



UNIVERSITY OF SALAMANCA

**PLANNING, SURVEYING, MODELLING AND VISUALIZATION TECHNIQUES
IN THE FIELD OF CULTURAL HERITAGE**

INTERNATIONAL PhD DISSERTATION
Belén Jiménez Fernández-Palacios

Department of Cartographic and Land Engineering
Higher Polytechnic School of Avila, University of Salamanca

Copyright © 2017 by Belén Jiménez Fernández-Palacios

All rights reserved. No part of the material protected by this copyright may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without written consent from the author (belenjfp@gmail.com).

AUTHOR Belén Jiménez Fernández-Palacios
SUPERVISORS Dr. Fabio Remondino, Dr. Diego González Aguilera
Ávila, June 2017

Supervisors’ report

Planning, surveying, modelling and visualization techniques in the field of Cultural Heritage

presented at the Department of Cartographic and Land Engineering
by Belén Jiménez Fernández-Palacios

Informe de los Directores de Tesis

La Tesis Doctoral con mención internacional titulada “Planning, surveying, modelling and visualization techniques in the field of Cultural Heritage”, presentada por Belén Jiménez Fernández-Palacios, se inserta en la línea de investigación de documentación, modelización y visualización del patrimonio arquitectónico por medio de geotecnologías que pretenden reunir tres factores críticos: automatización, consecución de modelos densos de alta calidad geométrica y radiométrica y empleo para ello de medios de bajo coste.

Se trata de una línea muy activa y relevante en la comunidad internacional con múltiples propuestas de mejora que se estimulan unas a otras gracias a lo cual estamos viviendo un periodo en franco progreso de las Geotecnologías en este campo en cuestión. El trabajo desarrollado se sitúa de forma significativa y eficaz en el contexto de dichas aportaciones y logros con un alto grado de sintonía y de contribución al avance del conocimiento científico y tecnológico.

Se trata asimismo de una línea de investigación promovida y desarrollada por el Grupo de Investigación 3D Optical Metrology Unit (3DOM) del instituto de investigación Bruno Kessler Foundation (FBK) en Trento (Italia), donde la doctoranda trabajó durante 4 años.

Las geotecnologías en general y las técnicas láser y fotogramétricas en particular vienen experimentando una serie de innovaciones de gran alcance que han transformado profundamente su contexto de aplicación frente a las aplicaciones más clásicas (Cartografía y Topografía) en las que se venía trabajando años atrás. Estas innovaciones se articulan fundamentalmente en torno a la capacidad de captura masiva de información, la hibridación de sensores, el empleo de técnicas de bajo coste y la automatización de determinados procesos para generar productos de calidad con propiedades métricas.

Además, en los últimos diez años, las tecnologías láser y fotogramétricas han demostrado ser técnicas complementarias, lo que las ha situado en un horizonte muy prometedor y

competitivo en todos los contextos y más concretamente en el ámbito del Patrimonio.

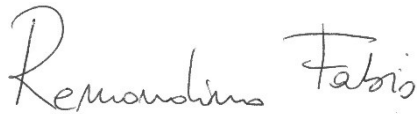
La Tesis aborda un adecuado Estado de la Cuestión de manera que permite identificar claramente la oportunidad estratégica de la aportación que se realiza como lo demuestra el hecho de que la Tesis se articula en torno a la modalidad de compendio de artículos publicados en revistas científicas y tecnológicas con impacto reconocido.

Estos artículos han verificado los correspondientes procesos de evaluación crítica y revisión por parte de expertos internacionales de trayectoria reconocida. Estas contribuciones se centran en:

- El desarrollo de una metodología que permite la documentación, modelización y visualización del Patrimonio a través de diferentes tecnologías y considerando tres niveles de escala: artefacto, arquitectura y paisaje.
- La utilización de geotecnologías como la fotogrametría, el láser escáner e incluso sensores híbridos como el Mapping Mobile System para la documentación y modelización del patrimonio.
- La utilización de técnicas de visualización y optimización de los datos para elementos del Patrimonio apoyadas en tecnología de realidad virtual y aumentada.

La Tesis concluye con el correspondiente apartado de Conclusiones en el que de forma precisa y concreta se especifican las principales aportaciones realizadas de tal manera que puedan ser objeto de crítica y de proyección hacia el desarrollo de futuros trabajos integrados en línea de investigación.

En Ávila, a 5 de junio de 2017,



Fabio Remondino

Diego González Aguilera

Reports for the International Doctorate Mention

Planning, surveying, modelling and visualization techniques in the field of Cultural Heritage

Attached below are two assessment reports written
by expert doctors belonging to a non-Spanish Institution



30 May 2017

Object: Evaluation letter of Ms Jiménez Fernández-Palacios’ PhD thesis

To whom it may concern

With pleasure I am writing this evaluation letter about the PhD thesis of Ms Belén Jiménez Fernández-Palacios regarding “Planning, surveying, modelling and visualization techniques in the field of Cultural Heritage” (University of Salamanca, Department of Cartographic and Land Engineering).

The thesis deals with advanced 3D surveying, 3D modelling and 3D visualisation techniques applied to a range of scales (from the artefact, up to the architectural and landscape ones) in the framework of Cultural Heritage. The main research topic focuses on identifying, analysing and establishing the most suitable solution depending on the specific “object” to be surveyed and the specific scale, with particular attention to the aspects related to sensor integration, data fusion, efficient data management and dissemination of the acquired heritage information.

The subject of the thesis is indeed relevant, given on one hand the overall relevance of the topics related to digital preservation of Cultural Heritage, and on the other hand the continuous technological advances in terms of sensors, software solutions, and new applications being built upon digital Cultural Heritage, which of course open new scenarios (but also new scientific research questions) when it comes to exploiting the added value of three dimensional, metric, semantically enriched and optimised virtual models. In particular, the concept of “geographical” scale intrinsically qualifies any object to be surveyed. In other words, the selection of the proper methodology highly depends first on the “size”, and then on the planned final use(s) the digital model will be used for. The higher the number of final uses, the more flexible and complex the methodology must be throughout the whole steps, from data acquisition, to data integration, 3D modelling, and data presentation/dissemination.

The overall structure of the thesis is clear and well-balanced, it is written in a good English and in an understandable way. The thesis consist mainly of a compendium of articles already published in peer-reviewed well-known international scientific journals, as requested by the regulation of the University of Salamanca. In addition, the thesis contains an introductory section which describes the overall reasons of the work and the three case studies presented later in the following chapters. These represent the central and principal part of the thesis and correspond each to one scientific

article focussing on the artefact scale (section 1), the architectonical scale (section 2) and the landscape scale (section 3), respectively. The last part of the thesis contains the conclusions, and a critical reasoning about the possible future research questions which might deserve new or deeper investigation.

As far as the three central chapters are concerned, they are well-written and they describe the goals, the specific challenges and the proposed solutions clearly. The number of case studies, at each different scale, show and prove the validity of the proposed solutions. The fact of being already published after a blind peer-review process is itself another proof of quality of the work carried out by Ms Jiménez Fernández-Palacios.

In conclusion, for the above mentioned reasons, the work presented in the thesis yields convincing results, conclusions and recommendations for future work, mostly from the technical point of view. In my opinion, it fulfils the requirements in terms of quality and quantity of innovative contents, as well as scientific soundness.

Therefore, I recommend Ms Belén Jiménez Fernández-Palacios to obtain the degree of International Doctor at the University of Salamanca in Spain and I would like to congratulate both her and her supervisors for this work.

Best regards,



Dr. Giorgio Agugiaro
Scientist
Sustainable Buildings and Cities
Center for Energy
AIT Austrian Institute of Technology GmbH



May 2017

RE: PhD Thesis Review

To whom it may concern:

I have read “Planning, surveying, modelling and visualization techniques in the field of Cultural Heritage”—a PhD thesis submitted by Belén Jiménez Fernández-Palacios (Department of Cartographic and Land Engineering, University of Salamanca). The thesis focuses on research and development of new optimization and visualization methods for complex 3D cultural heritage datasets that are scale-dependent. Three case studies investigate applications at three scales—artifact, architecture, and landscape—to identify the best acquisition and post-processing techniques for complex 3D data based on scale. The approaches presented in the thesis are important to cultural heritage because they provide new avenues for the analysis, management, and dissemination of complex reality-based 3D models.

The thesis begins with an introduction laying out main goals and the key objectives to achieve goals as well as the importance of the study to cultural heritage and beyond. Three techniques developed in the thesis include augmented reality, virtual reality, and web visualization. Of key importance and an important impact of the thesis is the development of new automatic and semi-automatic segmentation methods to optimize complex 3D models—methods that are greatly needed in cultural heritage and other fields to not only allow for more time-efficient post-processing but also for the visualization of research-quality complex 3D data.

Three peer-review articles in impact journals comprise the thesis. The first article is “ARCube—the augmented reality cube for archaeology” presents a low-cost and easy to use pipeline with customized tools for augmented reality applications of small archaeological artifacts—both for research and education purposes. The second article is “Access to complex reality-based 3D models using virtual reality solutions” presents a new virtual reality application to visualize and disseminate 3D models with associated archaeological content to enrich research and education. The article offers a pipeline for managing detailed 3D architecture models with high quality geometry and textures that can be interacted with in real-time using integrated gesture-based (Kinect) and immersive (Oculus Rift) technologies. The pipeline offers a sophisticated yet straightforward approach to disseminate complex 3D cultural heritage content that can be applied to a wide range of projects. Importantly, because the 3D data quality is maintained, it makes possible explorations of the potential value of gesture-based immersive interaction for scientific research. The third article is “Mobile LiDAR System: New Possibilities for the Documentation and Dissemination of Large Cultural Heritage Sites” compares terrestrial laser scanning to mobile LiDAR to evaluate accuracy vs. speed for landscape scale data for web-based visualization. Three key concepts are investigated: data acquisition, processing time, and data optimization (smart filtering). Three different optimization approaches are applied to determine for which circumstances (e.g., geometry, occlusions) each approach should be used. The end goal is to

develop a method that balances time-efficiency with data quality for web visualization. The results are very promising involving geometry-dependent adaptive sampling dependent that optimizes feature geometry while maintaining essential details; thus, allowing for a drastic reduction in acquisition time and an 88% reduction in point cloud size allowing for online dissemination of high quality 3D landscape data.

The thesis concludes with a concise and informative summary of the thesis’ goals, objectives, solutions, and a discussion of the significant contribution it makes to dealing with complex 3D data for cultural heritage and beyond. The thesis is well written and clearly organized with a framing introduction to set the stage for the three articles and a strong conclusion to summarize key ideas and the relevance of the thesis. This is an excellent thesis that provides invaluable contributions to 3D modeling and visualization including new optimization, segmentation, and visualization methods for diverse types of dissemination including augmented reality, virtual reality, and web-based applications. I congratulate Belén Jiménez Fernández-Palacios and her superiors on an excellent thesis that is sure to have great contributions to 3D modeling and visualization in cultural heritage. I most strongly recommend that Belén Jiménez Fernández-Palacios receive the degree for International Doctor from the University of Salamanca in Spain.

Sincerely,

Heather Richards-Rissetto

Heather Richards-Rissetto
Assistant Professor, Anthropology
Faculty Fellow, Center for Digital Research in the Humanities (CDRH)
University of Nebraska-Lincoln
840 Oldfather Hall, Lincoln, NE 68588-0368
Email: richards-rissetto@unl.edu

List of Publications

List of Publications

The presented Doctoral Thesis is composed of a compendium of three scientific articles which were previously published in scientific journals of international impact:

ARCube - The augmented reality cube for archaeology

Belén Jiménez Fernández-Palacios^{1, 2}, Francesco Nex ¹, Alessandro Rizzi³ and Fabio Remondino^{1, 4}

¹ 3D Optical Metrology Unit, Bruno Kessler Foundation, Via Sommarive 18, Trento, Italy.

³ SMART3K S.R.L., Via Sommarive 18, Trento, Italy.

¹ Researcher, ²PhD Student at the University of Salamanca (USAL), ³Research and development manager, ⁴Head of Unit.

Archaeometry, July 2015. Volume 57, Issue Supplement S1, Pages 250–262.

DOI: 10.1111/arcm.12120

Access to complex reality-based 3d models using virtual reality solutions

Belén Jiménez Fernández-Palacios ^{1, 2}, Daniele Morabito ² and Fabio Remondino ²

¹Department of Cartographic and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, Avila 05003, Spain.

²3D Optical Metrology Unit, Bruno Kessler Foundation, Via Sommarive 18, Trento, Italy.

Journal of Cultural Heritage, October 2016. Volume 23 (2017), Pages 40-48.

DOI: 10.1016/j.culher.2016.09.003

Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites

Pablo Rodríguez-González ¹, Belén Jiménez Fernández-Palacios ¹, Ángel Luis Muñoz-Nieto ¹, Pedro Arias-Sanchez ² and Diego Gonzalez-Aguilera ¹

¹TIDOP Research Group, University of Salamanca, Polytechnic School of Avila. Hornos Caleros, 50, 05003 Avila, Spain.

² Department of Natural Resources & Environmental Engineering, University of Vigo, School of Mining Engineering, Maxwell s/n, 36310 Vigo, Spain.

Remote Sensing, February 2017, Volume 9, Issue 3, Page 189.

DOI: 10.3390/rs9030189

“L’art évoque le mystère sans lequel le monde n’existerait pas”

Rene Magritte, Écrits complets, Flammarion, 1979

Resumen

El constante avance y desarrollo en técnicas de digitalización, modelación y visualización 3D abre nuevas vías de comunicación para la información. Por una parte, las geotecnologías se consolidan fundamentales para la digitalización y la modelación, por ser técnicas de alta precisión, no invasivas y de no contacto. Una amplia gama de sensores activos y pasivos permiten registrar la información 3D, mediante el uso de sistemas aéreos, móviles o terrestres. La información geométrica y radiométrica generada permite crear una fiel representación de la realidad, precisa, detallada y foto-realística, siendo de gran utilidad para la documentación, la conservación, el estudio y el análisis del objeto u escena en cuestión. Se generan complejos y pesados conjuntos de datos, que apuntan a la optimización como fase clave del procesado, donde es necesario reducir el peso final del producto sin perder detalles significantes, para una correcta gestión y visualización de los datos en tiempo real. La solidez de las geotecnologías queda demostrada en innumerables áreas de trabajo, desde la ingeniería civil y forestal, hasta la geología u arqueología, entre otros. Por otra parte, las nuevas técnicas de visualización 3D permiten explorar objetos y navegar a través de escenas reconstruidas digitalmente, al tiempo que emergen nuevos dispositivos que permiten gestionar y visualizar la información de forma interactiva y/o inmersiva. Las técnicas y dispositivos de visualización 3D encuentran su principal campo de aplicación en el diseño y desarrollo de video juegos, su uso se extiende rápidamente y es cada vez más frecuente encontrarlas en diferentes campos como la medicina, el turismo, la simulación o la arqueología.

La presente Tesis Doctoral aplica las técnicas de digitalización, modelación y visualización 3D a diferentes escalas (artefacto, arquitectura y paisaje) y siempre focalizadas en el campo del Patrimonio Cultural. El objetivo es la búsqueda de la solución más adecuada en función del caso de estudio, integrando, donde fuera necesario, diferentes sensores, técnicas y/o dispositivos que permitan una eficiente gestión y divulgación de la información del patrimonio.

Abstract

The continued advances and developments in 3D recording, modeling and visualization techniques have opened up new ways of conveying information. On the one hand, geotechnologies are fundamental to 3D recording and modeling due to their being highly accurate, non-invasive and non-contact techniques. A wide range of active and passive sensors enable the recording of 3D information using aerial, mobile or terrestrial systems. The geometric and radiometric information generated allows for the creation of a faithful 3D representation of reality, which is accurate, detailed and photo-realistic and thus useful for documentation, conservation, study and analysis of the object or scene in question. Vast and complex datasets are generated, which point to optimization as the key phase of processing. For a correct management and visualization of real-time data, it is necessary to reduce the final weight of the product without losing significant details. The strength of geotechnologies has been demonstrated in countless fields of work from - among others - civil engineering and forestry, to geology or archaeology. On the other hand, new 3D visualization techniques permit the exploration of digital objects and navigation of reconstructed scenes while new devices allow the management and visualization of data in an interactive and/or immersive way. 3D visualization techniques and devices are employed to best effect in the design and development of video games, however their uses are rapidly diversifying and it is becoming more and more common to find them in different areas, from medicine to tourism, from simulation to archaeology.

The presented Doctoral Thesis applies 3D recording, modeling and visualization techniques to different scales of size (artefact, architecture and landscape), while always focusing on the field of Cultural Heritage. The main goal is the research of the most suitable solution based on the case study and integrating, where necessary, different sensors, techniques and/or devices that allow an efficient management and dissemination of heritage information.

Índice

1. Introducción1

 1.1. Motivación2

 1.2. Objetivos12

 1.3. Estructura14

2. Sección I - Escala artefacto17

 Resumen.....18

 Artículo I - ARCube - The augmented reality cube for archaeology23

3. Sección II - Escala arquitectura51

 Resumen.....52

 Artículo II - Access to complex reality-based 3d models using
virtual reality solutions.....57

4. Sección III - Escala paisaje.....77

 Resumen.....78

 Artículo III - Mobile LiDAR System: new possibilities for the
documentation and dissemination of large Cultural Heritage sites83

5. Conclusiones y perspectivas futuras119

 5.1. Conclusiones120

 5.2. Perspectivas futuras128

Referencias135

Anexo I: Datos estadísticos de las revistas.....145

Anexo II: Otros méritos.....167

Curriculum Vitae.....173

Notas185

Contents

1. Introduction.....1

 1.1. Motivation3

 1.2. Aims.....13

 1.3. Structure.....15

2. Section I - Artefact scale17

 Abstract19

 Article I - ARCube - The augmented reality cube for archaeology.....23

3. Section II - Architecture scale51

 Abstract53

 Article II - Access to complex reality-based 3d models using
virtual reality solutions.....57

4. Section III - Landscape scale77

 Abstract79

 Article III - Mobile LiDAR System: new possibilities for the
documentation and dissemination of large Cultural Heritage sites83

5. Conclusions and future research119

 5.1. Conclusions121

 5.2. Future research129

References135

Annex I: Quality indexes and impact factor of the international journals.....145

Annex II: Others merits.....167

Curriculum Vitae.....173

Notes185

1.
Introduction

1.1. Motivación

La cultura puede considerarse un ser vivo, que crece, se desarrolla, se transforma e incluso perece. El Patrimonio Cultural heredado, ya sea material o inmaterial, crea un vínculo con el pasado que permite documentar, estudiar y conocer a fondo la historia. Por un lado, el *patrimonio material* está representado por artefactos, monumentos, edificios y conjuntos históricos, áreas arqueológicas y lugares paisajísticos naturales que constituyen una simbología histórico-cultural para la población que habita un determinado lugar. Por otro lado, el *patrimonio inmaterial* abarca las normas, éticas, prácticas, tradiciones, costumbres, rituales y conocimiento de la cultura de una determinada civilización.

A lo largo del tiempo, el Patrimonio Cultural se ha visto constantemente amenazado por grandes peligros. Las causas intrínsecas del deterioro habitual de un bien material, a través del paso tiempo, dependen del objeto en sí (ej. materiales de construcción) (Rives and Talegon, 2006). Pero existen además causas extrínsecas ajenas al bien material, que provocan grandes erosiones, dependiendo de factores externos difíciles u imposibles de controlar, tales como; los factores ambientales (ej. luz, temperatura, humedad o contaminación) (Watt et al., 2009), biológicos (ej. aves, líquenes, hongos, etc.) (Sterflinger y Piñar, 2013), antropogénicos (ej. desgaste por uso o manipulación, abandono) (Mohd Shukuri y Awang, 2014), catastróficos (ej. desastres naturales como incendios, inundaciones o terremotos) (Drdácký et al., 2007) e incluso aun peor, bélicos (ej. destrucción por parte del hombre) (Fisher, 2017).

Las **técnicas de digitalización y modelación 3D** (Stylianidis y Remondino, 2016) aplicadas al campo del Patrimonio Cultural son de gran utilidad para la preservación de los bienes materiales, ya que permiten documentar su estado actual de una forma precisa y detallada, sin necesidad de entrar en contacto con el objeto de estudio y dañarlo. Geotecnologías como la fotogrametría terrestre y aérea (UAV) (Remondino, 2014), el Láser Escáner Terrestre (TLS), Aerotransportado (ALS) y los Sistemas LiDAR Móviles (MLS) (Vosselman y Maas, 2010), junto con los Sistemas de navegación por satélite (GNSS) permiten la digitalización y monitorización

1.1. Motivation

Culture can be considered a living being, which grows, develops, transforms and even perishes. Inherited Cultural Heritage, both material and non-material, creates a strong link to the past that allows for the in depth documentation, study and understanding of history. On the one hand, *tangible heritage* constitutes artefacts, monuments, buildings and architectural complexes, as well as archaeological sites and natural landscapes. These establish a historical-cultural symbolism for the population that inhabits a certain place. On the other hand, *intangible heritage* encompasses the rules, ethics, practices, traditions, customs, rituals and knowledge around the culture of a specific civilization.

Over the years, Cultural Heritage has been constantly threatened by great dangers. The intrinsic causes of the habitual deterioration of a physical fabric through the passage of time depend on the object itself (e.g. building materials) (Rives and Talegon, 2006). However, there are also extrinsic causes beyond the physical material itself, which cause great erosion. These are based around external factors which are difficult or impossible to control, such as environmental (e.g. light, temperature, humidity or pollution) (Watt et al., 2009), biological (e.g. birds, lichens or fungi) (Sterflinger and Piñar, 2013), anthropogenic (e.g. wear and tear, abandonment) (Mohd Shukuri and Awang, 2014), catastrophic factors (e.g. natural disasters such as fires, Earthquakes) (Drdácký et al., 2007) and even worse, war damage (e.g. destruction by man) (Fisher, 2017).

3D recording and modeling techniques (Stylianidis and Remondino, 2016) are very useful for the preservation of the physical materials of Cultural Heritage, since they allow the documentation of the current state in an accurate and detailed way, without the need to come into contact with the studied case and risk damaging it. Geotechnologies such as terrestrial and aerial (UAV) photogrammetry (Remondino, 2014), Terrestrial Laser Scanning (TLS), Airborne (ALS) and Mobile LiDAR Systems (MLS) (Vosselman and Maas, 2010) together with Global Navigation Satellite Systems (GNSS) allow digitalization and monitoring from different elevations. Active and passive

desde diferentes alturas. Sensores activos y pasivos generan densas nubes de puntos que permiten obtener complejas reconstrucciones 3D foto-realísticas basadas en la realidad (Remondino, 2009). Por otro lado, sensores térmicos (Sidiropoulou-Velidou et al., 2012), multi-espectrales (Del-Pozo-Aguilera et al., 2016), la Espectroscopia Raman (Casadio et al., 2016), la magnetometría o el Radar de Sondeo (GPR) (Gaffney et al., 2012), entre otros, permiten el estudio de patologías, el análisis de los datos o la búsqueda de nuevos yacimientos. A menudo encontramos casos de estudio complejos o grandes áreas, donde un enfoque multi-resolución (Remondino et al., 2009), la integración sensorial (Conde et al., 2016) (Nex y Rinaudo, 2011) o la fusión de datos (Ramos y Remondino, 2015) es la mejor opción a la digitalización. Los archivos generados permiten estudiar el objeto en cuestión en cualquier momento, así como extraer información geométrica y radiométrica útil para su conservación, restauración o reconstrucción física (facsimil¹) (Lowe et al., 2010) (Lowe y Ahmon, 2004). A día de hoy, los avances técnicos permiten reconstruir incluso áreas inexistentes del Patrimonio Cultural perdido (Grün et al., 2004) (Wahbeh et al., 2016).

Las técnicas de levantamiento y modelación 3D forman actualmente parte fundamental de la conservación preventiva, que tiene como objetivo impedir, retrasar y reducir el posible deterioro o pérdida del Patrimonio Cultural material, ya sea debido al impacto social, económico u ambiental. Se trata de proteger los bienes patrimoniales de tal forma que puedan ser transmitidos a futuras generaciones, salvaguardando su conservación, su significado y su valor artístico, histórico y social. La desventaja solo se encuentra en el peso de los datos que dichas técnicas generan, por lo que la optimización (Guidi y Angheleddu, 2016) (Jiménez Fernández-Palacios et al., 2013) y la segmentación (Manferdini y Remondino, 2012) de los modelos digitales se convierte en un paso de vital importancia para la carga y gestión de los datos (Ponchio y Dellepiane, 2016), fines analíticos (ej. CAD, (H)BIM o FEM) (Chiabrando et al., 2016) (Sánchez-Aparicio et al., 2016), didácticos y/o divulgativos (Torres-Martínez et al., 2016).

sensors generate dense point clouds allowing for the construction of complex reality-based 3D models (Remondino, 2009). On the other hand, thermal (Sidiropoulou-Velidou et al., 2012) and multi-spectral (Del-Pozo-Aguilera et al., 2016) sensors, Raman spectroscopy (Casadio et al., 2016), magnetometry or Ground Penetrating Radars (GPR) (Gaffney et al., 2012), among others, enable the carrying out of pathological studies, data analysis or searches of new archaeological sites. Often, complex case studies or large areas are surveyed, where a multi-resolution (Remondino et al., 2009), sensory integration (Conde et al., 2016) (Nex and Rinaudo, 2011) or data fusion approach (Ramos and Remondino, 2015) is the best option for 3D recording and modeling. The generated 3D data enables study of the object at any moment, as well as the extraction of geometric and radiometric information useful for conservation, restoration or physical reconstruction purposes (facsimile¹) (Lowe et al., 2010) (Lowe and Ahmon, 2004). Nowadays, technological advances even allow for the reconstruction of pre-existing areas of Cultural Heritage now lost to us (Grün et al., 2004) (Wahbeh et al., 2016).

3D surveying and modeling techniques are a fundamental part of preventive conservation, whose aims are to prevent, delay and reduce the possible damage or loss of tangible Cultural Heritage, whether due to social, economic or environmental impacts. The aim is to protect patrimonial assets and ensure their passing on to future generations, as well as to safeguard their conservation and artistic, historical and social value. The unique disadvantage is the weight of data that these techniques generate. This is why the techniques of optimization (Guidi and Angheleddu, 2016) (Jiménez Fernández-Palacios et al., 2013) and segmentation (Manferdini and Remondino, 2012) are a fundamental step forward for data loading and management (Ponchio and Dellepiane, 2016), analyses (e.g. CAD, (H)BIM or FEM) (Chiabrando et al., 2016) (Sánchez-Aparicio et al., 2016) or dissemination (Torres-Martínez et al., 2016).

Asimismo, las **técnicas de visualización 3D** abren un vasto campo de aplicaciones, mediante nuevas tecnologías y dispositivos que permiten al usuario interactuar con objetos digitales y navegar a través de una escena reconstruida. Además, un modelo digital basado en la realidad que representa un bien material puede ser enriquecido con información, bien referente al objeto en sí o bien con información del patrimonio inmaterial referente al lugar y a la cultura (ej. textos, documentos, imágenes y videos monoscópicos o estereoscópicos, etc.). Realizar una reconstrucción digital a partir de fragmentos (Arbace et al., 2013) contextualizar un objeto, enriquecerlo con información histórica y analizarlo (Stefani et al., 2013), recrear escenas a través de la interpretación de los datos adquiridos (Pescarin et al., 2006) y realizar simulaciones a través del tiempo (4D) (Rodríguez-González et al., 2017), son algunas de las aplicaciones que nos ofrecen las nuevas tecnologías. La visualización Web explota los recursos online para servir de base a navegadores, aplicaciones, sistemas y plataformas (De Luca et al., 2010) (Potenziani et al., 2015) (Schwerin et al., 2013) tanto para la visualización de modelos 3D como para el análisis de los datos a distancia. A día de hoy, tecnologías de vanguardia como la realidad aumentada (Carmigniani y Furht, 2011) y la realidad virtual (Christou et al., 2006) se consolidan, gracias a su versatilidad y a la interacción intuitiva del usuario a través del uso de diferentes dispositivos como smartphones (Pietroni, 2012), cascos (ej. Oculus Rift, HoloLens, etc.) (Gonizzi Barsanti et al., 2015) y sensores 3D (ej. Kinect, Leap Motion, etc.) (Pescarin et al., 2013) (Richards-Rissetto et al., 2012). Nacidas para los video-juegos han demostrado con creces su utilidad en innumerables disciplinas (ej. el mundo del entretenimiento, la educación, el turismo, la arquitectura, la industria o la simulación) y ahora revolucionan el mundo de los museos (Pescarin, 2014) (Pietroni et al., 2012).

Un aspecto fundamental para la reconstrucción, el análisis y la visualización del Patrimonio Cultural es el concepto de **escala de trabajo**, el cual representa un factor determinante y estratégico en la toma de decisiones, estando directamente relacionado con la elección de las tecnologías de digitalización, modelización y visualización 3D más adecuadas. Conocer los problemas que presentan la captura de información, la modelización y la visualización en

Likewise, **3D visualization techniques** open up a vast field of applications, using new technologies and devices that allow the user to interact with digital objects and navigate through reconstructed scenes. In addition, reality-based digital models, which constitute physical materials, can be improved by adding information either in reference to the tangible object or with information about the intangible heritage concerning place and culture (e.g. texts, documents, monoscopic or stereoscopic images and videos, etc.). Some of the applications that new technology offers are as follows: contextualization of an object by performing a digital reconstruction from fragments acquired (Arbace et al., 2013); enrichment of an object with historical information and analysis of same (Stefani et al., 2013); recreation of scenes based on the interpretation of data acquired (Pescarin et al., 2006); simulations of trends over set time periods (4D) (Rodríguez-González et al., 2017). Web visualization exploits online resources to create browsers, applications, systems and platforms (De Luca et al., 2010) (Potenziani et al., 2015) (Schwerin et al., 2013) for both remote visualization and data analysis of 3D models. Nowadays, cutting edge technologies such as augmented reality (Carmigniani and Furht, 2011) and virtual reality (Christou et al., 2006) are well developed, thanks to their versatility and intuitive user interaction through the use of different devices such as smartphones (Pietroni, 2012), headsets (e.g. Oculus Rift, HoloLens, etc.) (Gonizzi Barsanti et al., 2015) and 3D sensors (e.g. Kinect, Leap Motion, etc.) (Pescarin et al., 2013) (Richards-Rissetto et al., 2012). Invented originally for video games, these technologies have proven their usefulness in countless disciplines (e.g. the world of entertainment, education, tourism, architecture, industry or simulation) and now they are revolutionizing the museum world (Pescarin, 2014) (Pietroni et al., 2012).

