

[Sign In / Sign Up \(/user/login\)](#)[Submit \(https://susy.mdpi.com/user/manuscripts/upload?journal=remotesensing\)](https://susy.mdpi.com/user/manuscripts/upload?journal=remotesensing)

### Search for Articles:

### Advanced Search

[Journals \(/about/journals\)](#) / [Remote Sensing \(/journal/remotesensing\)](#) / [Special Issues \(/journal/remotesensing/special\\_issues\)](#) /

[Sensors & Methods in Cultural Heritage](#)



**remote sensing** [\(/journal/remotesensing\)](#)

IMPACT  
FACTOR  
**4.509**  
Journal

CITESCORE  
**6.1**  
SCOPUS  
Index

[Submit to Special Issue \(https://susy.mdpi.com/user/manuscripts/upload?form\[journal\\_id\]=16&form\[special\\_issue\\_id\]=30759\)](https://susy.mdpi.com/user/manuscripts/upload?form[journal_id]=16&form[special_issue_id]=30759)

[Review for Remote Sensing \(https://susy.mdpi.com/volunteer/journals/review\)](https://susy.mdpi.com/volunteer/journals/review)

[Edit a Special Issue \(/journalproposal/sendproposalspecialissue/remotesensing\)](#)

## Journal Menu

### ► Journal Menu

- [Remote Sensing Home \(/journal/remotesensing\)](#)
- [Aims & Scope \(/journal/remotesensing/about\)](#)
- [Editorial Board \(/journal/remotesensing/editors\)](#)
- [Reviewer Board \(/journal/remotesensing/submission\\_reviewers\)](#)
- [Topics Board \(/journal/remotesensing/topic\\_editors\)](#)
- [Instructions for Authors \(/journal/remotesensing/instructions\)](#)
- [Special Issues \(/journal/remotesensing/special\\_issues\)](#)
- [Sections & Collections \(/journal/remotesensing/sections\)](#)
- [Article Processing Charge \(/journal/remotesensing/apc\)](#)
- [Indexing & Archiving \(/journal/remotesensing/indexing\)](#)
- [Editor's Choice Articles \(/journal/remotesensing/editors\\_choice\)](#)
- [Most Cited & Viewed \(/journal/remotesensing/most\\_cited\)](#)
- [Journal Statistics \(/journal/remotesensing/stats\)](#)
- [Journal History \(/journal/remotesensing/history\)](#)
- [Journal Awards \(/journal/remotesensing/awards\)](#)
- [Society Collaborations \(/journal/remotesensing/societies\)](#)
- [Editorial Office \(/journal/remotesensing/editorial\\_office\)](#)

## Journal Browser

### ► Journal Browser

2017 BEST GUEST EDITOR



[\\_ \(https://serve.mdpi.com/www/my\\_files/cliik.php?oaparams=0&bannerid=2073&zoneid=4cb=d6fc61451&boadest=htt](https://serve.mdpi.com/www/my_files/cliik.php?oaparams=0&bannerid=2073&zoneid=4cb=d6fc61451&boadest=htt)

# Special Issue "Sensors & Methods in Cultural Heritage"

- [Special Issue Editors](#)
- [Special Issue Information](#)
- [Keywords](#)
- [Published Papers](#)



A special issue of *Remote Sensing* (/journal/remotesensing) (ISSN 2072-4292). This special issue belongs to the section "[Engineering Remote Sensing](#) (/journal/remotesensing/sections/engineering\_remote\_sensing)".

Deadline for manuscript submissions: **31 December 2020**.

## Share This Special Issue



(mailto:?)

[\\_ \(mailto:?\)](mailto:?&subject=From%20MDPI%3A%20%22Sensors%20%26%20Methods%20in%20Cultural%20Heritage)



(https://twitter.com/intent/tweet?

[\\_ \(https://twitter.com/intent/tweet?](https://twitter.com/intent/tweet?text=Sensors+%26+Methods+in+Cultural+Heritage&hashtags=mdpiremotesensing&url=https%3A%2F%2Fwww.mdpi.com%2Fsi%2F30759&via=MDPI)



( http://www.linkedin.com/shareArticle?

[\\_ \( http://www.linkedin.com/shareArticle?](http://www.linkedin.com/shareArticle?mini=true&url=https%3A%2F%2Fwww.mdpi.com%2Fsi%2F30759&title=Sensors%20%26%20Methods%20in%20Cultural%20Heritage%26source%3Djournal)



(https://www.facebook.com/sharer.php?u=https://www.mdpi.com/si/30759)

## Special Issue Editors



**Dr. Pablo Rodríguez-González**

[Website \(https://sciprofiles.com/profile/63978\)](https://sciprofiles.com/profile/63978) [SciProfiles \(https://sciprofiles.com/profile/63978\)](https://sciprofiles.com/profile/63978)

*Guest Editor*

Department of Mining Technology, Topography and Structures, University of León, Avda. Astorga, s/n, 24401 Ponferrada, Spain

**Interests:** photogrammetry; drones; laser scanning; radiometric calibration; remote sensing; RGB-D sensors; 3D modeling; mobile mapping

**Special Issues and Collections in MDPI journals**

**Dr. Isabella Toschi**

[Website \(http://3dom.fbk.eu/\)](http://3dom.fbk.eu/)

*Guest Editor*

Bruno Kessler Foundation, Via Santa Croce, 77, 38122 Trento, Italy

**Interests:** Photogrammetry; Laser scanning; Airborne mapping; 3D modelling; Calibration; Mobile mapping systems

**Special Issues and Collections in MDPI journals**



Prof. Dr. Diego González-Aguilera

**Website** (<https://ieeexplore.ieee.org/author/38277213200>)

Guest Editor

Cartographic and Land Engineering Department, Higher Polytechnic School of Avila, University of Salamanca, Hornos Caleros, 50 05003 Avila, Spain

**Interests:** photogrammetry; laser scanning; 3D modeling; topography; cartography

**Special Issues and Collections in MDPI journals**

(/toggle Desktop layout cookie)



Dr. Fabio Remondino

**Website** (<http://3dom.fbk.eu/people/profile/remondino>) **SciProfiles** (<https://sciprofiles.com/profile/7187>)

Guest Editor

3D Optical Metrology, FBK, Via Sommarive, 18 – POVO, TRENTO, 38123, Italy

**Interests:** photogrammetry; data fusion; SLAM; 3D mapping

**Special Issues and Collections in MDPI journals**

## Special Issue Information

Dear Colleagues,

Advance in the knowledge of the tangible components (position, size, shape) and intangible components (identity, habits) of an historic building or site is a fundamental and complex task in any project related to the conservation of cultural heritage (CH). In recent years new Geomatic techniques have proven their usefulness and added value in the field of Cultural Heritage (CH) in the tasks of recording, modelling, conserving and visualizing. In addition, current developments in building information modelling (HBIM), allow to integrate and simulate different sources of information generating a digital twin of any complex CH construction. As a result, experts in the area have increased the number of available sensors and methodologies. However, the quick evolution of geospatial technologies makes necessary to revise their use, integration and application in CH. This process is difficult to adopt due to the new options which are opened for the study, analysis, management and valorization of CH. Therefore, the aim of the present Special Issue is to cover the last and relevant topics, trends and best practices in geospatial technologies and processing methodologies for CH sites and scenarios, and also to introduce the new tendencies.

This special issue originates from the CIPA Symposium "CIPA 2019—*Documenting the past for a better future*", which is held in September 2019 in Avila, Spain. One of the main symposium's scope was to bring together scientists, developers and advanced users who apply **sensors and methods in CH**. The symposium focused primarily on multi-source and multi-sensor approaches; low-cost sensors and open-source algorithms for 3D modelling; automation in data alignment; image matching and 3D reconstruction; point cloud analysis; 4D modelling; Heritage Building Information Modelling (HBIM); accuracy requirement and assessment in CH; Underwater heritage documentation; Virtual, Augmented and Mixed Reality (VR/AR/MR) applied to the visualization and conservation of CH. The most exciting and innovative papers presented at the symposium will be selected to be extended and included in this cornerstone Special Issue. It is hoped that this special issue provides the advice and guidelines required for any CH professional making the best possible use of this sensors and methods in CH.

We would like to invite you to contribute by submitting articles about your recent research, experimental work, reviews and/or case studies related to the field of 3D recording, modelling, conserving and visualizing of CH. Contributions may be from, but not limited to, the following topics:

- 3D documentation in CH (photogrammetry, laser scanning, UAVs, mobile/handheld recording, 3D modelling, best practices, guidelines)
- Underwater heritage documentation
- Data and sensor fusion in CH (integration, registration, algorithms)
- Point cloud processing in CH (filtering, segmentation, classification, modelling)
- Semantic classification of point clouds in CH.
- Heritage Building Information Modelling (HBIM)
- Accuracy assessment in CH
- Virtual, Augmented and Mixed Reality (VR/AR/MR) in CH

Dr. Pablo Rodríguez-González

Dr. Isabella Toschi

Dr. Diego González-Aguilera

Prof Dr. Fabio Remondino

Guest Editors

### Manuscript Submission Information

Manuscripts should be submitted online at [www.mdpi.com](http://www.mdpi.com) (<https://www.mdpi.com/>) by **registering** (<https://www.mdpi.com/user/register/>) and **logging in to this website** (<https://www.mdpi.com/user/login/>). Once you are registered, **click here to go to the submission form** (<https://susy.mdpi.com/user/manuscripts/upload/?journal=remotesensing>). Manuscripts can be submitted until the deadline. All papers will be peer-

reviewed. Accepted papers will be published continuously in the journal (as soon as accepted) and will be listed together on the special issue website. Research articles, review articles as well as short communications are invited. For planned papers, a title and short abstract (about 100 words) can be sent to the Editorial Office for announcement on this website.

Submitted manuscripts should not have been published previously, nor be under consideration for publication elsewhere (except conference proceedings papers). All manuscripts are thoroughly refereed through a single-blind peer-review process. A guide for authors and other relevant information for submission of manuscripts is available on the [Instructions for Authors \(https://www.mdpi.com/journal/remotesensing/instructions\)](https://www.mdpi.com/journal/remotesensing/instructions) page. **Remote Sensing (https://www.mdpi.com/journal/remotesensing/)** is an international peer-reviewed open access semimonthly journal published by MDPI.

Please visit the [Instructions for Authors \(https://www.mdpi.com/journal/remotesensing/instructions\)](https://www.mdpi.com/journal/remotesensing/instructions) page before submitting a manuscript. The **Article Processing Charge (APC) (https://www.mdpi.com/about/apc/)** for publication in this **open access (https://www.mdpi.com/about/openaccess/)** journal is 2200 CHF (Swiss Francs). Submitted papers should be well formatted and use good English. Authors may use MDPI's [English editing service \(https://www.mdpi.com/authors/english\)](https://www.mdpi.com/authors/english) prior to publication or during author revisions.

## Keywords

- Cultural Heritage
- Photogrammetry
- Range-based sensors
- Mobile sensors
- 3D modelling
- Sensor fusion and data integration
- Point cloud processing (filtering, segmentation, classification, modelling)
- HBIM
- VR/AR/MR

## Published Papers (3 papers)

[Download All Papers](#)

Order results

Content type

Result details

Normal







[Show export options](#) ▾

Research

Open Access Article

 [\(2072-4292/12/16/2644/pdf\)](#)

**Novel Pole Photogrammetric System for Low-Cost Documentation of Archaeological Sites: The Case Study of “Cueva Pintada” (2072-4292/12/16/2644)**

by  [Susana Del Pozo \(https://sciprofiles.com/profile/66534\)](https://sciprofiles.com/profile/66534),  [Pablo Rodríguez-González \(https://sciprofiles.com/profile/63978\)](https://sciprofiles.com/profile/63978),  [David Hernández-López \(https://sciprofiles.com/profile/131856\)](https://sciprofiles.com/profile/131856),  [Jorge Onrubia-Pintado \(https://sciprofiles.com/profile/author/eURiSTBTRFpiMGxuZitiZmdhUU1QbnlvOXQzRnduNjg3eTd4S0E1bkNIRT0=\)](https://sciprofiles.com/profile/author/eURiSTBTRFpiMGxuZitiZmdhUU1QbnlvOXQzRnduNjg3eTd4S0E1bkNIRT0=),  [Diego Guerrero-Sevilla \(https://sciprofiles.com/profile/1083370\)](https://sciprofiles.com/profile/1083370) and  [Diego González-Aguilera \(https://sciprofiles.com/profile/455\)](https://sciprofiles.com/profile/455)  
*Remote Sens.* **2020**, *12*(16), 2644; <https://doi.org/10.3390/rs12162644> (<https://doi.org/10.3390/rs12162644>) - 17 Aug 2020

**Abstract** Close-range photogrammetry is a powerful and widely used technique for 3D reconstruction of archaeological environments, specifically when a high-level detail is required. This paper presents an innovative low-cost system that allows high quality and detailed reconstructions of indoor complex scenarios with unfavorable lighting [...]. [Read more.](#)





(This article belongs to the Special Issue [Sensors & Methods in Cultural Heritage \(https://www.mdpi.com/journal/remotesensing/special\\_issues/sensor\\_cultural\\_heritage\)](#).)

► [Show Figures](#)






[\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-ag-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g001-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g002-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g003-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g004-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g005-550.jpg\)](#), [\(remotesensing/remotesensing-12-02644/article\\_deploy/html/images/remotesensing-12-02644-g006-550.jpg\)](#)

 [02644/article\\_deploy/html/images/remotesensing-12-02644-g007-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g008-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g009-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g010-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g011-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g012-550.jpg](#) [02644/article\\_deploy/html/images/remotesensing-12-02644-g013-550.jpg](#)

Open Access Article

  [\(\(2072-4292/12/16/2598/pdf\)\)](#)  

## **A Hierarchical Machine Learning Approach for Multi-Level and Multi-Resolution 3D Point Cloud Classification** [\(\(2072-4292/12/16/2598\)\)](#)

by  [Simone Teruggi](https://sciprofiles.com/profile/1205033) (<https://sciprofiles.com/profile/1205033>) ,  [Eleonora Grilli](https://sciprofiles.com/profile/665836) (<https://sciprofiles.com/profile/665836>) ,  [Michele Russo](https://sciprofiles.com/profile/682003) (<https://sciprofiles.com/profile/682003>) ,  [Francesco Fassi](https://sciprofiles.com/profile/222375) (<https://sciprofiles.com/profile/222375>) and  [Fabio Remondino](https://sciprofiles.com/profile/7187) (<https://sciprofiles.com/profile/7187>).

*Remote Sens.* **2020**, *12*(16), 2598; <https://doi.org/10.3390/rs12162598> (<https://doi.org/10.3390/rs12162598>) - 12 Aug 2020

**Abstract** The recent years saw an extensive use of 3D point cloud data for heritage documentation, valorisation and visualisation. Although rich in metric quality, these 3D data lack structured information such as semantics and hierarchy between parts. In this context, the introduction of point [...] **Read more.** (This article belongs to the Special Issue **Sensors & Methods in Cultural Heritage** ([/journal/remotesensing/special\\_issues/sensor\\_cultural\\_heritage](#).)


► **Show Figures**

[\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-ag-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g001-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g001a-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g001b-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g002-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g003-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g004-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g005-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g006-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g007-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g008-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g009-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g010-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g011-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g012-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g013-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g014-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g015-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g016-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g017-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g018-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g019-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g020-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g021-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g022-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g023-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g024-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g025-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g026-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g027-550.jpg\)](#) [\(/remotesensing/remotesensing-12-02598/article\\_deploy/html/images/remotesensing-12-02598-g028-550.jpg\)](#)

Open Access Article

  [\(\(2072-4292/12/16/2526/pdf\)\)](#)  

## **[A Hybrid Approach to Reassemble Ancient Decorated Block Fragments through a 3D Puzzling Engine \(2072-4292/12/16/2526\)](#)**

by  **[Roberto de Lima-Hernandez \(https://sciprofiles.com/profile/518760\)](#)** and **[Maarten Vergauwen \(https://sciprofiles.com/profile/719979\)](#)**  
*Remote Sens.* **2020**, *12*(16), 2526; **<https://doi.org/10.3390/rs12162526>** (**<https://doi.org/10.3390/rs12162526>**), - 06 Aug 2020

**Abstract** The reassembling of severely damaged tangible heritage is a primordial task for archaeologists who not only aim to further study the past but also to preserve ruined ancient monuments. As a consequence, various researchers have proposed methods to automatically solve this problem by [...]

