. Extending the application to a more extensive knowledge base and a different case study will help detect possible improvement areas and possible corrections and adjustments to the proposed framework.

Future work will explore the application of ontology to different segmentation processes and through different technologies to obtain a more flexible and adaptable representation of the interpretative process, which is at the core of all the investigation and documentation activities for the built heritage valorization.

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During the 2020s and beyond, the feld of computational design and fabrication will face a number of new challenges and opportunities offered by Artifcial Intelligence (AI) and Machine Learning (ML). These technologies represent a new era of data-driven intelligence, which is steadily gaining increasing infuence in other felds, but as yet has had little impact in architecture. At the core of this new technological shift, data will be collected, processed, shared, and used as a decision-making tool to resolve a multitude of social, economic, and environmental issues.

In view of this paradigm shift, the conference attempts to provide the ground for presenting and discussing possibilities offered by data-driven intelligence across a range of thematic areas. These diverse themes might in turn infuence and provide the ground for reconsidering architectural knowledge and practice in the future. In parallel, the conference attempts to critically refect upon, discuss and question the future of applying data-driven intelligence in architectural knowledge and practice. What are the risks posed by the use of data-driven intelligence in architecture? In this new era, what will the role of architects be? Does this mark the beginning of a reconsideration of the way architects participate in the creation of knowledge and practice, or will it bring about their marginalisation? What will the social, economic, and environmental impact of data-driven intelligence be?

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