The work scale concept is a fundamental key to the reconstruction, analysis and dissemination of Cultural Heritage objects and sites. It is a determinant and strategic factor for decision making, being directly related to the choosing of the more suitable technologies for 3D recording, modeling and visualization. Knowing the problems that data capture represents, modeling and real-time visualization of large digital datasets allows us to investigate in depth

tiempo real de grandes conjuntos de datos digitales, permite investigar a fondo las posibles soluciones en función del caso de estudio y su complejidad. Como consecuencia, la presente Tesis Doctoral aborda y estudia dichos problemas en base a la escala², donde la línea de investigación principal se plantea a partir de tres casos generales de estudio, clasificando el Patrimonio Cultural como: *artefacto*³, *arquitectura*⁴ y *paisaje*⁵ (Kraak y Ormeling, 2011). La búsqueda de soluciones comienza por resolver los problemas que presentan los objetos de pequeñas dimensiones con el objetivo de llegar a cubrir las exigencias generadas por las grandes áreas. Dicha elección se establece, no porque los objetos de pequeñas dimensiones presenten problemas más simples para la adquisición o la visualización de los datos, sino porque debido a su tamaño, el peso de los datos generados es menor y por tanto se agiliza el tiempo de procesado, minimizándose los problemas de gestión de datos.

A continuación se detallan las características generales de cada grupo, en base a la escala de trabajo, motivación por la cual serán elegidas las técnicas y metodologías más adecuadas para cada situación:

Un pequeño objeto (escala artefacto), gracias a su peso y tamaño, se puede mover, girar, o incluso transportar, para realizar una adecuada y completa adquisición de los datos. Un artefacto presenta con frecuencia formas complejas, incisiones, rasgos, o detalles sutiles que deben ser documentados y reconstruidos digitalmente, a menudo con una resolución sub-milimétrica. El usuario puede sostenerlo y observarlo desde su exterior, pero por lo general no desde su interior.

Un monumento u edificio histórico (escala arquitectura) ha sido construido sobre el terreno (suelo urbano o rural). Está anclado, no se puede mover y menos aún transportar. Tiene, generalmente, una dirección dominante a lo largo del eje Z. Puede contener uno o varios ambientes y en función de la complejidad de su arquitectura podemos encontrar oclusiones provocadas por estructuras, sombras, vegetación, etc. que dificulten la toma de datos. Generalmente es necesario capturar la información desde diferentes posiciones hasta cubrir

the possible solutions based on the case study and its complexity. As a consequence, this Doctoral Thesis outlines and studies the problems in relation to scale², where the main line of research is based on three general cases of study, classifying Cultural Heritage as: *artefact*³, *architecture*⁴ and *landscape*⁵ scale (Kraak and Ormeling, 2011). The search for solutions begins by solving the problems presented by small objects with the aim of meeting at a later stage the requirements generated by large areas. This choice is established, not because small objects present simpler problems for data acquisition and visualization, but because due to their size the weight of the generated data is smaller and so processing time is streamlined, thus minimizing the problems of data management.

Outlined below are the general characteristics of each group, based on the scale of work. These constitute the fundamental motives for choosing the most appropriate techniques and methodologies for each situation:

A small object (artefact scale), due to its weight and size, can be moved, rotated, or even transported. It allows for data capture in an appropriate and complete way. Often, artefacts possess complex shapes, incisions, features, or subtle details that must be digitally documented and reconstructed with a sub-millimeter resolution. In general, the user can hold and observe it from the exterior, but not from its interior.

A monument or historical building (architecture scale) has been built on the ground (urban or rural land). It is anchored, cannot be moved and even less transported. It generally has a dominant direction along the Z axis, can contain more than one environment and, depending on its architectural complexity, structures, shadows or vegetation - among others - can cause occlusions which make data collection difficult. Commonly it is necessary to source information from different positions until the area of interest is completely covered. Often it can be seen both from the exterior and from the interior. In these cases, it is necessary to digitize both parts and to integrate them in order to obtain a complete representation of reality. Architecture scale may contain objects classified as artefact scale.

por completo el área de interés. Pueden llegar a ser vistos tanto desde el exterior como desde su interior. En estos casos será necesario digitalizar ambas partes, e integrarlas, para obtener así una fiel representación de la realidad. La escala arquitectura puede contener elementos clasificados como escala artefacto.

Un área histórica o arqueológica (escala paisaje), es una extensa área que forma parte del terreno urbano y/o rural. Inmóvil, puede estar formado por uno, múltiples y/o diferentes ambientes, tanto edificados como exentos de construcción. Se desarrolla, principalmente, en los ejes X e Y. Es probable encontrar oclusiones que afecten a la adquisición de los datos, de la misma naturaleza que en la escala arquitectura, sin embargo, en función de la complejidad y la extensión del complejo arquitectónico o paisaje, estas oclusiones pueden ser mayores y por tanto representar problemas más graves en la toma de datos, incrementando los tiempos de recogida de la información. Debido a las grandes extensiones que presenta la escala paisaje, estas zonas suelen ser vistas por el usuario desde su interior, siendo necesaria una perspectiva aérea para abarcarlas en su totalidad. La escala paisaje puede contener a su vez elementos clasificados como escala arquitectura y/o escala artefacto.

A historical or archaeological area (landscape scale) is an extensive area that forms part of the urban and/or rural terrain. Immobile, it may consist of one, multiple and/or different environments. Whether artificially constructed or not, it is developed mainly on the X and Y axes. Occlusions are commonly present and of the same nature as in the architecture scale, which can affect the acquisition of data. However, due to the complexity and the extension of the architectural complex or landscape, these occlusions can be larger and therefore represent more serious problems for data collection, thus increasing the acquisition time. Due to the large dimensions of the landscape scale, they are usually seen by the user from the interior, making an aerial perspective necessary if it is to be seen in its entirety. Landscape scale may contain scenes and objects classified as architecture and/or artefact scale.

1.2. Objetivos

La investigación desarrollada por la presente Tesis Doctoral tiene como **objetivos generales**:

- Estudiar y evaluar las diferentes *técnicas de digitalización y modelación 3D* (sensores activos y pasivos) para su aplicación al campo del Patrimonio Cultural.
- Investigar y desarrollar nuevas *metodologías de optimización* para una adecuada gestión y visualización en tiempo real de complejos conjuntos de datos 3D.
- Investigar y desarrollar nuevas vías de *análisis, gestión, visualización y difusión* de complejos *modelos 3D* para promover el conocimiento del Patrimonio Cultural.

Para cubrir tales necesidades, y dada la gran disparidad de casos existentes, nacen nuevos **objetivos específicos**:

- Integrar técnicas, sensores y metodologías^{7,9,10} en función de la escala y la complejidad del caso de estudio, para digitalizar, modelizar y visualizar objetos o escenas 3D del Patrimonio Cultural.
- Aplicar, desarrollar y evaluar técnicas específicas de realidad aumentada⁶, realidad virtual⁷ y visualización Web¹¹ en aplicaciones relacionadas con el Patrimonio Cultural.
- Desarrollar nuevos métodos de segmentación automática⁶ y semi-automática⁸ para la optimización de complejos modelos 3D a diferentes escalas de trabajo.
- Fusión de datos métricos y no métricos 2D y 3D^{7,11}, añadiendo información temporal como cuarta dimensión 4D¹².

1.2. Aims

The line of research developed by the presented Doctoral Thesis has the following **general objectives**:

- Study and evaluation of the different *3D recording and modeling techniques* (active and passive sensors) applied to the field of Cultural Heritage.
- Research and development of new *optimization methodologies* for a real-time management and visualization of complex 3D data sets.
- Research and development of new ways of *analysis, management, visualization and dissemination* of complex reality-based 3D models to promote knowledge of Cultural Heritage.

In order to cover those needs, and given the great disparity of existing case studies, new **specific objectives** emerge:

- The integration of techniques, sensors and methodologies^{7,9,10} according to the scale and complexity of the case study, in order to 3D record, model and visualize Cultural Heritage objects and sites.
- The application, development and evaluation of specific techniques of augmented reality⁶, virtual reality⁷ and web visualization¹¹ for Cultural Heritage applications.
- The development of new automatic⁶ and semi-automatic⁸ segmentation methods to optimize complex 3D models at different work scales.
- Fusion of metric and non-metric 2D and 3D data^{7,11}, adding temporary information as a fourth dimension 4D¹².

1.3. Estructura

La presente Tesis Doctoral, regida a través del Reglamento de Doctorado de la Universidad de Salamanca (regulado por el R.D. 1393/2007), se basa en la modalidad de compendio de artículos científicos, publicados por Revistas Internacionales de Impacto. Está compuesta por tres artículos originales indexados en JCR y su estructura se desarrolla a través de cinco secciones, detalladas a continuación:

Una sección introductoria a modo de preámbulo que expone las motivaciones que crean y guían la línea de investigación desarrollada a través de tres casos de estudio, donde el Patrimonio Cultural material es clasificado en base a la escala de trabajo, como: artefacto, arquitectura y paisaje. Asimismo se establecen los objetivos generales y específicos de la investigación llevada a cabo. Tres secciones que constituyen el cuerpo de la Tesis Doctoral y que se concretan en los tres estudios realizados a diferentes escalas del Patrimonio Cultural, publicados todos ellos en revistas científicas de impacto. Una sección final donde se exponen las conclusiones generales y/o específicas para cada caso de estudio: artefacto, arquitectura y paisaje. Asimismo, son presentadas nuevas perspectivas y posibles líneas de investigación, dejando una puerta abierta a futuros estudios.

1.3. Structure

The presented Doctoral Thesis, governed by the Doctorate Regulation of the University of Salamanca (regulated by R.D. 1393/2007), is based on the form of a compendium of scientific articles published by international journals of impact factors. It is composed of three original articles indexed in JCR and its structure is developed through the five sections detailed below:

An introductory section as a preamble, explaining the relevant reasons that created and guided the line of research developed through three case studies, where the material Cultural Heritage is classified according to the work scale as: artefact, architecture and landscape. Likewise, the general and specific aims of the research carried out are established. Three sections that constitute the basis of the Doctoral Thesis, focus on the three case studies carried out at the different scales of Cultural Heritage and are all published in scientific journals of impact factor. A final section where the general and specific conclusions for each case study are presented: artefact, architecture and landscape. Furthermore, new perspectives and possible research lines are proposed, opening a door to future studies.

2.

Section I - Artefact scale

Sección I - Escala artefacto

La presente sección contiene el artículo “*ARCube - The augmented reality cube for archaeology*” (ARCube – El cubo de realidad aumentada para la arqueología) publicado en Julio de 2015 en la Revista Internacional de Impacto (JCR) Archaeometry.

Resumen

La línea de investigación desarrollada en el presente artículo se centra en el estudio de los objetos clasificados anteriormente como escala artefacto y tiene como finalidad la utilización de técnicas de realidad aumentada para crear un mejor acceso a la información, visualizar y analizar el Patrimonio Cultural.

En primer lugar, se verifica la gran utilidad de las técnicas de digitalización 3D de alta precisión, como el láser escáner por triangulación y la fotogrametría de corto alcance, para la reconstrucción y modelización digital 3D de dichos objetos.

En segundo lugar, se especifican las motivaciones por las cuales se apuesta por el uso de la realidad aumentada para la visualización de artefactos, las tecnologías que lo permiten, y el desarrollo del sistema de bajo coste llamado ARCube, para la visualización y el análisis de hallazgos arqueológicos (escala artefacto). ARCube permite interactuar virtualmente con complejos objetos 3D, girándolos en 360º posibilita una adecuada exploración de todos los detalles, en alta resolución y en tiempo real.

Para obtener una fluida visualización de complejos objetos digitales en tiempo real, son desarrollados nuevos métodos de segmentación u optimización: (i) el método de la pirámide, (ii) el método de visibilidad frontal y (iii) el método del vector normal. Además, ARCube ofrece una visualización interactiva de los hallazgos arqueológicos a escala 1:1, entre el objeto digital y real. El sistema de bajo coste, para la visualización interactiva de hallazgos arqueológicos, permite el estudio de objetos digitales fomentando tanto la investigación

Section I - Artefact scale

This section contains the scientific article entitled: “*ARCube - The augmented reality cube for archaeology*” published in July 2015 by the International Journal (JCR) of Archaeometry.

Abstract

The line of research developed in this article focuses on the study of the objects previously classified as artefact scale and the main goal is the use of augmented reality techniques to create better access to information, and to visualize and analyse Cultural Heritage objects.

First of all, the usefulness of high-resolution 3D recording techniques, such as triangulation laser scanning and close-range photogrammetry, is verified for the digital reconstruction and modeling of artefact scale.

Secondly, this paper specifies the motivations for the use of augmented reality for the visualization of complex artefacts, the technologies that allow it, and the development of the low cost-system known as ARCube for the visualization and analysis of archaeological findings of artefact scales. ARCube enables us to interact virtually with complex digital 3D objects by rotating them in 360º, which allows an adequate exploration of all details, in high resolution and in real time.

To obtain a fluid real-time visualization of complex digital objects, new segmentation methods for optimization purposes are implemented: (i) the pyramid method, (ii) the frontal visibility method and (iii) the normal vector method. In addition, ARCube offers an interactive visualization of archaeological findings at a 1: 1 scale between the digital and the real object.

The case studies carried out for the artefact scale come from the archaeological sites of Mezzocorona and Dalmeri in Trento, as well as the Etruscan Museum of Chianciano in

como la educación, ofreciendo nuevas vías de investigación a la arqueología.

Los objetos estudiados para la escala artefacto provienen de las zonas arqueológicas de Mezzocorona y Dalmeri, en Trento, así como del Museo Etrusco de Chianciano, en Toscana, Italia. Todos ellos fueron escogidos por sus diferentes características geométricas y radiométricas (forma, textura y color) con el objetivo de realizar múltiples test garantizando así la fiabilidad de la metodología propuesta.

Tuscany, Italy. The artefacts were chosen based on their different geometric and radiometric features (shapes, materials and colours) with the aim of performing multiple tests and thus guaranteeing the reliability of the proposed methodology.

Article I

ARCube - The augmented reality cube for archaeology

ARCube—THE AUGMENTED REALITY CUBE FOR ARCHAEOLOGY*

B. JIMÉNEZ FERNÁNDEZ-PALACIOS,^{1,2†} F. NEX,¹ A. RIZZI³ and F. REMONDINO¹

¹3D Optical Metrology Unit, Fondazione Bruno Kessler, Via Sommarive 18, Trento, Italy

²Department of Cartographic and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, Avila 05003, Spain

³SMART3K S.R.L., Via Sommarive 18, Trento, Italy

Augmented Reality (AR) allows the direct and intuitive access of digital objects visualized in real time on computer screens. AR applications are commonly used in many different areas, such as entertainment, sports and tourism, while their use in archaeology is still limited. When employed, current archaeological AR applications use expensive devices or flat targets, which are insufficient for visualizing complex artefacts. In this paper, we present a low-cost, automated method called the ARCube System, which allows the expansion and enrichment of AR applications focused on archaeological objects. In this paper, the newly developed ARCube System is described by presenting several archaeological examples to show the system's ability to visualize and investigate archaeological finds. The reported tests demonstrate the method's reliability on a variety of objects characterized by different shapes and sizes. The ARCube System allows users to interact with digital 3D models, rotate them through 360° and explore details in high resolution (without any risk of damaging the find). The system renders 1:1 scale between digital and actual object and offers a low-cost flexible system for the interactive visualization of archaeological finds that can be beneficial to public research (e.g., museum exhibits) and education (e.g., the classroom) and may possibly lead to new avenues of archaeological research.

KEYWORDS: AUGMENTED REALITY, COMPLEX 3D MODELS, VISUAL INSPECTION, ARCHAEOLOGY, MULTI-TARGET

INTRODUCTION

Augmented Reality applications offer a live, direct or indirect, view of a physical, real-world environment in which elements are augmented (or modified) by computer-generated sensory inputs such as sound, video, graphics, maps or global navigation satellite system (GNSS) positions (<http://www.fondazioneaquileia.it/>; [Ciolfi and Bannon 2002](#); [Pacheco *et al.* 2014](#)), adding information to real scenes. In contrast to virtual reality, where the real world is replaced by a simulated one, AR is typically in real time and in semantic context with environmental elements ([Balog *et al.* 2007](#)). The number of Augmented Reality (AR) applications has been increasing, and now includes gaming, entertainment, education and visualization (<http://www.mashable.com>; <http://www.tripwiremagazine.com>). It is a cutting-edge technology that varies from conventional applications, such as visualizing the virtual ball position on TV during sporting events, up to more complex applications, when digital information about objects and their environment is overlaid on to the real world (Fig. 1). While AR has many entertainment uses, it also has possibilities for industry: motor companies such as Toyota, Kia and BMW have developed applications that use AR glasses to assist mechanics in performing automobile maintenance; simulators of robot-assisted

*Received 3 May 2013; accepted 10 March 2014

†Corresponding author: email bjfernandez@fbk.eu

© 2014 University of Oxford

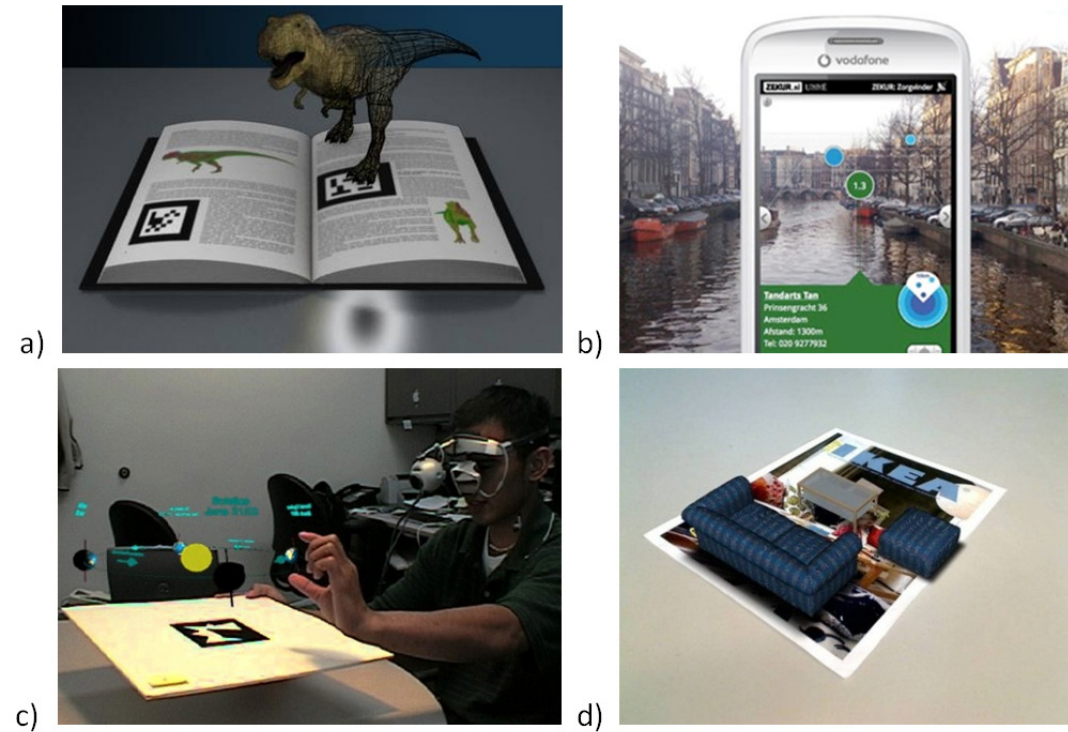


Figure 1. Original image, *ARCube - The augmented reality cube for archaeology*, *Archaeometry*.



Figure 1 (a) Already available AR applications for pop-up books (from <http://www.junaio.com>), (b) tourist information, (c) educational purposes (from <http://www.hitlabnz.org>) and (d) commercial applications (from <http://goldsealnews.com>).

surgery systems based on AR techniques have been developed for training surgeons (Matu *et al.* 2014). In addition, many companies, such as iPhone, Google and BlackBerry, have developed apps based on AR that superimpose additional real-time information on images acquired by smartphones, such as the location of shops, road information and so on (<http://www.junaio.com>; <http://www.augmented-reality.fr/cest-quoi-la-realite-augmentee/des-exemples-dutilisation-de-la-realite-augmentee/>; <http://www.augmentedrealitytrends.com/>). Last but not least, Google has started some revolutionary projects, such as Project Glass, for the development of an AR head-mounted display (HMD) (<http://www.googleglassproject.org/>).

The wide range of applications suggests that AR devices could also be very important for investigating archaeological objects. Advanced AR technology can enable archaeologists to edit and interact with digital artefacts in a real-world context. It offers a non-destructive way for archaeologists, art historians and other scholars to examine objects, providing high-resolution detail of objects (depending on the quality of the 3D model) without damaging, dirtying or altering the objects. Researchers located in different locations can simultaneously investigate the same objects, thus facilitating data sharing and collaboration, and ultimately enriching unique experiences for visitors in museums as well as becoming an intuitive device for educational purposes.

AR in archaeology has already been employed in the development of interactive tour guides using smartphones (Wang *et al.* 2011; Niedermair and Ferschin 2012), tablet devices (Vassilios *et al.* 2003) or interactive books (so called AR pop-up books) for very specific applications (Papagiannakis *et al.* 2005; <http://www.electricarchaeology.ca>). More expensive applications have been developed using special glasses and screens (Benko *et al.* 2004; Zöllner *et al.* 2009).

Many of these archaeological applications tend to focus on entertainment, gaming or tourism (Fig. 1) (Barceló 2000; Vassilios *et al.* 2003; Caarls *et al.* 2009; Noh *et al.* 2009; Garagnani and Manferdini 2011); however, the use of AR for research applications is limited to a few examples (<http://www.ucl.ac.uk/museums/petrie/research/research-projects/3dpetrie>), because AR is often considered insufficient for scientific use in the visualization of scaled, detailed and metrically correct objects. Then, another shortcoming arises because most applications employ a single coded target tracked by a webcam that does not allow for pivoting of the object, but that allows the visualization of objects only when they are tilted at less than 50° with respect to the webcam. When the tilt angle exceeds 50°, current software cannot correctly set the target in the space. The result is that 3D models are not properly visualized on screen. For archaeology, this problem is particularly relevant because the use of planar targets limits AR visualization to plates or other flat objects, and complex objects (such as figurines, projectile points, statues and jewellery) cannot be easily visualized. As a result, information necessary for research purposes is unavailable (i.e., not visualized).

The ARCube System overcomes some of these limitations: the proposed methodology allows the visualization of complex 3D objects, just by handling a simple cube (the ARCube) and showing the digital replica of the object on the screen. The methodology is based on AR open-source software and low-cost devices; ARCube is flexible for a large number of applications and it prevents the finds from being damaged or soiled, thus becoming a valid instrument for both research and exhibition purposes.

While several free and open-source software programs are available, such as ARSights (<http://www.arsights.com>), ArToolkit (Woods *et al.* 2003) and BuildAR (<http://www.buildar.co.nz>), these software toolkits typically employ single flat targets and thus, they cannot be used ‘out of the box’, but must be adapted to archaeological applications. For these reasons, the new multi-target cube (the ARCube) was developed in order to manage all the possible aspects of complex archaeological 3D models. A 3D Studio Max plug-in was developed to automatically split the 3D model into different overlapping faces and load them in the AR environment for a correct and complete visualization. The presented methodology is a further advancement of an initial work (Jiménez Fernández-Palacios *et al.* 2012), where the potentiality of the approach was shown, but some problems still persisted in the visualization of complex 3D models. In the following sections, the newly developed methodology will be presented and then several tests on reality-based 3D models will be presented to demonstrate the reliability of this methodology for visualizing and accessing archaeological artefacts.

PROCESSING FOR SUB-MODEL GENERATION AND AR VISUALIZATION

The methodology is composed by both hardware and software devices that are concatenated in subsequent steps, as shown in Figure 2. Starting from a 3D model, it is possible to automatically generate a set of sub-models that can be directly loaded in an AR software package. In the following paragraphs, the description of the ARCube and the AR software used is first presented. Then, the methodology to preprocess 3D models for AR applications and the created 3D Studio Max plug-in are reported.

The ARCube device and AR open-source software

The ARCube (Fig. 3 (a)) comprises six targets, one on each face. Each target loads a different part of the 3D model; thus each target must be correctly recognized. Each part of the model has to be

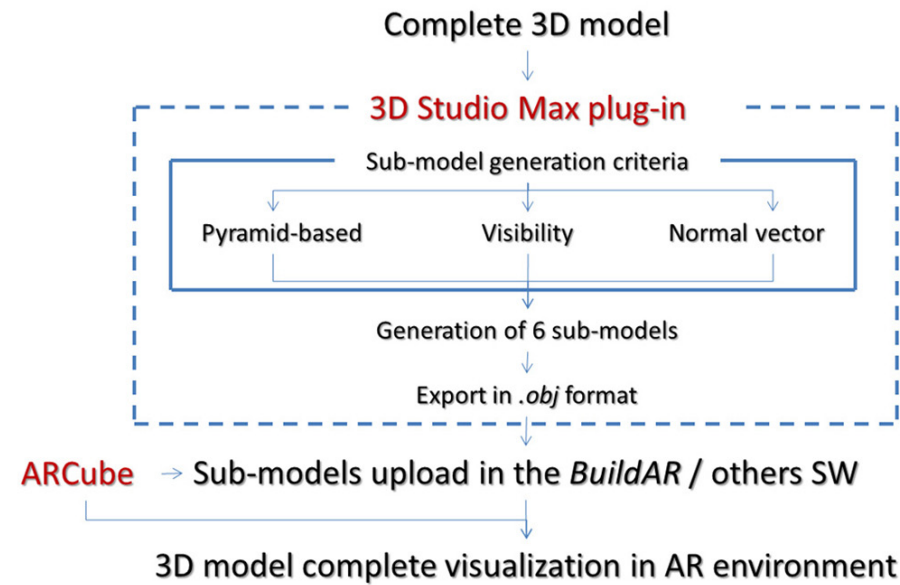


Figure 2. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.

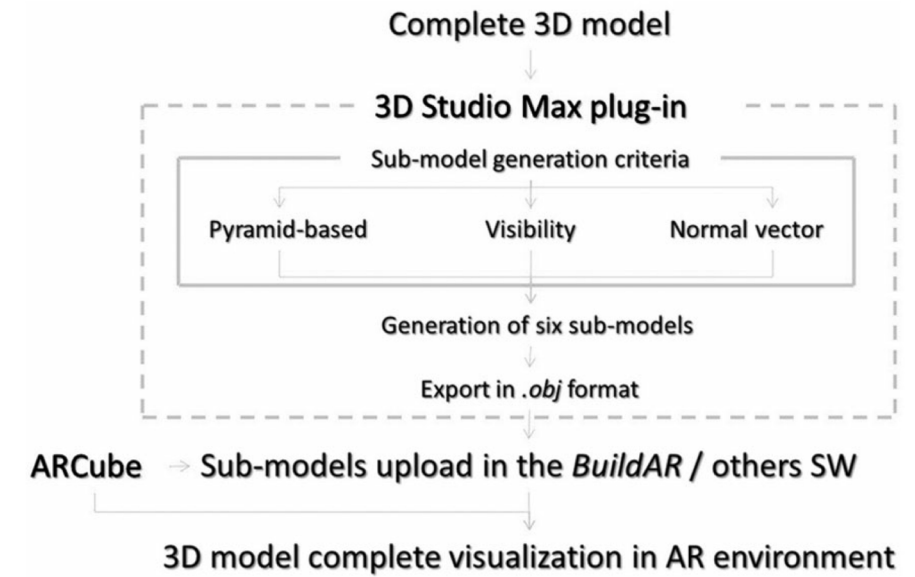


Figure 2 The presented methodology workflow.

associated to a defined face of the cube in an unequivocal way to correctly display the object's geometry. For these reasons, several tests were done to identify the best way to split the 3D models and the most appropriate type of target. The distance of the cube from the webcam was varied, the illumination conditions were changed and different alphanumeric characters on the targets were evaluated, to determine which of them were the most suitable and recognizable without any ambiguity. Finally, the letters A, B, C, D, F and G were chosen, as they assured good results in the tests. Each cube face measures 8×8 cm, because: (1) this is the mean value usually suggested by AR software developers; (2) it allows many archaeological artefacts to be visualized at a 1:1 scale or to be rescaled at a suitable scale; (3) it assures a sufficient resolution for target recognition at a distance up to 1.5 m from the webcam (i.e., with a resolution of 2 megapixels and a focal length of 3.7 mm); and (4) the white edges bound the area where the cube can be handled without preventing the target recognition. For the visualization, the BuildAR software (free version) was used, because it is able to simultaneously manage several models of thousands of triangles and it can work with different file formats.

As for the ARCube, each of its six targets has a reference system that is independent from the others, and the link between the faces and the model tiles must respect the criteria used in their generation, in order to build the correct geometry of the object. Because of this, a rototranslation is applied to each model tile to fit the corresponding ARCube target; each tile of the 3D model is loaded separately into the software and associated to a different target (with the same name). The developed 3D Studio Max plug-in generates models that can be visualized on screen without the need of any further transformation (Fig. 3 (b)). In this way, a key advantage for archaeologists consists of the streamlined and automated AR visualization: the user just has to show the ARCube on the webcam and the model will be visualized on the screen.

ARCube methodology—pre-processing of 3D models

The pre-processing procedure consists of dividing a complete 3D model (normally produced using techniques such as laser scanning, photogrammetry, CG modelling etc.) into six

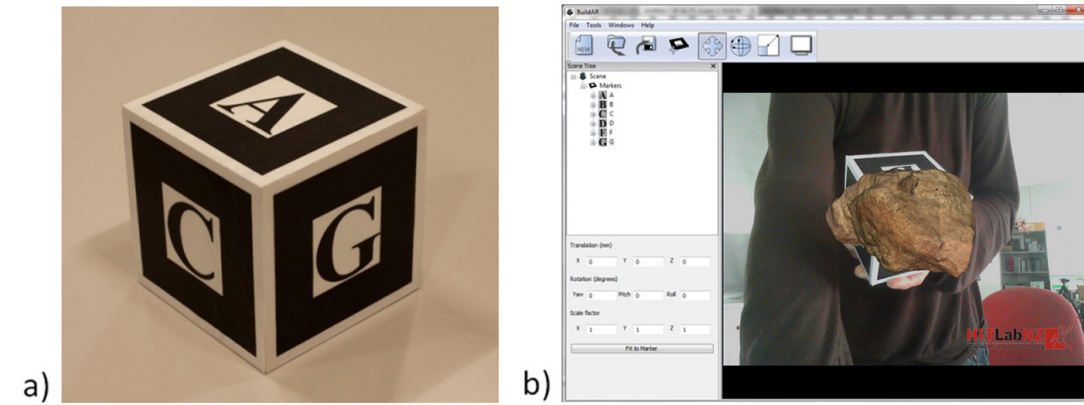


Figure 3. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.