**[Read more.](#)**

(This article belongs to the Special Issue **[Sensors & Methods in Cultural Heritage](#)** (**[/journal/remotesensing/special\\_issues/sensor\\_cultural\\_heritage](/journal/remotesensing/special_issues/sensor_cultural_heritage)**))

► **Show Figures**

**[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-ag-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-ag-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g001-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g001-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g002-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g002-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g003-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g003-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g004-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g004-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g005-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g005-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g006-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g006-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g007-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g007-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g008-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g008-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g009-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g009-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g010-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g010-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g011-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g011-550.jpg)** **[/remotesensing/remotesensing-12-02526/article\\_deploy/html/images/remotesensing-12-02526-g012-550.jpg](/remotesensing/remotesensing-12-02526/article_deploy/html/images/remotesensing-12-02526-g012-550.jpg)**

**[Show export options](#)** ▾

displaying articles 1-3

**[Remote Sens.](#)** (**</journal/remotesensing>**), EISSN 2072-4292, Published by MDPI AG **[Disclaimer](#)**

**[RSS](/rss/journal/remotesensing)** (**</rss/journal/remotesensing>**). **[Content Alert](/journal/remotesensing/toc-alert)** (**</journal/remotesensing/toc-alert>**)

Further Information

**[Article Processing Charges](#)** (**</apc>**)

**[Pay an Invoice](#)** (**</about/payment>**)

**[Open Access Policy](#)** (**</openaccess>**)

**[Contact MDPI](#)** (**</about/contact>**)

**[Jobs at MDPI](https://careers.mdpi.com)** (**<https://careers.mdpi.com>**)

Guidelines

**[For Authors](/authors)** (**</authors>**)

**[For Reviewers](/reviewers)** (**</reviewers>**)

**[For Editors](/editors)** (**</editors>**)

**[For Librarians](/librarians)** (**</librarians>**)

**[For Publishers](/publishing_services)** (**[/publishing\\_services](/publishing_services)**)

**[For Societies](/societies)** (**</societies>**)

MDPI Initiatives

**[Institutional Open Access Program](#)** (**</ioap>**)

**[Sciforum](https://sciforum.net)** (**<https://sciforum.net>**)

**[Preprints](https://www.preprints.org)** (**<https://www.preprints.org>**)

**[Scilit](https://www.scilit.net)** (**<https://www.scilit.net>**)

**[SciProfiles](https://sciprofiles.com)** (**<https://sciprofiles.com>**)

**[MDPI Books](https://www.mdpi.com/books)** (**<https://www.mdpi.com/books>**)

**[Encyclopedia](https://encyclopedia.pub)** (**<https://encyclopedia.pub>**)




**[MDPI Blog](http://blog.mdpi.com/)** (**<http://blog.mdpi.com/>**)

Follow MDPI

**[LinkedIn](https://www.linkedin.com/company/mdpi)** (**<https://www.linkedin.com/company/mdpi>**)

Facebook (<https://www.facebook.com/MDPIOpenAccessPublishing>)

MDPI  
Twitter (<https://twitter.com/MDPIOpenAccess>)

 (/toggle\_desktop\_layout\_cookie)  

Subscribe to receive issue release  
notifications and newsletters from  
MDPI journals

Select options 

Enter your email address...

Subscribe

© 1996-2020 MDPI (Basel, Switzerland) unless otherwise stated

[Disclaimer](#) [Terms and Conditions \(/about/terms-and-conditions\)](#) [Privacy Policy \(/about/privacy\)](#)

Article

# A Hierarchical Machine Learning Approach for Multi-Level and Multi-Resolution 3D Point Cloud Classification

Simone Teruggi <sup>1,\*</sup>, Eleonora Grilli <sup>2</sup>, Michele Russo <sup>3</sup>, Francesco Fassi <sup>1</sup> and Fabio Remondino <sup>2</sup>

<sup>1</sup> 3DSurveyGroup–ABCLab–Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italy; francesco.fassi@polimi.it

<sup>2</sup> 3D Optical Metrology (3DOM) unit, Bruno Kessler Foundation (FBK), Via Sommarive 18, 38121 Trento, Italy; grilli@fbk.eu (E.G.); remondino@fbk.eu (F.R.)

<sup>3</sup> Department of History, Representation and Restoration of Architecture, Sapienza University of Rome, Via del Castro Laurenziano 7/a, 00161 Rome, Italy; m.russo@uniroma1.it

\* Correspondence: simone.teruggi@polimi.it; Tel.: +39-3406696323

Received: 29 June 2020; Accepted: 10 August 2020; Published: 12 August 2020



**Abstract:** The recent years saw an extensive use of 3D point cloud data for heritage documentation, valorisation and visualisation. Although rich in metric quality, these 3D data lack structured information such as semantics and hierarchy between parts. In this context, the introduction of point cloud classification methods can play an essential role for better data usage, model definition, analysis and conservation. The paper aims to extend a machine learning (ML) classification method with a multi-level and multi-resolution (MLMR) approach. The proposed MLMR approach improves the learning process and optimises 3D classification results through a hierarchical concept. The MLMR procedure is tested and evaluated on two large-scale and complex datasets: the Pomposa Abbey (Italy) and the Milan Cathedral (Italy). Classification results show the reliability and replicability of the developed method, allowing the identification of the necessary architectural classes at each geometric resolution.

**Keywords:** machine learning; 3D architectural heritage; multi-resolution; point cloud; classification; Random Forest

## 1. Introduction

In the last 20 years, various research activities, based on active and passive sensors, provided reliable methodologies for the acquisition and generation of dense point clouds and textured 3D models of heritage structures [1,2]. These 3D data are typically used for accurate documentation, digital preservation, and visualisation [3–6]. Nowadays, the amount of available 3D datasets has exponentially increased but, at the same time, it is becoming very important to enrich point clouds with semantic information of the digitised objects [7,8]. The association of semantic meaning to geometric data, using machine or deep learning (ML/DL) methods, leads to a simplification in 3D reading, also accelerating data management and interpretation. In general, 3D point clouds are coupled with RGB colours, intensity and other information depending on the used acquisition instrument and technique. If, on one hand, this kind of data benefits from accurate metric information, on the other hand it lacks structured information such as semantics and hierarchy between parts. For this reason, the introduction of semantic meaning, employing automated classification procedures, can play an important role in the data usage and analysis, useful, e.g., for heritage understanding, restoration, valorisation, etc.



The use of classified point clouds, i.e., 3D data with a semantic meaning, has become popular in different fields of application, such as robotics [9,10], precision farming [11], autonomous driving [12,13], indoor navigation [14,15], urban planning [16,17], geospatial [18,19] and Cultural Heritage (CH) [5,20]. The heritage sector is slightly behind the other fields in term of automated and reliable procedures, due to the complexity and variability of the 3D data. Despite this, the identification of precise architectural components in point clouds can be very useful because it allows the direct use of 3D point clouds for architectural interpretation inside and conservation activities planning, avoiding the modelling phase typical of HBIM (Historic Building Information Modelling). This latter phase is a time-consuming process which can also lead to a great simplification of detailed surfaces, losing the metric reliability intrinsic present in the acquired point clouds.

### *Aim and Structure of the Paper*

This paper presents and evaluates an automatic classification method, based on a multi-level and multi-resolution (MLMR) approach combined with a machine learning (ML) algorithm. The MLMR method hierarchically classifies 3D data at different geometric resolutions to facilitate the learning process and optimise the classification results. To test the developed methodology, two large-scale and complex datasets (Section 3) are used, namely the Cathedral/Duomo of Milan (Italy) and the Abbey of Pomposa (Italy). Both heritage scenarios feature a large amount of 3D points, a great diversity of geometries and styles, a richness in decoration and a lack in the regularity of the architectural elements. By using such different and complex architectural structures, the paper intends to demonstrate the applicability of the developed methodology (Section 4) to different scenarios and replicability (resolution dependent) in the time of the methods using different series of data of the same building. The method relies on ML and not deep learning (DL), due to the complexity of the considered 3D heritage data and the lack of specific training samples suitable to classify such complex heritage scenarios.

Contrary to other methods that use sub-groups of classes (e.g., façade with/without shadows [21]) to facilitate the classification and then join them into a unique class, the proposed approach relies on geometric information and hierarchically splits the data in sub-classes while the geometric details are increasing.

## **2. State of the Art**

In the architectural heritage field, the process of structuring and classifying 3D survey data have seen various applications such as supporting the scan-to-BIM process [22–25], monitoring and restoration purposes [3,6,26], maintenance architecture planning [27,28], and damage detection and quantification [29–31].

Apart from being time consuming, in most cases, the introduction of manual intervention for subdividing the datasets brings a certain degree of subjectivity. In recent years, relevant progress has come in automatic classification processes by using Artificial Intelligence methods (ML and DL) that, in contrast, are objective and replicable.

In supervised ML, the algorithms take some manually annotated part of the datasets and hand-crafted features (i.e., geometric and/or radiometric attributes) as inputs, from which they learn patterns that are then predicted to the whole dataset. On the other hand, DL refers to those processes (neural networks—NN) that directly learn features and semantics from a large quantity of annotated data, which is generally not available in the heritage sector. To cope with this problem, the research proposed by [32] aims to facilitate the annotation process necessary to train DL algorithms. The authors, through a series of rule-based functions, isolate some specific architectural classes within the point cloud, such as columns and beams.

More specifically to the heritage field, a supervised learning approach which transfers the classification information from 2D textures to 3D models is proposed in [21]. Grilli et al. [33] presented a classification approach that works directly on point clouds, training a Random Forest (RF) classifier with geometric features. The method iteratively extracts the most relevant features considering a set of

geometric characteristics strictly related to the architectural element dimensions. The same author has then verified the possibility to generalise the classification model across different architectural scenarios in [34].

A popular DL approach relies on convolutional neural networks (CNN) that recombine sets of neurons in different layers, in order to process a set of input vectors to a known set of outputs [35,36]. PointNet [37], and its later improvement PointNet++ [38], is a unified architecture that learns both global and local point features and is suitable to perform classification, part segmentation, and semantic scene segmentation. Results are encouraging, featuring an overall accuracy of around 90%, but the selected classes and training sets are constituted of simple objects with replicated shapes (mug, plane, table, car, etc.). This latter point proved to be critical when applying CNN to CH point clouds.

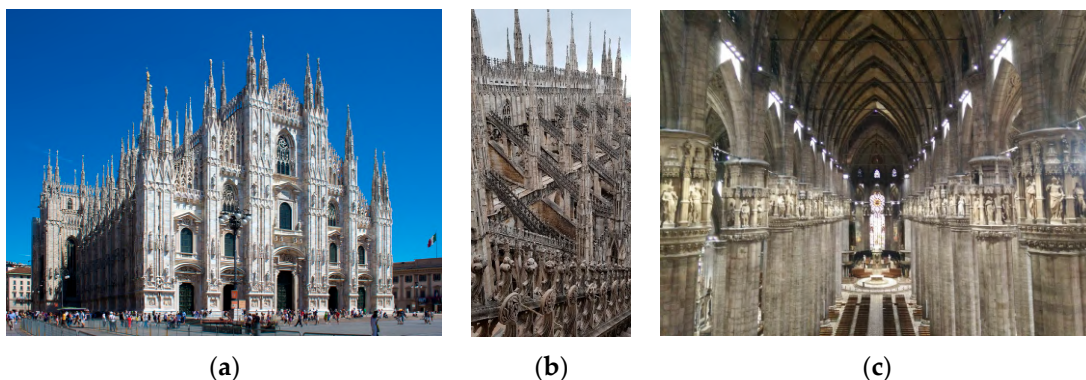
Due to the inherent complexity and uniqueness that each CH object has, it is really complicated to have a well-distributed and representative heritage training set. Nonetheless, some application exists, built for specific case studies. Malinverni et al. [5] proposed a DL approach based on PointNet++ neural network, which has been re-trained on data coming from a real survey. The dataset needs to be manually segmented by domain experts and must be broad enough to comprise enough classes for each case study, which in the CH context is quite tricky. Recently, a Dynamic Graph Convolutional Neural Network (DGCNN) supported by meaningful features (normal and HSV colours) has been employed in [39]. The DGCNN has been trained on the ArCH dataset [40], which includes 10 manually labelled point clouds subdivided into 11 classes. The resulting model has then been tested in two different ways—over a partially labelled dataset and on an unseen scene—providing promising results.

The first attempt of comparison between machine and deep learning approaches for heritage classification has been presented in [41]. The authors demonstrated that, for some specific case studies, the machine learning approaches could achieve better results in shorter times.

### 3. Case Studies

#### 3.1. Milan Cathedral

Milan Cathedral (Figure 1) is one of the most important monumental heritages in Italy. It is a late Gothic Cathedral, whose construction began in 1386 and finished in 1805, with some final details completed in 1965. It is the largest church in Italy, the third largest in Europe and the fifth in the world. The external length of the Cathedral is 158 m, the transept is 93 m long, and the maximum height of the Cathedral (from the internal floor to the head of the Madonnina) is 108.50 m. Overall it covers an area of approximately 12,000 m<sup>2</sup> and a gross volume of 440,000 m<sup>3</sup>. As with all gothic cathedrals, it is very rich in decorations, counting in total 3400 statues, 135 gargoyles and 700 figures that decorate the internal spaces as capitals, altars and windows. On the external facades, there are 135 spires and 30 decorative reverse arches that seem to support the flanks of the impressive building.

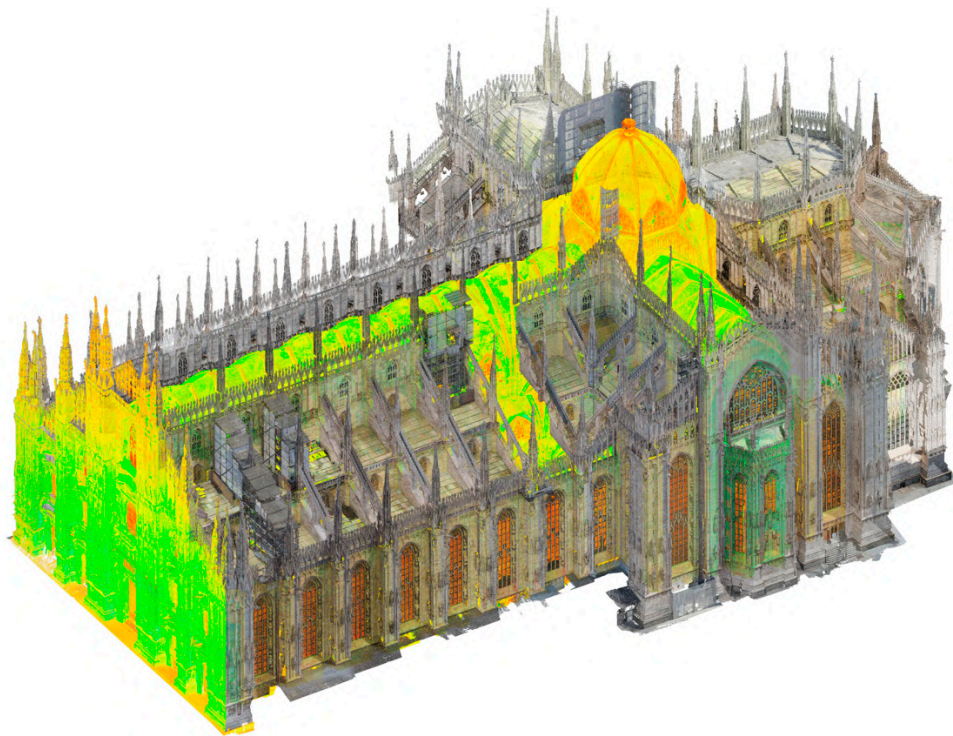


**Figure 1.** (a) Milan Cathedral main facade. (b) A detail of the complex roof with repetitive buttresses. (c) Internal view of the main nave and its capitals.