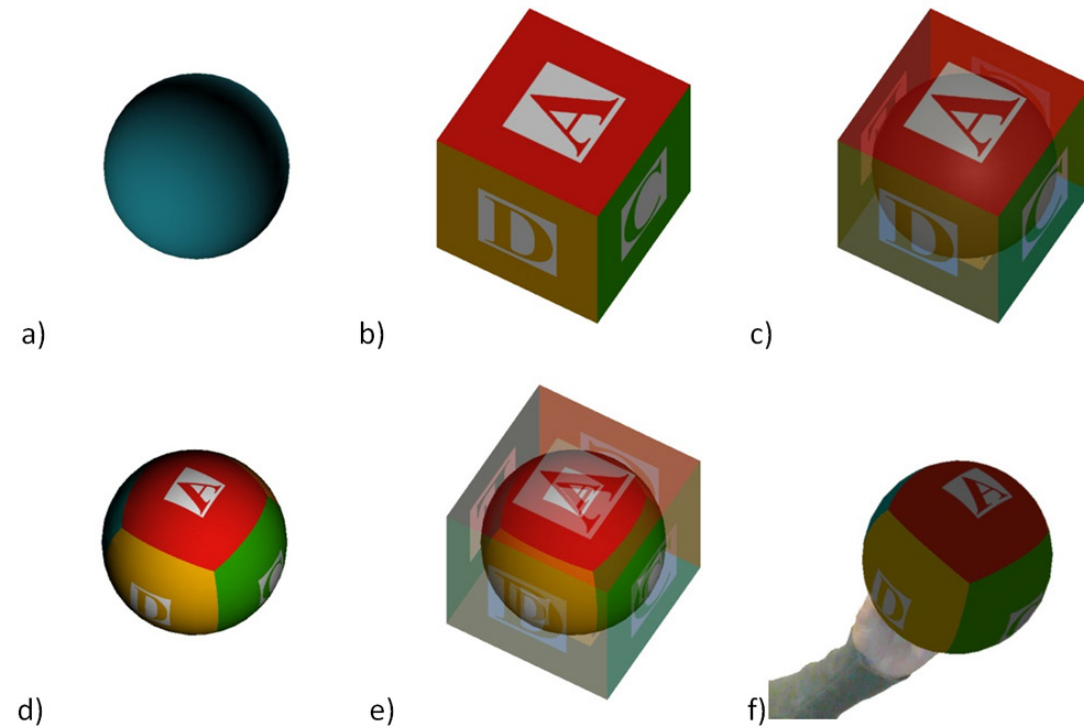


Figure 4. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.

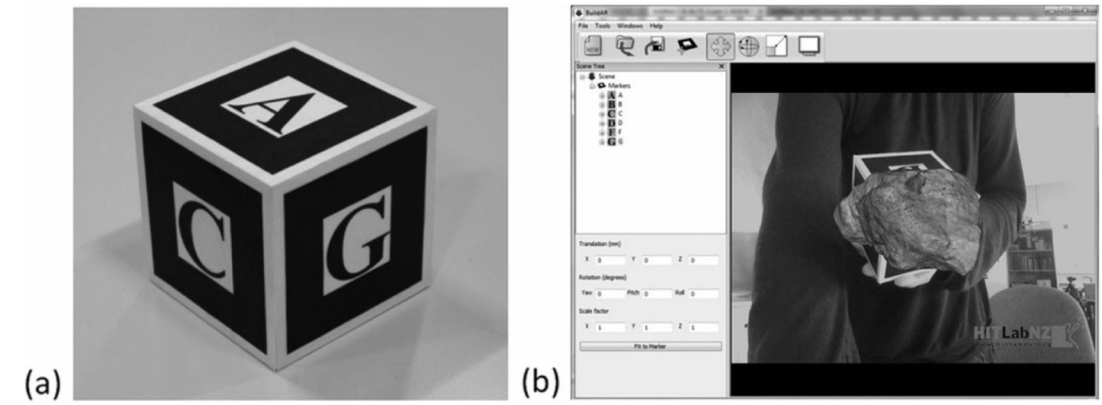


Figure 3 (a) The ARCube device and (b) a screenshot of the employed open-source BuildAR software for the visualization of archaeological artefacts.

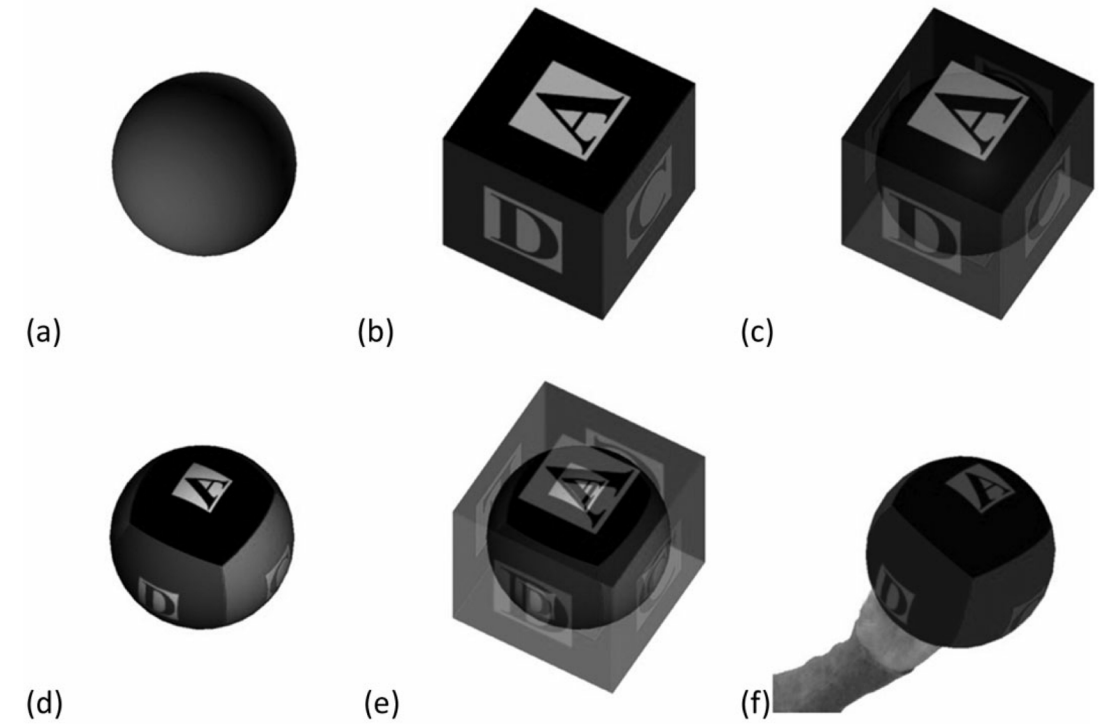


Figure 4 The steps of the methodology: (a) starting from a 3D model (i.e., a sphere), the virtual replica of the ARCube (b) envelopes the considered 3D model (c); the used 3D model (sphere) is divided into six sub 3D models (d), each corresponding to a side of the cube (e); the 3D model is finally visualized in an AR scene.

sub-models that can be directly loaded into the AR software. The pre-processing methodology is split into a series of steps, and for simplicity's sake, a sphere, rather than an actual artefact, is used to explain the methodology (Fig. 4 (a)) in the following.

The ARCube, which is concentric with the sphere, is reproduced virtually and each side of the virtual cube is then named in the same way as the real one, in order to define an unequivocal

association between them and the real cube (Fig. 4 (b)). The virtual cube is initially sized to envelop the test model, in order to approximate its shape and dimension (Fig. 4 (c)).

Then, the test model is divided into six parts (Fig. 4 (d)). To allow sub-models to be loaded and visualized in the AR software, each sub-model is associated with a face on the virtual cube (Fig. 4 (e)) and then to its corresponding target using a letter (A, B, C, D, F or G) (Fig. 4 (f)).

The six sub-models can be generated by intersecting the model with six pyramids, with the vertex in the barycentre of the model (Jiménez Fernández-Palacios *et al.* 2012). This approach needs some additional manual intervention (i.e., translations from the geometric barycentre of the model) to allow a correct automated splitting of objects with complex convex and concave shapes. For this reason, two additional methods for sub-model generation have been implemented. The first method performs a visibility analysis from different points of view, while the second method segments the object according to the values of the local normal vectors to the model surface. In the following sections, the process of subdividing a complex 3D model (a skull model) is shown in order to explain these three methods (pyramid generation, front face visibility and normal vectors) that have been implemented. The pictures shown in Figure 5 refer to the generation of the sub-model that is associated to target A of the cube.

Sub-model generation criteria As already mentioned, the methods are as follows:

(1) *The pyramid method* (Jiménez Fernández-Palacios *et al.* 2012). This method starts with the generation of six pyramids. Each generated pyramid has its base in correspondence with one side (the base of the pyramid and the cube's face are equal) while the top of the pyramid is in the barycentre's cube. The same process is repeated for each side of the cube in order to obtain the six pyramids. The test model is intersected by the pyramids and is divided into six independent sub-models (Fig. 5 (a)).

(2) *The front face visibility method*. Six points of view, each one corresponding to a different face of the virtual ARCube, are defined. Then, all the front face polygons of the model with respect to a defined point of view are selected (Fig. 5 (b)). In this way, each face of the cube is associated to the visible part of the model.

(3) *The normal vector method*. In this method, six different directions are defined, each one perpendicular to a different face of the cube. Then, the values of the normal vector for each polygon of the model are computed and are compared to the normal directions of the faces of the cube. For each face of the cube, the polygons with normal vectors close to the corresponding direction are selected: polygons with normal vector directions that differ by less than 30–40° from the cube face direction are usually selected (Fig. 5 (c)).

These methods can be implemented together in order to assure a complete visualization of the model in every condition. The points selected by at least one of the above-described methods are considered in the sub-model generation of the corresponding face of the cube. If the model is completely concave, the normal vector and the front face methods will provide very similar results: on the other hand, the normal vector method will also allow the loading of hidden and occluded parts with similar normal directions corresponding to convex parts of the model.

For not just a slice (i.e., the newly generated sub-models) but the complete 3D model to be visualized in the AR scene, a smooth transition between each sub-model and its adjacent sub-models must be guaranteed, especially when the cube is rotated. For this reason, overlapping sub-models are usually generated using overlapping pyramids or higher difference values in the normal vector method, as will be described in the 'Case study' section.

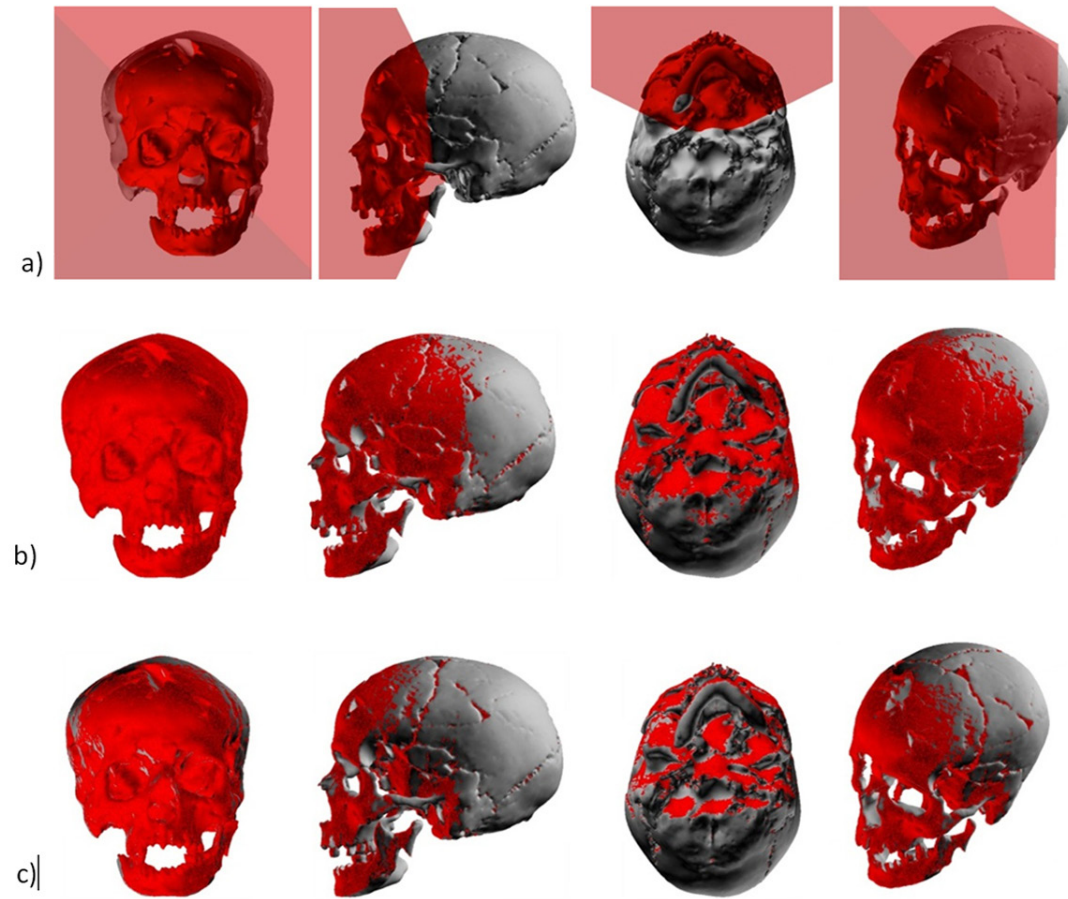


Figure 5. Original image, ARCube - The augmented reality cube for archaeology, Archaeometry.

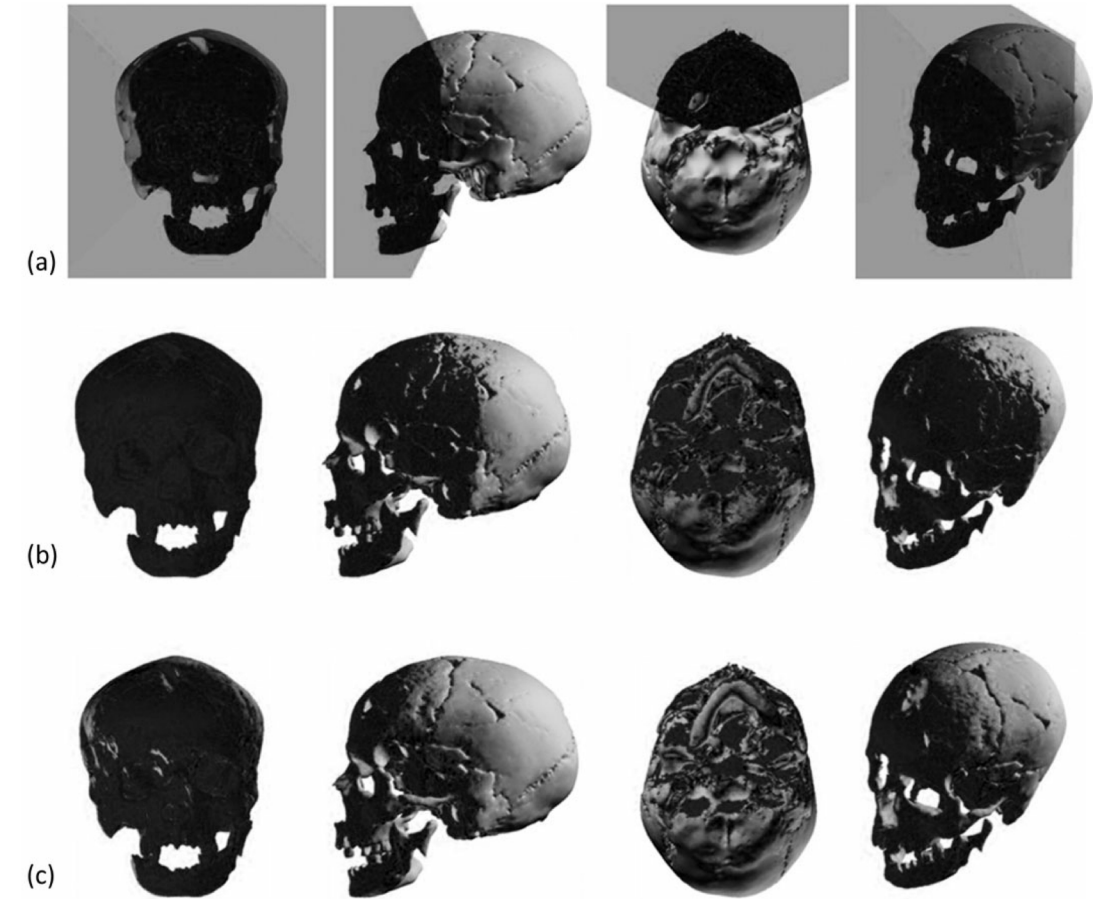


Figure 5 The sub-model generation criteria: (a) the generation of a sub-model using the pyramid method; (b) the generation of a sub-model using the front face visibility method; and (c) the generation of a sub-model using the normal vector method.

The ARCube plug-in for 3D Studio Max

Based on the pre-processing described above, an automatic procedure has been developed in order to obtain a split 3D model that can be directly imported into an AR software program (i.e., BuildAR). 3D Studio Max was chosen because it is commonly used by architects, archaeologists and other professionals for 3D modelling and it permits a straightforward workflow. A number of open-source software programs (e.g., Blender) would have been suitable for this task too.

The MaxScript language, which is natively available in order to customize 3DS Max Design 2011, was used to create the ARCube plug-in (Fig. 6): the script allows users to create personal windows, buttons and dialogue messages to facilitate the user's experience and completely automate the process. Initially, the 3D model is loaded and the export folder is defined in the plug-in window. The barycentre of the object is automatically defined to translate the system coordinate origin on to it; a scaling value can be defined if necessary, to scale the object. The shape and the minimum and maximum dimensions are automatically evaluated by the software in order to generate a virtual box sufficient to envelop the whole model and generate the sub-models in the correct way.

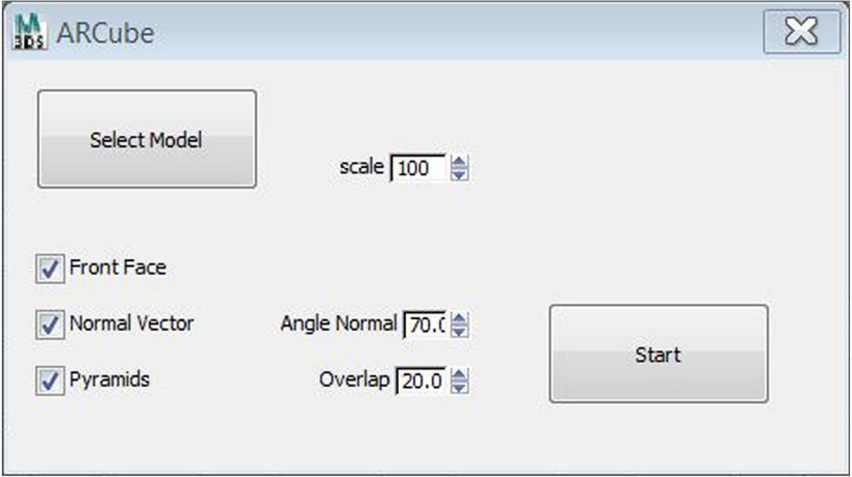


Figure 6. Original image, ARCube - The augmented reality cube for archaeology, Archaeometry.



Figure 7. Original image, ARCube - The augmented reality cube for archaeology, Archaeometry.

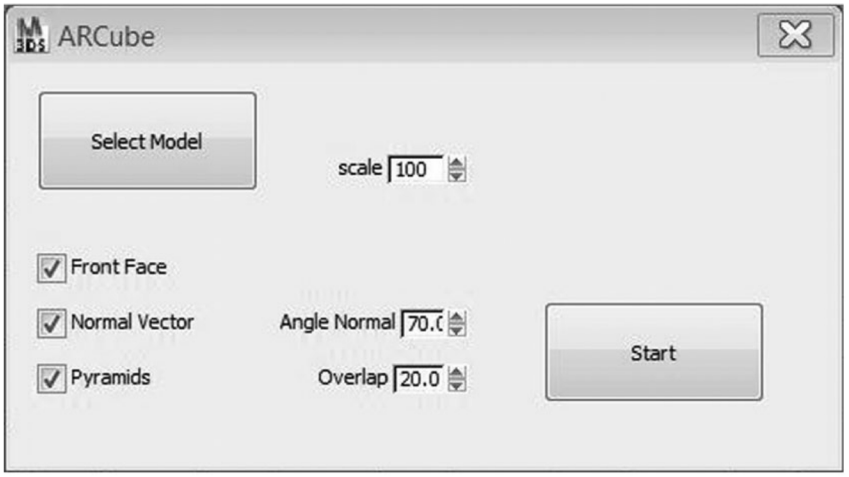


Figure 6 The ARCube plug-in.

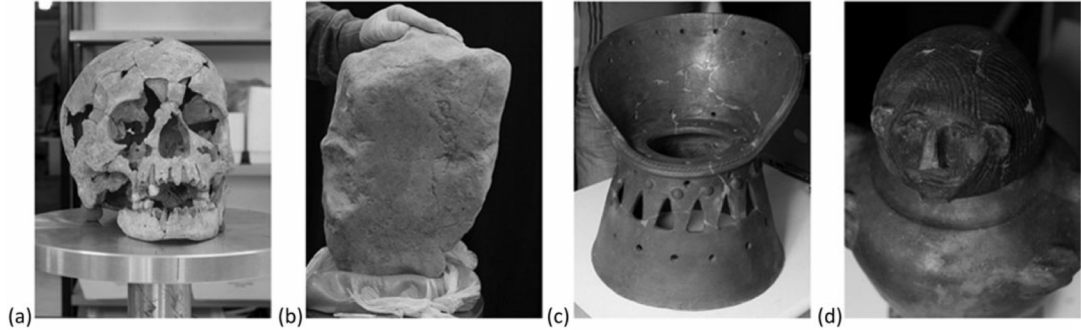


Figure 7 Test artefacts: (a) the Mezzocorona skull; (b) Dalmeri's Stone; (c) the funeral throne of Chianciano Terme; and (d) the monkey's head.

In the pyramid method, the dimensions of the pyramid depend on the overlap value defined as the input: the vertex is in the centre of the system coordinates (0,0,0) and the bases are parallel to one side of the box. When the overlap is set to zero, each side of the adjacent pyramid is coincident with the sides of the adjacent pyramid. However, when the overlap is greater, the base of each pyramid will be proportionally bigger than the side of the corresponding box. The normal vector method can be set defining the threshold angle for the process of aggregation of polygons. When this method is selected, the maximum difference angle between the normal vector direction and the face direction can be defined: high values imply that a greater part of model is selected. Finally, the front face method does not need any parameter setting.

After the parameters have been set, the plug-in is started and it automatically generates tiles for the models. Each face of the cube has an independent X,Y,Z reference system, which requires that each tile is rotated and translated from the 3D model into the new target reference system. The plug-in performs these functions automatically and the tiles are finally exported in .obj format.

CASE STUDY: APPLYING AR TO ARCHAEOLOGICAL ARTEFACTS

This section presents four practical cases. They are (a) the Mezzocorona skull, (b) Dalmeri's Stone, (c) the funeral throne of Chianciano Terme and (d) a monkey's head (Fig. 7). These four

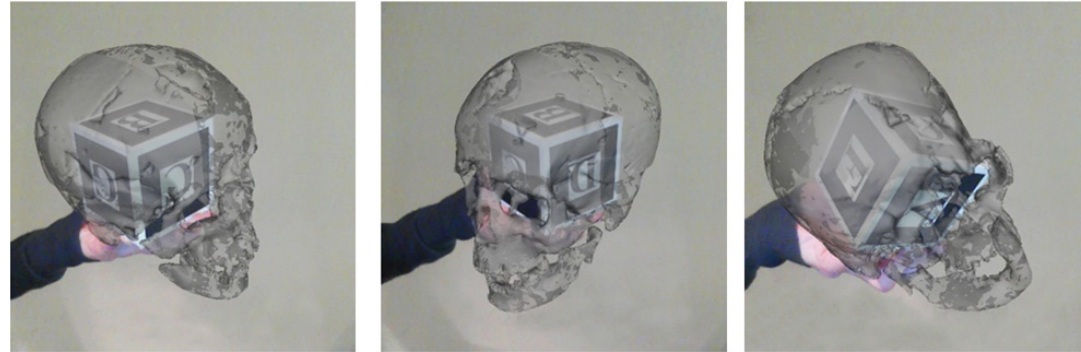


Figure 8. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.

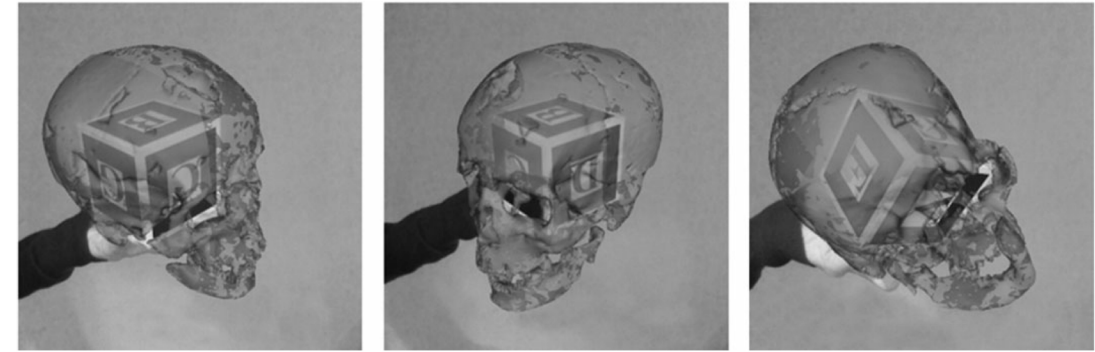


Figure 8 An AR visualization of the woman's skull from the archaeological area in Mezzocorona, Trento, Italy.

artefacts were selected because they represent a range of physical characteristics, including different shapes, materials, colours and dimensions, that can be used to evaluate the performance, suitability and quality of AR visualization. The cube can visualize 3D models with dimensions sufficient to 'include' the cube during on-screen visualization (the lower dimension is higher than the cube side). The 3D models were acquired using triangulation-based laser scanners. Each test model has a sub-millimeter resolution (0.3 mm) to guarantee good quality in its visualization: in this way, details such as incisions or fractures necessary for highly accurate measurements during research or conservation studies were correctly captured. The models were textured with high-resolution digital images acquired using a Nikon D3X camera, in order to create photo-realistic 3D models that can assist in archaeological analysis.

The Mezzocorona skull

This test was performed using the 3D model of a woman's skull of the ancient Bronze Age (Fig. 7 (a)). The skull was discovered in the funeral area of Mezzocorona (Tomb no. 10), in the 'Borgo Nuovo' area, an archaeological site located in the Trentino region (Italy). The artefact is preserved at the 'Soprintendenza per i Beni Librari Archivistici e Archeologici' in Trento (Italy) and it was surveyed in order to achieve a physical replica at a 1:1 scale for the reproduction of a prehistoric woman. The artefact is about 200 mm wide and 160 mm high. The 3D model was acquired by using the ShapeGrabber triangulation-based laser scanner and the complete model consists of approximately 1 800 000 triangles.

Due to its complex geometry, this archaeological object was chosen to show the different methods used to generate sub-models. The original 3D model was simplified to 500 000 polygons in order to reduce the size of the model and the time needed for the sub-model generation.

The pyramid and visibility methods were chosen in order to guarantee the visibility of the whole model. The final 3D model is shown in Figure 8 in semi-transparent mode, which also allows us to see the ARCube behind the digital model.

Dalmeri's Stone

Dalmeri's Stone (RD_211) (Fig. 7 (b)), an anthropomorphic figure with a hat (Dalmeri and Neri 2008), was excavated at the archaeological site of 'Riparo Dalmeri' in the Trentino region (Italy). This irregularly shaped granite stone was painted about 6000 years ago and remnants



Figure 9. Original image, *ARCube - The augmented reality cube for archaeology*, *Archaeometry*.



Figure 9 An AR visualization of the painted stone (RD_211) belonging to the Palaeolithic 'Riparo Dalmeri' archaeological site (Trento, Italy).

of ochre are still visible on its surface. The ShapeGrabber triangulation-based laser scanner was used to acquire the 3D data. The artefact is approximately 310 mm high and 140 mm wide and the AR visualization was done at a 1:1 scale; the final model contains ~372 000 triangles. The pyramid method was demonstrated to be ideal to visualize this artefact, which is characterized by regular geometry. An overlap of about 20% between adjacent tiles was used in order to guarantee a smooth transition between models when the cube is rotated. In Figure 9, different views of the virtual artefact illustrate the complete visualization of the find provided by the ARCube.

The model looks well defined on the screen due to the high density of polygons in the geometric data and the very high resolution of the images used in the model texture.

The funeral throne of Chianciano Terme

The third test is a throne (Fig. 7 (c)) that was part of an Etruscan funeral urn (seventh century BC), which was discovered in an Etruscan tomb. Today, the artefact is housed in the Archaeological Etruscan Museum of Chianciano Terme, Italy.

The artefact is cylindrical and the diameter varies from 250 mm in the centre to 380 mm at the bottom and its height is approximately 440 mm. The 3D data were collected using the ShapeGrabber triangulation-based laser scanner and the 3D model comprises about 3 million triangles. The results of this test were previously presented in Jiménez Fernández-Palacios *et al.* (2012). In that paper, the problems in complete visualization of the model arising from the artefact's elongated and convex shape were described. To overcome these problems, the new methodology for generation of sub-models has been applied. In particular, the pyramids were set with a large overlap value, to guarantee reconstruction of the complete model. On the other hand, a different threshold of 40° was used in the normal vector estimation. In comparison to the original test (based solely on the pyramid method), the visualized 3D model is complete, indicating that the integration of the normal vectors method can achieve better results (Fig. 10).