The Cathedral is built with bricks and covered with *Candoglia* marble. The highest parts, where the structures are thinner and lighter, are directly made of marble. Marble is the most critical aspect that affects the lifetime of the Cathedral and its preservation state as it degrades very quickly due to the mineralogical composition. Therefore, many parts of the Cathedral, especially the external ones, must be replaced periodically, which implies continuous and non-stop maintenance work. The institution responsible for these activities is the *Veneranda Fabbrica del Duomo di Milano* that for more than 630 years has been in charge of the ordinary maintenance of the structures, including cleaning, vegetation removal, and scheduled inspections in order to guarantee the safety of the hanging structures.

### 3.1.1. 3D Survey

To support the exceptional maintenance activities, a number of focussed survey operations were conducted in the last 10 years, producing 3D data and 2D classical representation at a 1:50 scale for the Main Spire, the altars of the transept, and the Dome Cladding [42]. More recently, detailed point clouds of the entire Cathedral at an average and uniform resolution of 5 mm (Figure 2 and Table 1) were produced using Terrestrial Laser Scanning (TLS) for the interior spaces [43], photogrammetry for the exteriors [44] and integrating both techniques in narrow service spaces [45,46].



**Figure 2.** The entire 3D point cloud of the Milan Cathedral (more than 3 billion points). TLS data are shown with their intensity colours (green, yellow, orange) whereas photogrammetric point clouds have RGB colour information.

**Table 1.** Summary of 3D survey data acquisition and process for the Milan Cathedral.

Architectural Elements	Method	# Acquisitions	# 3D Points	Mean Resol. (mm)	Subsampling (cm)
External Areas	Photogrammetry, Leica RTC360	16,080 photos, 54 scans	1.5 billion	5	2–5
Internal Spaces	Leica HDS 7000, Leica C10	238 scans	2.1 billion	5	2–5



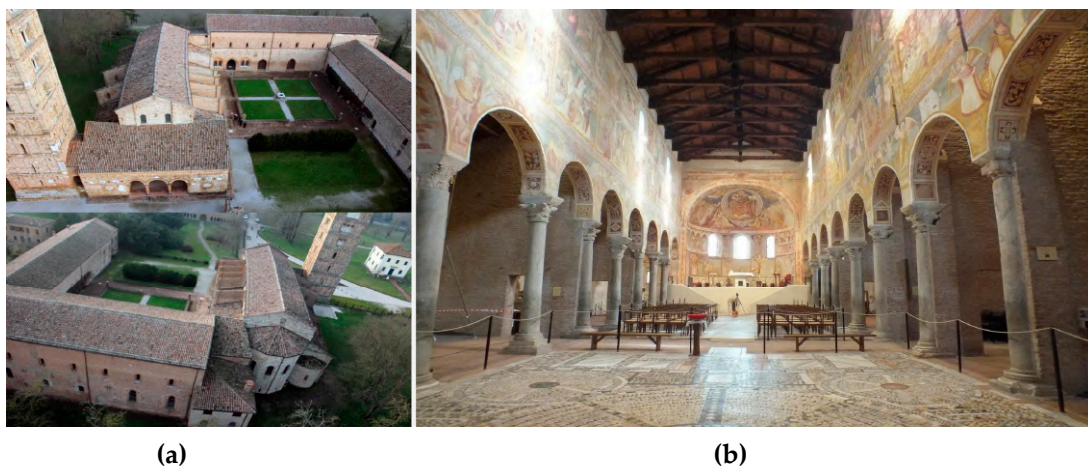
### 3.1.2. Classification Needs

Given the necessary continuous maintenance works and the large amount of data to be handled, the semantic classification of the Milan Cathedral's point cloud can become a digital support for conservation activities. In particular, the following activities can be foreseen:

- Derivation of measurements and 2D representations from anywhere in the Cathedral.
- Identification, counting and visualisation of single architectural elements.
- A better interpretation of the architectural structures at point cloud level, avoiding long and tedious modelling processes.
- Keeping track of every restoration activity, treating the point cloud as a complete 3D navigable information system where it is possible to reference information, data, and a catalogue of archive documents.
- Generation of a BIM-like web-based information system platform, usable in the field within a mixed-reality system.

### 3.2. Pomposa Abbey

The IX century Benedictine monastery of Santa Maria di Pomposa is situated in the province of Ferrara and represents one of the most important Abbeys of Northern Italy. The main building of the complex is the Basilica, consecrated in 1026 AD, that presents a layout that recalls the typical Ravenna style, in which the inner space is subdivided into three naves through continuous colonnades, bounded with relative pulvini (Figure 3). The central nave ends with a hemispherical apse that corresponds to an outer pentagonal shape. The actual framework is the result of different significant transformations occurred through the centuries, and that have basically changed the original Roman aspect [47,48]. Several survey campaigns have been conducted in the past [49,50] in order to analyse and monitor the structural behaviour, preserving the Abbey from possible damages. These inspections verified that the massive bell tower caused distortions of the church. In order to reduce this structural problem, a sequence of walls was added in the side aisles [51,52]. The actual church frame represents a non-regular case study from the geometric point of view, including columns inserted in transverse masonries, irregular structural walls and roof elements, and roto-translation of single beams.



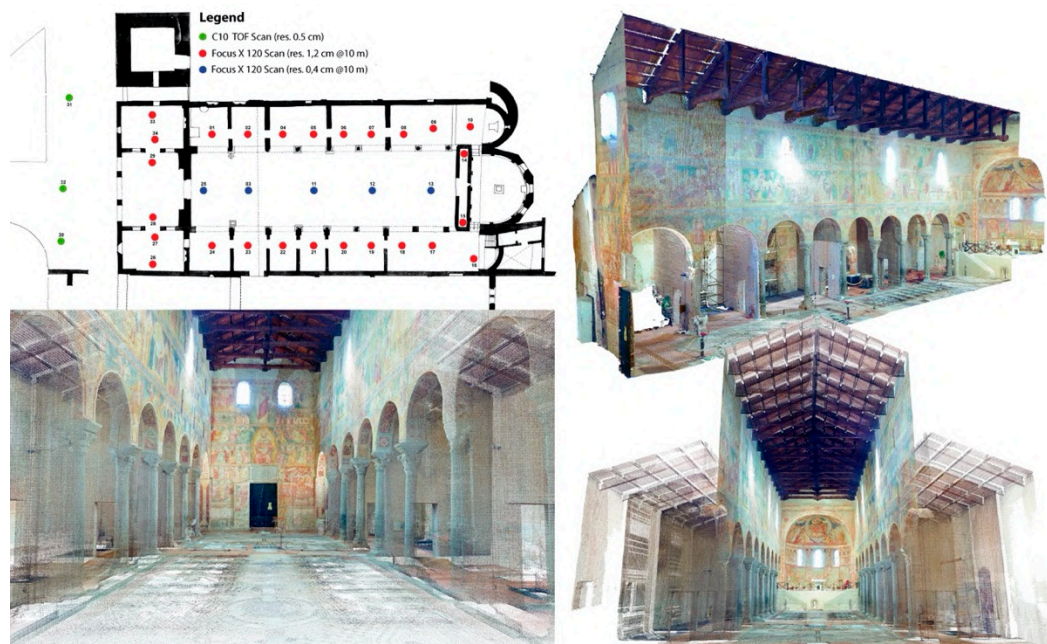
**Figure 3.** Two views of the Abbey complex (a) as seen from a drone/UAS platform. (b) Main nave of the church.

#### 3.2.1. 3D Survey

A 3D survey campaign of the Abbey was conducted to acquire the global structure of the church and its annexed buildings. The survey project was an opportunity to test different approaches and

technologies, aiming at finding the best solution for the high-resolution documentation of a big architectonic complex [53]. The survey campaign included both image- and range-based techniques.

The photogrammetric technique was devoted to roofs data acquisition with a UAS platform, while laser scanning was used for the internal and external architectural elements. The exterior was digitized with a pulsed TOF Leica C10 from 21 stations, selecting a 0.5-cm sampling step for the main façade and a 2-cm sampling step for the other parts. On the other hand, the interior spaces were digitized using a phase-shift TOF Faro Focus X 120 placed in 31 different positions (Figure 4 and Table 2). The final point cloud was obtained with an ICP alignment of internal and external clouds, subsampled at 2 and 5 cm in order to optimise data management.



**Figure 4.** Survey schema of the indoor acquisition campaign and three visualisations of the interior coloured point cloud of the Abbey.

**Table 2.** Summary of 3D survey data acquisition and process for the interior of the Pomposa Abbey.

Architectural Elements	Instruments	# Acquisitions	# 3D Points	Mean Resol. (mm)	Subsampling (cm)
External Areas	Leica C10	21	161 mil.	5, 20	2, 5
Internal Spaces	Faro Focus X 120	31	580 mil.	10	2, 5

### 3.2.2. Classification Needs

The point cloud classification has considered only the interior datasets of the church (Table 2), which presents several interesting architectural features and a more complex geometric framework compared with the exterior part. The enrichment of the point cloud with semantic information can be useful in particular for the following:

- Derivation of measurements and 2D representations.
- Monitoring the building behaviour over time, by verifying masonries, columns and roof roto-translations: a comparison of 3D point clouds acquired over time can be considered a valuable solution to exactly and completely describe the whole fabric.
- Geometric quality check of the individual elements belonging to the same class, highlighting possible alterations in the structural composition of the building.

- Quantification of the building from a material and functional point of view, a crucial step for both a conservative intervention and damage evaluation (e.g., after a destructive event).

#### 4. Developed Methodology

The complexity and uniqueness of the chosen dataset highlighted some limits in applying a DL approach for these specific studies. Indeed, the richness in elements and their variety, even among the same classes (i.e., all the capitals of the Milan Cathedral are unique and different from each other) pointed out the difficulty in collecting a representative annotated dataset which was large enough to train a neural network. Moreover, even considering the possibility to find representative datasets [41], the time necessary to manually annotate them would exceed the time required to classify the case studies entirely.

Starting from these considerations, the developed classification method uses a Random Forest (RF) classifier [54], following the successful supervised approach based on geometric features introduced in [34] and the study on features importance in Random Forest [20,33]. Compared to DL approaches, RF methods do not need a significant amount of manually annotated datasets to be effective. On the other hand, it becomes fundamental to select features able to highlight the discontinuities between the different architectural elements.

The high-density, high-resolution point clouds considered in this paper allow for a precise geometrical description of the CH object. However, if these the 3D representations allow the richness of construction details (i.e., decoration, small statues, beams, etc.) to be appreciated, on the other hand huge point clouds of large and complex structures have two main problems:

- The size of the dataset and the number of geometrical features to be extracted makes the computational process challenging. If the latter can be solved choosing only essential features, a subsampling of the acquired point cloud could help to handle the high number of points, but it would lower the details visible in the dataset.
- The large number of semantic classes to be identified might induce misclassification issues: initial experiments have shown that with a higher number of classes a lower accuracy of the classification is achieved (Sections 7.1.1 and 7.2.1).

Considering these problems, it becomes difficult to classify very large datasets in one single step, as traditional classification approaches do. Therefore, a multi-level and multi-resolution (MLMR) approach is proposed (Figure 5), which follows these steps:

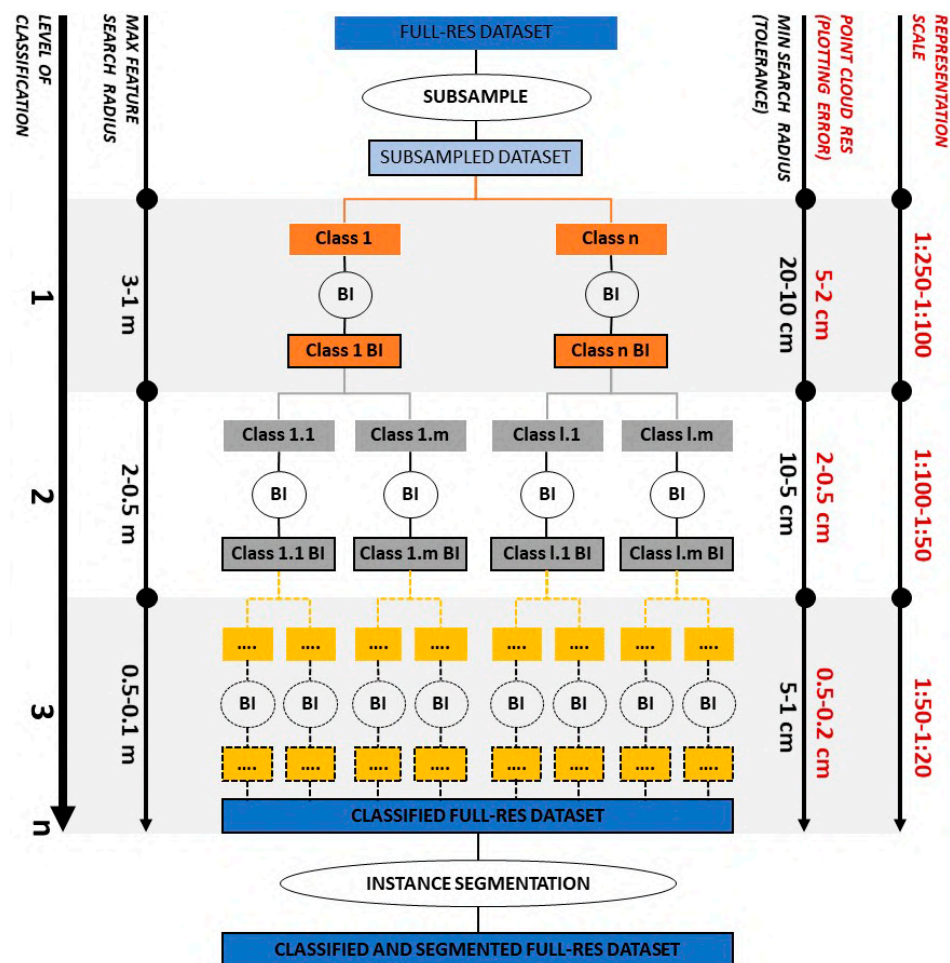
1. The full-resolution point cloud is subsampled in various geometric levels.
2. Given certain manually annotated areas corresponding to the classes of interest of the first geometric level, a RF model is trained and then all classes are predicted on the entire point cloud.
3. Classification results coming from this first step are back interpolated (BI) on a higher resolution version of the dataset, using a nearest neighbourhood algorithm. To do so, the class value assigned to each point is transferred to a certain number of elements evaluated inside a specific cluster; the number of nearest neighbourhoods to be evaluated depends on the point cloud resolution. The higher the resolution, the higher the number of points in the neighbourhood.
4. The next geometric level is considered with its new classes (e.g., columns are divided in base, shaft and capitals) and a new classification procedure is applied.
5. Classification results are again back interpolated on a higher resolution version of the point cloud until the full geometric resolution is reached.

It should be mentioned that each architectural element can be classified in more and more details, according to the employed point cloud resolution at the corresponding level, and then back interpolated on a higher resolution version. The process is iterative, and the last classification level will correspond to the full-resolution point cloud. Moreover, the subsampling of the point cloud will depend on both



the complexity of the object to be classified and the elements to be recognised. Macro-categories of objects allow for a lower resolution, while the higher resolution is used for details.

The proposed hierarchical methodology is graphically summarised in Figure 5. The diagram aims also to provide for a general indication in terms of geometric resolution of the point cloud and geometric feature ready to be used at each classification step. These values, and the methodology itself, can be considered sufficiently generalisable to be used for the classification of architectural elements in the monumental field. The parameters (resolution and feature radii) can vary case by case according to the characteristics and dimensions of the objects. However, it can be seen that they correspond to the smallest detail that can be represented at a given representation scale and its metric tolerance, in a logic of representation at an increasing level of detail.



**Figure 5.** Multi-level and multi-resolution (MLMR) workflow. The diagram provides also general indications in terms of point cloud resolution and minimum/maximum search radius of the geometric features, which have to be chosen at each step of the classification process. BI stands for Back Interpolation, i.e., classification results at a certain level are back interpolated to a higher resolution level of the point cloud until the full geometric resolution is reached.

As a final and additional step, after the full classification of the point cloud, it is possible to apply the so-called instance segmentation to each architectural class. In this way, for example, each column of the dataset can have its own index. To do so, the label connected component function available in CloudCompare [55] was used. Still, instead of working on pixels arranged in a grid, the octree structure of the point cloud from which it defines the grid step is used to perform the search in the 3D

space. The tool separates the cloud into smaller ones based on a minimum distance between elements and a minimum number of points that a component must have.

## 5. Semantic Classes and Classification Levels

### 5.1. Milan Cathedral

Following the *Veneranda Fabbrica* conservation and restoration rules as well as the hierarchical subdivision of the monument in areas, zones, sectors, architectural elements and marble blocks reported in [56], we consider an automatic classification of the cathedral into three different levels (Figure 6).

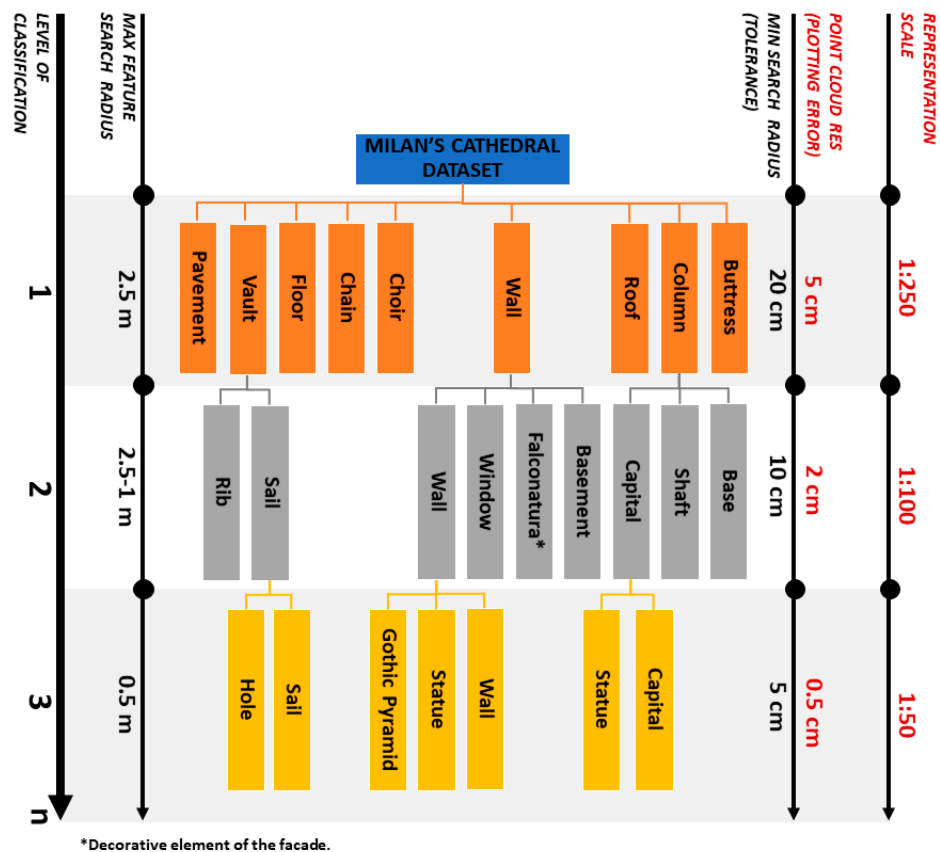


Figure 6. Classification levels and classes for the Milan Cathedral.

The first level of classification has the function to identify macro-architectonic elements. The classification process is performed on the point cloud at a 5-cm resolution, extracting geometric features with radii between 20 cm and 2.5 m.

In the second level of classification, the previously identified architectural elements are divided into sub-components (e.g., columns are split in its bases, capitals and shafts). This step is performed using a 2-cm resolution point cloud, reducing to 10 cm and 1 m the min/max feature search radii.

Finally, the third and most challenging level of classification aims at the subdivision of each component in its ashlar (i.e., monolith elements as statues, gothic decoration, holes, etc.). For this, the full resolution point cloud is used with a min and max search radius of 0.5 and 5 cm, respectively.

### 5.2. Pomposa Abbey

Considering monitoring needs, the classification has been subdivided into three different levels (Figure 7).



The first level refers to the main structural framework of the church, defining a global functional subdivision of the entire dataset: floor, façades, columns, arches, and roof. In order to recognise these macro-categories, the point cloud has been processed at a 5-cm resolution.

The second level is devoted to a more in-depth classification process, recognising multiple sub-classes within the categories coming from the first level of classification. Façades are divided into walls and windows, columns into bases, shafts and capitals, and roof are broken down into dome, side, central and front cover. At this level, each architectural element was recognised at the 2-cm resolution point cloud.

The third level refers to the roof which presents complex and variable structures. A diverse classification process was run for each different roof structure, highlighting its main structural elements (e.g., rafters, purlins, panels, tie beams, wall plates, crown posts, etc.). To finalise this structural study, the suitable resolution of the point cloud was 2 cm.

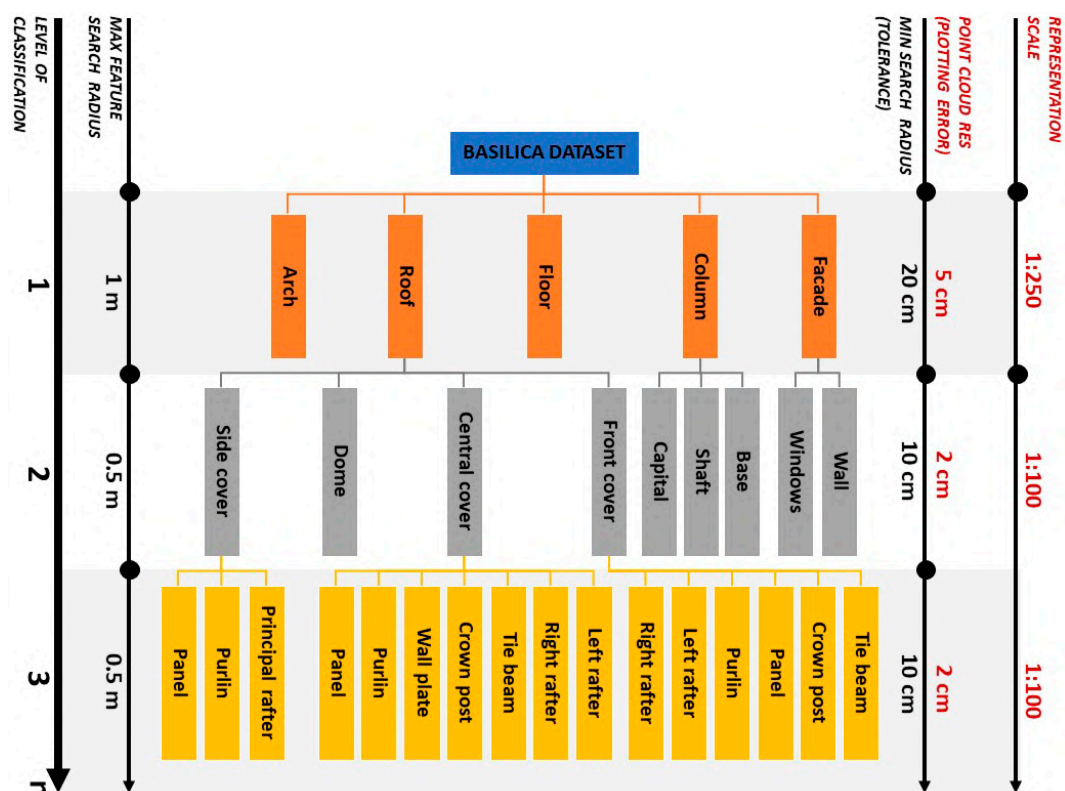


Figure 7. Classification levels and classes for the Pomposa Abbey.

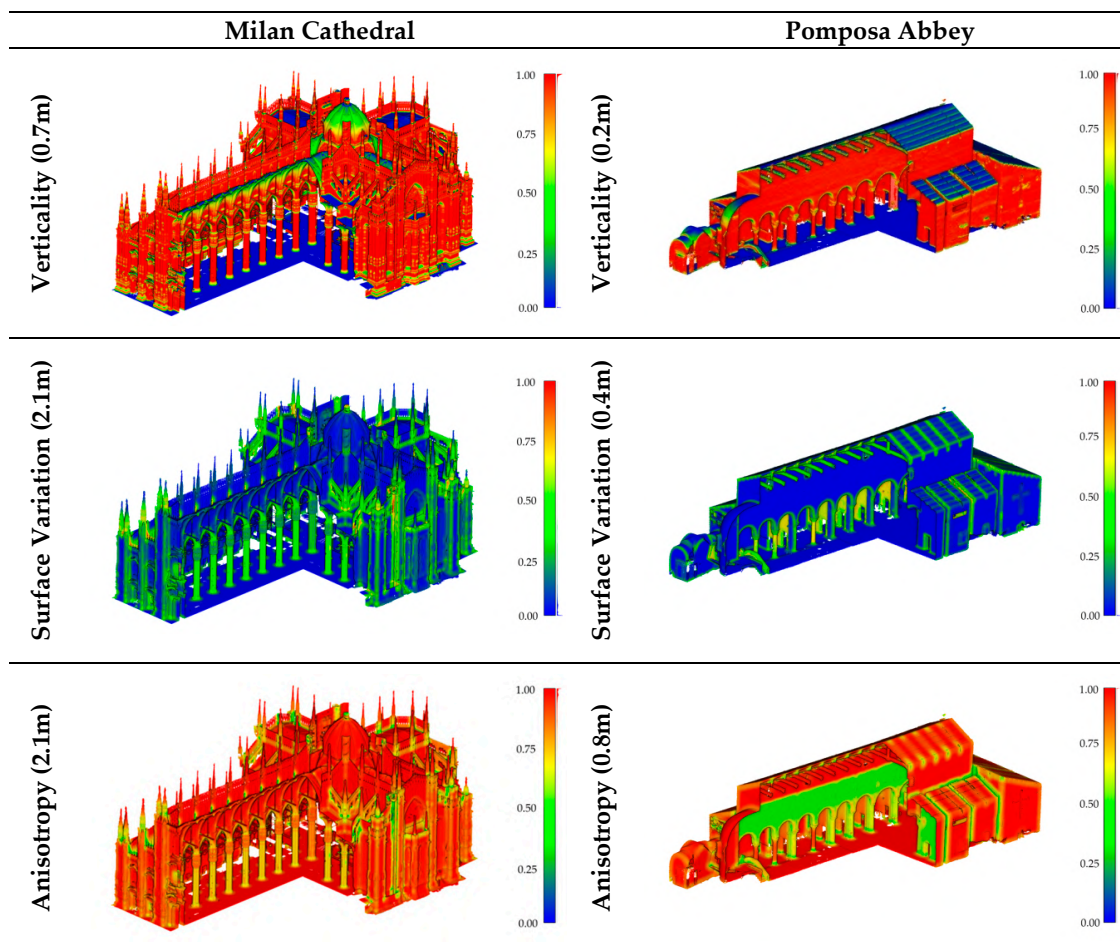
## 6. Data Processing

### 6.1. Geometric Features Extraction

The necessary features for the classification are based on the covariance matrix [57] computed within a local neighbourhood of a 3D point. For both case studies, the considered local neighbourhoods are directly related to the dimension of the architectural elements. Moreover, as various features affect the classification results in different ways, the geometric features with the smallest impact on the training process have been iteratively removed [33]. The experiments showed that, independently from the object to be classified and the point cloud resolution, the features with a more significant impact on the classification results are (Figure 8):

- Anisotropy: allows the recognition of 3D elements such as columns, buttresses and spires over 2.5D elements such as walls and vaults.

- Planarity: highlight linear and planar items such as chains and floors and their vertical counterparts such as column shaft and walls.
- Linearity: similarly to planarity, it helps in identifying linear structures.
- Surface variation: it emphasises changes in the shapes allowing, for example, to detect corners or edges.
- Sphericity: similarly to surface variation, it helps in identifying spherical and cylindrical elements, such as columns.
- Verticality: it points out vertical and horizontal surfaces allowing the recognition of walls and floors as well as column shafts.



**Figure 8.** Visual comparison of geometric features. The colour of the plot represents the feature scale. The used search radii are reported in brackets.

Among these covariance features, planarity and linearity, and surface variation and sphericity behave pairwise similarly. However, all of them have been used at the same time to improve the performance of the RF classifier. In fact, as the algorithm splits all the available information among its decision trees, redundancy in geometric features allows us to have the correct relations in every tree, allowing for a better classification.

## 6.2. Training and Classification

Beside extracting geometric features, some portion of each dataset—at each classification level—has been manually annotated in order to train the RF algorithm. Figures 9 and 10 show the training sets used at the first level of classification (5-cm resolution) of Milan Cathedral and Pomposa Abbey,

respectively. For the first case study (30 mil. points), the training sample is composed of ca 2.5 mil. annotated points for the exterior surfaces and ca 2.6 mil. points for the interior spaces. For the Pomposa Abbey, some 115,444 points are used for the training set out of ca 1.1 mil. points composing the whole cloud.

Table 3 reports numbers of used points in the training and classification times for all three classification levels. Figure 11 indicates the percentage of time spent in each working phase. It is important to say that the computation time for the extraction of the geometric features varies in relation to the dimension of the point cloud, the number of features and their search radius. Even if the processing time increases with the dimension of a given training sample, it can still be considered negligible if compared to DL approaches. Regarding the first level of classification, on an 18-core processor workstation, the training phase for the Milan Cathedral took about 5 min (2.5 mil. points), while 43 s were necessary to classify the remaining exterior point cloud (12 mil. points). With regards to the Pomposa Abbey, the training and classification processes took 5 and 3 s, respectively.

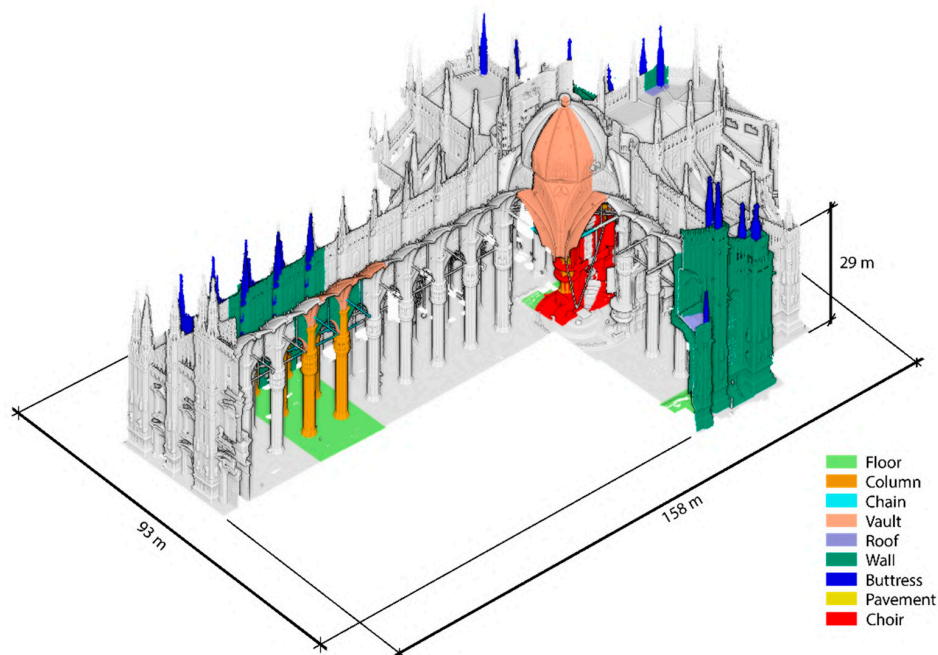


Figure 9. Annotated portions at classification level 1 for the Milan Cathedral.