The monkey's head

The last test was performed on a monkey's head (Fig. 7 (d)) that formed part of an Etruscan funeral urn found in an Etruscan tomb (seventh century BC). This artefact is now located in the



Figure 10. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.



Figure 11. Original image, *ARCube - The augmented reality cube for archaeology, Archaeometry*.



Figure 10 An AR visualization of an Etruscan throne (part of a funeral urn).

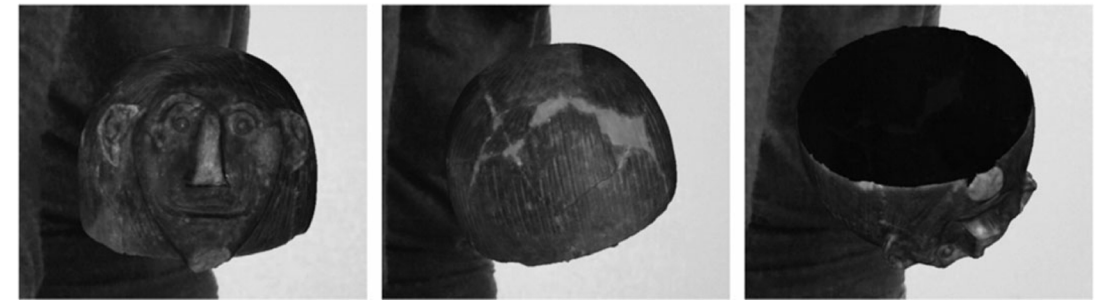


Figure 11 An AR visualization of the monkey's head found in an Etruscan tomb.

Archaeological Etruscan Museum of Chianciano Terme, Italy. The produced 3D model of the artefact was generated by the NextEngine scanner and comprises about 575 000 triangles.

The height of the artefact is similar to the width dimensions (about 180 mm × 160 mm), but this artefact is also convex, as in the previous test. For this reason, the strategy to achieve a complete 3D visualization is the same, using both the pyramids method and the normal vector method. In order to guarantee a smooth transition between sub-models, an overlap of 20% between adjacent tiles is used. As shown in Figure 11, the visualized 3D model looks complete both in its external and internal aspects.

DISCUSSION

The paper has presented a new methodology for the visualization and management of archaeological artefacts in AR environment. Compared to Kinect and 3D glasses, ARCube takes an opposite approach: Kinect and 3D glasses assume that observers move around the inspected object, while ARCube allows them to be inspected by rotating and moving the small cube only; in this way, the presented approach has proved to be particularly suitable for small artefacts.

Several tests have been presented, using laser scanner generated textured 3D models to evaluate the reliability of the method under challenging operational conditions. The developed plug-in splits the 3D models into six different sub-models, oriented in a common reference system, to reproduce the complete object geometry. Only the visible parts of the object are loaded on the screen managing high-resolution models. The object can be moved interactively

by the operator and it is visualized on the screen in real time. The sub-model generation is performed using three different methods: pyramid generation, front face visibility and normal vector estimation. Good results can be achieved using standard values in most cases. In any event, simply by modifying few parameters, a complete visualization can also be guaranteed with complex geometries. The performed tests have shown the reliability of the methodology on a large variety of objects characterized by different shapes and sizes. The front face visibility and normal vector estimation allowed us to optimize the visualization in the funeral throne model, overcoming the limits of the former implementations. The tracking of the target still suffers from the illumination conditions and therefore homogeneous illumination is suggested for a reliable visualization.

The software correctly tracks targets, allowing an efficient visualization of the model as shown in the following video: <http://youtu.be/BxhX8DzHL2w>. The visibility of the complete artefact is always assured by the faces of more than one active cube at any time and by using overlapping models. The textural quality of the 3D models partly depends on the illumination and contrast on the screen and on the possibility of interactively changing these values in the model. In any event, the high geometric and textural quality of the tested models allowed sharp and well-defined shapes and colours in the AR scene, providing a realistic visualization of the objects.

In general, the better the hardware (the PC and webcam) performs, the better is the definition. Various different PCs and different model resolutions were considered: the tracking and the visualization processes proved to be effective in most cases. BuildAR (the free version) has shown its reliability and handiness, but it does not allow programming and customizations. Other open-source toolkits will be tested and customized to add some features, such as the interactive variation in the model illumination to increase the visualization quality and highlight different details on its surface. The developed MaxScript will be converted and tested in other programming languages to process the data using open-source software only.

CONCLUSIONS

In this paper, a new application using Augmented Reality (AR) tools was described and applied to interactively visualize archaeological finds. Although a huge number of software programs devoted to AR applications have been developed, the ARCube System exploits a 3D target instead of 2D targets, as proposed in the already existing applications. The 2D targets are useful to visualize one side of the artefacts only: the tracking process is guaranteed when rotations between the target and the webcam do not exceed 50° and back-face visualization of the model is not allowed. The complete visualization of artefacts on the screen can be guaranteed by the ARCube System, as it exploits six 2D targets integrated together. The improvements and the optimization of Jiménez Fernández-Palacios *et al.* (2012) were presented. The ARCube is an automated, turnkey and low-cost solution that could be successfully applied both for reseach and educational purposes by enabling 360° interaction with fully reconstructed 3D archaeological artefacts in real-world contexts. Compared to other devices (such as 3D glasses and Kinect), it represents a low-cost solution, which is easy to use and does not require any additional energy supply, making it particularly suitable for the visualization of small artefacts.

ACKNOWLEDGEMENTS

We would like to thank Dr Giampaolo Dalmeri (Museo Tridentino di Scienze Naturali, Trento, Italy), the Museum of Chianciano Terme (Italy) and the Association Historia (<http://>

www.historiaweb.it/) for kindly allowing the surveying and modelling of the artefacts. We would especially like to thank Dr Heather Richards-Rissetto (Middleburt College, Vermont, USA) for her valuable suggestions and comments.

REFERENCES

Balog, A., Pribeanu, C., and Iordache, D., 2007, Augmented Reality in schools: preliminary evaluation results from a summer school, *International Journal of Social Sciences*, **2**(3), 163–6.

Barceló, J. A., 2000, Visualizing what might be: an introduction to virtual reality techniques in archaeology, in *Virtual reality in archaeology* (eds. J. A. Barceló, M. Forte and D. H. Sanders.), 9–35, Archaeopress, Oxford.

Benko, H., Ishak, E. W., and Feiner, S., 2004, Collaborative mixed reality visualization of an archaeological excavation, in *Proceedings of IEEE and ACM ISMAR 2004, Arlington, VA, 2–5 November*, 132–40, IEEE Computer Society, Los Alamitos, CA.

Caarls, J., Jonker, P., Kolstee, Y., Rotteveld, J., and Van Eck, W., 2009, Augmented Reality for art, design and cultural heritage—system design and evaluation, *EURASIP Journal on Image and Video Processing*, 716160; doi:10.1155/2009/716160.

Ciolfi, L., and Bannon, L. J., 2002, Learning from museum visits: shaping design sensitivities, in *Technical report*, Interaction Design Centre, Department of Computer Science & Information Systems, University of Limerick, Ireland.

Dalmeri, G., and Neri, S., 2008, Riparo Dalmeri: l’uomo e due stili di raffigurazione. Analisi formale di quattro pietre decorate con figure antropomorfe, *Preistoria Alpina*, **43**, 299–315.

Garagnani, S., and Manferdini, A. M., 2011, Virtual and augmented reality for cultural heritage, in *SIGraDi Cultura aumentada 2011*, XV Congreso de la Sociedad Iberoamericana de Gráfica Digital, Santa Fe, 555–9.

Jiménez Fernández-Palacios, B., Rizzi, A., and Nex, F., 2012, Augmented Reality for archaeological finds, in *Progress in cultural heritage preservation: proceedings of 4th International Conference, EuroMed 2012, Limassol, Cyprus, 29 October – 3 November 2012* (eds. M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino and R. Caffo), 181–90, LNCS 7616, Springer-Verlag, Berlin.

Matu, F. O., Thøgersen, M., Kraus, M., Galsgaard, B., and Møller Jensen, M., 2014, Stereoscopic augmented reality system for supervised training on minimal invasive surgery robots, in *Proceedings of Virtual reality International Conference, 9–11 April, 2014*, Laval, France.

Niedermair, S., and Ferschin, P., 2012, An Augmented Reality framework for on-site visualization of archaeological data, in *Proceedings of the 16th CHNT Conference*, Vienna, Austria (abstract only).

Noh, Z., Sunar, M. S., and Pan, Z., 2009, A review on Augmented Reality for virtual heritage system, in *Learning by playing. Game-based education system design and development: proceedings of 4th International Conference on E-Learning and Games, Edutainment 2009, Banff, Canada, 9–11 August 2009* (eds. M. Chang, R. Kuo, Kinshuk, G.-D. Chen and M. Hirose), 50–61, LNCS 5670, Springer-Verlag, Berlin.

Pacheco, D., Omedas, P., Wierenga, S., Knoch, H., Wilbricht, S., Billib, S., and Verschure, P. F. M. J., 2014, Spatializing experience: a framework for the geolocalization, visualization and exploration of historical data using VR/AR technologies, in *Proceedings of Virtual reality International Conference, 9–11 April, 2014*, Laval, France.

Papagiannakis, G., Schertenleib, S., O’Kennedy, B., Arevalo-Poizat, M., Magnenat-Thalmann, N., Stoddart, A., and Thalmann, D., 2005, Mixing virtual and real scenes in the site of ancient Pompeii, *Computer Animation & Virtual Worlds*, **16**(1), 11–24.

Vassilios, V., Karigiannis, J., and Ioannidis, N., 2003, Augmented Reality Touring of Archaeological Sites with the ARCHEOGUIDE System, in *Cultivate Interactive*, issue 9, 7 February.

Wang, Y., Yang, J., Zhai, L., Zhong, Z., Liu, Y., and Jia, X., 2011, Prototyping a mobile AR based multi-user guide system for Yuanmingyuan garden, in *Recent trends of mobile collaborative Augmented Reality systems* (eds. L. Alem and W. Huang), 127–33, Springer-Verlag, Berlin.

Woods, E., Mason, P., and Billinghamurst, M., 2003, MagicMouse: an inexpensive 6-degree-of-freedom mouse, in *Graphite 2003*, Melbourne, 11–13 February.

Zöllner, M., Keil, J., Wuest, H., and Pletinckx, D., 2009, An Augmented Reality presentation system for remote cultural heritage sites, in *VAST 2009. VAST-STAR, short and project papers proceedings* (ed. K. Debattista), 112–16, University of Malta, Msida.

Sección II - Escala arquitectura

La presente sección contiene el artículo “*Access to complex reality-based 3D models using virtual reality solutions*” (Accesibilidad a complejos modelos 3D basados en la realidad a través de recursos de realidad virtual) publicado en Octubre de 2016 en la revista Internacional de Impacto (JCR) Cultural Heritage.

Resumen

El presente artículo estudia las técnicas de levantamiento, modelado y visualización 3D para los objetos clasificados anteriormente como escala arquitectura. La línea de investigación tiene como finalidad visualizar y divulgar los contenidos digitales 3D relativos al presente caso de estudio a través de la realidad virtual, para obtener una mejor comunicación de la información del Patrimonio Cultural.

En primer lugar, se verifica la gran utilidad de las técnicas de digitalización 3D de alta precisión, como el láser escáner terrestre, la fotogrametría de corto alcance y la fotografía panorámica, para la reconstrucción y modelización digital del presente caso de estudio.

En segundo lugar, se demuestra la utilidad y la integración de dispositivos de realidad virtual para la visualización de modelos 3D basados en la realidad, los cuales permiten al usuario disfrutar de una experiencia inmersiva, navegando a través de escenarios del patrimonio reconstruidos digitalmente. Para ello, se crea una nueva aplicación de realidad virtual, integrando las gafas Oculus Rift con el sensor de profundidad Kinect con el fin de obtener una navegación interactiva en tiempo real a través de complejas escenas digitales 3D o 4D (temporal), permitiendo a su vez el acceso a contenidos digitales. De esta forma, zonas arqueológicas o entornos frágiles, con prohibiciones o limitaciones de acceso debido a políticas de conservación, también pueden ser virtualmente visitados e inspeccionados.

Además se demuestra que, la interfaz de realidad virtual desarrollada no sólo puede

Section II - Architecture scale

This section contains the scientific article entitled: “*Access to complex reality-based 3d models using virtual reality solutions*” published in October 2016 by the International Journal (JCR) of Cultural Heritage.

Abstract

This article studies the 3D surveying, modeling and visualization techniques for objects previously classified as architecture scale. The purpose of this line of research is to visualize and disseminate 3D digital content related to the presented case study using virtual reality technologies, in order to obtain a clearer understanding of the Cultural Heritage information.

Firstly, the usefulness of high-resolution 3D surveying techniques, such as terrestrial laser scanning, photogrammetry and panoramic photography, is verified for digital reconstruction and modeling of the presented case study.

Secondly, the utility and integration of virtual reality devices is demonstrated for the visualization of reality-based 3D models, which allow the user to enjoy an immersive experience by navigating through digitally reconstructed heritage scenarios. For these purposes a new virtual reality application is created, integrating the Oculus Rift headset together with the Kinect depth sensor, to obtain an interactive real-time navigation through complex 3D or 4D (temporary) digital scenes, while allowing access to digital content. Also demonstrated is that the developed virtual reality interface can not only be used for the visualization of complex 3D models but also for different purposes such as visualization of heritage sites through panoramic images (e.g. virtual tour).

The scenarios studied for the architecture scale are different Etruscan tombs which come from the necropolis of Tarquinia, a UNESCO World Heritage Site since 2004, and Vulci (Italy),

utilizarse para la visualización de complejos modelos 3D sino también para diferentes propósitos tales como la visualización del patrimonio a través de imágenes panorámicas (ej. tour virtual).

Los escenarios estudiados para la escala arquitectura son diferentes tumbas etruscas y provienen de las necrópolis de Tarquinia, declarada por la UNESCO Patrimonio Mundial en 2004, y Vulci (Italia), así como los templos grecorromanos de Paestum, en Salerno (Italia), declarados Patrimonio Mundial por la UNESCO desde 1998. Una vez más, todos ellos fueron escogidos por sus diferentes características geométricas y radiométricas (forma, textura y color) para garantizar la fiabilidad de la metodología propuesta.

as well as the Greco-Roman Temples of Paestum, in Salerno (Italy), a UNESCO World Heritage Site since 1998. Once again, all of these were chosen for their different geometric and radiometric features (shapes, materials and colours) to ensure the suitability of the proposed approach.

Article II

Access to complex reality-based 3d models using virtual reality solutions



Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en



Original article

Access to complex reality-based 3D models using virtual reality solutions



Belen Jiménez Fernández-Palacios^{a,b}, Daniele Morabito^b, Fabio Remondino^{b,*}

^a Department of Cartographic and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, Avila 05003, Spain
^b 3D Optical Metrology (3DOM) Unit, Bruno Kessler Foundation (FBK), Via Sommarive 18, Trento, Italy

ARTICLE INFO

Article history:
Received 6 January 2016
Accepted 5 September 2016
Available online 4 October 2016

Keywords:
Archaeology
Virtual reality
Oculus Rift
Microsoft Kinect
Large 3D models
Visualization
Access

ABSTRACT

Cultural Heritage is a precious resource that witnesses our past and that should be transmitted to future generations. The creation of digital 3D representation of monuments and sites have been demonstrated to be a reliable method for preservation and historical purposes. In order to preserve a high level of detail, the reconstructed point cloud will typically contain millions of points, which could result in several GB of data when stored on disk. For these reasons, a challenge for the scientific community is to find new ways to visualize and disclose 3D digital contents, obtaining a better access and communication of the Cultural Heritage information. In this paper, Virtual Reality (VR) devices are employed to provide not only a simple visualization but also an immersive experience for digitally reconstructed heritage scenarios. Oculus Rift (VR visualization headset) and Kinect (depth sensor for user interaction) are integrated in order to interact and navigate in a complex 3D or 4D (temporal) archaeological scene as well as to have access to digital media contents of several MB of size. In this way, archaeological sites or fragile environments with forbidden access due the preservation policies can also be virtually visited and inspected.
© 2016 Published by Elsevier Masson SAS.

Research aims

The paper presents a visualization pipeline developed to exploit and access large and complex heritage 3D contents in an easy and interactive way through VR methodologies. In particular the work focused on (i) visualizing and managing complex reality-based 3D models with a real-time fluent interaction, (ii) investigating the integration of specific VR devices – such as Oculus Rift and Microsoft Kinect – for heritage applications and (iii) offering to the scientific community, as well as common users, an innovative way to promote the knowledge of Cultural Heritage sites.

1. Introduction

Nowadays, the incessant development in the field of 3D recording techniques together with the latest technological progress in hardware, software and digital content delivery allow the remote exploration of complex archaeological sites and

monuments. Actual reality-based 3D surveying techniques like laser scanning [1] and photogrammetry [2] are currently able to produce precise, detailed and photo-realistic 3D digital representations useful for documentation, archaeological and architectural analyses, visualization, divulgation and educational purposes, museum exhibitions or virtual tourism. According to the location, dimension and complexity of the heritage sites as well as the project goals, these 3D methodologies are very often combined exploiting the intrinsic advantages of each technique [3–8]. In a reality-based 3D digitization project, the main goal is to produce an accurate and photo-realistic digital replica of the surveyed reality, considering not only the specifications of the desired output (e.g. 3D models or other suitable representations) but also cost's and execution time's minimization. The design and realization of such activities require not only expertise in several disciplines but also the knowledge of the employed sensors as well as the understanding of the application and its environment. According to [9], the steps for a reality-based 3D digitization project are:

- Site overview (or object examination) and planning.
- Selection of the appropriate 3D surveying and recording technology and parameters (or a combination of multiple technologies).
- Data collection after positions planning and configuration design.
- Data acquisition workflow based on best practice.

* Corresponding author at: Department of Cartographic and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, Avila 05003, Spain.
E-mail addresses: belenjfp@gmail.com (B. Jiménez Fernández-Palacios), morabito@fbk.eu (D. Morabito), remondino@fbk.eu (F. Remondino).

- e. Selection of data processing tools, 3D model representation method and suitable file formats.
- f. Selection of software tools able to handle processing and visualization requirements.

Following this workflow, detailed 3D models are normally generated, consisting of millions of polygons and high resolution images, making them very “heavy” and difficult to be handled by common computers. In fact, despite technological developments, the management of large polygonal datasets can be limited by several technical problems, i.e. very long processing and editing time or real-time visualization constrained by the graphics card performance. Computer performance is highly needed otherwise it is necessary to reduce the final size of the models in terms of geometry and textures. From a geometric point of view, it is possible to reduce the number of vertices and optimize the geometry [10]. In addition, in order to maintain a high quality visualization and not to miss geometric details for studies and analysis purposes, normal and displacement maps can be used [11–13]. From a radiometric point of view, it is possible to reduce and compress the high resolution images or, if necessary, a single texture can be generated for each model [12]. In all cases, it is necessary to find a compromise between accuracy, size and visualization of the 3D model. The scientific community continuously looks for new ways to document, visualize, study, manage and divulge digital replicas of Cultural Heritage sites without losing quality or information. In particular the focus is now towards new solutions in the field of Virtual, Augmented and Mixed Reality to find reliable ways to share, access and communicate the outcomes of a 3D digitization projects.

New ICT (Information and Communication Technology) technologies are quickly advancing and they allow different ways to access digital 3D information. Informatics resources are being exploited to create new platforms, applications and systems, with the aim of managing complex reality-based 3D models in real-time. Web-based platforms have been developed to visualize, study and manage them, for research and dissemination purposes without installing specific software [13–16]. Virtual Tours (VT) applications [17] allow the user to visit and explore heritage sites through a pre-defined path of panoramic images, supporting also digital media contents such as texts, documents, images, as well as sophisticated 3D models. Augmented Reality (AR) applications [18] allow to integrate and interact with this kind of 3D models into a real-world environment, through computer-generated sensory inputs (images, video, GNSS, etc.). 3D reconstruction can be applied not only to existing archaeological sites, historical buildings and artefacts but also to recreate environments. Virtual Reality (VR) is an immersive multimedia technique which replaces the real world with a virtual one where the physical presence is simulated [19,20]. In addition, Mixed Reality (MR) combines both the virtual world and the real world in order to create new environments where digital and physical objects coexist [21].

As a consequence, in order to exploit new resources and technologies, as well as to valorize and divulge Cultural contents, VR has been tested to create an immersive and reality-based virtual world, taking advantage of accurate 3D models. VR is a technological system that generates scenes and virtual representations that can be visualized by the user in a CAVE or through Headset Mounted Display (HMD), such as Oculus Rift VR [22–24], Samsung Gear VR [25], Neo Pro [26] or Project Morpheus (today known as Playstation VR), the Sony VR headset [24]. Also, thanks to low-cost supports as Google Cardboard [27] or OpenDive [28,29], smartphones can be used as virtual headsets. These technologies can be exploited to recreate the user's head movements in real time. Moreover, it is possible to capture whole user body movements using several devices, projecting real movements into the virtual world and enhancing self-awareness. Among them, we can find different

kinds of devices: (i) deep sensor for user interaction such as Kinect [30–32], Structure [33], Leap Motion [34], etc., (ii) gloves equipped with sensors [35] designed to simulate the perception of different stimuli such as Control VR [36], (iii) bracelets [37,38], etc. In this way, VR allows the user to fully immerse into and interact with a virtual world.

The vast growth of computer performances (especially of graphics cards) has allowed the combination of new display technologies – such as VR tool – with 3D models in order to provide a better understanding of phenomena or facts by its 3D simulation and interaction with specialized equipment. VR can be applied to several daily life activities, such as gaming, entertainment and education but also industry-related applications, including engineering and telecommunications [39]. VR can help engineers to visualize different technical solutions in a 3D environment. VR can be also applied to fields where safe training is required, such as in medicine, (especially surgery and neurology) [40], in military contexts and in emergency situations (flight simulators) [41,42]. These new technologies play an important role in museums to recreate different epochs and give the possibility to explore them again [43–45]. VR is paving the road to a new and exciting way to communicate information, where the user is completely immersed in an interactive world. For instance, Europeana (a multi-lingual online collection of millions of digitized items from European museums, libraries, archives and multimedia collections) experimented VR technology, together with ArchiVision (a Dutch design agency). They developed a virtual museum (“The museum of the future”) where a user can play with masterpieces from the Dutch Rijksmuseum [46]. The V-Must project (Virtual Museum Transnational Network) aimed to provide tools and support to develop virtual museums with communicative and educational purposes. They used VR technologies and devices for the exhibition “Keys to Rome, The City of Augustus”, where the focus was the Augustan age. Companies like ArcTron [47] or ETT [48] are beginning to include VR applications exploiting the Oculus Rift technology among their products. Research centres and universities [18,49] are also involved in using VR for heritage applications.

2. Developed pipeline

The workflow is based on the Unity game engine coupled with natural interface devices to create a VR application able to visualize and disclose digitized Cultural Heritage properties to any user. Several case studies have been performed (Section 3), using 3D datasets surveyed with laser scanning and photogrammetry, in order to test the reliability and replicability of the VR methodology under different operative conditions. The pipeline manages detailed 3D models without losing quality, in terms of geometry and textures, with a fluent real-time interaction. This is a mandatory requirement to fully exploit all the contents of a 3D modelling project for visualization, communication, analyses and educational purposes. An intuitive interface was implemented where the user, assisted by the tracking system of the Oculus Rift headset, can obtain the model metadata. This methodology, coupled with Kinect, allows also to obtain complete control of the user's body movements.

2.1. VR implementation and devices

The implementation of the developed architecture (the hardware used to visualize and manage the data) (Fig. 1) merged open-source software/script and proprietary software. In particular Unity (3D engine) and OpenNI (Open Natural Interaction) were employed. Unity is a commercial game engine application that allows fast implementation time and the management of external devices for the integration of the user's body movements during

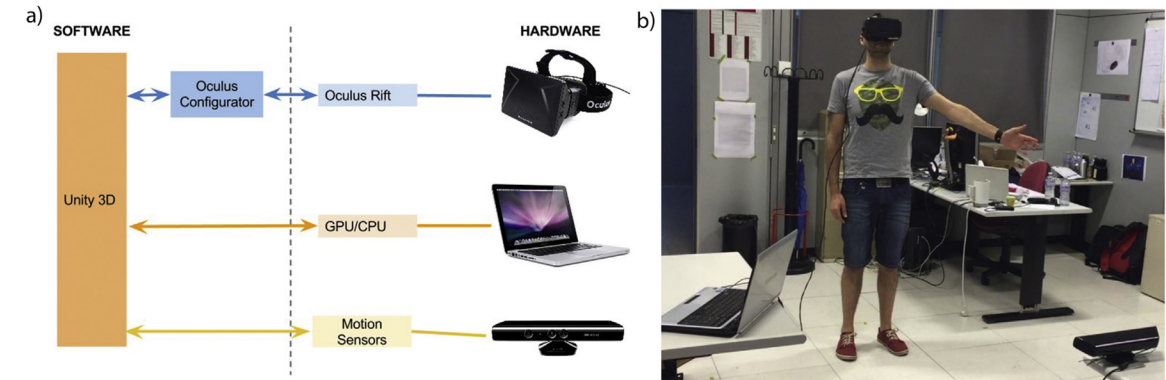


Fig. 1. (a) Software and hardware layers of the experimental architecture: a laptop (GPU: Intel HD4000 – 1 GB RAM, CPU: Intel Core i5 2.5 GHz – 4GB RAM) controls Kinect and Oculus Rift devices through Unity engine and related wrappers. (b) The set-up of the developed procedure: the Oculus device for the immersive visualization and the Kinect sensor to observe the body movements and activate multimedia contents.

the visual simulation. OpenNI is an open source software project focused on certifying and improving interoperability of natural (as well as organic) user interfaces, i.e. devices that capture body movements to allow a more natural interaction of users with computers.

From a hardware point of view, the set-up integrated an Oculus Rift and a Microsoft Kinect. Oculus Rift is a VR headset designed specifically for video games to make the gaming experience more immersive. Thanks to its hardware, Oculus Rift allows to replicate the natural movements of the user's head, increasing the perception of the user within the VR environment. Three important features make Oculus Rift (Development Kit 2) a very powerful and valuable device for VR applications: a display (960×1080 per eye), an internal tracking (accelerometer, gyroscope and magnetometer) and a viewing optics (100° nominal field of view). On the other hand, the Microsoft Kinect device was used given its flexibility, low-cost, portability and acquired experience with past projects. Kinect is a motion sensing input device used for video games and created by Microsoft. This device is composed by an RGB camera, IR depth sensor, motorized tilt function, a multi-array microphone and custom processor running proprietary software and it can be used to make applications thanks to software developer kit by Microsoft and OpenNI library. It allows the user to take remote control of the application, in an interactive way, from a distance that ranges between 0.8 and 4 m. Comparing to the other available low-cost solutions, Kinect is able to track and reconstruct full and partial markerless skeletal with a discrete precision, it has a good working range and it can be easily integrate with other sensors/devices.

In order to design a user-friendly interface, Oculus Rift and Kinect were tested with different kind of people (from children to adults). Based on the performed tests, the most natural and intuitive movements were chosen. Using Oculus Rift, the head movements allow the user to take control of the application (to obtain information, to change 3D scene, etc.). On the other hand, the Kinect sensor should only control the movement of the user's body into the VR scene. This is possible only when the user remains into the Kinect's field of view. The user will be able to walk forward through a slight thrash and respectively rotate (clockwise or counter-clockwise) by a slight movement of his right or left arm.

The two devices were integrated using OpenNI inside Unity, implementing an interaction process between the user and the digital contents. This method exploits a pointer centred in the main camera (Oculus Rift developed interface) and moves according to the head movements. The pointer is similar to the mouse pointer and it allows the visualization of visual contents. Invisible hot spots

were placed in different points of interest. Once the user looks at a specific part of the virtual scene (named "hidden hot-spots") the access to the information becomes visible. The method is able to control these hot-spots and, depending on the pointer position, it also controls if the contents should be displayed or not (Fig. 2).

3. Case studies and results

Different digital 3D datasets have been used to test and assess the suitability and performance of the developed VR visualization application and to consider the potentiality of the presented methodology. For these purposes, various reality-based 3D models have been chosen based on their variety, in terms of dimension, shape, material, colour and size. In particular, we considered 3D models of various Etruscan tombs composed of multiple frescoed chambers. The used 3D models were produced collecting data through accurate 3D recording techniques such as laser scanning and photogrammetry (see [50,51] for more technical details). A Leica ScanStation, Time-of-Flight (TOF) terrestrial laser scanner (TLS), was used to acquire geometric data. This geometric data was recorded from different positions in order to survey the areas of interest with an average sampling step of 3–5 mm. The obtained unstructured point clouds were cleaned and aligned in a common reference system, followed by the generation of the final structured polygonal 3D models. The produced surfaces were edited and optimized, removing redundant data and merging together all the vertices within a specified threshold (tolerance). In addition, in order to create photo-realistic 3D models, a Nikon 3DX camera with fixed lenses (Nikkor 24 and 50 mm) was used to acquire high resolution images.