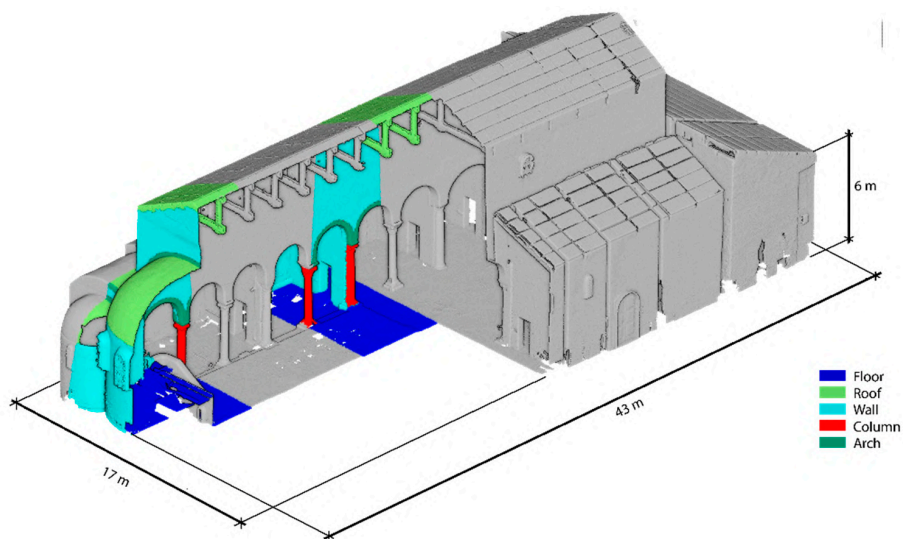
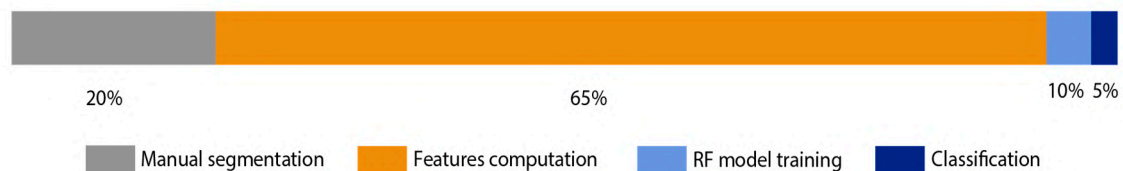


Figure 10. Annotated portions at classification level 1 for the Pomposa Abbey.

**Table 3.** Examples of training and classification times in relation to the number of used points in some areas of the two case studies.

	Level 1		Level 2		Level 3	
	Milan Cathedral (Exteriors)	Pomposa Abbey	Milan Cathedral (Pillars)	Pomposa Abbey (Columns)	Milan Cathedral (Capitals)	Pomposa Abbey (Central Roof)
# of Training Points	2,580,368	115,444	1,011,994	21,389	3,309,947	62,258
Training Time (Sec)	363	5	17	0.65	142	4.25
# of Classified Points	12,680,681	1,102,569	14,645,986	47,006	47,651,835	832,549
Classification Time (Sec)	43.5	2.7	12.62	0.15	174.89	29.8

**Figure 11.** Comparison of normalized time necessary for the different phases of the classification process, from manual annotation to final classification of the dataset.

## 7. Results and Discussion

Considering the reduced dimension of the manually annotated portions used to train the classifier, the achieved results in both case studies were successful (Table 4 and Table 7). The metrics used to evaluate these results are Precision, Recall and F1-score. They were computed by comparing, for each dataset, a manually annotated portion with the same portion automatically predicted.

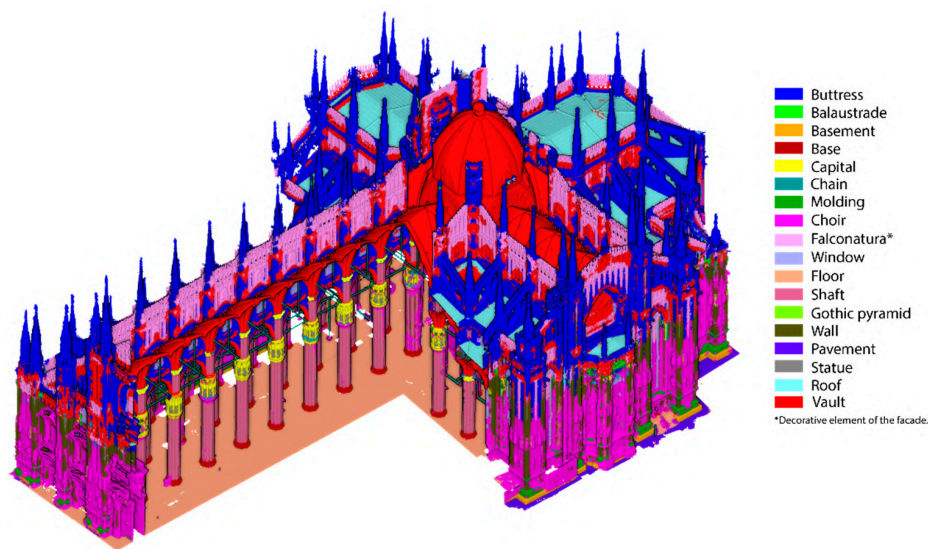
In the next sections, the achieved results will be discussed, focussing on advantages and criticalities related to the semantic segmentation of such complex architectures. Sections 7.1.1 and 7.2.1 will show the classification results achieved with a traditional classification approach (non-hierarchical, but in one step with all semantic classes) in comparison to the proposed MLMR method.

### 7.1. Milan Cathedral

#### 7.1.1. One-Step Classification

The Cathedral dataset was classified in one step using a Random Forest method and all 18 semantic classes (see Figures 13 and 14). To perform a one-step (non-hierarchical) classification, due to the huge dimension of the dataset (more than 3 bil. points), the data were subsampled at a 5-cm resolution, unavoidably lowering its details. The training dataset contained all 18 classes and the classification result got an average F1-score of 67%. Results (Figure 12) show that with this approach it is difficult to distinguish elements with similar geometry but belonging to different classes (e.g., ornaments on the capitals of the main nave and ornaments on the choir area). Furthermore, many detailed elements present discontinuities that are equal or smaller than 5 cm, making their recognition complicated.





**Figure 12.** Milan’s Cathedral non-hierarchical classification results with 18 classes (average F1-score: 67%).

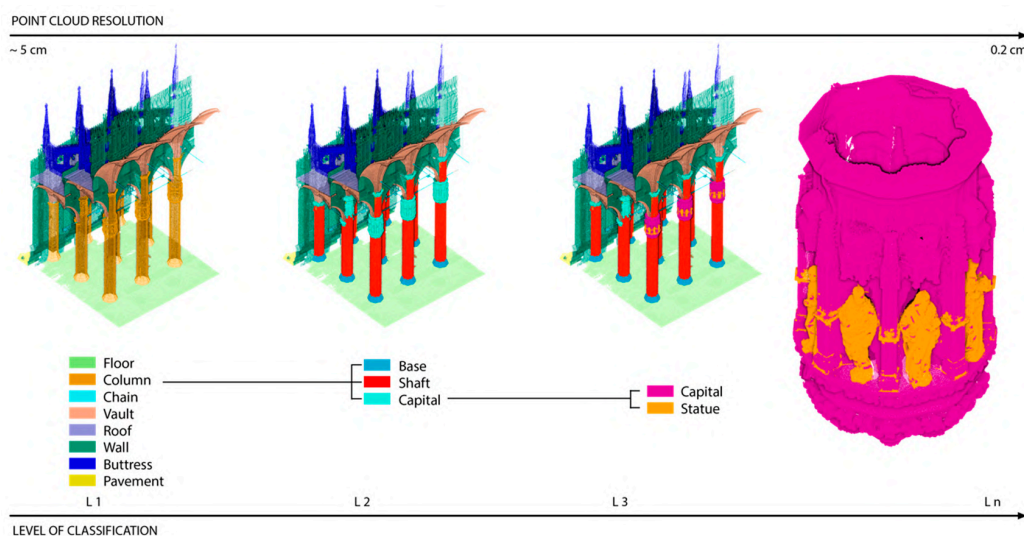
**Table 4.** Milan Cathedral: the F1-scores average values for all three classification levels (in brackets the geometric resolutions of the point clouds). Please consider that each level has a different number of classes.

	Level 1 (5 cm)	Level 2 (2 cm)	Level 3 (0.5 cm)
F1 (%)	93.75	99.35	91.80

Therefore, dividing the classification into different geometric levels facilitates the distinction of similar elements as well as allows to process only specific parts of the dataset at the full 5-mm resolution.

### 7.1.2. MLMR Classification

Figures 13 and 14 show some examples of the subsequent levels of classification, relative to both Cathedral interiors and exteriors. Table 4 shows an average of the F1-score values, computed at each classification level. The classification results, applied to the whole dataset, are shown in Figure 15.



**Figure 13.** MLMR classification levels (till capital details) for the Milan Cathedral.

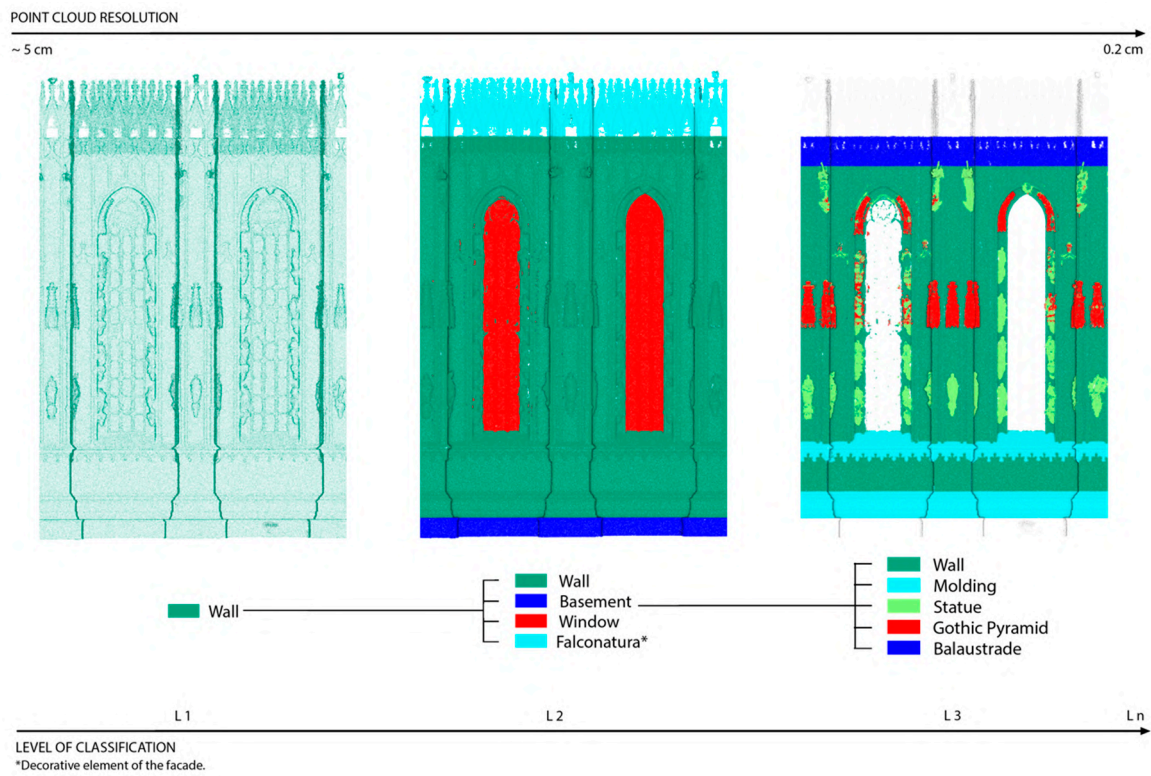


Figure 14. MLMR classification levels for the external walls of the Milan Cathedral.

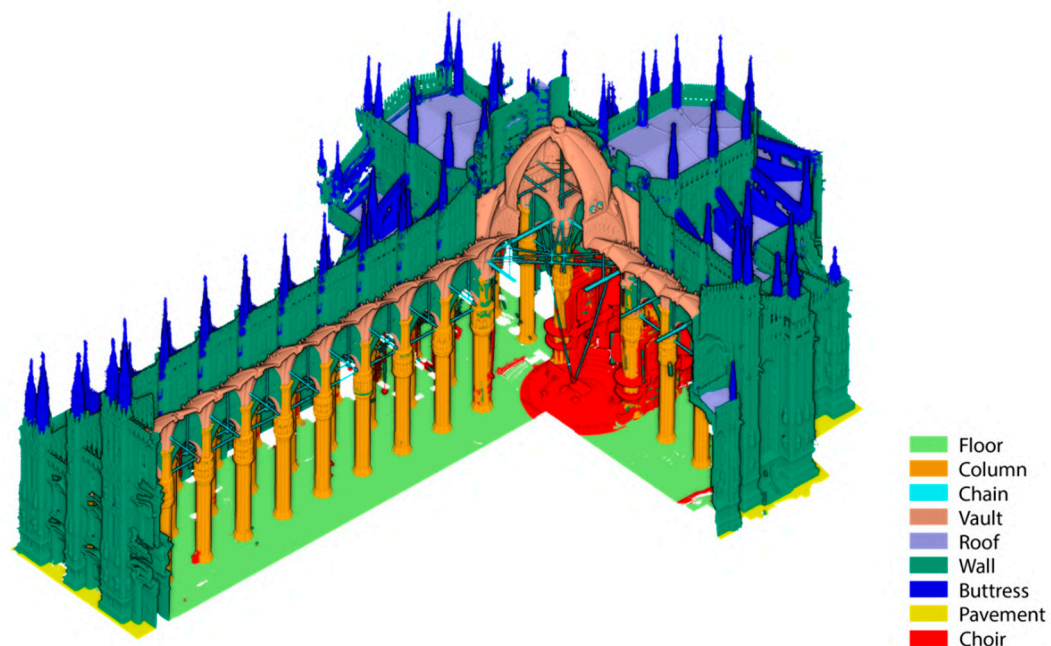


Figure 15. Classification results (nine classes) at level 1 for the entire Milan Cathedral.

At the first level of classification, it was possible to identify the main elements of the construction visible in a 5-cm resolution point cloud (i.e., for the interior: floors, columns, chains, vaults, walls, and choir; for the exterior: walls, buttresses, roofs, and street). The use of a low-resolution point cloud allowed us to process the whole dataset at once. This kind of operation would have been critical from the hardware and computation point of view if using the full resolution point clouds. In Tables 5 and 6,

it is possible to observe the classification metrics achieved per class in the first level of classification (level 1).

**Table 5.** Classification metrics at level 1 for the interiors of Milan Cathedral.

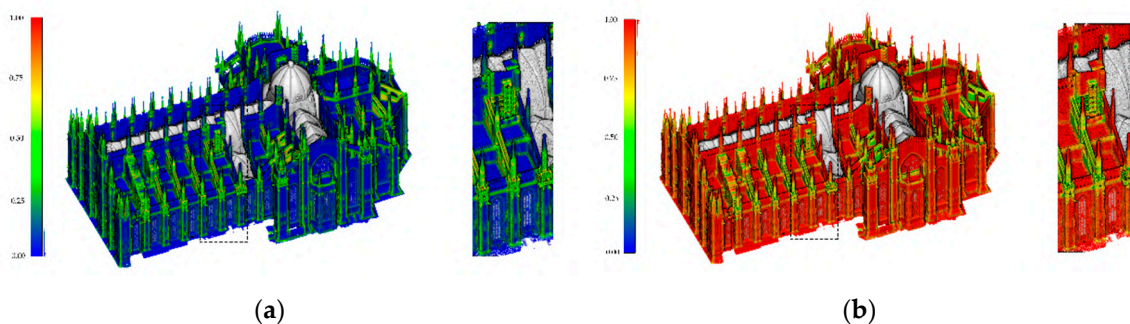
	Chains	Choir	Walls	Floor	Columns	Vaults	AVERAGE	WEIGHTED AVERAGE
<b>PREC. (%)</b>	67.52	85.19	94.08	98.03	90.15	98.28	88.88	93.05
<b>RECALL (%)</b>	89.96	85.41	93.42	94.37	94.85	94.54	92.09	93.05
<b>F1 (%)</b>	71.14	85.30	93.75	96.17	92.45	96.37	90.46	93.02

**Table 6.** Classification metrics at level 1 for the exteriors of Milan Cathedral.

	Buttresses	Walls	Street	Roofs	AVERAGE	WEIGHTED AVERAGE
<b>PREC. (%)</b>	92.75	97.34	99.66	99.03	97.19	96.44
<b>RECALL (%)</b>	92.62	97.47	99.06	98.42	96.89	96.44
<b>F1 (%)</b>	92.68	97.40	99.36	98.72	97.04	96.44

The main classification errors in the first level of classification were due to the following areas: (i) too small with respect to the resolution level, (ii) ambiguous from a geometrical point of view, or (iii) too similar to elements belonging to a different class. For example, it has been difficult to classify chains, which are approximately 8 cm thick, at a 5-cm resolution point clouds.

A second type of problem was found in the area which surrounds the choir. The class choir comprises different architectural elements including pipe organs, benches and altars. The decision to classify them in one class is coherent with the *Veneranda Fabbrica* rules. However, the heterogeneity of its parts and noise in the 3D point model caused classification problems in neighbouring regions. In fact, as the RF classifier relies on geometrical features of the local points to classify them, it was not able to easily distinguish classes with similar characteristics. An analogue issue has been encountered on the outside part of the Cathedral. Here, the RF classifier could classify only those buttresses that were entirely surveyed. Errors appeared in those parts where, due to building site requirements, it was impossible to survey one of the two buttresses' faces. In that case, the classifier confused the buttresses with walls, both being 2.5D. In Figure 16, it is possible to see the different behaviour of the same geometric features on complete and incomplete elements.



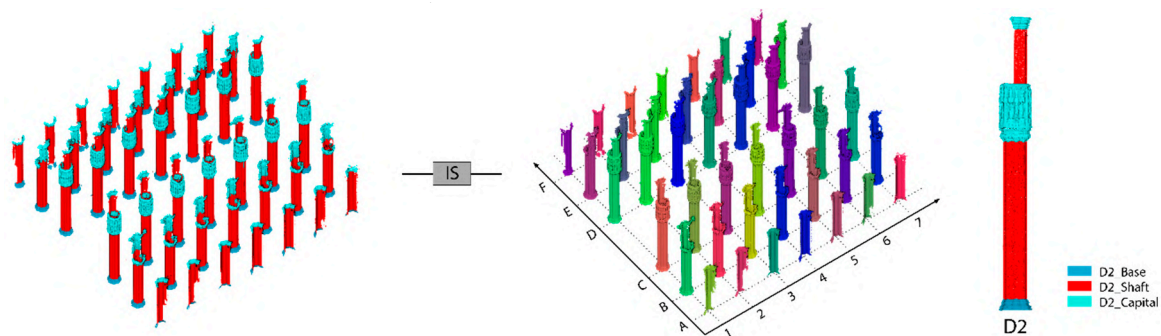
**Figure 16.** Different features behaviour on complete and incomplete objects. (a) Surface variation (1.2); (b) Anisotropy (1.4).

Before transferring the classification results from levels 1 to 2, misclassification errors have been manually adjusted. In fact, errors at top levels would severely affect classification at the subsequent, more detailed steps.

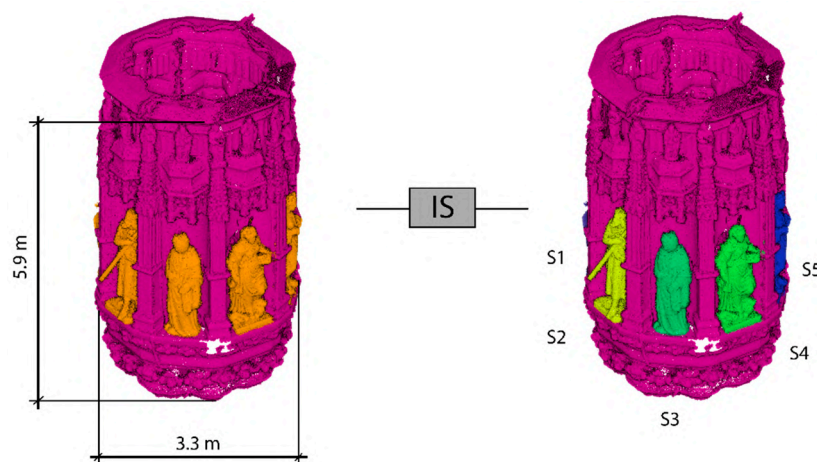


At the second level of classification, the precision of the results increased (see also Table 4) as the geometric resolution of the point cloud increased. This allowed to identify more peculiar architectural elements. Finally, the third classification level (5-mm resolution) included the most complex shapes to be classified (e.g., statues incorporated inside the capitals): the accuracy metrics slightly decreased due to the complex shapes but also the presence of occlusions in the point clouds as well as geometric similarities between elements (e.g., statues and gothic pyramids).

The final step of the classification process was the instance segmentation, applied to all the single and repeated elements belonging to the same classes (Figures 17 and 18). The instance segmentation allowed to associate a different index to an architectural component of the same class (e.g., statues, capitals, bases, shafts, etc.). This indexing allows for (i) a better management in a HBIM context and (ii) a quick and precise identification of the elements on which to intervene (in accordance to *Veneranda Fabbrica* intervention rules).



**Figure 17.** Example of instance segmentation on the pillars of the main nave.



**Figure 18.** Example of instance segmentation on a capital of the main nave in order to distinguish the various statues (S1, S2, etc.).

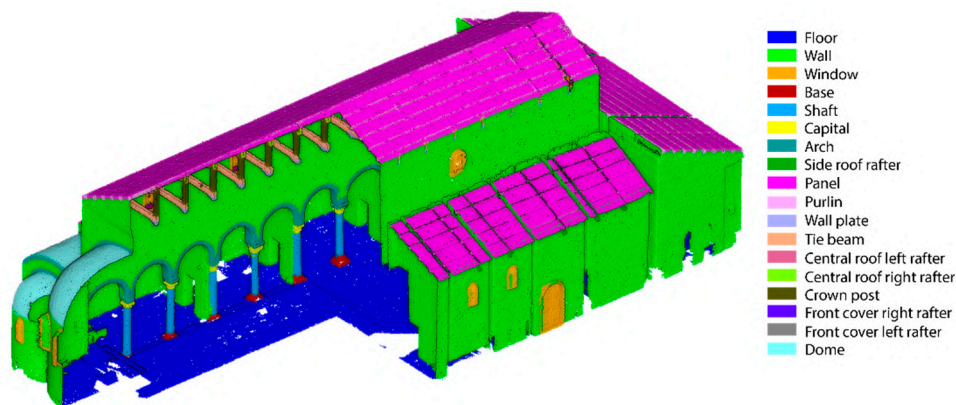
## 7.2. Pomposa Abbey

### 7.2.1. One Step Classification

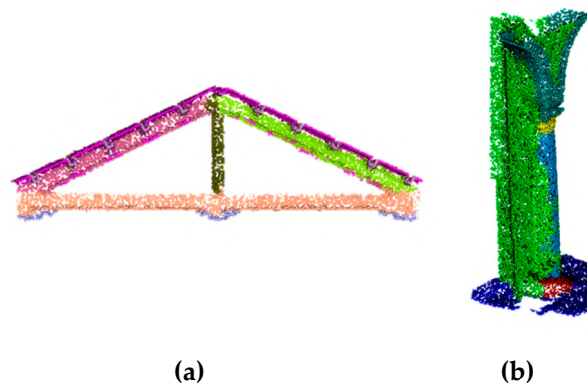
A traditional non-hierarchical classification was applied to the Abbey dataset searching for 18 classes of architectural interest (see Figure 21). Results, shown in Figure 19, seems quite encouraging, with an average F1-score of 75%. However, in order to be used in daily practice, the classification results need some manual misclassification adjustments (Figure 20). The relative acceptable results can be explained by the fact that Pomposa Abbey, even if complex, present less ambiguity among classes with respect to the Milan's Cathedral. The RF can distinguish among walls and structural parts in the trusses because they are geometrically different (contrary to the statues on the choir and those on the



capitals in Milan’s Cathedral). Moreover, the point cloud resolution is low and does not necessarily requires an initial subsampling step.



**Figure 19.** One step (non-hierarchical) classification results for the Pomposa Abbey with 18 classes (average F1-score: 75%).



**Figure 20.** Misclassification details. (a) Truss. (b) Column.

### 7.2.2. MLMR classification

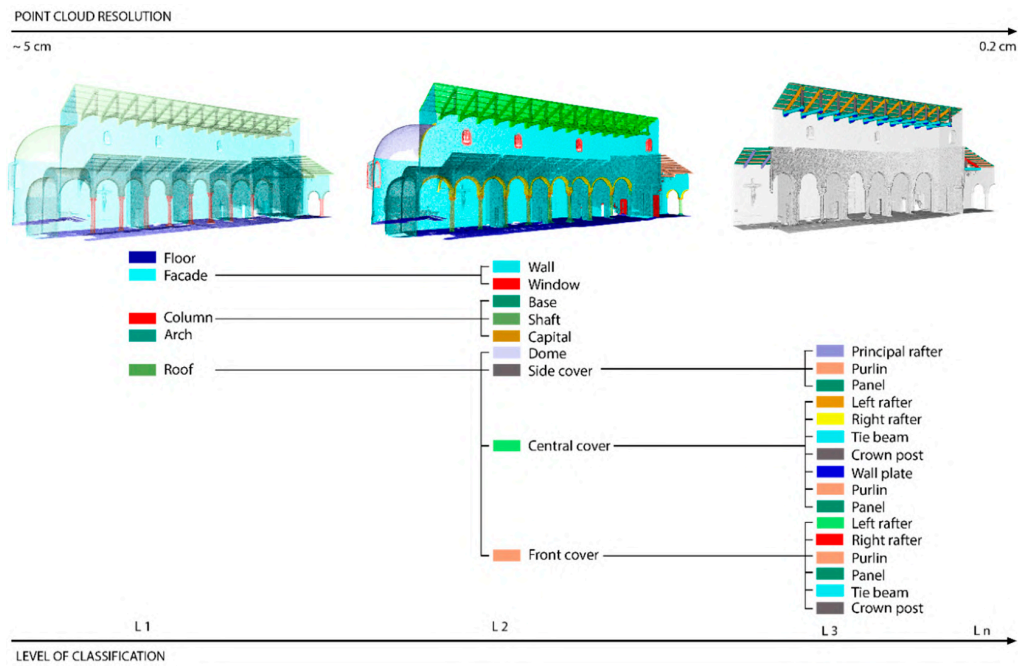
The developed MLMR classification approach was applied with three levels (Figure 21). Table 7 reports the F1-scores achieved in the three levels, with an accuracy always over 90%. Working on different levels has facilitated the process of architectural content recognition, avoiding errors that are common when more classes share the same properties (e.g., columns and crown posts). The slight decrease in accuracy for level 3 is due to the fact that, despite an increase of the classes (from 9 to 18), the geometric resolution of the point cloud is like level 2 (2 cm).

**Table 7.** Pomposa Abbey: the F1-scores average values for all three classification levels (in brackets the geometric resolutions of the point clouds). Please consider that each level has a different number of classes. The classification levels 2 and 3 are performed on the point cloud at a 2-cm resolution, i.e., the native resolution.

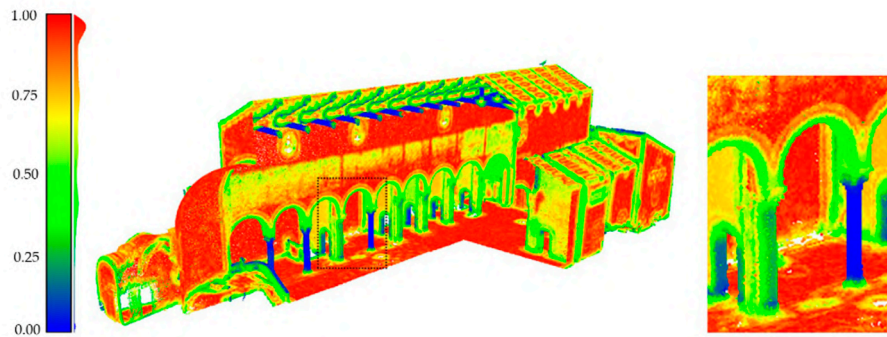
	Level 1 (5 cm)	Level 2 (2 cm)	Level 3 (2 cm)
F1 (%)	95.1	97.8	94.6

At the first classification level, the most complex parts to classify were those columns that are directly inserted in the transverse walls. As shown in Figure 22a, geometric features such as planarity or linearity, that generally help in highlighting columns, responded differently on columns

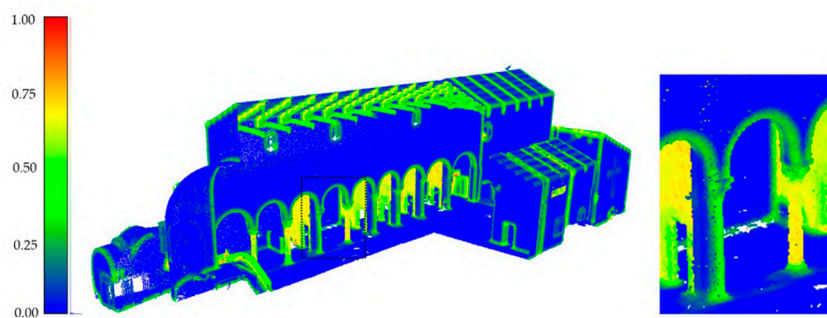
and semi-columns. Still, the integration with other covariance features, such as Surface Variation (Figure 22b), allows quite precise identification of semi-columns.



**Figure 21.** MLMR classification (18 classes overall) for the Pomposa Abbey. Please note that tie beam, panel and purlin are repeated among the sub-classes.



(a)



(b)

**Figure 22.** Different behaviours of geometric features over columns and semi-columns: (a) Planarity (0.6) and (b) Surface variation (0.4).

Once columns and semi-columns have been isolated (Figure 23), the subsequent level of classification, based on a higher resolution, allowed the identification of further elements and details, such as base, capital, shaft, etc. (Figure 24).

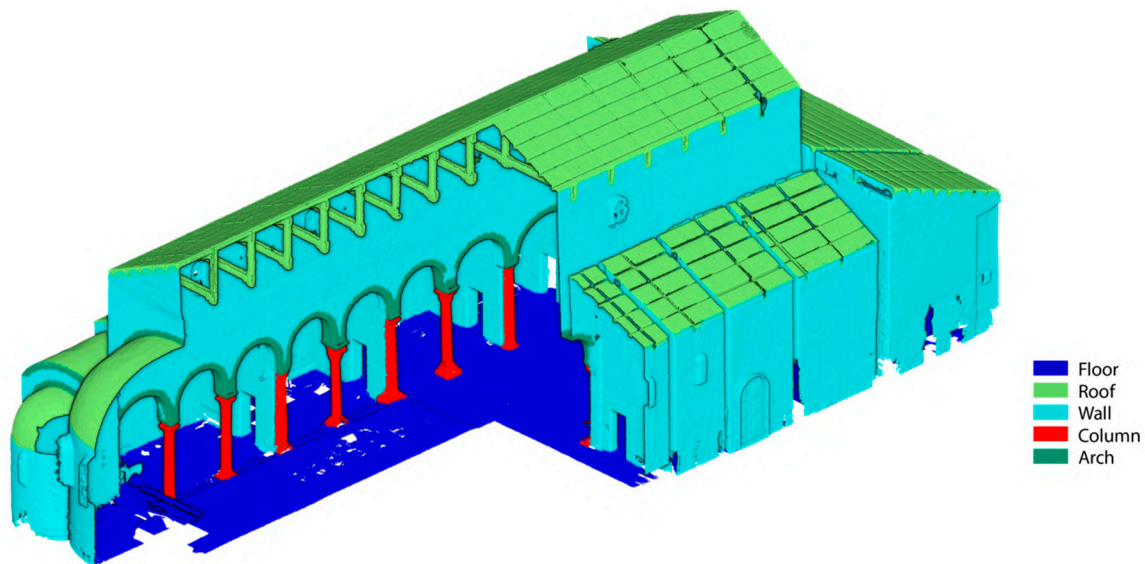


Figure 23. Classification results (five classes) at level 1 for the entire Pomposa abbey.