According to the complexity of the objects and the final purposes, the TLS 3D models were textured using different approaches: (i) panoramic and normal images were mapped onto the reconstructed 3D geometry of the painted chambers through photogrammetric techniques whereas (ii) virtual textures were used to realistically reproduce materials (e.g. *tufo*) in specific areas of the heritage sites. Furthermore orthophotos and rectified images showing virtually restored frescoes were used to map damaged areas and create hypothetical reconstructions ("virtual restoration"). The resulting photo-realistic 3D models are composed by millions of polygons and high resolution images, with a file size (in OBJ format) ranging from 200 MB to 700 MB (Fig. 3 and Table 1). Due to the huge size of the 3D models and the hardware used the upload time can be too long. In addition, a small delay can be noticed which could affect the fluidity of the 3D scene. To avoid this, the

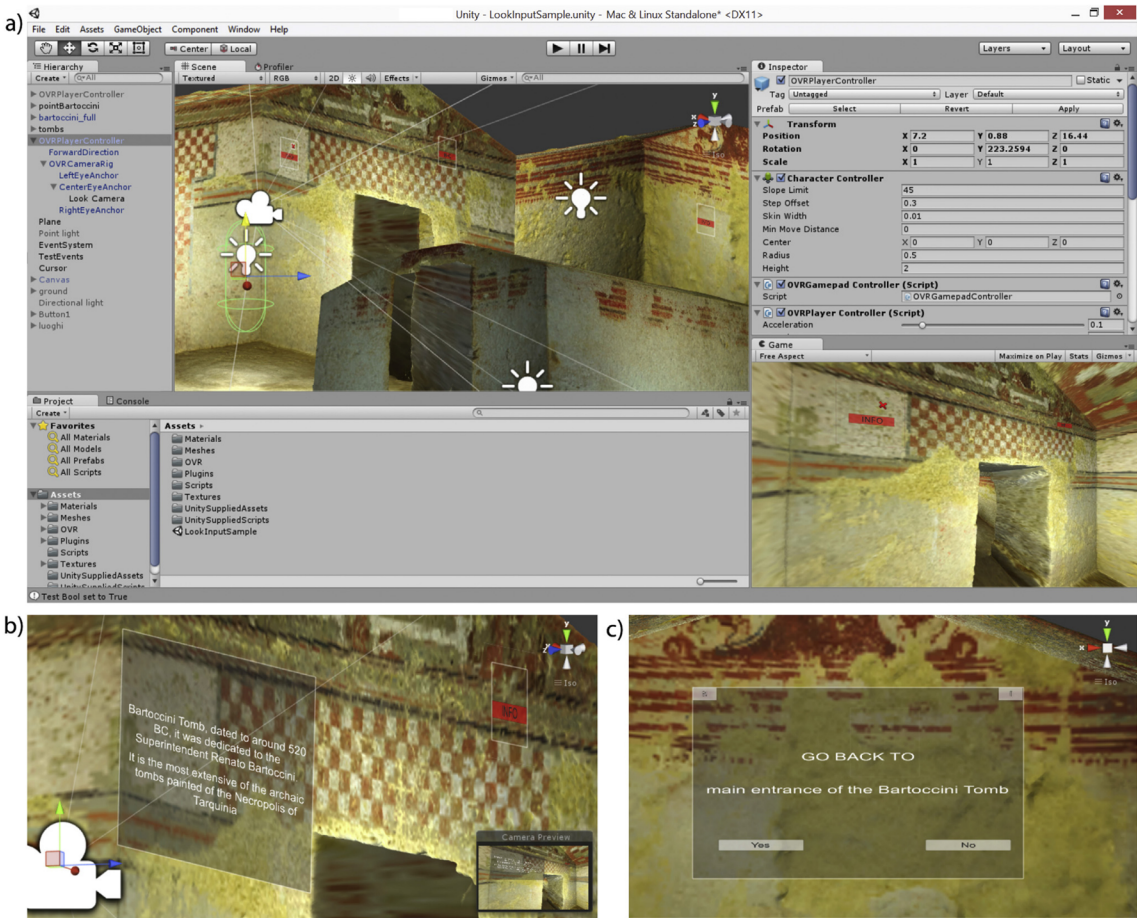


Fig. 2. A typical workspace inside Unity: (a) workspace for digital content visualization and data interaction through Oculus Rift, (b) retrieval of historical data information and (c) scene change.

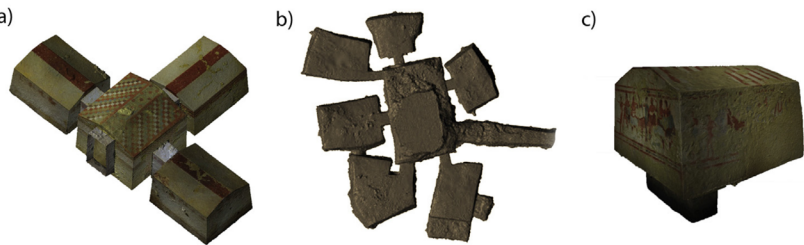


Fig. 3. Cases studies: 3D models of the (a) Bartoccini tomb, (b) Inscriptions tomb and (c) Bettini tomb.

	Bartoccini	Inscriptions	Bettini
Period of the heritage site	VI cent. BC	IV-II cent. BC	V cent. BC
Location of the heritage site	Tarquinia (Italy)	Vulci (Italy)	Tarquinia (Italy)
Dimensions of the site	4 rooms, 44 m ²	7 rooms, 90 m ²	1 room, 12 m ²
Num. of polygons	ca 3 millions	ca 5 millions	ca 2 millions
Size of the original 3D model (including texture)	ca 520 MB	ca 700 MB	ca 200 MB
Num. of polygons (reduced model)	ca 450,000	ca 750,000	ca 300,000
Size of the optimized 3D model (including texture)	71.4 MB	92.7 MB	53.1 MB

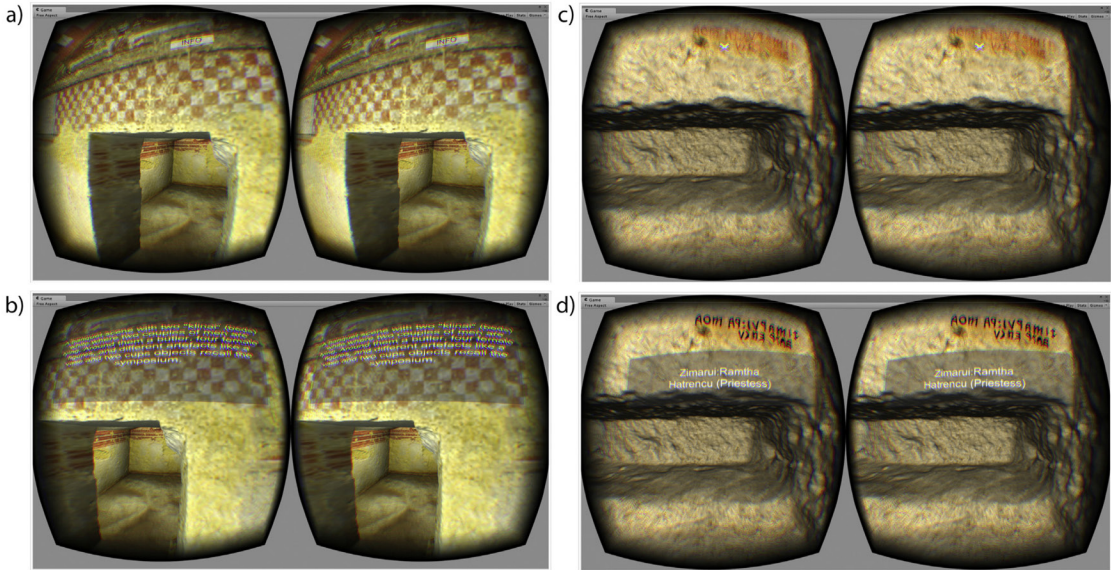


Fig. 4. Two examples of the VR application seen through the Oculus eyes: (a) the Bartoccini tomb with (b) a hotspot to text information and (c) the Inscription tomb with (d) a view to an engraving and its translation.

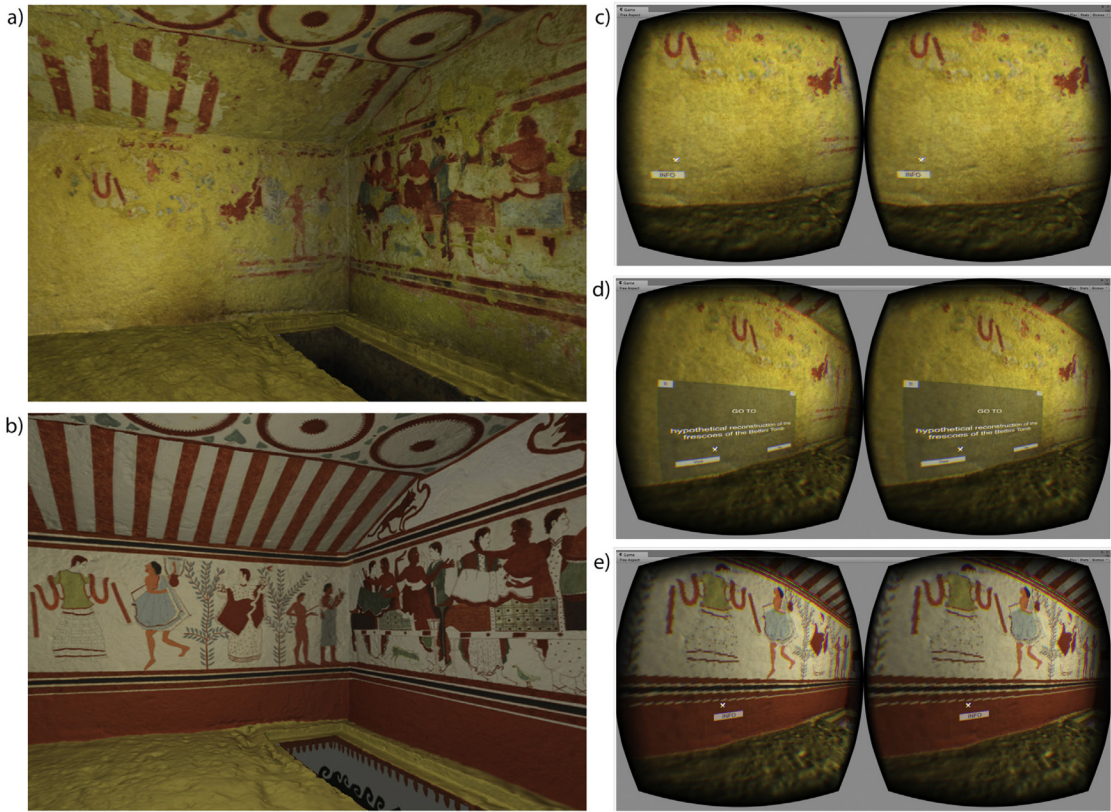


Fig. 5. (a) The current condition and (b) the virtual restoration of the frescoes in the Bettini tomb based on iconographic studies and historical information. The VR application for the immersive and real-time access to the Bettini digital 3D model: (c) the 3D model seen in the Oculus eyes, (d) the developed user interface to change scene and (e) the access to the virtual restoration of the frescoes.



Fig. 6. The VR application deployed for the immersive access of the Paestum Virtual Tour: (a) access to the Basilica monument, (b) internal view of the Basilica and access to the additional media content and (c) historical information. (d) Users enjoying the immersive VT with the Oculus headset during the 2015 EU Research Night.

final photo-realistic 3D models were reduced using different optimization techniques. It could be possible to reduce drastically the 3D data by CAD modelling but this involves the loss of complex surface details. Normal maps were used to optimize the geometry without losing visible quality [13]. To achieve a reduction the number of faces, the mesh of the reality-based 3D models have been optimized (using the “ProOptimizer” tool in 3ds Max), from high to low resolution. The texture mapping was preserved and the material information was maintained in the optimized polygonal models. Then, the geometry of the high resolution 3D models detail were projected onto a low resolution 3D models through normal maps (using the “Render to Texture” tool, in 3ds Max). In this way, it was possible to maintain the visual appearance at high resolution, reducing the weight of the 3D models. In the other hand, unwrapping techniques were used to obtain singles texture and reduce the texture size. The final optimized 3D models ranging from 50 MB to 90 MB (Fig. 3 and Table 1). In the following three case studies are presented: (a) the Bartoccini tomb, (b) the Inscriptions tomb and (c) the Bettini tomb. In Section 3.4 a further development of the VR application to a Virtual Tour (VT) of an archaeological areas is presented.

3.1. Bartoccini tomb

The Etruscan Bartoccini tomb (VI cent. BC) is composed of four rooms – a principal burial chamber, with beautiful frescoes, which give access to the other three rooms. The tomb is approximately 2.7 m high with an area of ca. 44 m². The survey delivered ca. 1.5 millions of points and the final polygonal model is composed of ca. 3 millions of faces. The texturing was done using high resolution panoramic images mapped onto the polygonal 3D model of the tomb. The final file size is ca. 520 MB (including the texture). These characteristics deny a fluent and interactive real-time access to the virtual tomb to non-expert heritage users. Contrarily the developed VR application allows to walk-through the digitized tomb, access to digital contents and easily analyze the chambers frescoes (Fig. 4a and b).

3.2. The Inscriptions tomb

The Etruscan Inscriptions tomb (IV-II cent. BC) is composed of seven rooms – a central atrium with access to six burial chambers. The hypogeum is approximately 3.4 m high with an area of

ca 90 m². The tomb lacks of frescoes, however it is characterized by many inscriptions on the walls (in Etruscan and Latin language) which describe persons from different families buried there. The survey collected ca. 2.4 millions of points, delivering a final polygonal model with ca 5 mil faces. Due to the homogeneity of the material (*tufo*) and the complex geometry that characterizes the tomb (irregular rooms full of tombstones and sarcophagus creating occlusions), virtual textures were used to texture the materials, while, high resolution images were used to map the inscriptions through photogrammetric methods. The final file size is ca. 700 MB (including the texture). The textured 3D model was imported in Unity and different lights were used in order to highlight not only the three-dimensional perception but also to better recreate the real environment. The inserted hot-spots allow the user to interactively obtain historical information about the tomb and visualize the various inscriptions [52] together with their translation (Fig. 4c and d).

3.3. Bettini tomb

The Etruscan Bettini tomb (V cent. BC) is a single room structure with a gabled roof, various frescoes and a burial moat dug in the ground. The tomb is approximately 2.5 m high with an area of ca. 12 m². The final photo-realistic 3D model of the tomb has ca. 2 millions of polygons. The geometry of the chamber was texture-mapped through panoramic projections while the burial moat, due to its narrow dimensions, was textured by flat projections of high resolution images. The file size of the tomb is ca. 200 MB (including the texture). It faithfully represents the current status of the Etruscan burial with many ruined frescoes. For conservation and archaeological purposes, a virtual hypothetical reconstruction of the frescoes was performed using Etruscan paintings analyses [53] and iconographic studies of similar tombs and materials (Fig. 5a and b). For this purpose, orthophotos and rectified images of the current status of the tomb were produced using high resolution images (acquired by a Nikon D3X camera, 24.5 megapixel Full-Frame (36 × 24 mm) sensor with fixed lenses Nikkor 24 and 50 mm) and reality-based 3D models. The obtained flat images were used to design the hypothetical reconstruction of the frescoes and subsequently restored digital images were used to texture the geometry of the 3D model. In this way, a new 3D model of the virtual hypothetical status of the Bettini tomb was created. Both 3D models (actual and hypothetical situation) were imported in Unity in a common reference system, overlapped with the same origin and orientation and used to create a temporal VR visualization to compare the different situations (Fig. 5c–e). Thanks to the Kinect sensor, which observes the gesture of the user while he/she navigating inside the tomb, within the Oculus headset the different temporary scenes can be activated and observed.

3.4. Further application

The developed VR application can be used not only for huge and complex reality-based 3D models but also for different purposes such as Virtual Tours (VT) of archaeological sites. In order to verify the reliability of the presented methodology, a VT realized for the archaeological area in Paestum [54] was tested. The Paestum VT is composed of 20 very high-resolution panoramic images spread all over the site (ca 1 × 0.6 km). In addition, historical information related to the main monuments was collected to enrich the tour. The high resolution panoramic images as well as the historical digital information are integrated inside Unity, and through Oculus Rift an immersive visualization of the enriched images is realized (Fig. 6). The user can navigate through the different panoramic

scenes and landscapes and retrieve access to the information of archaeological site without being at the site.

4. Conclusions

The paper presents the interactive and immersive visualization and access of large and complex reality-based 3D model using Virtual Reality (VR) techniques. The developed and implemented methodology rely on VR devices and natural user interfaces integrated using a game engine software. The outcomes allow to access, visualize and divulge digital archaeological sites which are normally not accessible due to hardware limitations and large file sizes. Unity plays a fundamental role (i) for the management of complex reality-based 3D models and high resolutions panoramic images and (ii) for the integration, synchronization and processing of various devices and data. Indeed Unity must communicate with different devices in order to coordinate a second display (Oculus Rift) and acquire and process the 3D data observed by the Kinect. The presented VR solution includes also an easy and intuitive user interface that allows the user, once immersed into a virtual world, to explore a 3D scene and, simultaneously, to retrieve digital media contents (like historical data). Such user interface was realized considering to whom the application is addressed (scientific community, tourists, students, etc.), in order to design and implement it with the best results, in an intuitive and user-friendly way.

The limitations of the developed VR solution are the uploading time of large 3D datasets into Unity, the actual constraint of CPU and GPU as well as the working range of the Kinect sensor. All these issue will for sure be soon solved by the continuous ICT developments. Nevertheless the presented work represents an innovative application in the Cultural Heritage field. Even huge and complex reality-based 3D models could be integrated into a unique VR application, in order to exploit the intrinsic advantages of the different digital datasets. It can be used not only for visualization, enriching unique experiences for visitors in museums, exhibitions and educational purposes but also for scientific applications of heritage sites. VR technology can offer scholars to visit digital archaeological areas, like in a real-world context. It enables a non-destructive way for archaeologists, historians, and other academics to inspect archaeological sites, providing accurate and precise details of monuments (based on the resolution of the 3D model used), without damaging, dirtying or altering heritage sites. Advanced tools allow the access to digital media contents, thus the VR application becomes a container of data. Furthermore, it is possible to travel through a temporary space as the 3D data visualized in the VR application can represent the same Cultural Heritage site at different times, turning into a reality-based 4D virtual world. Adding multiples layers allows to create different levels of information (e.g. different conservation states, various hypothetical reconstructions, etc.). As a result, the users will be able to virtually travel to locations with difficult access, distances places or different eras in order to know the past and present of the site. Additionally, people with limited mobility can virtually visit, explore and enjoy Cultural Heritage sites through reality-based VR applications. In the researcher field, scientists, archaeologists, conservator and architects could be able to use the VR application as a database with dedicated cultural information (textual information, images, metadata, etc.), aside from planning, predicting, simulating and visualizing future interventions. Scientists and researchers located in different places could visualize and investigate the same archaeological sites, at the same time, in order to facilitating collaborative research and data sharing.

The presented methodology was showcased during the 2015 EU Research Night (Fig. 6d) and it is now on show in the travelling multimedia exhibition about the Etruscan civilization.

Acknowledgments

The authors are really thankful to the Soprintendenza per i Beni Archeologici dell'Etruria Meridionale, the Soprintendenza per i Beni Archeologici della Toscana and Historia (<http://www.historiaweb.it>) for the collaboration in the Etruscans 3D project. A special thanks also to the Soprintendenza per i Beni Archeologici di Salerno, Avellino, Benevento e Caserta as well as to Dr Fausta Fiorillo and Prof. Salvatore Barba (Department of Civil Engineering, University of Salerno, Italy) for their support and collaboration in the Paestum project (<http://paestum.fbk.eu>).

References

[1] G. Vosselman, H. Maas, *Airborne and Terrestrial Laser Scanning*, CRC, Boca Raton, 2010, ISBN 978-1904445-87-6.

[2] F. Remondino, S. El-Hakim, Image-based 3D modelling: a review, *Photogramm. Rec.* 21 (115) (2006) 269–291.

[3] K. Lambers, H. Eisenbeiss, M. Sauerbier, D. Kupferschmidt, T. Gaisecker, S. Sotoodeh, T. Hanusch, Combining photogrammetry and laser scanning for the recording and modelling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru, *J. Archaeol. Sci.* 34 (10) (2007) 1702–1712.

[4] G. Guidi, F. Remondino, M. Russo, F. Menna, A. Rizzi, S. Ercoli, A multi-resolution methodology for the 3D modeling of large and complex archaeological areas, *Int. J. Archit. Comput.* 7 (1) (2009) 39–55.

[5] F. Remondino, S. El-Hakim, S. Girardi, A. Rizzi, S. Benedetti, L. Gonzo, 3D Virtual Reconstruction and Visualisation of Complex Architectures – The 3D-ARCH Project, vol. 38(5/W1), *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Trento (Italy), 2009.

[6] F. Nex, F. Rinaudo, LiDAR or photogrammetry? Integration is the answer, *Ital. J. Remote Sens.* (2011) 107–121, <http://dx.doi.org/10.5721/ItJRS20114328>.

[7] P. Grussenmeyer, E. Alby, T. Landes, M. Koehl, S. Guillemin, J. Hullo, E. Smigiel, Recording approach of heritage sites based on merging point clouds from high resolution photogrammetry and terrestrial laser scanning, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 34 (B5) (2012) 553–558.

[8] P. Bastonero, E. Donadio, F. Chiabrando, A. Spanò, Fusion of 3D models derived from TLS and image-based techniques for CH enhanced documentation, *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* II-5 (2014) 73–80.

[9] F. Remondino, F. Menna, A. Koutsoudis, C. Chamzas, S. El-Hakim, Design and implement a reality-based 3D digitisation and modelling project, in: *Proceedings of the IEEE Conference Digital Heritage*, vol. 1, 2013, pp. 137–144, <http://dx.doi.org/10.1109/DigitalHeritage.2013.6743723>.

[10] L. Pecchioli, M. Pucci, F. Mohamed, B. Mazzei, Browsing in the virtual museum of the Sarcophagi in the Basilica of St. Silvestro at the Catacombs of Priscilla in Rome, in: *Proc. of the 18th Int. Conference on IEEE Virtual Systems and Multimedia (VSM)*, 2012.

[11] Th. Kersten, 3D scanning and modelling of the Bismarck monument by terrestrial laser scanning for integration into a 3D city model of Hamburg, in: M. Ioannides, D. Fellner, A. Georgopoulos, D.G. Hadjimitsis (Eds.), *Digital Heritage, 3rd International Conference, EuroMed 2010, Lemessos, Cyprus, November 8–13, Lecture Notes in Computer Science*, vol. 6436, Springer Link, 2010, pp. 179–192.

[12] L. Cipriani, F. Fantini, S. Bertacchi, 3D models mapping optimization through an integrated parameterization approach: cases studies from Ravenna, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* XL-5 (2014) 173–180, <http://dx.doi.org/10.5194/isprsarchives-XL-5-173-2014>.

[13] B. Jiménez Fernández-Palacios, C. Stefani, J. Lombardo, L. De Luca, F. Remondino, Web visualization of complex reality-based 3D models with NUBES, in: *Proceedings of the IEEE Conference Digital Heritage, Marseille, France, 28 Oct–1 Nov*, vol. 1, 2013, pp. 701–704.

[14] J. Von Schwerin, H. Richards-Rissetto, G. Agugiaro, F. Remondino, G. Girardi, The MayaArch3D project: a 3D web system for querying ancient architecture and landscapes, in: *Proceedings of the Int. Conference Digital Humanities, Hamburg, Germany, 16–22 July*, 2012.

[15] J. Von Schwerin, H. Richards-Rissetto, F. Remondino, M.G. Spera, M. Auer, N. Billen, L. Loos, L. Stelson, M. Reindel, Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of Copan, Honduras, *J. Archaeol. Sci. Rep.* 5 (2016) 85–104, <http://dx.doi.org/10.1016/j.jasrep.2015.11.005>.

[16] M. Potenziani, M. Callieri, M. Dellepiane, M. Corsini, F. Ponchio, R. Scopigno, 3DHOP: 3D heritage online presenter, *Comput. Graph.* 52 (November) (2015) 129–141, ISSN 0097-8493.

[17] Y. Bastanlar, N. Grammalidis, X. Zabulis, E. Yilmaz, Y. Yardimci, G. Triantafyllidis, 3D reconstruction for a cultural heritage virtual tour system, *ISPRS Arch. Photogramm. Remote Sens.* 37 (5) (2008) 1023–1028, Beijing, China.

[18] B. Jiménez Fernández-Palacios, F. Nex, A. Rizzi, F. Remondino, ARCube – the augmented reality cube for archaeology, *Archaeometry* (2014), <http://dx.doi.org/10.1111/arcm.12120>.

[19] J.A. Barceló, Visualizing what might be. An introduction to virtual reality in archaeology visualizing archaeological data, in: *Virtual Real. Archaeol.* 2000. No. Goldstein 1996, 2000, pp. 9–36.

[20] Y. Boas, Overview of Virtual Reality Technologies, 2013, Mms.Ecs.Soton.Ac.Uk.

[21] G. Papagiannakis, S. Schertenleib, B. O’Kennedy, M. Arevalo-Poizat, N. Magnenat-Thalmann, A. Stoddart, D. Thalmann, Mixing virtual and real scenes in the site of the ancient Pompeii, *Comput. Anim. Virtual Worlds* 16 (1) (2005) 11–24, Series: Comput. Animat. & Virtual Worlds (UK).

[22] Oculus, V. R. Website. <https://www.oculus.com/> (accessed 07.04.16).

[23] P.R. Desai, P.N. Desai, K.D. Ajmera, K. Mehta, A review paper on oculus rift – a virtual reality headset, *IJETT Int. J. Eng. Trends Technol.* 13 (July (4)) (2014) 175–179, ISSN: 2231-5381.

[24] I. Goradia, J. Doshi, L. Kurup, A review paper on oculus rift & project Morpheus, *Int. J. Curr. Eng. Technol.* 4 (5) (2014) 3196–3200, E-ISSN: 2277-4106, P-ISSN: 2347-5161.

[25] Samsung Gear VR. <http://www.samsung.com/global/microsite/gearvr/> (accessed 07.07.16).

[26] Neo Pro. <http://light-and-shadows.com/> (accessed 07.07.16).

[27] Kinect. <https://www.microsoft.com/en-us/kinectforwindows/> (accessed 07.07.16).

[28] Google Cardboard. <https://www.google.com/get/cardboard/> (accessed 04.09.16).

[29] OpenDive. <http://www.durovis.com/opendive.html> (accessed 04.09.16).

[30] F. Tschirschwitz, T. Kersten, K. Zobel, Interactive 3D visualisation of architectural models and point clouds using low-cost-systems, in: M. Ioannides, N. Magnenat-Thalmann, E. Fink, R. Zarnic, A.-Y. Yen, E. Quak (Eds.), *Proceedings of the 5th International Conference EuroMed, Limassol, Cyprus, November 3–8, Lecture Notes in Computer Science (LNCS)*, vol. 8740, Springer International Publishing, Switzerland, 2014, pp. 268–278.

[31] N. Villaroman, D. Rowe, B. Swan, Teaching natural user interaction using OpenNI and the Microsoft Kinect sensor, in: *Proceedings of Conference Information Technology Education, ACM (SIGITE’11)*, West Point, NY, USA, October 20–22, 2011, p. 227, <http://dx.doi.org/10.1145/2047594.2047654>.

[32] H. Richards-Rissetto, F. Remondino, G. Agugiaro, J. Robertsson, J. Von Schwerin, G. Girardi, Kinect and 3D GIS in archaeology, in: G. Guidi, L. Addison (Eds.), *Proceedings of the 18th Int. Conference on Virtual Systems and Multimedia (VSM)*, Milan, Italy, 2012, pp. 331–337, <http://dx.doi.org/10.1109/VSM.2012.6365942>.

[33] Structure. <http://www.structure.io/> (accessed 07.04.16).

[34] Leap Motion. <https://www.leapmotion.com/> (accessed 04.09.16).

[35] D.A. Bowman, C. Wingrave, J. Campbell, Using Pinch Cloves™ for both natural and abstract interaction techniques in virtual environments, in: *HCI International*, 2001, pp. 629–633.

[36] Control VR. <http://controlvr.com/> (accessed 04.09.16).

[37] Thalmic. <https://www.thalmic.com/myo/> (accessed 04.09.16).

[38] K. Pietroszek, A. Kuzminykh, J.R. Wallace, Smartcasting: a discount 3D interaction technique for public displays, in: *OzCHI, Sydney, Australia, ACM*, 2014, ISBN: 9781450306539.

[39] A. Sherstyuk, D. Vincent, A. Treskunov, Towards Virtual Reality games, in: *Proceedings of the 8th International Conference Virtual Real. Contin. Appl. Ind. (VRCAL)*, 2009, p. 315, <http://dx.doi.org/10.1145/1670252.1670322>.

[40] H.G. Hoffman, W.J. Meyer, M. Ramirez, L. Roberts, E. Seibel, B. Atzori, S. Sharar, D.R. Patterson, Feasibility of articulated arm mounted oculus rift virtual reality goggles for adjunctive pain control during occupational therapy in pediatric burn patients, *Cyber Cyberpsychol. Behav. Soc. Netw.* 17 (6) (2014) 397–401, <http://dx.doi.org/10.1089/cyber.2014.0058>.

[41] A. Rizzo, J. Morie, J. Williams, J. Pair, J. Buckwalter, Human emotional state and its relevance for military VR training, in: *Proceedings of the 11th International Conference on Human–Computer Interaction, Las Vegas, Nevada, USA, 22–27 July*, 2005.

[42] E.J. Tatton III, The Future Impact of Immersive Virtual Reality Simulations on the Suburban Training Experience of Firefighters in Westchester, NY, Master of Science Degree, School of Arts and Science State University of New York Polytechnic Institute Utica, New York, 2014.

[43] A. Magnelli, Use of Oculus Rift for an immersive “time-shift” experience in the Medieval Ages, in: *Proceedings of the Conference on Cultural Heritage and New Technologies, Vienna, Austria, 3–5 November*, 2014.

[44] M. Forte, N. Lercari, E. Shiferaw, R. Kopper, Reshaping remote sensing and virtual reality at Çatalhöyük, in: *Proceedings of the 5th International Conference on Remote Sensing in Archaeology, The Age of Sensing, Duke University Durham, North Carolina, USA, 13–15 October*, 2014.

[45] S. Pescarin, A. Pagano, M. Wallergård, W. Hupperetz, C. Ray, Evaluating Virtual Museums: archeovirtual case study, CAA2012, in: *Proceedings of the 40th Conference in Computer Applications and Quantitative Methods in Archaeology, Southampton, United Kingdom, 26–30 March*, 2012.

[46] Dutch Rijksmuseum. The museum of the future. www.rijksmuseum.nl/en (accessed 04.09.16).

[47] ArcTron. http://www.arctron.de/en/services/multimedia/interactive_systems/ (accessed 04.09.16).

[48] ETT. <http://www.ettolutions.com/News.aspx?id=738/> (accessed 07.04.16).

[49] Universidad de Alicante, Patrimonio Virtual Website. <http://www.patrimoniovirtual.com/2013/09/12/oculus-rift-sumergiendonos-en-realidad-virtual/> (accessed 04.09.16).

[50] F. Remondino, A. Rizzi, B. Jiménez Fernández-Palacios, G. Agugiaro, G. Baratti, R.D.E. Amics, The Etruscans in 3D: from space to underground, in: *Proc. 23rd Int. CIPA Symposium, Prague, Czech Republic*, 2011.