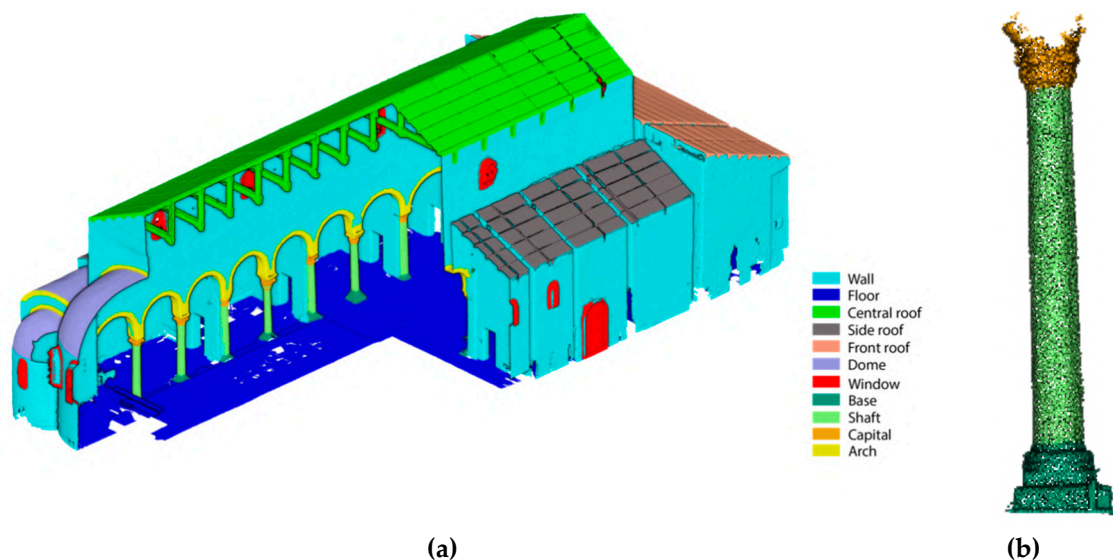
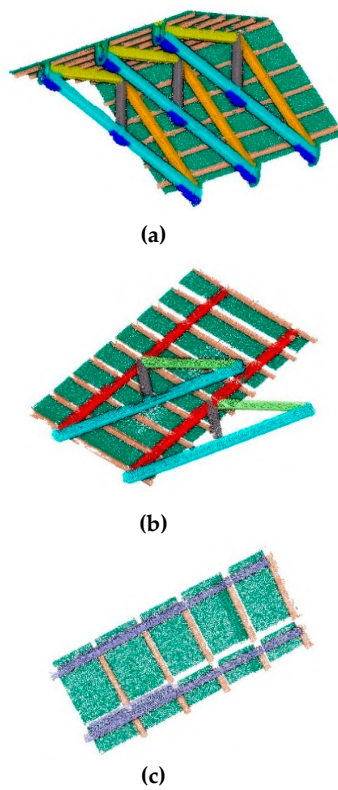


Figure 24. Classification results (11 classes) at level 2 for the entire Abbey (a). A closer view of a column with its sub-elements (b).

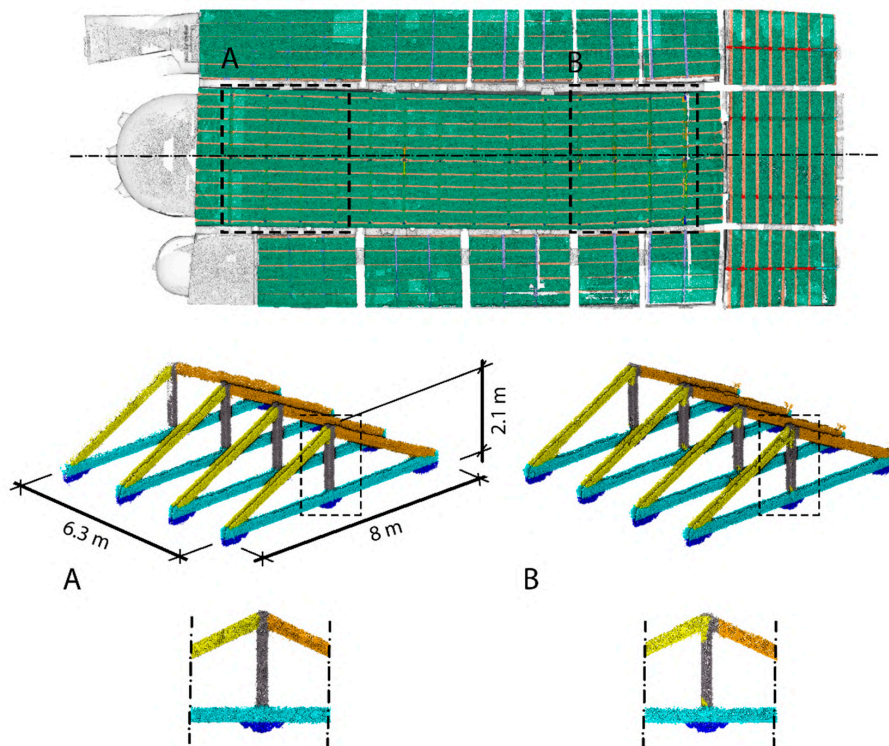
The second classification level split the roof into the dome, central, front and side cover, as each part presents a different structural behaviour. Therefore, these roof parts and wooden structures were considered in the last classification level. The parts could be further subdivided, extracting all their various components (Figure 25), but using specific features for each part.

In all cases, the Surface Variation, extracted at radii proportional to the size of the beams, has been essential to highlight the various elements. But, after a strategic re-orientation of the parts, the X and Y coordinates were used as features for the central and front cover, respectively, to distinguish the principal rafters. This latter strategy allowed us to notice the presence of deformations in the central cover, starting from the observation of some anomalies in the classification results (Figure 26).



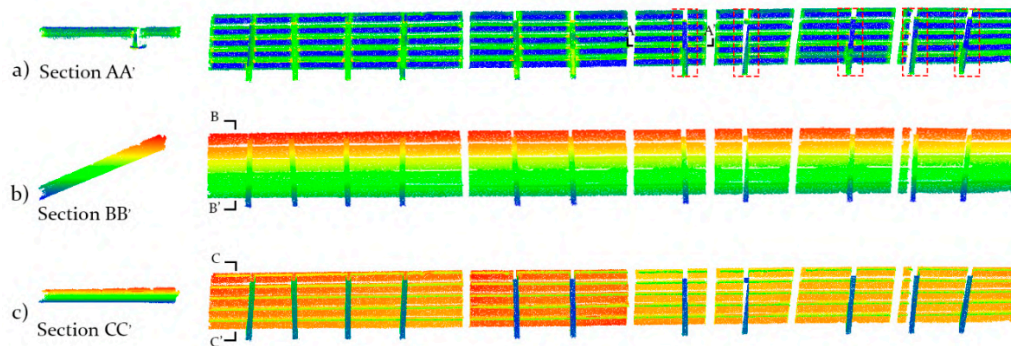


**Figure 25.** Results at classification level 3 for the Pomposa Abbey's roof: (a) central; (b) front; (c) side cover. Colour legend as in Figure 18.



**Figure 26.** Top view with x-axis deviation highlighted and subsequent anomalies in the classification results of the wooden roof. Some closer views: (A) correct; (B) error in properly distinguishing the elements.

With regards to the side cover classification, in early stages of experimentation, different problems were encountered as complete and incomplete beams (coming from occlusions in the dataset) responded differently to the feature extraction (Figure 27a). To cope with this issue, a temporary rotation was applied to the side covers, to make them horizontal, so that we could benefit from the Z coordinates for distinguishing rafters, purlins, and panels (Figure 27b,c).



**Figure 27.** Bottom-up views with relative sections of the side cover: (a) surface variation behaviour with critical areas highlighted; (b) scalar field of the original and (c) rotated Z coordinates.

Classification metrics per classes at level 3 are reported in Tables 8–10. This level includes very fine details of the roof (purlins, tie beams, etc.) which were classified at the same geometric detail of level 2; hence, the reached accuracy metrics are slightly worse.

**Table 8.** Classification metrics at level 3 for the central cover of the Pomposa Abbey’s roof.

	Purlin	Panel	Wall Plate	Tie Beam	Principal Rafter (Right)	Principal Rafter (Left)	Crown Post	AVERAGE	WEIGHTED AVERAGE
PREC. (%)	96.66	86.99	95.71	97.21	90.11	94.54	86.44	89.67	88.05
RECALL (%)	61.53	92.29	95.09	97.64	92.10	93.12	89.41	88.74	89.04
F1 (%)	68.27	89.56	95.40	97.43	91.09	93.82	87.90	89.20	88.39

**Table 9.** Classification metrics at level 3 for the front cover of the Pomposa Abbey’s roof.

	Panel	Purlin	Crown Post	Principal Rafter (Left)	Tie Beam	Principal Rafter (Right)	AVERAGE	WEIGHTED AVERAGE
PREC. (%)	96.86	97.13	83.87	67.36	99.57	87.52	88.72	95.77
RECALL (%)	98.47	93.70	92.24	68.63	99.36	87.87	90.05	95.79
F1 (%)	97.66	95.38	87.86	67.99	99.46	87.70	89.34	95.77

**Table 10.** Classification metrics at level 3 for the side cover of the Pomposa Abbey’s roof.

	Panel	Principal Rafter	Purlin	AVERAGE	WEIGHTED AVERAGE
PREC. (%)	97.25	98.41	97.7	97.79	97.46
RECALL (%)	100.00	96.16	85.23	93.80	97.45
F1 (%)	98.61	97.27	91.04	95.64	97.38

Finally, the instance segmentation of the whole wooden roof (Figure 28) provided additional results useful for conservation and monitoring activities, allowing to identify components that have to be replaced. Moreover, the abstraction of structural elements could become preliminary to simulations with finite element methods/analysis systems (FEM/FEA).

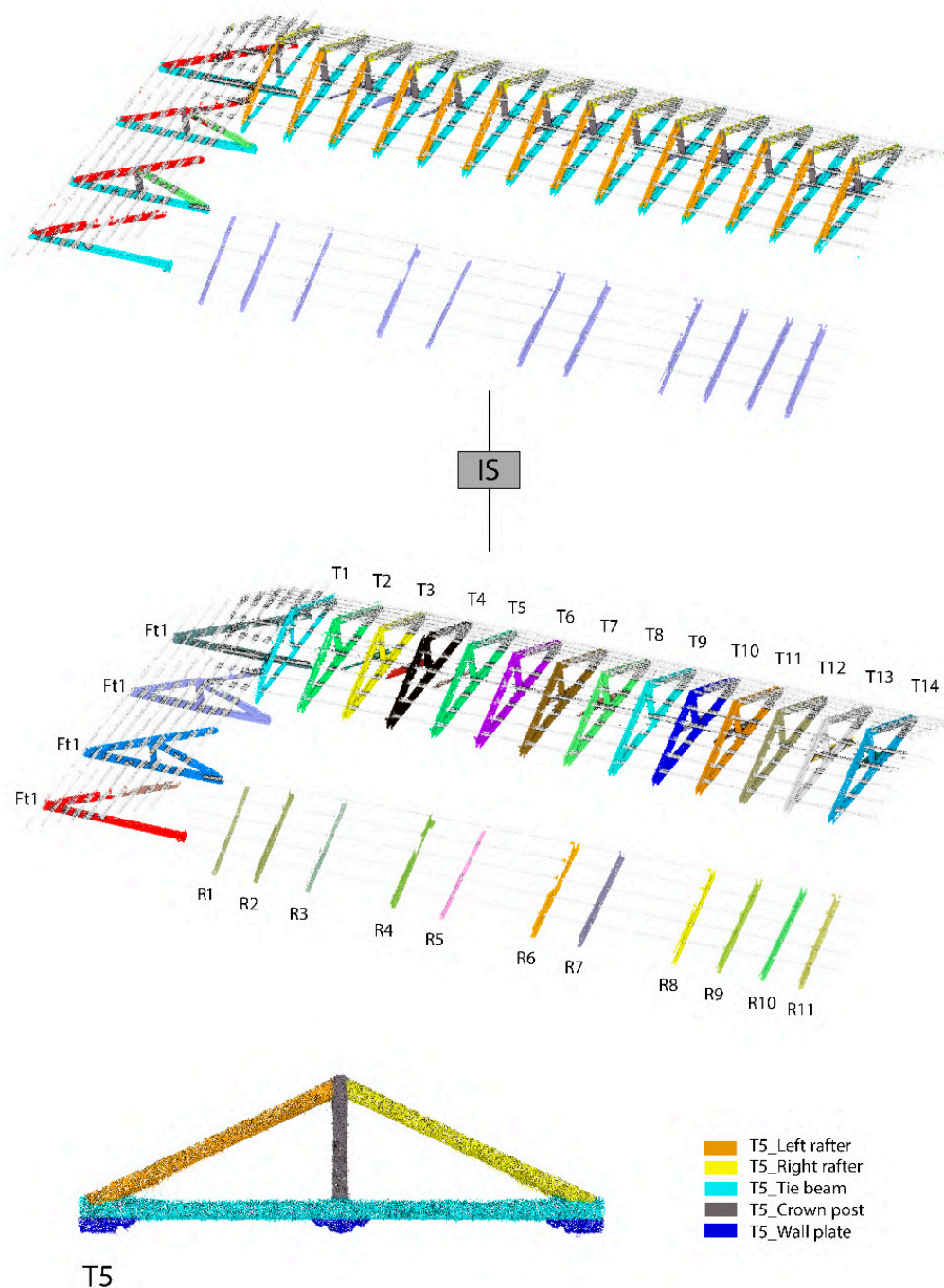


Figure 28. Instance segmentation of the roof structures.

## 8. Conclusions

The paper presented a new hierarchical classification procedure (MLMR) to semantically enrich 3D point clouds of complex heritage structures. The achieved classification results show how enriched point clouds could support a better understanding of complex heritage architectures as well as operations like restoration, communication and on-site facility management. The cognitive contribution of an

expert operator is fundamental at the beginning of the process. The following are still required from an expert operator: (i) the identification of the classification rules, (ii) the class definition, and (iii) the choice of training and validation sets (data annotation). These steps are crucial to adapt the process to different case studies.

The innovative aspects of the presented work are as follows:

- The use of machine learning techniques to quickly classify large and complex 3D architectures without the need of large training datasets.
- The definition of general rules (e.g., identification of geometric features), replicable in various heritage scenarios, in terms of relations among classification levels, point cloud resolution and minimum/maximum feature search radii.
- The hierarchical segmentation (until single instances) of 3D surveying data which could facilitate HBIM processes.
- The speed of the process: once training and validation sets are defined, the prediction to the entire dataset is achieved in a few minutes.
- The objectivity of the classification procedure: objective rules are applied uniformly throughout the entire process, making the process repeatable and independent from subjective choices of an operator.

As possible lines of future research, some aspects may deserve further attention and development:

- Better investigation of the relationship between classification levels, point cloud resolution and features search radii: it is necessary to understand if the automatic classification with specific features can be generalised concerning data density, or if it is case dependent.
- Verification of the usefulness of the classification process for the scan-to-BIM process, checking if the extracted semantic structures and instances facilitate the preparatory work for the construction of BIM models.
- Checking if the semantically segmented point clouds could facilitate the generation of polygonal meshes.
- Extension of the instance segmentation, not only to repeated and separated elements but also to those classes that present differences in composition or material, even if contiguous and similar in shape (e.g., walls).
- Creation of a more user-friendly classification framework to be used by non-experts in the sector.
- Testing the possibility to automatically process the data acquired on-site with mobile scanner instruments for real-time monitoring applications.
- Improvement of the classification details by integrating information coming from images, which generally feature higher resolution, hence allows for a better identification/distinction of small elements (e.g., classification of each single marble block composing the Milan Cathedral).

**Author Contributions:** The article presents a research contribution that involved all authors in equal measure, starting from a 3D dataset acquired by different research groups. In drafting preparation, F.R. supervised the overall work, writing the introduction, aim and conclusions of the paper; S.T. and E.G. dealt with the state of the art, methodology, data processing and results; F.F. was responsible of Milan Cathedral description, paper conclusions and methodology generalisation; M.R. dealt with Pomposa Abbey description, paper introduction and conclusions. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research partially received external funding from the project "Artificial Intelligence for Cultural Heritage" (AI4CH) joint Italy-Israel lab which was funded by the Italian Ministry of Foreign Affairs and International Cooperation (MAECI).

**Acknowledgments:** The paper is partially funded by the the project "Artificial Intelligence for Cultural Heritage" (AI4CH), a joint Italy-Israel lab which was funded by the Italian Ministry of Foreign Affairs and International Cooperation (MAECI). The authors are thankful to all participants in the surveying acquisition campaigns and data processing of the two case studies. A special thank goes to A.M. Manferdini for her contribution in the survey and data analysis of the Pomposa Abbey. The authors would also thank the *Veneranda Fabbrica del Duomo di Milano* and its director Eng. Francesco Canali for his support and availability to allow our research activities.



**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Remondino, F.; Georgopoulos, A.; Agrafiotis, P. *Latest Developments in Reality-Based 3D Surveying and Modelling*; MDPI AG: Basel, Switzerland, 2018. [\[CrossRef\]](#)
2. Gonzalez-Aguilera, D.; Remondino, F.; Nocerino, E. *Remote Sensed Data and Processing Methodologies for 3D Virtual Reconstruction and Visualization of Complex Architectures*; MDPI AG: Basel, Switzerland, 2016. [\[CrossRef\]](#)
3. Apollonio, F.I.; Basilissi, V.; Callieri, M.; Dellepiane, M.; Gaiani, M.; Ponchio, F.; Rizzo, F.; Rubino, A.R.; Scopigno, R.; Sobra', G. A 3D-centered information system for the documentation of a complex restoration intervention. *J. Cult. Herit.* **2018**, *29*, 89–99. [\[CrossRef\]](#)
4. Nocerino, E.; Menna, F.; Toschi, I.; Morabito, D.; Remondino, F.; Rodriguez-Gonzalvez, P. Valorisation of history and landscape for promoting the memory of WWI. *J. Cult. Herit.* **2018**, *29*, 113–122. [\[CrossRef\]](#)
5. Malinverni, E.S.; Pierdicca, R.; Paolanti, M.; Martini, M.; Morbidoni, C.; Matrone, F.; Lingua, A. Deep learning for semantic segmentation of 3D point cloud. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W15*, 735–742. [\[CrossRef\]](#)
6. Roussel, R.; Bagn eris, M.; De Luca, L.; Bomblet, P. A digital diagnosis for the « Autumn » statue (Marseille, France): Photogrammetry, digital cartography and construction of a thesaurus. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W15*, 1039–1046. [\[CrossRef\]](#)
7. Grilli, E.; Menna, F.; Remondino, F. A review of point clouds segmentation and classification Algorithms. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W3*, 339–344. [\[CrossRef\]](#)
8. Griffiths, D.; Boehm, J. A Review on Deep Learning Techniques for 3D Sensed Data Classification. *Remote Sens.* **2019**, *11*, 1499. [\[CrossRef\]](#)
9. Maturana, D.; Scherer, S. VoxNet: A 3D Convolutional Neural Network for real-time object recognition. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, 28 September–2 October 2015; pp. 922–928. [\[CrossRef\]](#)
10. Jiang, H.; Yan, F.; Cai, J.; Zheng, J.; Xiao, J. End-to-end 3D Point Cloud Instance Segmentation without Detection. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, Washington, DC, USA, 16–18 June 2020; pp. 12796–12805.
11. Milioto, A.; Lottes, P.; Stachniss, C. Real-Time Semantic Segmentation of Crop and Weed for Precision Agriculture Robots Leveraging Background Knowledge in CNNs. In Proceedings of the IEEE International Conference on Robotics and Automation, Brisbane, Australia, 21–25 May 2018. [\[CrossRef\]](#)
12. Wang, L.; Zhang, Y.; Wang, J. Map-Based Localization Method for Autonomous Vehicles Using 3D-LIDAR. In *IFAC-PapersOnLine*; Elsevier: Amsterdam, The Netherlands, 2017; Volume 50, pp. 276–281. [\[CrossRef\]](#)
13. Hu, Q.; Yang, B.; Xie, L.; Rosa, S.; Guo, Y.; Wang, Z.; Trigoni, N.; Markham, A. RandLA-Net: Efficient Semantic Segmentation of Large-Scale Point Clouds. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, Seattle, DC, USA, 16–18 June 2020; pp. 11108–11117.
14. Kim, W.; Seok, J. Indoor Semantic Segmentation for Robot Navigating on Mobile. In Proceedings of the International Conference on Ubiquitous and Future Networks, Prague, Czech Republic, 3–6 July 2018; pp. 22–25. [\[CrossRef\]](#)
15. Poux, F.; Billen, R. Voxel-based 3D Point Cloud Semantic Segmentation: Unsupervised Geometric and Relationship Featuring vs Deep Learning Methods. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 213. [\[CrossRef\]](#)
16. Xu, S.; Vosselman, G.; Elberink, S.O. Multiple-entity based classification of airborne laser scanning data in urban areas. *ISPRS J. Photogramm. Remote Sens.* **2014**, *88*, 1–15. [\[CrossRef\]](#)
17. Zhu, Q.; Li, Y.; Hu, H.; Wu, B. Robust point cloud classification based on multi-level semantic relationships for urban scenes. *ISPRS J. Photogramm. Remote Sens.* **2017**, *129*, 86–102. [\[CrossRef\]](#)
18. Weinmann, M.; Schmidt, A.; Mallet, C.; Hinz, S.; Rottensteiner, F.; Jutzi, B. Contextual classification of point cloud data by exploiting individual 3D neighbourhoods. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *II-3/W4*, 271–278. [\[CrossRef\]](#)
19.  zdemir, E.; Remondino, F.; Gokar, A. Aerial point cloud classification with deep learning and machine learning algorithms. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 843–849. [\[CrossRef\]](#)
20. Grilli, E.; Remondino, F. Classification of 3D Digital Heritage. *Remote Sens.* **2019**, *11*, 847. [\[CrossRef\]](#)



21. Grilli, E.; Dinunno, D.; Petrucci, G.; Remondino, F. From 2D to 3D supervised segmentation and classification for cultural heritage applications. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *2*, 399–406. [[CrossRef](#)]
22. Son, H.; Kim, C. Semantic As-built 3D Modeling of Structural Elements of Buildings based on Local Concavity and Convexity. In *Advanced Engineering Informatics*; Elsevier: Amsterdam, The Netherlands, 2017; Volume 34, pp. 114–124. [[CrossRef](#)]
23. Lu, Q.; Lee, S. Image-based technologies for constructing as-is building information models for existing buildings. *J. Comput. Civ. Eng.* **2017**, *31*, 04017005. [[CrossRef](#)]
24. Rebolj, D.; Pučko, Z.; Babič, N.Č.; Bizjak, M.; Mongus, D. Point cloud quality requirements for Scan-vs-BIM based automated construction progress monitoring. *Autom. Constr.* **2017**, *84*, 323–334. [[CrossRef](#)]
25. Bassier, M.; Yousefzadeh, M.; Vergauwen, M. Comparison of 2D and 3D wall reconstruction algorithms from point cloud data for as-built BIM. *J. Inf. Technol. Constr.* **2020**, *25*, 173–192. [[CrossRef](#)]
26. Valero, E.; Bosche, F.; Forster, A.M. Automatic segmentation of 3D point clouds of rubble masonry walls, and its application to building surveying, repair and maintenance. *Autom. Constr.* **2018**, *96*, 29–39. [[CrossRef](#)]
27. Sánchez-Aparicio, L.J.; Del Pozo, S.; Ramos, L.F.; Arce, A.; Fernandes, F. Heritage site preservation with combined radiometric and geometric analysis of TLS data. *Autom. Constr.* **2018**, *85*, 24–39. [[CrossRef](#)]
28. Bosché, F. Automated Recognition of 3D CAD Model objects in Laser Scans and Calculation of As-built Dimensions for Dimensional Compliance Control in Construction. In *Advanced Engineering Informatics*; Elsevier: Amsterdam, The Netherlands, 2010; Volume 24, pp. 107–118. [[CrossRef](#)]
29. Ordóñez, C.; Martínez, J.; Arias, P.; Armesto, J.; Martinez-Sanchez, J. Measuring building façades with a low-cost close-range photogrammetry system. *Autom. Constr.* **2010**, *19*, 742–749. [[CrossRef](#)]
30. Mizoguchi, T.; Koda, Y.; Iwaki, I.; Wakabayashi, H.; Kobayashi, Y.; Shirai, K.; Hara, Y.; Lee, H.-S. Quantitative scaling evaluation of concrete structures based on terrestrial laser scanning. *Autom. Constr.* **2013**, *35*, 263–274. [[CrossRef](#)]
31. Kashani, A.G.; Graettinger, A.J. Cluster-Based Roof Covering Damage Detection in Ground-Based Lidar Data. *Autom. Constr.* **2015**, *58*, 19–27. [[CrossRef](#)]
32. Murtiyoso, A.; Grussenmeyer, P. Virtual Disassembling of Historical Edifices: Experiments and Assessments of an Automatic Approach for Classifying Multi-Scalar Point Clouds into Architectural Elements. *Sensors* **2020**, *20*, 2161. [[CrossRef](#)] [[PubMed](#)]
33. Grilli, E.; Farella, E.M.; Torresani, A.; Remondino, F. Geometric features analysis for the classification of cultural heritage point clouds. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W*, 541–548. [[CrossRef](#)]
34. Grilli, E.; Remondino, F. Machine Learning Generalisation across Different 3D Architectural Heritage. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 379. [[CrossRef](#)]
35. Llamas, J.; Lerones, P.M.; Medina, R.; Zalama, E.; García-Bermejo, J.G. Classification of Architectural Heritage Images Using Deep Learning Techniques. *Appl. Sci.* **2017**, *7*, 992. [[CrossRef](#)]
36. Yasser, A.M.; Clawson, K.; Bowerman, C.; Mustafá, Y. Saving cultural heritage with digital make-believe: Machine learning and digital techniques to the rescue. In Proceedings of the 31st British Computer Society Human Computer Interaction Conference, Sunderland, UK, 3–6 July 2017; pp. 97–101. [[CrossRef](#)]
37. Charles, R.Q.; Su, H.; Kaichun, M.; Guibas, L.J. PointNet: Deep Learning on Point Sets for 3D Classification and Segmentation. In Proceedings of the Conference on Computer Vision and Pattern Recognition (CVPR), Honolulu, HI, USA, 21–26 July 2017; pp. 77–85. [[CrossRef](#)]
38. Qi, C.R.; Yi, L.; Su, H.; Guibas, L.J. PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space. In Proceedings of the Conference on Neural Information Processing Systems (NIPS), Long Beach, CA, USA, 24 January 2019.
39. Pierdicca, R.; Paolanti, M.; Matrone, F.; Martini, M.; Morbidoni, C.; Malinverni, E.S.; Frontoni, E.; Lingua, A.M. Point Cloud Semantic Segmentation Using a Deep Learning Framework for Cultural Heritage. *Remote Sens.* **2020**, *12*, 1005. [[CrossRef](#)]
40. Matrone, F.; Lingua, A.; Pierdicca, R.; Malinverni, E.S.; Paolanti, M.; Grilli, E.; Remondino, F.; Murtiyoso, A.; Landes, T. A benchmark for large-scale heritage point cloud semantic segmentation. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *XLIII-B2*, 4558–4567.

41. Grilli, E.; Özdemir, E.; Remondino, F. Application of machine and deep learning strategies for the classification of heritage point clouds. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-4/W18*, 447–454. [[CrossRef](#)]
42. Fassi, F.; Achille, C.; Fregonese, L. Surveying and modelling the main spire of Milan Cathedral using multiple data sources. *Photogramm. Rec.* **2011**, *26*, 462–487. [[CrossRef](#)]
43. Achille, C.; Fassi, F.; Mandelli, A.; Perfetti, L.; Rechichi, F.; Teruggi, S. From A Traditional to A Digital Site: 2008–2019. The History of Milan Cathedral Surveys. In *Research for Development*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 331–341. [[CrossRef](#)]
44. Perfetti, L.; Fassi, F.; Gulsan, H. Generation of gigapixel orthophoto for the maintenance of complex buildings. Challenges and lesson learnt. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 605–614. [[CrossRef](#)]
45. Perfetti, L.; Polari, C.; Fassi, F. Fisheye photogrammetry: Tests and methodologies for the survey of narrow spaces. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *42*, 573–580. [[CrossRef](#)]
46. Mandelli, A.; Fassi, F.; Perfetti, L.; Polari, C. Testing different survey techniques to model architectonic narrow spaces. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W5*, 505–511. [[CrossRef](#)]
47. Salmi, M. *L'abbazia Di Pomposa*; Amilcare Pizzi: Milano, Italy, 1966.
48. Russo, E. Profilo Storico-artistico Della Chiesa Abbaziale di Pomposa. In *L'arte sacra nei Ducati Estensi, Proceedings of the II Settimana Dei Beni Storico-Artistici Della Chiesa Nazionale Negli Antichi Ducati Estensi, Ferrara, Italy, 13–18 September 1982*; Fellani, G., Ed.; Sate: Ferrara, Italy, 1984.
49. Addison, A.; Gaiani, M. Virtualized architectural heritage: New tools and techniques. *IEEE MultiMedia* **2000**, *7*, 26–31. [[CrossRef](#)]
50. El-Hakim, S.F.; Beraldin, J.A.; Picard, M.; Vettore, A. Effective 3d modeling of heritage sites. In Proceedings of the Fourth International Conference on 3-D Digital Imaging and Modeling, 2003. 3DIM 2003, Banff, AB, Canada, 6–10 October 2003; IEEE: Piscataway, NJ, USA; pp. 302–309. [[CrossRef](#)]
51. Cosmi, E.; Guerzoni, G.; Di Francesco, C.; Alessandri, C. Pomposa Abbey: FEM Simulation of Some Structural Damages and Restoration Proposals. In *Structural Studies, Repairs and Maintenance of Historical Buildings, WIT Transaction of The Built Environment*; Brebbia, C.A., Ed.; WIT Press: Wessex, UK, 1999; Volume 42. [[CrossRef](#)]
52. Francesco, C.; Di Mezzadri, G. Indagini e Rilievi per Interventi Strutturali Nella Chiesa Abbaziale di Santa Maria di Pomposa. In *Il Cantiere Della Conoscenza, Il Cantiere Del Restauro, Proceedings of Convegno Di Studi, Bressanone, Italy, 27–30 June 1989*; Biscontin, G., Dal Colle, M., Volpin, S., Eds.; Libreria Progetto: Bressanone, Italy, 1989.
53. Russo, M.; Manferdini, A.M. Integration of image and range-based techniques for surveying complex architectures. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2014**, *2*, 305–312. [[CrossRef](#)]
54. Breiman, L. Random Forest. *Mach. Learn.* **2001**, *45*, 5–32. [[CrossRef](#)]
55. Cloud Compare (Version 2.11.0) [GPL software]. Available online: <http://www.cloudcompare.org/> (accessed on 3 August 2020).
56. Fassi, F.; Parri, S. Complex Architecture in 3D: From Survey to Web. *Int. J. Herit. Digit. Era* **2012**, *1*, 379–398. [[CrossRef](#)]
57. Chehata, N.; Guo, L.; Mallet, C. Airborne lidar feature selection for urban classification using random forests. *Laser Scanning 2009 IAPRS* **2009**, *XXXVIII*, 207–212. Available online: <https://hal.archives-ouvertes.fr/hal-02384719/> (accessed on 10 August 2020).