- [51] B. Jiménez Fernández-Palacios, A. Rizzi, F. Remondino, Etruscans in 3D – surveying and 3D modeling for a better access and understanding of heritage, *Virtual Archaeol. Rev.* 4 (8) (2013) 85–89, ISSN: 1989-9947.
- [52] Studi etruschi. Vol. XXXI. Serie II, Istituto di studi Etruschi ed Italici. Leo S. Olschki – Book Co. Italia Srl.
- [53] S. Steingraeber (Ed.), *Catalogo ragionato della pittura Etrusca*, Jaca Book, 1985, ISBN 88-16-60046-2.
- [54] F. Fiorillo, B. Jiménez Fernández-Palacios, F. Remondino, S. Barba, 3D surveying and modelling of the archaeological area of Paestum, Italy, *Virtual Archaeol. Rev.* 8 (4) (2013) 55–60.

Sección III - Escala paisaje

La presente sección contiene el artículo “*Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites*” (Sistema Móvil LiDAR: nuevas posibilidades para la documentación y difusión de los grandes sitios del Patrimonio Cultural) publicado en Febrero de 2017 en la revista Internacional de Impacto (JCR) Remote Sensing.

Resumen

Este trabajo se encuadra dentro del proyecto europeo Cultural Heritage Through Time (CHT2), que tiene como objetivo establecer una metodología clara y eficiente para estandarizar enfoques híbridos y visualizar conjuntos de datos heterogéneos a través de plataformas virtuales vía web que faciliten el análisis 4D. La experiencia, los conocimientos adquiridos y los resultados obtenidos a través del trabajo realizado en la sección precedente, escala arquitectura, demuestran que las tecnologías de visualización 3D utilizadas son replicables para la escala paisaje, sin embargo, resulta indudable que existen tres grandes cuellos de botella para este caso de estudio: el tiempo de adquisición y el tiempo de procesado y la optimización de datos. Por ello, la línea de investigación de la sección escala paisaje tiene como objetivo presentar soluciones y nuevas metodologías a los problemas encontrados.

El Sistema Móvil LiDAR (MLS) es una tecnología emergente que combina múltiples sensores. Sensores activos junto con sistemas de navegación global e inercial son sincronizados en una misma plataforma móvil con el objetivo de producir nubes de puntos tridimensionales de precisión, con información geoespacial. Permiten obtener una gran cantidad de información 3D georreferenciada, de una forma rápida y eficiente, la cual puede ser usada para una gran variedad de aplicaciones como la digitalización y la reconstrucción 3D de complejas áreas urbanas y/o paisajes.

En primer lugar, el Sistema Móvil LiDAR es aplicado en el campo del Patrimonio Cultural, con el objetivo de evaluar su potencial para fines documentarios, divulgativos, o analíticos. El

Section III - Landscape scale

This chapter contains the scientific article entitled “*Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites*” published in February 2017 by the International Journal (JCR) of Remote Sensing.

Abstract

This work is forms part the Cultural Heritage Through Time (CHT2) European project, which aims to establish a clear and efficient methodology for standardizing hybrid approaches and visualizing heterogeneous datasets through virtual web platforms focused on 4D analysis. The acquired experience and knowledge as well as the results obtained through the work done in the previous section - architecture scale - have shown that the 3D visualization technologies may also be employed for landscape scale. However, there are undoubtedly three major issues inherent to this case study: data acquisition and processing time and data optimization. Therefore, the research line of this landscape scale section aims to present solutions and new methodologies for the encountered problems.

Firstly the LiDAR Mobile System (MLS) is applied in the field of Cultural Heritage with the objective of evaluating its potential for documentary, disseminative and analytical purposes. It has been compared to the Terrestrial Laser Scanner (TLS) the active sensor most commonly used for large areas of Cultural Heritage when comparing the data acquisition and processing time, accuracy and resolution of the points cloud obtained.

Secondly, an optimization methodology is proposed based on a detailed study of the geometry, classifying the structures in three clusters to segment it according to its curvature: (i) planar or low curvature; (ii) cylindrical, mild transitions and medium curvature; and (iii) the abrupt transitions of high curvature. The 3D point clouds obtained for each group are analysed and optimized and the results presented.

sistema móvil LiDAR ha sido comparado con el láser escáner terrestre, el sensor activo más utilizado para estos casos (grandes áreas del Patrimonio Cultural), confrontando el tiempo de adquisición de los datos, la precisión y la resolución de las nubes de puntos obtenidas. Las discrepancias entre ambas tecnologías fueron analizadas comparando directamente las nubes de puntos generadas por ambas, destacando los errores que afectan a las estructuras arquitectónicas.

En segundo lugar y como consecuencia de la gran cantidad de datos obtenidos en ambos casos, se propone una metodología de optimización basada en un estudio detallado de la geometría, a partir de la segmentación de las estructuras. Para ello, las estructuras se clasifican en tres grupos principales según sus características geométricas y de acuerdo a su curvatura: (i) plana o baja curvatura, (ii) cilíndrica, transiciones suaves y curvatura media y (iii) transiciones abruptas o alta curvatura. Las nubes de puntos 3D obtenidas para cada grupo son analizadas y optimizadas, teniendo en cuenta el paso de muestreo espacial de referencia, de acuerdo a un intervalo de confianza y a las propias características de las curvaturas. Los resultados presentados sugieren que el Sistema Móvil LIDAR es un enfoque óptimo, que permite una adquisición de datos a alta velocidad, proporcionando una precisión adecuada apta para grandes áreas del Patrimonio Cultural.

El caso de estudio para la escala paisaje es la Muralla Medieval de Ávila (España). Rodea el casco histórico de la ciudad con un perímetro de 2,516 m y 87 torres de defensa. Debido a las grandes dimensiones y a las características geométricas de la Muralla, con tramos análogos de características similares, el estudio de precisión fue llevado a cabo en la llamada “Puerta del Alcázar”, declarada Monumento Nacional desde 1884. Más tarde, en 1985, la antigua ciudad de Ávila y sus iglesias extramurales fueron declaradas Patrimonio de la Humanidad por la UNESCO.

The landscape scale case study is the Medieval Wall of Avila (Spain). The wall surrounds the historic center of the city with a perimeter of 2,516 m and 87 defence towers. Due to the great dimensions and the geometry of the wall, with analogous sections of similar features, the assessment study was carried out in the so called “Puerta del Alcázar”, declared a National Monument since 1884. Later, in 1985, the ancient city of Avila and its extramural churches were declared a World Heritage Site by UNESCO.

Article III

**Mobile LiDAR System: new possibilities for the documentation and dissemination of
large Cultural Heritage sites**

Article

Mobile LiDAR System: New Possibilities for the Documentation and Dissemination of Large Cultural Heritage Sites

Pablo Rodríguez-Gonzálvez ^{1,*}, Belén Jiménez Fernández-Palacios ¹, Ángel Luis Muñoz-Nieto ¹, Pedro Arias-Sanchez ² and Diego Gonzalez-Aguilera ¹

¹ TIDOP Research Group, University of Salamanca, Polytechnic School of Avila. Hornos Caleros, 50, 05003 Avila, Spain; belenjfp@gmail.com (B.J.F.-P.); almuni@usal.es (Á.L.M.-N.); daguilera@usal.es (D.G.-A.)

² Department of Natural Resources & Environmental Engineering, University of Vigo, School of Mining Engineering, Maxwell s/n, 36310 Vigo, Spain; parias@uvigo.es

* Correspondence: pablorgsf@usal.es; Tel.: +34-920-353-500

Academic Editors: Rosa Lasaponara, Nicola Masini and Prasad S. Thenkabail
Received: 10 November 2016; Accepted: 20 February 2017; Published: 23 February 2017

Abstract: Mobile LiDAR System is an emerging technology that combines multiple sensors. Active sensors, together with Inertial and Global Navigation System, are synchronized on a mobile platform to produce an accurate and precise geospatial 3D point cloud. They allow obtaining a large amount of georeferenced 3D information in a fast and efficient way, which can be used in several applications such as the 3D recording and reconstruction of complex urban areas and/or landscapes. In this study the Mobile LiDAR System is applied in the field of Cultural Heritage aiming to evaluate its performance with the purpose to document, divulgate, or to develop an architectural analysis. This study was focused on the Medieval Wall of Avila (Spain) and, specifically, the performed accuracy tests were applied in the “Alcazar” gate (National Monument from 1884). The Mobile LiDAR System is then compared to the most commonly employed active sensors (Terrestrial Laser Scanner) for large Cultural Heritage sites in regard to time, accuracy and resolution of the point cloud. The discrepancies between both technologies are established comparing directly the 3D point clouds generated, highlighting the errors affecting the architectural structures. Consequently, and based on a detailed geometrical analysis, an optimization methodology is proposed, establishing a segmented and classified cluster for the structures. Furthermore, three main clusters are settled, according to the curvature: (i) planar or low curvature; (ii) cylindrical, mild transitions and medium curvature; and (iii) the abrupt transitions of high curvature. The obtained 3D point clouds in each cluster are analyzed and optimized, considering the reference spatial sampling, according to a confidence interval and the feature curvature. The presented results suggest that Mobile LiDAR System is an optimal approach, allowing a high-speed data acquisition and providing an adequate accuracy for large Cultural Heritage sites.

Keywords: cultural heritage; mobile LiDAR system; point cloud; terrestrial laser scanner; accuracy assessment; optimization

1. Introduction

Recent advances in Geomatics Science enable the use of a wide range of sensors to record, catalogue and analyze Cultural Heritage (CH) sites: from RGB and multispectral cameras [1,2] and Terrestrial Laser Scanner (TLS) [3], to Ground Penetrating Radar (GPR) [4] and Raman Spectroscopy [5]. Furthermore, airborne LiDAR (Laser Imaging Detection and Ranging) is used as a remote sensing device for 3D surveying and modeling of extensive archaeological sites [6,7]. Nowadays, hybrid

sensors such as Mobile LiDAR Systems (MLS) [8,9] bring added value to record large and complex sites. Although the most common solution based on MLS are boarded on vans and applied in the field of civil engineering and construction [10], MLS has been useful in other fields, such as geology [11]; agriculture, biology or forestry [12–14]; and even in the inspection of high-voltage power lines [15]. The last developments allow the use of MLS boarded in a backpack [16] or even in autonomous robots [17], offering a flexible solution in terms of accuracy, flexibility, point density and access to indoor and non-transitable areas [18–22]. These specific solutions are still under development and several approaches are being experienced and tested [23,24].

MLS process and management optimization has become a key point. Even though MLS reduces extremely data collection phase, it still requires a lot of time and resources consumption to extract meaningful information [25] and even more time for 3D modeling. At this point, and for large and unstructured point cloud, some authors [26] showed that it is more efficient to carry out the simplification of the point cloud before creating a mesh. In terms of workflow optimization, it may be useful when the presence of particular characteristics (e.g., breaklines) is desirable [27]. MLS optimization, understood not only as decimation but a smart filtering, has proven to be relevant in different fields, such as infrastructures management [28], reverse engineering [29], object detection [30], object fitting [31] and visualization optimization through Web services by means of mobile devices [32].

It is a well-known fact that CH information systems such as Nubes Project [33,34] and Cultural Heritage Information System Projects [35–37] become the basis for an effective management of CH. However, they are also extremely important for its dissemination and decision making. These Systems and Projects are usually based on 3D Web interfaces [38]. Thus, it is clear that, in order to guarantee and improve the specific visualization requirements of 3D Web systems, the MLS complex geometric datasets need to be optimized.

Based on the remarks above, this paper aims to analyze the suitability of MLS for CH documentation and dissemination purposes from a two-fold approach. Firstly, an accuracy assessment is performed. For this purpose, the acquired MLS data were compared with a ground truth defined by a millimetric laser scanner point cloud. Secondly, the data suitability, in terms of 3D point cloud optimization for the data dissemination, is evaluated.

This manuscript is organized as follows. After the Introduction, sensors and devices are described in Section 2. In Section 3, the multi-sensor integration methodology and multi-data process workflow proposed are detailed. In Section 4, the representative study case of the Medieval Wall of Avila (Spain) is shown. Finally, in Sections 5 and 6, discussion and conclusions are respectively discoursed.

2. Materials

The evaluated mobile LiDAR technology is a LYNX Mobile Mapper manufactured by Optech (Figure 1) [9,39]. This system is composed of two LiDAR sensors, four RGB cameras and an Applanix POS LV 520 IMU. The system is configured to take 500,000 points per second with a scan frequency of 200 Hz. The maximum range of the sensors is 200 m, with a precision of 8 mm (one sigma) and permission to obtain up to 4 echoes of the signal and the intensity reflected by the objects at a 1550 nm wavelength (Table 1). Along with the geometric measurement system, the MLS incorporates a multisensory camera to acquire the radiometric texture of the scanned elements.

In this study, the MLS is mounted on a car, achieving speeds up to 40 km/h during the data capture.

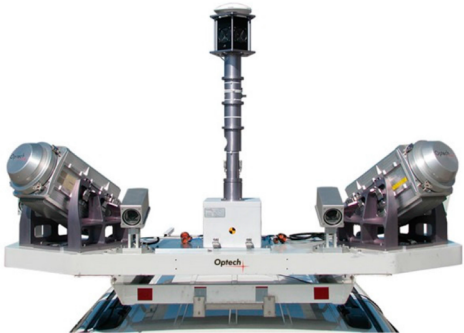


Figure 1. LYNX Mobile Mapper manufactured by Optech.

Table 1. Technical specifications of Optech LYNX Mobile Mapper.

MLS Technical Parameters	
X, Y position	0.020 m
Z position	0.050 m
Roll and pitch	0.005°
True heading	0.015°
Measuring principle	Time of Flight (ToF)
Maximum range	200 m
Range precision	8 mm (1σ)
Range accuracy	±10 mm (1σ)
Laser measurement rate	75–500 kHz
Measurement per laser pulse	Up to 4 simultaneous
Scan frequency	80–200 Hz
Laser wavelength	1550 nm (near infrared)
Scanner field of view	360°
Operating temperature	10–40 °C
Angular resolution	0.001°

The use of MLS is not completely straightforward. It requires an initial data acquisition plan, especially for the large cultural heritage sites. In this regard, any error in the INS will be directly propagated to the point cloud, being especially complicated in scenarios with the presence of narrow streets (e.g., urban CH sites), or dense vegetation, which could provide a loss in accuracy by the multi-path and occlusion of the GNSS signal [40]. Besides, the boresight angles and level-arm (related to the MLS assembly), which are kept constant throughout the whole scanning process, require to be precisely determined to avoid any loss in the overall accuracy [41]. To this end, some regular surfaces (e.g., road surface) should be measured prior to the data acquisition for its calibration. The most critical aspect in data acquisition planning is the boresight, which could cause that same scene acquisition in different trajectories to not overlap correctly. Additionally, the height of the CH buildings could be a limitation to the system due to the vertical angle, so those trajectories closer to the object should be avoided to reduce the occlusions in the final point cloud.

To assess the quality of the MLS, a Time-of-Flight (ToF) [42,43] TLS Trimble GX is employed, found on direct time measurement. It is typically more precise than the phase-shift (PS) ones [43,44], for instance, measurement amplitude-modulated continuous wave method (AMCW) based on indirect time, with lower range but further point acquisition speed. The main technical specifications are shown in Table 2. In a ToF System, the distance to the surface and the position of the points (X, Y, Z) are calculated from the time of the flight of the pulse; a laser pulse is emitted towards the object and, once it is reflected from the object surface, returns to the equipment. The distance to the object can be determined by half of the round-trip range. Nowadays, both technologies are competing;

PS technology increasing its range, while ToF technology improving the acquisition speed. Regarding the TLS accuracy evaluation, please refer to [45,46].

Table 2. Technical specifications of the Trimble GX laser scanner.

TLS Technical Parameters	
Measuring principle	Time of Flight (ToF)
Laser wavelength	534 nm (visible-green)
Scanner field of view	360° H × 60° V
Range precision	1.4 mm at 50 m
Measurement range	2–350 m
Spot size (beam diameter)	3 mm a 50 m
Scanning speed	5000 points/sec

In order to georeference the TLS point cloud in a global coordinate reference system (ETRS89) 50 GPS control points were acquired. The GPS points, well distributed through the entire area of interest, were surveyed using two Leica 1200 GPS. This device is a dual frequency receiver which was used with Real Time Kinematic (RTK) method. The a-priori precision of this measurement method is 1 cm in horizontal plane and 2 cm in vertical axis.

3. Methods

In this section the two geomatics techniques employed, as well as the specific assessment methodology and the developed algorithms for the optimization of point clouds, are described. In Figure 2 the global pipeline for the geometric accuracy and optimized assessment data aimed at 3D web visualization and dissemination is shown.

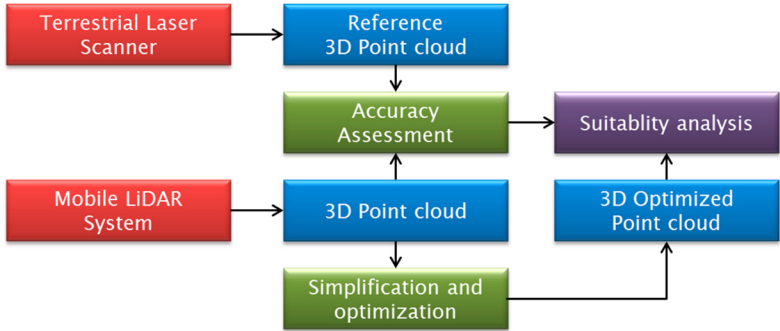


Figure 2. Pipeline for the assessment of Mobile LiDAR Systems (MLS) for Cultural Heritage recording and modeling.

3D data acquired by active sensors (TLS and MLS) are processed following a conventional workflow. In the case of TLS, the obtained unstructured point clouds (individual scans) are cleaned, edited and aligned in a common local reference system. The alignment process can be automatically carried out through Iterative Closest Point (ICP) points [47], by automatic recognition of objects [48] or using artificial targets [49]. The 3D point cloud obtained with millimetric resolution can include the intensity levels (I) and/or the color information (RGB). Finally, the aligned point cloud is georeferenced in a global reference system by means of targets of known coordinates. Regarding the MLS, three main types of sensors take part in data acquisition using three independent reference systems. A multi-sensor calibration is mandatory to determine the translational and rotational offsets among the different sensors and bring all the data into the same reference system [50]. As a result, the unstructured point cloud is already aligned in a global reference system by means of the navigation/positioning sensors with centimetric absolute precision (typically). The 3D point cloud obtained uses to have also

a centimetric resolution, including at least the intensity levels of returned pulses or even the color information (RGB).

3.1. Accuracy Assessment Protocol

Since the MLS involves several sensors (e.g., IMU, LiDAR, GNSS, etc.) to acquire a georeferenced 3D point cloud, the aim of this step is to analyze, in the CH field, the quality of the MLS point cloud using a ground truth provided by a TLS. To dismiss the uncertainties associated to the global coordinate geo-referencing, a registration phase with the Iterative Closest Point (ICP) technique is carried out, prior to the MLS point cloud evaluation [51]. As a result, only those errors affecting the 3D point cloud of the architectural elements are analyzed. Particularly, discrepancies are computed in consonance with Multiscale Model to Model Cloud Comparison (M3C2) [52], which performs a direct comparison of the 3D point clouds (TLS to MLS), avoiding the preliminary phase of meshing.

In order to prevent possible bias effects affecting the data processing, the normality assumption, i.e., the hypothesis that errors follow a Gaussian distribution, are checked according to graphical methods such as QQ-plot [53] well-suited for very large samples [54]. If the samples are not normally distributed, either due to the presence of outliers or because of a different population hypothesis, a robust model based on non-parametric estimation should be employed. In this case, the median (m) and the median absolute deviation (MAD) are used as robust measures instead of the mean and standard deviation, respectively. The MAD is defined as the median (m) of the absolute deviations from the data's median (m_x):

$$MAD = m(|x_i - m_x|) \tag{1}$$

where the x_i values come from the discrepancies (Euclidean distance) between both point clouds (TLS and MLS).

The computation of the discrepancies maps is carried out by Cloud Compare v2.7.0 software [55], being a point cloud-to-point cloud based on the M3C2 plugin [52]. The robust statistical estimators are computed by a custom script as well as the in-house statistical software (STAR (Statistics Tests for Analyzing of Residuals)) [56].

3.2. Point Cloud Optimization

Despite recent technological breakthroughs, it is still common to face some limitations since 3D datasets obtained by active sensors (TLS and MLS) produce complex reality-based 3D point clouds which are generally large. For extensive CH sites, the geometric component hinders the access for analysis purposes through Web visualization, worsen when mobile devices (e.g., tablets or smartphones) are used, due to the vast amount of information. Depending on the device used and the size of the 3D models, a delay might occur that could affect the fluidity of the 3D scene. Moreover, the 3D point cloud acts as mainframe for the extraction of semantic and/or vector information, avoiding the meshing step. The common algorithms used to generate a mesh are time-consuming, since they require human intervention to correct topological errors (e.g., non-manifold edges, loose edges, overlapping faces, self-intersections, etc.) that could be generated, and the holes filling required to rebuild those areas affected by errors and occlusions. Thus, different simplification and optimization strategies would be desirable to be applied to the 3D point clouds, while keeping the relevant information for the subsequent studies and/or operations in the global pipeline of CH conservation and management.

The proposed optimization methodology (Figure 3) is based on an idealization process and an adaptive sampling according to a confidence interval and local feature curvature. Thus, the more significant are the points, the more 3D points are kept to represent those complex areas of the site. On the contrary, for those parametric and simple geometrical CH elements such as planes, the point cloud is considerably reduced in size.

The point cloud optimization strategy has been developed following three global phases: (i) a preparation phase to setup the raw point cloud acquired from MLS; (ii) a clustering phase based on a curvature segmentation; and (iii) a final weighted sampling phase.

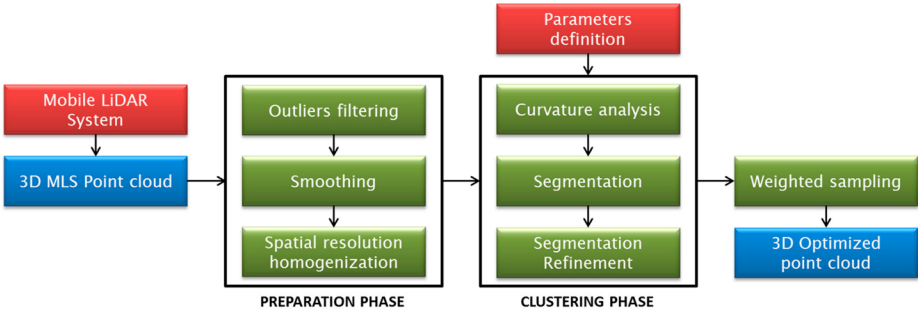


Figure 3. Pipeline for 3D point cloud optimization.

The *preparation phase* involves three sub steps in the following order:

- An initial outliers filtering of the MLS point cloud based on the absolute deviation (Euclidean distance) of the points from a fitted local plane in a spherical vicinity. The absolute threshold is not set very strictly to avoid false positives. In the case a plane cannot be fitted in the neighborhood, the point is also excluded.
- Next, in order to ease the simplification, a local smoothing process by means of a moving least squares [57] is applied. This operation involves a point displacement regarding the original positions; however, the spherical search volume is chosen in relation to the precision obtained from the accuracy assessment studies (see Section 3.1) to avoid a precision deterioration of the final optimized point cloud.
- Finally, a reduction of high point density areas, due to the MLS acquisition methodology, is applied. For this task, a spatial sampling is carried out. The sampling value determines the final results. Since there are several options for this sampling value, all of them being related to the input point cloud precision, the proposed one is to setup the 95% confidence interval of the error dispersion from the accuracy assessment studies. By this procedure, it is possible to guarantee the optimized final results.

Once the point cloud is ready, the *curvature clustering* phase is carried out following the next three sub steps:

- Initially, the local curvature is computed in a wide spherical neighborhood to reduce noise effects. The spherical radius for the curvature calculation is defined in relation to the main geometrical elements of the CH site (i.e., a-priori length and height).
- Next, the 3D point cloud is segmented according to the computed local curvature and the a-priori approximate knowledge of the main geometrical primitives presented (e.g., planes and radius of cylinders). These coarse values allow defining a discrete number of clusters according to a similar curvature values. The final number of clusters is increased in one, since the highest curvature values are related to non-parametric areas, as the break-lines, borders, corners, abrupt areas, surface discontinuities or geometric and topological errors.
- Finally, since the curvature computation and clustering could be affected by local errors, especially in transition areas, a refinement based on connected component analysis is carried out to reclassify them in the more suitable cluster. This analysis is based on an octree representation of the point cloud, so a reference subdivision level has to be set. In order to find connected components, the octree level has to be set slightly higher than the homogenized spatial resolution. Since the

spatial resolution was homogenized in the *preparation phase*, and an octree level has to be fixed, it is possible to relate easily the component’s area by the number of points. For the main features of the CH site, it is possible to define their minimum area. As result, the components inside a cluster that do not verify this minimum area are reallocated to the neighbor cluster in crescent curvature. No points are removed.

Lastly, a *weighted sampling* is applied to all the points inside a cluster based on the associated feature (e.g., plane, cylinder, etc.) and based on the maximum and minimum curvature values of the cluster. The highest curvature cluster is kept unmodified, since encloses all the conflictive areas. The others cluster thresholds, low and medium curvature, are established according to its geometric elements. For instance, the number of points of a wall could be drastically reduced if points can be assimilated/idealized as a plane. In the cases of other elements as towers, the arc to chord approximation was used. Thus, a final 3D optimized point cloud is obtained, retaining all the geometrical relevant information for subsequent tasks, as vectorization, reverse engineering, finite element (FEM) analysis and information management through HBIM or even for Web visualization.

4. Experimental Results

The case study was the Medieval Wall of Avila. Its construction is the most important example of military architecture of the Spanish Romanesque style as well as an exceptional model of European medieval architecture [58]. The construction of the city wall is perfectly adapted to the topography. The wall was used not only to defend the town from possible invasions and protect the people from possible pests or epidemics, but also to control the trade of the city with the outside. The southern sectors are shorter as they are built upon a cliff that acts as a natural defense. The western and northern sections grow in height, reaching the tallest and thickest points located in the east section. There are nine gates giving access to the town, of which the most spectacular is “*Puerta del Alcázar*” (Gate of the Fortress). In 1884, it was declared a National Monument and in 1985, the old city of Ávila and its extramural churches were declared a World Heritage site by UNESCO. Some references state that the building dates back to 1090. Other researchers have argued instead that the wall’s construction most likely continued through into the 12th century. Its large size is a clear example of a challenging CH sites for the recording and documentation processes. Despite its linear nature (Figure 4), the towers and wall distribution, the gates, and neighbor city buildings add difficulties for acquisition and processing. Since the case study presents a repetitive pattern (i.e., wall–tower–wall) along its whole extension, only a significant part of its extension was evaluated. Thus, the obtained results could be extrapolated to the whole medieval Wall. The main geometric information is shown in Table 3.

Table 3. Avila’s Medieval Wall main dimensions.

Parameter	Value
Perimeter	2516 m
No. of towers	87
No. of Battlement elements (current/original)	2113/2379
No. of gates	9
Width of the wall	Between 2.6 and 2.8 m
Average height of the wall	11.5 m
Average height of the towers	15 m

The 3D point cloud of the whole medieval wall coming from the TLS was carried out using the process described in [59]. The spatial resolution achieved was 15 mm for an average scanning distance of 20 m. The georeferencing of the TLS into a global coordinate system (ETRS89) was done by a GNSS network of 50 control points, using two Leica 1200 GPS, distributed in the towers and the upper part of the wall as well as along its base. The registration errors of the individual TLS scans have been

evaluated by a network of control points, analyzing its propagation in a close object. The discrepancies reached up to 5 cm as stated in [59]. The TLS workload involved 159 h for the 2.5 km perimeter wall.

The 3D point cloud obtained (Figure 5) by means of MLS of the whole Medieval Wall of Avila was carried out according to the process described in [60]. The spatial resolution acquired was 60 mm for an average scanning distance of 25 m. The georeferencing of the LiDAR 3D point cloud into a global coordinate system was done by the integrated IMU sensor (Applanix POS LV 520) on the LYNX Mobile Mapper.

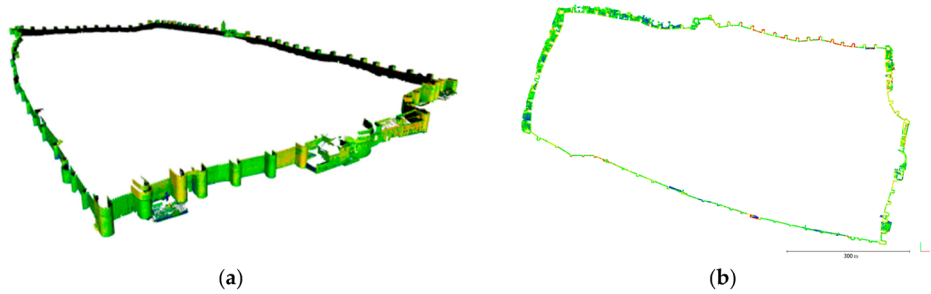


Figure 4. TLS 3D point cloud (a); and XY view (b) of the Wall of Avila.

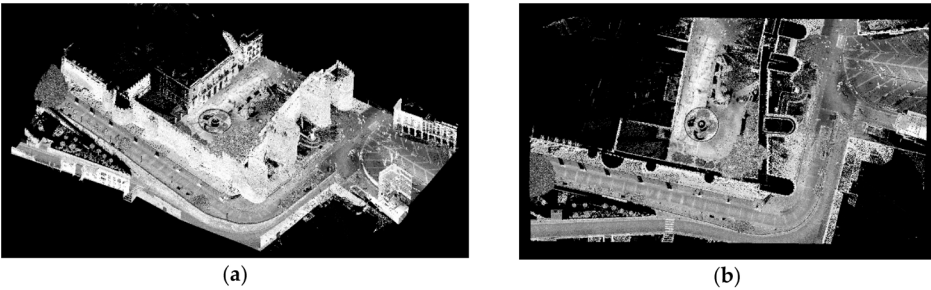


Figure 5. MLS 3D point cloud (a); and XY view (b) of the “Puerta del Alcázar” (Gate of the Fortress) of the Wall of Avila.

MLS and TLS workload, in terms of time consumption and accuracy, is compared in Table 4.

Table 4. Comparison between MLS and TLS field work and processed point cloud.

	Trimble GX	LYNX Mobile Mapper
Measuring principle	Time of Flight (ToF)	Time of Flight (ToF)
Range	350 m to 90% reflectivity 200 m to 35% reflectivity 155 m to 18% reflectivity	250 m to 10% reflectivity
Resolution	15 mm	60 mm
Scanning speed	up to 5000 points per second	up to 500 lines/sec
Scanned area (approximate)	30,000 m ²	250,000 m ²
No. of stations	98	1
No. of points	300,000,000	185,000,000
No. of images	215	420
Geodetic reference system-projection	ETRS89 and UTM30	ETRS89 and UTM30
Acquisition time	150 h (laser) + 4 h (camera) + 5 h (GNSS)	1 h
Processing time	435 h	15 h

4.1. Point Cloud Accuracy Assessment

The accuracy assessment was focused in the named “Alcazar” door, one of the highest wall entrances (Figure 6), and its vicinity, originally annex to the “Alcazar” fortress, where the defensive system was reinforced with a barbican and a ditch.

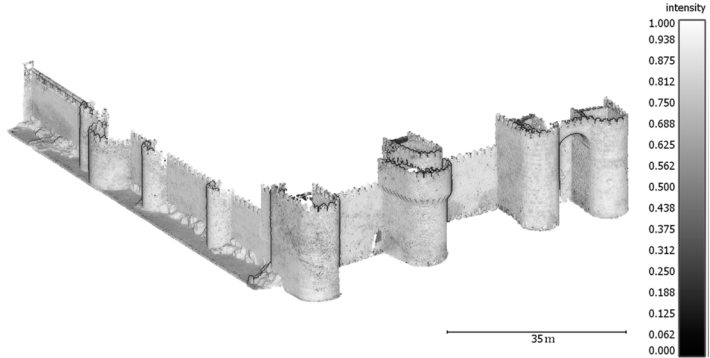


Figure 6. Segmented MLS point cloud of the analyzed zone (southeast walls), coded according to the intensity values.

The georeferencing error of the MLS is dependent on three factors: the GNSS system, the trajectory compensation and the calibration method of its sensors. The georeferencing error of the TLS is associated with the two GPS receivers used. Thus, in order to evaluate the accuracy of a MLS point cloud, a registration phase with ICP was carried out. Consequently, a comparison of both 3D point clouds was done (TLS and MLS). After the removal of the non-overlap areas (e.g., parts acquired by the MLS but not by the TLS), the discrepancies map was computed, as shown in Figure 7, separately for the east walls (Figure 7a) and the south walls (Figure 7c), which delimited the fortress. These discrepancies were computed using the point cloud-to-point cloud comparison, obtained as the result of the signed error between both point clouds.

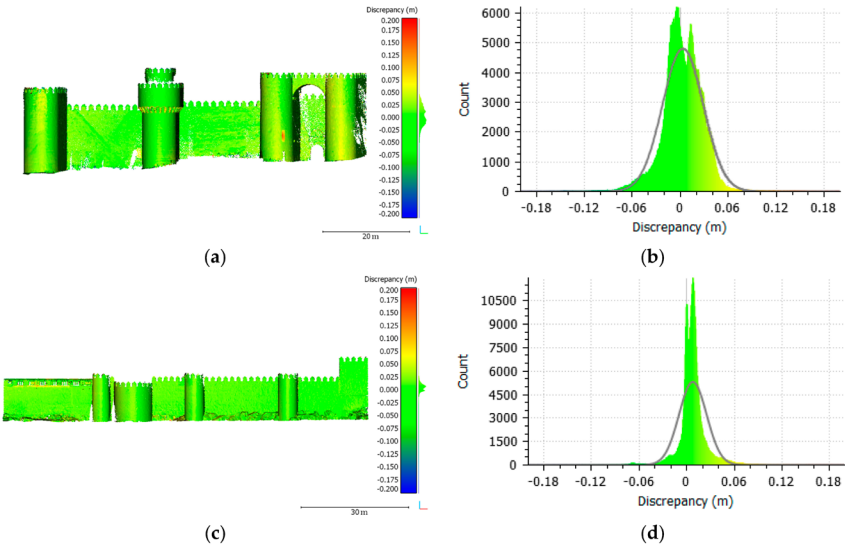


Figure 7. Relative discrepancies maps between MLS and TLS in the “Alcazar” fortress (Left) and its associated histogram (Right) for the: east walls (a,b); and south walls (c,d).

The obtained values were analyzed with a QQ-plot to confirm the non-normality of the sample (Figure 8). This fact was hinted by the histogram shape (Figure 7b,d), but since it is directly dependent on the bin size, it cannot be used as decision criterion. Since this sample does not follow a normal distribution (Figure 8), it is not possible to infer the central tendency and dispersion of the population according to Gaussian statistics parameters such as mean and standard deviation. For that reason, the accuracy assessment was computed based on robust alternatives, using non-parametric assumptions such as the median and the MAD value shown in Table 5.

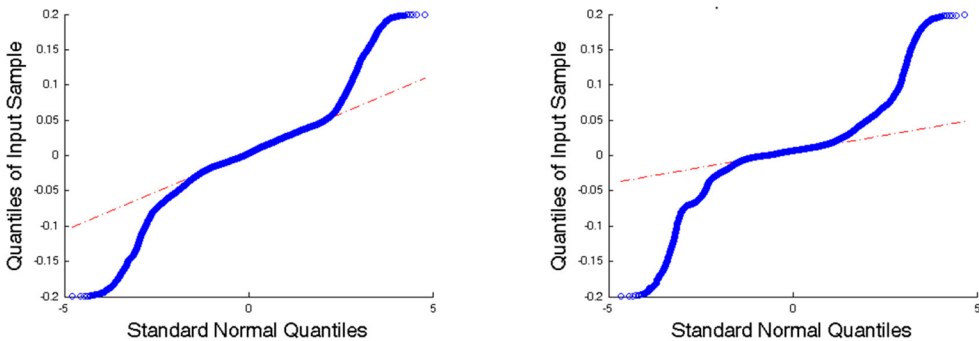


Figure 8. QQ-plots of relative discrepancies between MLS and TLS in the “Alcazar” fortress for the: east walls (**left**) and south walls (**right**).

Table 5. Robust statistical descriptors associated to relative discrepancies.

Statistics	Value		
	East	South	Global
Mean	0.003 m	0.008 m	0.005 m
Standard deviation	±0.026 m	±0.017 m	±0.023 m
Median	0.003 m	0.007 m	0.005 m
MAD	±0.015 m	±0.006 m	±0.011 m
Quantile 25	−0.011 m	0.000 m	−0.006 m
Quantile 75	0.019 m	0.013 m	0.016 m

In this analysis, the median value is close to zero (2.8 mm in the east wall), as was expected after the application of the ICP registration algorithm. However, a slightly higher value of 6.9 mm is appreciated in the south wall, which points to some registration error, but it is inside the expected range. Moreover, in Table 5, the dispersion value (MAD) is according to the expected error, confirming the MLS a-priori reference values, especially in the south wall, which has a simple geometry (Figure 7c). The analysis of the error sample by means of the non-parametric estimator for the quantile, yields that the 95% of the error points are inside the [−0.046 m; 0.047 m] interval. This reference value is used in the optimization phase to carry out the point cloud simplification.

It is worth noting that, despite the symmetrical shape of the sample in the east wall (as shown in the first and third quartile), there is a high difference (up to three times) between the standard deviation and the MAD having as reference the south wall. The conclusions would seem wrong without an adequate statistical parameter selection.

In conclusion, the spatial resolution achieved by the MLS and his distribution is directly related to the sensor–object distance; therefore, there will be areas with higher point density than others (Figure 9). Moreover, in Figure 9, some diagonal stripes are shown by cause of inhomogeneity in the acquisition phase due to the oblique laser scanner heads arrangement in the vehicle (Figure 1). This fact is not a critical issue, but reinforces the necessity of a 3D point cloud data optimization that copes with those redundant areas.

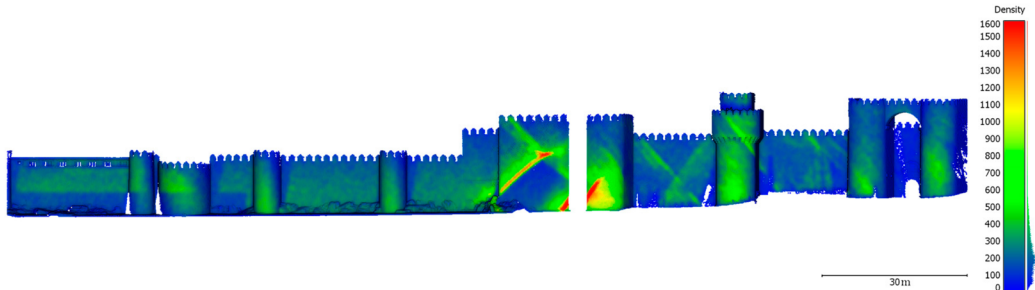


Figure 9. MLS point density distribution (points/m²) for the southeast walls.

According to an ideal equilateral triangles distribution for a circular neighborhood [61], the average point density achieved is 58.8 mm, decreasing up to a spatial resolution of 135 mm for the farthest zones (e.g., battlements and upper parts of towers). In addition, the occlusion in these zones underestimates the density computation since the point vicinity is incomplete.

4.2. Optimization Analysis

In the Medieval Wall of Avila, two main features are clearly recognized: the planar walls and the cylindrical towers. On the one hand, the walls are considered to have zero curvature, but due to the construction processes and the deterioration of the structures caused by the course of time, the actual conservation state does not keep this property. Therefore, a slight curvature of 0.005 m⁻¹ (200 m radius) can be assumed. Additionally, the individual stones of the wall also contribute to local groups of higher curvature, so this threshold is extended to the annexed towers. On the other hand, in the case of the towers, the diameters of the cylinders range from 4.5 to 10 m. Accordingly, the upper limit for the curvature cluster is set as 0.4 m⁻¹. The rest of the elements (e.g., battlements, arrow slits or natural rocks) are contained in a final cluster of higher local curvature.

The size of these main elements (walls and towers) suggests a wide neighborhood for the computations to balance the curvature precision and noise effects. The minimum height of 10 m and the typical wall width of 20 m favors this large neighborhood. By a selection of a spherical diameter of 2 m for the curvature computation, implicitly, a security buffer of 1 m is kept between the different clusters. Additionally, a minimum area of 1 m² per cluster is set as threshold for the clustering refinement.

As the final parameter definition, the sampling interval for the homogenization is chosen as 5 cm, which, according to Section 4.1, is the nearest round value corresponding to the 95% non-parametric confidence interval of the MLS point clouds. In the first step of the *preparation phase*, 0.4% of points were excluded as outliers, since they exceeded the point to local plane distance of 20 cm. As result, after the smoothing process and the spatial resolution homogenization, 521,090 points were obtained, which implies a 47.4% reduction of the original input.

Next, the curvature analysis is carried out for a spherical neighborhood of 1 m of radius, which is segmented according the three pre-established clusters: (i) planar or low curvature (<0.05 m⁻¹); (ii) cylindrical, mild transitions and medium curvature (0.05–0.40 m⁻¹); and (iii) the abrupt transitions of high curvature (>0.40 m⁻¹). The results are outlined in Figure 10.

Subsequently, these clusters are refined based on a connected components analysis. The octree level is chosen in relation to a reference spatial sampling of 0.12 m, which corresponds to 160 points per square meter. Table 6 shows the percentage of reallocated components per cluster and the final classification. For the low curvature cluster, the main planar elements are coded by only 47 components, the rest being small components (about two thousand) located in the transition area of the wall planes, and in the transition to the battlements. Despite the high number of affected components, more than 97% of cluster components, they only represent a small fraction of the classified 3D points in the

cluster. Similarly, for the cylindrical, mild transitions and medium curvature cluster, the reallocated components are located in the battlements and in some abrupt rocks distribution inside the curtain walls. In the case of the battlements, this behavior is caused due to their small size in relation to the curvature spherical vicinity used for the computation. However, due to the optimization protocol, they are moved to a cluster with crescent curvature in order to keep a higher spatial density. In the case of natural rocks aggrupation located in the wall, their curvature was lower than the threshold for the high curvature cluster ($>0.4\text{ m}^{-1}$). As result of the minimum area threshold, they were reallocated in the high curvature cluster since they were heterogeneously disposed in the curtain walls.

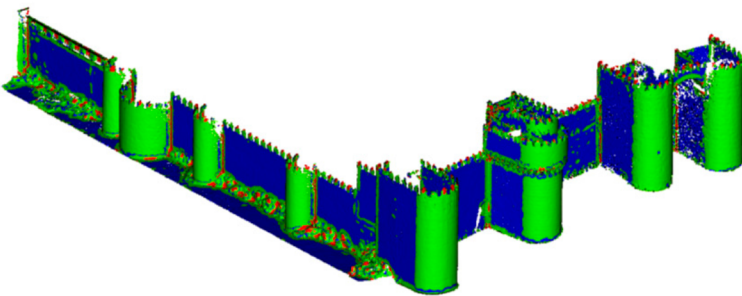


Figure 10. Initial MLS set of clusters: (i) planar or low curvature in blue; (ii) cylindrical, mild transitions and medium curvature in green; and (iii) the abrupt transitions of high curvature in red.

Table 6. Results of clustering refinement step (* the components are the result of the *curvature clustering* phase according to the main geometric elements of the CH site).

Cluster Curvature	Classification Legend	Initial Points	Components *	Reallocated Components	Reallocated Points	Final Points
Low	Blue	236,832	2022	1975 (97.7%)	13,716 (5.8%)	223,116
Medium	Green	263,580	1610	1563 (97.1%)	18,576 (7.0%)	258,720
High	Red	20,654	-	-	-	39,230

Finally, the weighted sampling is applied inside the clusters. For the low curvature, a resolution of 1 m is chosen, since the smooth process and plane-to-curve idealization. In the intermediate cluster, aimed for the towers, an arc to chord assimilation is applied. For a 50 cm chord, the idealization error will cause a sagittal of 13 mm for the worst case, which is inside the acceptable limits. Therefore, a 0.5 m weighted sampling is set. Lastly, the high curvature cluster is kept unmodified. The final point cloud has 58,476 points (Figure 11), which implies a reduction of 88.8% in relation to the spatially homogenized point cloud (521,090 points), and 94.1% in relation to the raw point cloud.

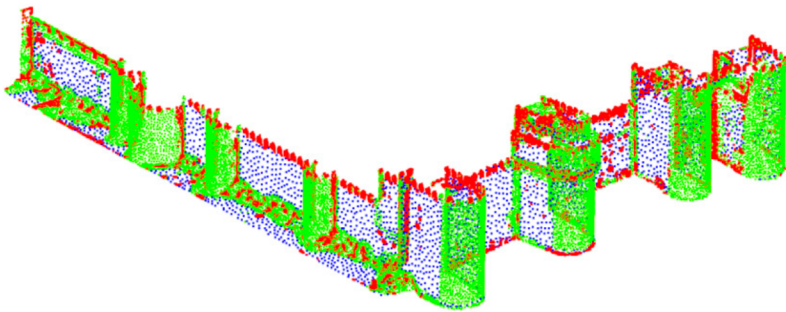


Figure 11. Final MLS point cloud optimization and simplification: (i) planar or low curvature in blue; (ii) cylindrical, mild transitions and medium curvature in green; and (iii) the abrupt transitions of high curvature in red.

5. Discussion

The novel use of MLS applied to the 3D surveying of large Cultural Heritage sites is evaluated and compared with the TLS, which is currently the most common technology used for this purpose.

MLS device combines different sensors on a mobile platform that allows obtaining an accurate and georeferenced 3D point cloud. Active sensors together with Inertial and Global Navigation System are synchronized in real time to collect and store data. The active sensor acquires detailed 3D points from a local coordinate system, while the IMU and GNSS systems provide and correct 3D points under a global reference frame. Moreover, some MLS can acquire RGB information captured by photographic or video cameras. Although the MLS spatial resolution depends on the active sensor (laser scanner) integrated on the mobile platform, usually the point clouds acquired by MLS cannot compete with TLS in terms of high resolution. Nevertheless, for large CH sites, the use of MLS could be more suitable, allowing the mapping of large and complex sites in an efficient way (e.g., historical cities or landscapes).

Otherwise, MLS reduces the data acquisition time thanks to the use of a mobile platform, while TLS needs multiple stations (sometimes even hundreds) to cover a large area. There are two main advantages of MLS technology compared to other 3D recording systems: (i) MLS is less expensive than airborne LiDAR systems boarded on airplanes or helicopters; and (ii) MLS can acquire accurate 3D data faster than TLS. On the contrary, its main disadvantage is that sometimes the transit with vans or cars is not possible due to conservation reasons or limitations of space (e.g., narrow streets). In this last case, it is possible to board the MLS on alternative platforms such as quads [62], backpack [16] or even autonomous robots [17].

MLS also reduces the data processing time in comparison with TLS, especially in large and complex CH sites. MLS directly produces a single point cloud, georeferenced with centimetric accuracy due to the IMU and GNSS calibrated sensors, whereas the 3D data captured by TLS have to be aligned in a relative or global reference system.

Finally, the visualization and management of large datasets still represent a bottleneck for both techniques (MLS and TLS). The ongoing development of 3D recording sensors and data capture technologies are advancing more rapidly than the management of large geometrical datasets. MLS and TLS usually produce massive point clouds (millions of points) requiring storage spaces of many GB. To advance this problem, 3D datasets (i.e., point clouds) need to be efficiently optimized and simplified for architectural and structural analysis (e.g., FEM), documentation and management (e.g., HBIM) or outreach purposes (e.g., Web Visualization). As additional benefits of the proposed point cloud optimization, the optimized point cloud will be improved for subsequent 3D modeling tasks based on meshing or reverse engineering procedures, improving the computational time and the resulting geometric definition.

In this paper, our main contribution was based on the use of algorithms and methodologies for the point cloud optimization, without any prior surface reconstruction. There are numerous algorithms to reduce the 3D point cloud in automatic way, but our approach was focused on an adaptive sampling that depends on the geometric features and also keeps the main structures without losing relevant details. The optimal solution was to find a compromise between the resolution acquired, the accuracy and the final size of the file, in order to obtain detailed 3D point clouds that could be stored, managed and visualized with a fluent real-time interaction.

6. Conclusions

This paper deals with a novel use of Mobile LiDAR System for the 3D recording of large Cultural Heritage sites. As part of the suitability assessment of this technology, an accuracy evaluation with a Terrestrial Laser Scanner was carried out. The obtained results, checked in an appropriate study case, allow us to confirm the suitability of Mobile LiDAR System techniques for 3D recording and modeling of large Cultural Heritage sites.

On the one hand, we were focused on time consumption. Comparing both 3D recording techniques, Mobile LiDAR System technology was a clear winner in terms of time used for data acquisition and data processing. Data coming from our study case shows that Mobile LiDAR System took only 1 h to sweep an area of 250,000 m² while the Terrestrial Laser Scanner took 159 h. This means considerable time saving.

On the other hand, spatial resolution was our concern. Terrestrial Laser Scanner could achieve a point cloud density of 15 mm (average of scanning distance: 20 m) while Mobile LiDAR System density was 60 mm (average of scanning distance: 25 m). In order to evaluate data accuracy of the Mobile LiDAR System, a comparison of both 3D point clouds was done, regarding the georeferencing error. Considering that the represented area involved a few kilometers, the results show that 95% of the MLS points acquired are inside of the tolerance range [−0.046 m; +0.047 m]. Even if Mobile LiDAR System provides a less dense point cloud, it is conclusive that it has enough spatial resolution and quality to provide the reconstruction of the most relevant architectural details in large Cultural Heritage sites.

In any case, due to the huge amount of acquired data, the final point clouds should be necessarily optimized for visualization and management purposes. A novel process for point cloud optimization is introduced to facilitate its handling by scholars from various disciplines. The proposed optimization methodology was based on a detail geometric analysis, allowing classifying the different structures into three main clusters (low, medium and high curvature). Different optimization parameters were used for each cluster according to their curvature, obtaining a reduced point cloud ca. 94.1% less in relation to the entire raw point cloud and guaranteeing an optimal solution for multiple purposes.

The results confirm that Mobile LiDAR System also shows more efficiency in terms of operation flexibility, acquisition and processing time, producing high quality and accurate data. However, shape complexity and surrounding characteristics, such as the environment location or the access restrictions, must be taken into account in further studies to define which is the best approach.

In the worst case, when the geometric complexity of the scene is high, the transit of vehicles is difficult or they are restricted access to the archaeological sites, the novel indoor LiDAR technologies (e.g., the backpack solution, mobile robots or the handheld LiDAR mapping system) could be used as an alternative outdoor solution.

To conclude, it would be interesting to extend our approach integrating different outdoors and indoors mobile techniques for large and complex Cultural Heritage sites.

Acknowledgments: The authors wish to thanks Insitu Engineering S.L. for providing the LiDAR data. The first author would also like to thank the University of Salamanca, for the financial support given through human resources grants (Special Program for Post-Doctoral Contracts). The authors would like to thank the editors and anonymous reviewers for their valuable feedback. This research has been partially supported by CHT2—Cultural Heritage through Time—funded by JPI CH Joint Call and supported by the Ministerio de Economía y Competitividad, Ref. PCIN-2015-071.

Author Contributions: All of the authors conceived and designed the study. Pablo Rodríguez-González, Diego Gonzalez-Aguilera and Ángel Luis Muñoz-Nieto acquired the TLS data and processed it. Pedro Arias-Sanchez acquired the MLS data and processed it. Pablo Rodríguez-González and Belén Jiménez Fernández-Palacios implemented the methodology and analysed the results. Pablo Rodríguez-González, Belén Jiménez Fernández-Palacios and Diego Gonzalez-Aguilera wrote the manuscript and all authors read and approved the final version.

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

References

- Guidi, G.; Micoli, L.L.; Gonizzi, S.; Brennan, M.; Frischer, B. Image-based 3D capture of cultural heritage artifacts an experimental study about 3D data quality. In Proceedings of the 2015 Digital Heritage, Granada, Spain, 28 September–2 October 2015; pp. 321–324.
- Del Pozo, S.; Herrero-Pascual, J.; Felipe-García, B.; Hernández-López, D.; Rodríguez-González, P.; González-Aguilera, D. Multispectral radiometric analysis of façades to detect pathologies from active and passive remote sensing. *Remote Sens.* **2016**, *8*, 80. [\[CrossRef\]](#)

3. Borrmann, D.; Heß, R.; Houshiar, H.; Eck, D.; Schilling, K.; Nüchter, A. Robotic mapping of cultural heritage sites. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W4*, 9–16. [\[CrossRef\]](#)

4. Puente, I.; Solla, M.; González-Jorge, H.; Arias, P. NDT documentation and evaluation of the Roman Bridge of Lugo using GPR and mobile and static LiDAR. *J. Perform. Constr. Facil.* **2013**, *29*, 06014004. [\[CrossRef\]](#)

5. Casadio, F.; Daher, C.; Bellot-Gurlet, L. Raman spectroscopy of cultural heritage materials: Overview of applications and new frontiers in instrumentation, sampling modalities, and data processing. *Top. Curr. Chem.* **2016**, *374*, 62. [\[CrossRef\]](#) [\[PubMed\]](#)

6. Johnson, K.M.; Ouimet, W.B. Rediscovering the lost archaeological landscape of southern New England using airborne light detection and ranging (LiDAR). *J. Archaeol. Sci.* **2014**, *43*, 9–20. [\[CrossRef\]](#)

7. Von Schwerin, J.; Richards-Rissetto, H.; Remondino, F.; Spera, M.G.; Auer, M.; Billen, N.; Loos, L.; Stelson, L.; Reindel, M. Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of Copan, Honduras. *J. Archaeol. Sci. Rep.* **2016**, *5*, 85–104. [\[CrossRef\]](#)

8. Hyypä, J.; Jaakkola, A.; Chen, Y.; Kukko, A. Unconventional LIDAR mapping from air, terrestrial and mobile. In *Photogrammetric Week, 2013*; Wichmann/VDE: Belin/Offenbach, Germany, 2013; pp. 205–214.

9. Puente, I.; González-Jorge, H.; Martínez-Sánchez, J.; Arias, P. Review of mobile mapping and surveying systems. *Measurement* **2013**, *46*, 2127–2145. [\[CrossRef\]](#)

10. Williams, K.; Olsen, M.; Roe, G.; Glennie, C. Synthesis of transportation applications of mobile LIDAR. *Remote Sens.* **2013**, *5*, 4652. [\[CrossRef\]](#)

11. Lim, S.; Thatcher, C.A.; Brock, J.C.; Kimbrow, D.R.; Danielson, J.J.; Reynolds, B.J. Accuracy assessment of a mobile terrestrial lidar survey at Padre Island National Seashore. *Int. J. Remote Sens.* **2013**, *34*, 6355–6366. [\[CrossRef\]](#)

12. Moskal, L.M.; Zheng, G. Retrieving forest inventory variables with terrestrial laser scanning (TLS) in urban heterogeneous forest. *Remote Sens.* **2012**, *4*, 1. [\[CrossRef\]](#)

13. González-Ferreiro, E.; Miranda, D.; Barreiro-Fernandez, L.; Bujan, S.; Garcia-Gutierrez, J.; Dieguez-Aranda, U. Modelling stand biomass fractions in Galician Eucalyptus globulus plantations by use of different LiDAR pulse densities. *For. Syst.* **2013**, *22*, 510–525. [\[CrossRef\]](#)

14. Bauwens, S.; Bartholomeus, H.; Calders, K.; Lejeune, P. Forest inventory with terrestrial LiDAR: A comparison of static and hand-held mobile laser scanning. *Forests* **2016**, *7*, 127. [\[CrossRef\]](#)

15. Zhang, S.; Wang, C.; Yang, Z.; Chen, Y.; Li, J. Automatic railway power line extraction using mobile laser scanning data. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B5*, 615–619. [\[CrossRef\]](#)

16. Lauterbach, H.; Borrmann, D.; Heß, R.; Eck, D.; Schilling, K.; Nüchter, A. Evaluation of a backpack-mounted 3D mobile scanning system. *Remote Sens.* **2015**, *7*, 13753–13781. [\[CrossRef\]](#)

17. Ziparo, V.A.; Zaratti, M.; Grisetti, G.; Bonanni, T.M.; Serafin, J.; Cicco, M.D.; Proesmans, M.; Gool, L.V.; Vysotska, O.; Bogoslavskyi, I.; et al. Exploration and mapping of catacombs with mobile robots. In Proceedings of the 2013 IEEE International Symposium on Safety, Security, and Rescue Robotics, Linköping, Sweden, 21–26 October 2013; pp. 1–2.

18. Bosse, M.; Zlot, R.; Flick, P. Zebedee: Design of a spring-mounted 3-D range sensor with application to mobile mapping. *IEEE Trans. Robot.* **2012**, *28*, 1104–1119. [\[CrossRef\]](#)

19. Zlot, R.; Bosse, M.; Greenop, K.; Jarzab, Z.; Juckes, E.; Roberts, J. Efficiently capturing large, complex cultural heritage sites with a handheld mobile 3D laser mapping system. *J. Cult. Herit.* **2014**, *15*, 670–678. [\[CrossRef\]](#)

20. Sirmacek, B.; Shen, Y.; Lindenbergh, R.; Zlatanova, S.; Diakite, A. Comparison of Zeb1 and Leica C10 indoor laser scanning point clouds. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *III-1*, 143–149. [\[CrossRef\]](#)

21. Calisi, D.; Giannone, F.; Ventura, C.; Salonia, P.; Cottefoglie, F.; Ziparo, V.A. ARIS—A Robotic Approach to Digitization of Indoor and Underground Cultural Heritage Sites. In Proceedings of the International Congress on Digital Heritage, Granada, Spain, 28 September–2 October 2015.

22. Calisi, D.; Giannone, F.; Ventura, C.; Salonia, P.; Cottefoglie, F.; Ziparo, V.A. Digitizing Indoor and Underground Cultural Heritage Sites with Robots. *Sci. Res. Inf. Technol.* **2016**, *6*, 23–30.

23. Rondeau, M.-C. New Technologies for city asset mapping: Setting the standard in city digitalisation. *GeoInformatics* **2015**, *18*, 20–21.

24. Rönnholm, P.; Liang, X.; Kukko, A.; Jaakkola, A.; Hyypä, J. Quality analysis and correction of mobile backpack laser scanning data. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *III-1*, 41–47. [\[CrossRef\]](#)

25. Sairam, N.; Nagarajan, S.; Ornitz, S. Development of mobile mapping system for 3D road asset inventory. *Sensors* **2016**, *16*, 367. [\[CrossRef\]](#) [\[PubMed\]](#)

26. Pauly, M.; Gross, M.; Kobbelt, L.P. Efficient simplification of point-sampled surfaces. In Proceedings of the Conference on Visualization, Boston, MA, USA, 27 October–1 November 2002; IEEE Computer Society: Boston, MA, USA, 2002; pp. 163–170.

27. Song, H.; Feng, H.-Y. A point cloud simplification algorithm for mechanical part inspection. In Proceedings of the Seventh International Conference on Information Technology for Balanced Automation Systems in Manufacturing and Services, Niagara Falls, ON, Canada, 4–6 September 2006; Shen, W., Ed.; Springer: Boston, MA, USA, 2006; pp. 461–468.

28. Charbonnier, P.; Tarel, J.-P.; Goulette, F. *On the Diagnostic of Road Pathway Visibility*; Transport Research Arena Europe: Bruxelles, France, 2010.

29. Yang, B.; Dong, Z. A shape-based segmentation method for mobile laser scanning point clouds. *ISPRS J. Photogramm. Remote Sens.* **2013**, *81*, 19–30. [\[CrossRef\]](#)

30. Sun, H.; Wang, C.; El-Sheimyb, N.; traffics Wang, P. Surrounding detection for terrestrial mobile mapping data quality evaluation. In Proceedings of the 6th International Symposium on Mobile Mapping Technology, São Paulo, Brazil, 21–24 July 2009.

31. Oude Elberink, S.; Khoshelham, K.; Arastounia, M.; Diaz Benito, D. Rail track detection and modelling in mobile laser scanner data. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2013**, *II-5/W2*, 223–228. [\[CrossRef\]](#)

32. Torres-Martínez, J.; Seddaiu, M.; Rodríguez-Gonzálvez, P.; Hernández-López, D.; González-Aguilera, D. A multi-data source and multi-sensor approach for the 3D reconstruction and web visualization of a complex archaeological site: The case study of “Tolmo De Minateda”. *Remote Sens.* **2016**, *8*, 550. [\[CrossRef\]](#)

33. Jiménez Fernández-Palacios, B.; Stefani, C.; Lombardo, J.; De Luca, L.; Remondino, F. Web visualization of complex reality-based 3D models with NUBES. In Proceedings of the IEEE Conference Digital Heritage 2013, Marseille, France, 28 October–1 November 2013; Volume 1, pp. 701–704.

34. Nubes Project. Available online: <http://www.map.cnrs.fr/nubes/> (accessed on 25 December 2016).

35. Cultural Heritage Information System Project. Available online: <http://lrv.ugr.es/chis/en/> (accessed on 25 December 2016).

36. Torres, J.C.; López, L.; Romo, C.; Arroyo, G.; Cano, P.; Lamolda, F.; Villafranca, M.M. Using a cultural heritage information system for the documentation of the restoration process. In Proceedings of the 2013 Digital Heritage, Marseille, France, 28 October–1 November 2013.

37. Von Schwerin, J.; Richards-Rissetto, H.; Agugiaro, G.; Remondino, F.; Girardi, G. QueryArch3D: A 3D WebGIS System linking 3D visualizations to archaeological data. In Proceedings of the Computer Applications and Quantitative Methods in Archaeology, Southampton, UK, 26–30 March 2012.

38. Prandi, F.; Devigili, F.; Soave, M.; Di Staso, U.; De Amicis, R. 3D web visualization of huge cityGML models. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-3/W3*, 601–605. [\[CrossRef\]](#)

39. Conforti, D.; Zampa, F. Lynx mobile mapper for surveying city centers and highways. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2011**, *XXXVIII-5/W16*, 219–222. [\[CrossRef\]](#)

40. Hofmann, S.; Brenner, C. Accuracy assessment of mobile mapping point clouds using the existing environment as terrestrial reference. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B1*, 601–608. [\[CrossRef\]](#)

41. Chan, T.O. Feature-Based Boresight Self-Calibration of a Mobile Mapping System. Master’s Thesis, University of Calgary, Calgary, AB, Canada, 2012.

42. Grussenmeyer, P.; Landes, T.; Doneus, M.; Lerma, J. Basics of range-based modelling techniques in cultural heritage 3D recording. In *3D Recording, Documentation and Management of Cultural Heritage*; Whittles Publishing: Dunbeath, UK, 2016.

43. Schulz, T. Calibration of a Terrestrial Laser Scanner for Engineering Geodesy. Ph.D. Thesis, Technical University of Berlin, Berlin, Germany, 2007.

44. Remondino, F. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sens.* **2011**, *3*, 1104–1138. [\[CrossRef\]](#)

45. Gonzalez-Jorge, H.; Rodriguez-Gonzalvez, P.; Gonzalez-Aguilera, D.; Varela-Gonzalez, M. Metrological comparison of terrestrial laser scanning systems Riegl LMS Z390i and Trimble GX. *Opt. Eng.* **2011**, *50*, 116201–116209.

46. González-Aguilera, D.; Rodríguez-Gonzálvez, P.; Armesto, J.; Arias, P. Trimble GX200 and Riegl LMS-Z390i sensor self-calibration. *Opt. Express* **2011**, *19*, 2676–2693. [CrossRef] [PubMed]

47. Besl, P.J.; McKay, N.D. A method for registration of 3-d shapes. *IEEE Trans. Pattern Anal. Mach. Intell.* **1992**, *14*, 239–256. [CrossRef]

48. Tombari, F.; Salti, S.; Di Stefano, L. Performance evaluation of 3D keypoint detectors. *Int. J. Comput. Vis.* **2013**, *102*, 198–220. [CrossRef]

49. Akca, D. Full automatic registration of laser scanner point clouds. In Proceedings of the Optical 3-D Measurement Techniques VI, Zurich, Switzerland, 22–25 September 2003; pp. 330–337.

50. Paparoditis, N.; Papelard, J.-P.; Cannelle, B.; Devaux, A.; Soheilian, B.; David, N.; Houzay, E. Stereopolis II: A multi-purpose and multi-sensor 3D mobile mapping system for street visualisation and 3D metrology. *Rev. Fr. Photogramm. Télédétec.* **2012**, *200*, 69–79.

51. Toschi, I.; Rodríguez-Gonzálvez, P.; Remondino, F.; Minto, S.; Orlandini, S.; Fuller, A. Accuracy evaluation of a mobile mapping system with advanced statistical methods. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W4*, 245–253. [CrossRef]

52. Lague, D.; Brodu, N.; Leroux, J. Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). *ISPRS J. Photogramm. Remote Sens.* **2013**, *82*, 10–26. [CrossRef]

53. Höhle, J. The assessment of the absolute planimetric accuracy of airborne lasers canning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2011**, *XXXVIII-5/W12*, 145–150.

54. Rodríguez-Gonzálvez, P.; Garcia-Gago, J.; Gomez-Lahoz, J.; González-Aguilera, D. Confronting passive and active sensors with non-gaussian statistics. *Sensors* **2014**, *14*, 13759–13777. [CrossRef] [PubMed]

55. Cloud Compare v.2.7.0. Available online: www.danielgm.net/cc/ (accessed on 7 October 2016).

56. Rodríguez-Gonzálvez, P.; González-Aguilera, D.; Hernández-López, D.; González-Jorge, H. Accuracy assessment of airborne laser scanner dataset by means of parametric and non-parametric statistical methods. *IET Sci. Meas. Technol.* **2015**, *9*, 505–513. [CrossRef]

57. Levin, D. The approximation power of moving least-squares. *Math. Comput. Am. Math. Soc.* **1998**, *67*, 1517–1531. [CrossRef]

58. Serna, M. Walls: Speaking of Towers, Battlements, Gates. *Diario de Ávila*, 13 October 2002.

59. Mancera-Taboada, J.; Rodríguez-Gonzálvez, P.; González-Aguilera, D.; Muñoz-Nieto, Á.; Gómez-Lahoz, J.; Herrero-Pascual, J.; Picón-Cabrera, I. On the use of laser scanner and photogrammetry for the global digitization of the medieval walls of Avila. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2010**, *XXXVIII*, 169–174.

60. Haala, N.; Peter, M.; Cefalu, A.; Kremer, J. Mobile lidar mapping for urban data capture. In Proceedings of the 14th International Conference on Virtual Systems and Multimedia, Limassol, Cyprus, 20–25 October 2008; pp. 95–100.

61. Rodríguez-Gonzálvez, P.; Nocerino, E.; Menna, F.; Minto, S.; Remondino, F. 3D surveying & modeling of underground passages in WWI fortifications. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W4*, 17–24.

62. Kurkin, A.; Pelinovsky, E.; Tyugin, D.; Kurkina, O.; Belyakov, V.; Makarov, V.; Zeziulin, D. Coastal remote sensing using unmanned ground vehicles. *Int. J. Environ. Sci.* **2016**, *1*, 183–189.



© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

5.

Conclusions and future research

5.1. Conclusiones

La Tesis Doctoral presentada se enmarca en el campo del Patrimonio Cultural y aplica, evalúa e integra las técnicas de digitalización, modelación y visualización 3D en busca de nuevos métodos y soluciones que permitan divulgar grandes conjuntos de datos, de forma eficiente y en tiempo real. Dada la gran variedad de casos existentes, los objetos o lugares del Patrimonio Cultural fueron clasificados en base a su escala, factor fundamental para la toma de decisiones. Tanto las técnicas y metodologías utilizadas, como los resultados obtenidos, han sido publicados a través de tres artículos científicos, uno para cada caso de estudio: escala artefacto, arquitectura y paisaje.

Sobre el estudio y la evaluación de las diferentes *técnicas de digitalización y modelación 3D* (sensores activos y pasivos) para su aplicación al campo del Patrimonio Cultural:

- El escáner laser y la fotogrametría demuestran su gran potencial para la conservación del Patrimonio Cultural, por ser técnicas no invasivas y de no contacto.
- La escala de un objeto u escena determina factores como la movilidad, la portabilidad, la accesibilidad y los tiempos de trabajo. Tales causas, facilitan o limitan la captura de datos, condicionando las técnicas y metodologías a utilizar cada caso.
- La información radiométrica es fundamental para el análisis y la visualización del Patrimonio Cultural. La unión de la fotogrametría con la visión computacional (Structure From Motion) se presenta como una potente herramienta de bajo coste, válida para todas las escalas, produciendo nubes de puntos con información RGB que compiten en densidad y resolución con las producidas por sensores activos.
- El uso de Vehículos Aéreos no Tripulados (UAV) ofrece una potente solución de bajo coste para la escala arquitectura y paisaje (urbano y rural), permitiendo digitalizar zonas inaccesibles.

5.1. Conclusions

The presented Doctoral Thesis is concerned with the field of Cultural Heritage. It applies, evaluates and integrates the 3D recording, modeling and visualization techniques which seek new methodologies and solutions for the visualization of huge datasets in an efficient way and in real time. Given the great diversity of existing cases, Cultural Heritage objects and sites were classified based on their scale, a factor fundamental to the decision-making process. The techniques and methodologies used as well as the results obtained have been published in three scientific articles, one for each case study: artefact, architecture and landscape scale.

Regarding the study and evaluation of the different *3D recording and modeling techniques* (active and passive sensors) applied to the field of Cultural Heritage:

- Laser scanner and photogrammetry have shown strong potential for Cultural Heritage conservation owing to their being non-invasive and non-contact techniques.
- The scale, of an object or scene, determines factors such as the mobility, portability, accessibility and working times. These parameters may facilitate or limit the data acquisition, thus conditioning the techniques and methodologies used in each case.
- Radiometric information is essential for the analysis and visualization of Cultural Heritage. The combination of photogrammetry and computer vision (Structure From Motion) is a powerful low-cost tool, suitable for the different scales, producing RGB point clouds that can compete in density and resolution with those produced by active sensors.
- The use of Unmanned Aerial Vehicles (UAVs) offers a powerful low-cost solution for the architecture and landscape (urban and rural) scale, allowing the digitization of inaccessible areas.

- La integración sensorial se consolida, principalmente para la escala arquitectura y paisaje urbano, donde las dimensiones y las características geométricas dificultan la normalización de una metodología concreta.
- Nuevos algoritmos y softwares permiten fusionar datos híbridos de forma automática, fomentando y facilitando la integración de sensores activos y pasivos.
- El uso de sistemas móviles permite reducir y optimizar el trabajo de campo y el procesamiento de los datos en extensas áreas, a la vez que permite reconstruir con precisión complejos espacios y edificios del Patrimonio Cultural.

Sobre la investigación y el desarrollo de nuevas *metodologías de optimización* para una adecuada gestión y visualización en tiempo real de complejos conjuntos de datos 3D:

- La investigación de técnicas y metodologías de optimización para la visualización 3D de complejos modelos digitales es un gran reto para la comunidad científica. Esta se consolida como un paso clave y necesario cualquiera que sea la escala de trabajo.
- La segmentación automática de una superficie, a través de los métodos de la pirámide, la visibilidad o el vector normal, fragmenta un modelo en sub-elementos de comunes características. Queda demostrado para la escala artefacto⁶ donde diferentes modelos fueron segmentados con éxito, permitiendo al software cargar únicamente las partes del modelo que se visualizan en la pantalla. Este proceso optimiza la aplicación mientras se mantiene la calidad geométrica y radiométrica de la información.
- El uso de mapas de normales⁷, desplazamientos y las técnicas de Unwrapping, ofrece una potente herramienta de optimización para la visualización 3D de complejos modelos digitales.
- La segmentación de una nube de puntos en base a su curvatura permite mantener los detalles geométricos mientras se simplifican las zonas planas. Queda demostrado con éxito

- Sensor integration is consolidated, mainly for architecture and urban landscape scale, where the dimensions and the geometric features make difficult the normalization of a concrete methodology.
- New algorithms and software permit the fusion of hybrid data in an automatic mode, encouraging and facilitating the data integration of active and passive sensors.
- The use of mobile systems permits the reduction and optimization of both the field work and data processing of large areas, while allowing for the accurate reconstruction of complex sites and buildings of Cultural Heritage.

Regarding the research and development of new *optimization methodologies* for a real-time management and visualization of complex 3D data sets.

- The research of optimization techniques and methodologies for 3D visualization of complex digital models is a significant challenge for the scientific community. This is considered a key step for whichever work scale applies.
- The automatic segmentation of a surface, through the pyramid method, visibility method or the normal vector method, fragments a model into sub-elements of common features. It has been demonstrated as successful for artefact scale⁶, where different models were efficaciously segmented. It enables the software to load only the parts of the model that are displayed on the screen. This process permits the optimization of the application while the digital model maintains the geometric and radiometric quality.
- The use of normal maps⁷, displacements and unwrapping techniques, offers a powerful optimization tool for 3D visualization of complex digital models.
- The point cloud segmentation based on its curvature enables the maintenance of the main geometric details while the plane zones are simplified. It is successfully demonstrated for

para la escala paisaje⁸, permite agilizar el procesado de los datos y generar directamente ligeros modelos digitales, pero también precisos y detallados.

- Los métodos de optimización propuestos han demostrado su eficacia en diferentes casos de estudio^{6,7,8} y son replicables en las distintas escalas: artefacto, arquitectura y paisaje.

Sobre la investigación y el desarrollo de nuevas vías de *análisis, gestión, visualización y difusión* de complejos modelos 3D basados en la realidad para promover el conocimiento del Patrimonio Cultural:

- La escala determina el punto de vista desde donde un espectador observa un objeto u escena y condiciona las técnicas y dispositivos de visualización 3D, para los diferentes casos de estudio. Su presencia, en una reconstrucción digital basada en la realidad, es de vital importancia ya que aproxima al usuario a la vida real.

- La realidad aumentada se adecua a cualquier escala o caso de estudio, donde la información digital genera un valor añadido al mundo real, mientras que la realidad virtual sumerge al usuario en un mundo envolvente adaptándose mejor a la escala arquitectura y/o paisaje.

- Las dos aplicaciones creadas^{6,7} demuestran el gran potencial de la realidad aumentada y virtual, soportando complejos modelos digitales foto-realísticos, y abriendo nuevas vías de comunicación para la investigación y divulgación del Patrimonio Cultural.

- La fusión de datos heterogéneos^{7,11} ha sido llevada a cabo con éxito, creando una base de datos jerárquica, con datos métricos y no métricos, 2D, 3D, y 4D¹² incluyendo información temporal.

- Los dispositivos Oculus Rift y Kinect⁷, caracterizados por su bajo coste, flexibilidad y portabilidad, han sido integrados con éxito, logrando una realidad virtual integral.

- Tanto la interacción como el rápido e intuitivo aprendizaje por parte del usuario demuestran

landscape scale⁸. It allows for a faster data processing, generating directly light digital models, which are both accurate and detailed.

- The optimization methods proposed have proven their effectiveness in different case studies^{6,7,8} and they are replicable at the different scales: artefact, architecture and landscape.

Regarding the research and development of new ways of *analysis, management, visualization and dissemination* of complex reality-based 3D models to promote knowledge of the Cultural Heritage:

- The scale determines the point of view from which a viewer observes an object or scene. It therefore dictates the 3D visualization techniques and devices for the different cases of study. The presence of the scale in a reality-based digital reconstruction is of vital importance as it brings the user closer to real life.

- Augmented reality is suitable to any scale or case study, where digital information adds a new value to the real world while, virtual reality immerses the user in a surrounding digital world which adapts better to architecture and/or landscape scale.

- The two applications created^{6,7} have successfully demonstrated the great potential of augmented and virtual reality, supporting complex photo-realistic digital models. It opens up new ways of communication for Cultural Heritage research and dissemination purposes.

- The fusion of heterogeneous datasets^{7,11} has been carried out successfully, creating a hierarchical database, with metric and non-metric information of 2D, 3D, and 4D¹² that also includes temporal information.

- Oculus Rift and Kinect devices⁷, characterized by their low cost, flexibility and portability, have been integrated successfully, thus achieving a complete virtual reality.

que, las técnicas de realidad aumentada y virtual, tienen un prometedor futuro. Revolucionan la educación y la divulgación museográfica del Patrimonio Cultural, donde el concepto de objeto o museo pasivo evoluciona en busca de la implicación activa del usuario y/o visitante.

- La visualización Web permite explotar los recursos online integrando las tecnologías que ofrecen la realidad aumentada y la realidad virtual.
- En general, la visualización 3D ofrece nuevas vías de comunicación, acceso a sitios lejanos, y a veces, incluso cerrados al público por políticas de conservación.

- Both interaction and the user’s quick and intuitive learning have shown that augmented and virtual reality techniques have a promising future. Both the education in and museographic dissemination of Cultural Heritage have been revolutionized, where the object or passive exhibit can evolve around the active involvement of the user and/or visitor.
- Web visualization exploits online resources, allowing for the integration of technologies that offer both augmented reality and virtual reality.
- 3D visualization offers new ways of communication and the possibility to access distant sites, sometimes even those closed to the public due to conservation policies.

5.2. Perspectivas futuras

La línea de investigación presentada por la Tesis Doctoral da soluciones a dos grandes desafíos de la comunidad científica, la optimización y la visualización de grandes conjuntos de datos, abriendo a su vez nuevas vías de investigación:

Sobre el estudio y la evaluación de las diferentes *técnicas de digitalización y modelación 3D* (sensores activos y pasivos) para su aplicación al campo del Patrimonio Cultural:

- Se sugiere el uso y/o integración de nuevos Sistemas Móviles LiDAR para extensas áreas interiores, como los sistemas de mano o los transportados en mochilas.
- Se plantea el uso de sistemas móviles robotizados en áreas del Patrimonio Cultural donde la presencia humana puede perjudicar o modificar gravemente las condiciones ambientales del entorno o donde las áreas difícil acceso y las condiciones seguridad lo requieran.

Sobre la investigación y el desarrollo de nuevas *metodologías de optimización* para una adecuada gestión y visualización en tiempo real de complejos conjuntos de datos 3D:

- Se proponen mejoras en la automatización del proceso de optimización de superficies para la aplicación ARCube⁶, como:

La detección automática del método más adecuado (pirámide, visibilidad o vector normal), en base a las características geométricas de la superficie de cada artefacto.

La integración y automatización de métodos conocidos de optimización como el cálculo de mapas de normales, desplazamientos e UV.

- Se sugiere mejoras en la automatización del proceso de optimización de nubes de puntos⁸, como:

5.2. Future research

The line of research presented in the Doctoral Thesis provides solutions to two great challenges for the scientific community: the optimization and visualization of massive 3D data sets, and thus spawns new methods of research:

Regarding the study and evaluation of the different *3D recording and modeling techniques* (active and passive sensors) applied to the field of Cultural Heritage:

- The use and/or integration of new LiDAR Mobile Systems for extensive indoor areas, such as backpacks and hand systems, is suggested.
- The use of mobile robotic systems for Cultural Heritage sites is proposed where human presence can seriously damage or modify the environmental conditions, for areas of difficult access and where safety conditions are required.

Regarding the research and development of new *optimization methodologies* for a real-time management and visualization of complex 3D data sets:

- Improvements to the automation of the surface optimization process for the ARCube⁶ application are suggested, such as:

The automatic detection of the most suitable methodology (pyramid, visibility or normal vector method), based on the geometric features of an artefact’s surface.

The integration and automation of known optimization methods such as the calculation of normal, displacement and UV maps.

- Improvements to the automation of the point cloud optimization process⁸ are suggested, such as:

Crear un sistema inteligente que identifique y etiquete los sub-elementos generados en base a sus características geométricas.

Extraer los metadatos relativos a los sub-elementos generados (ej. dimensiones, peso, índice de curvatura).

Generar una base de datos donde los sub-elementos sean clasificados y archivados a través de una estructura jerárquica.

Extracción automática vectorial de los límites segmentados para la modelación o el análisis de los datos (ej. CAD, (H)BIM o FEM).

Sobre la investigación y el desarrollo de nuevas vías de *análisis, gestión, visualización y difusión* de complejos modelos 3D basados en la realidad para promover el conocimiento del Patrimonio Cultural:

- Se plantean mejoras en el desarrollo y la interfaz de la aplicación ARCube⁶, como:

Convertir el plugin (MaxScript) desarrollado para la aplicación ARCube a un lenguaje de programación de código abierto.

El uso de kits de desarrollo de software (SDK) libres para la realidad aumentada, que permitan personalizar la aplicación y agregar nuevas funciones para el análisis de los datos.

- Se sugieren mejoras en el desarrollo y la interfaz de la aplicación de realidad virtual⁷ desarrollada, como:

La integración de las técnicas usadas de realidad aumentada⁶ (escala artefacto) con la realidad virtual⁷ (escala arquitectura y/o paisaje), para crear una realidad mixta.

Creating an intelligent system for identifying and labelling the sub-elements generated, based on their geometric features.

Automatic extraction of metadata related to the generated sub-elements (e.g. size, weight, curvature index).

Generating a database where the sub-elements are classified and achieved through a hierarchical structure.

Automatic vector extraction of the segmented limits useful for 3D modeling and data analysis (e.g. CAD, (H)BIM or FEM).

Regarding the research and development of new ways of *analysis, management, visualization and dissemination* of complex reality-based 3D models to promote knowledge of the Cultural Heritage:

- Improvements to the development and interface of the ARCube⁶ application are suggested, such as:

Converting the plugin (MaxScript) developed for the ARCube application into an open source programming language.

The use of free software development kits (SDK) for augmented reality, which allow the customization of the application and add new functionalities for data analysis purposes.

- Improvements to the development and interface of the implemented virtual reality application⁷ are suggested, such as:

Integration of the augmented⁶ (artefact scale) and virtual reality⁷ (architecture and/or landscape scale) techniques used, to create a mixed reality.

El desarrollo de cuentas personalizadas, que automaticen el acceso o el bloqueo de la información en función del nivel del usuario (ej. investigación, turismo o educación).

- Se propone el uso de gafas de realidad aumentada para la visualización de la escala arquitectura y paisaje del Patrimonio Cultural, replicando la estructura lógica (en cuanto respecta al acceso de la información) de la aplicación de realidad virtual desarrollada.
- Se propone el uso de dispositivos móviles (teléfonos inteligentes o tabletas) para la visualización in situ de la información en áreas históricas, a través de la realidad aumentada.
- Se propone la integración de las técnicas usadas para la realidad aumentada y/o virtual en una plataforma Web, para documentar, analizar y promover la información del Patrimonio Cultural.
- Se propone el uso de las técnicas de visualización 3D para la creación de visores y nuevas vías de comunicación para el público, que por razones de movilidad, no tenga acceso a las -áreas del Patrimonio Cultural.
- Se propone el uso de las técnicas de visualización 3D para la recreación de simulaciones temporales (pasada, presente y futura), posibles restauraciones, la prevención de riesgos y la monitorización.

Development of personalized accounts that provide access or automatically block the data information, according to the user level (e.g. research, tourism or education).

- The use of augmented reality headsets is proposed for visualizing the architecture and landscape scale of Cultural Heritage, replicating the logical structure (in terms of access to information) of the virtual reality application implemented.
- The use of mobile devices (smart phones or tablets) is proposed for the visualization in situ of the information in historical areas, through augmented reality.
- Integrating the techniques used for augmented and/or virtual reality on a web platform is proposed, to document, analyse and promote Cultural Heritage information.
- The use of 3D visualization techniques is proposed to create browsers and platforms, new ways of communication for the public, who for mobility reasons, do not have access to Cultural Heritage sites.
- The use of 3D visualization techniques is proposed to recreate temporal simulations (past, present and future), possible restorations, risk prevention and monitoring.

References

References

- Arbace, L., Sonnino, E., Callieri, M., Dellepiane, M., Fabbri, M., Laccarino Idelson, A., Scopigno, R., 2013: Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue. *Journal of Cultural Heritage*, 14, pp. 332–345.

- Carmigniani, J., Furht, B., 2011: Augmented Reality: An Overview. *Handbook of Augmented Reality*, pp 3-46.

- Casadio, F., Daher, C., Bellot-Gurlet, L., 2016: Raman spectroscopy of cultural heritage materials: Overview of applications and new frontiers in instrumentation, sampling modalities, and data processing. *Top. Curr. Chem*, 374, 62.

- Chiabrando, F., Sammartano, G., Spanò, A., 2016: Historical buildings models and their handling via 3d survey: From points clouds to user-oriented HBIM. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41, pp. 633–640.

- Christou, C., Angus, C., Loscos, C., Dettori, A., Roussou, M., 2006: A versatile large-scale multimodal VR system for cultural heritage visualization. *ACM symposium on Virtual reality software and technology*, pp. 133-140.

- Conde, B., Del Pozo, S., Riveiro, B., González-Aguilera, D., 2016: Automatic mapping of moisture affectation in exposed concrete structures by fusing different wavelength remote sensors. *Structural Control and Health Monitoring*, 23, pp. 923–937.

- De Luca, L., Busarayat, C., Stefani, C., Véron, P., Florenzano. M., 2010: NUBES: describing, analysing, documenting and sharing digital representations of heritage buildings. *Proceedings of Focus K3D conference on Semantic 3D Media and Content*, INRIA Sophia Antipolis - Méditerranée, France.

- Del Pozo-Aguilera, S., Sánchez-Aparicio, L. J., Rodríguez-Gonzálvez, P., Herrero-Pascual, J., Muñoz-Nieto, A. L., Hernández-López, D., González-Aguilera, D., 2016: Multispectral Imaging: Fundamentals, Principles and Methods to damage assessment in Construction. Book associated to the chapter: *Non-Destructive Techniques for the Evaluation of Structures and Infrastructure*. Editorial: CRC Press, pp. 139–166.

- Drdácý, M., Binda, L., Herle, I., Lanza, L., 2007: Protecting the cultural heritage from natural disasters. Policy Department Structural and Cohesion Policies, Culture and Education, European Parliament. ARCCHIP Advanced Research Centre for Cultural Heritage.

- Fisher, H. J., 2017: Violence Against Architecture: The Lost Cultural Heritage of Syria and Iraq”.

CUNY Academic Works.

- Gaffney, C., Gaffney, V., Neubauer, W., Baldwin, E., Chapman, H., Garwood, P., Moulden, H., Sparrow, T., Bates, R., Löcker, K., Hinterleitner, A., Trinks, I., Nau, E., Zitz, T., Floery, S., Verhoeven, G., Doneus, M., 2012: The Stonehenge hidden landscapes project. *Archaeological Prospection*, 19, pp. 147–155.
- Gonizzi Barsanti, S., Caruso, G., Micoli, L. L., Covarrubias Rodriguez, M., Guidi, G., 2015: 3D visualization of cultural heritage artefacts with virtual reality devices. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-5/W7, pp.165-172.
- Grün, A., Remondino, F., Zhang, L., 2004: Photogrammetric reconstruction of the great Buddha of Bamiyan, Afghanistan. *Photogrammetric Record*, 19(107), pp. 177–199.
- Guidi, G., Angheluddu, D., 2016: Displacement mapping as a metric tool for optimizing mesh models originated by 3D digitization. *Journal on Computing and Cultural Heritage*, 9(2), pp. 9:1-9:23.
- Jiménez Fernández-Palacios, B., Stefani, C., Lombardo, J., De Luca, L., Remondino, F., 2013: Web visualization of complex reality-based 3D models with NUBES. *Proc. IEEE Conference “Digital Heritage 2013”*, Vol. 1, pp. 701-704, Marseille, France.
- Kraak, M. J., Ormeling, F., 2011: *Cartography: visualization of spatial data*. Guilford Press. USA.
- Lowe, A., Macmillan-Scott, J., Voegelin, A. F., 2012: *The authorized facsimile of the burial chamber of Tutankhamun with sarcophagus, sarcophagus lid and the missing fragment from the south Wall*, Factum Arte Publisher, 72 pages.
- Lowe, A., Ahmon, J., 2004: *The tomb of Seti I: digital technology in conservation*. Factum Arte Publisher, 62 pages.
- Manferdini, A.M., Remondino, F., 2012: A review of reality-based 3D model generation, segmentation and web-based visualization methods. *Int. Journal of Heritage in the Digital Era*, 1 (1), pp. 103-124.
- Mohd Shukuri, N. B., Awang, H., 2014: Study of abandoned heritage buildings from the owners’ perspectives in George Town, Penang. *MATEC Web of Conferences* 17 (9), pp. 1–5.
- Nex, F.C. and Rinaudo, F. 2011: LiDAR or photogrammetry? Integration is the answer. *European journal of remote sensing: open access*, 43(2), pp. 107-121.
- Pescarin, S., 2014: Museums and virtual museums in Europe: reaching expectations. *SCIRES-IT Scientific Research and Information Technology*, 4, pp. 131–140.
- Pescarin, S., Pietroni, E., Ferdani, D., 2010: A procedural approach to the modeling of urban historical

contexts. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology (BAR International Series 2494).

- Pescarin, S., Pietroni, E., Rescic, L., Wallergard, M., Omar, K., Rufa, C., 2013: NICH. A preliminary theoretical study on natural interaction applied to cultural heritage contexts. Digital Heritage International Congress, 1, pp.355-362.

- Pietroni, E., 2012: An augmented experiences in cultural heritage through mobile devices: Matera tales of a city project, VSMM Virtual Systems and Multimedia, pp. 117-124.

- Pietroni, E., Ray, C., Rufa, C., Pletinckx, D., Van Kampen, I., 2012: Natural interaction in VR environments for cultural heritage and its impact inside museums: the Etruscanning Project. VSMM Virtual System and Multimedia, pp. 339-346.

- Ponchio, F., Dellepiane. M., 2016: Multiresolution and fast decompression for optimal web-based rendering. Graphical Models, 88, pp. 1-11.

- Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Ponchio, F., Scopigno, R., 2015: 3DHOP: 3D heritage online presenter. Computers & Graphics, 52, pp. 129-141.

- Ramos, M., Remondino, F., 2015: Data fusion in Cultural Heritage – A Review. ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XL-5/W7, pp. 359-363. 25th CIPA Symposium, Taipei, Taiwan.

- Remondino, F., 2009: Reality-based 3D modeling of heritage sites and objects. 1st Int. Congress “Arqueología e Informática Gráfica, Patrimonio e Innovación”, Sevilla, Spain.

- Remondino, F., 2014: Photogrammetry - Basic Theory. In “3D Recording and Modelling in Archaeology and Cultural Heritage - Theory and Best Practices”, F. Remondino and S. Campana (Eds), pp. 63-72, Archaeopress BAR Publication Series 2598, ISBN 9781407312309 (171 pages).

- Remondino, F., Girardi, S., Rizzi, A., Gonzo, L., 2009: 3D Modeling of complex and detailed Cultural Heritage using multi-resolution data. ACM Journal on Computing and Cultural Heritage, Vol. 2(1).

- Richards-Rissetto, H., Remondino, F., Agugiaro, G., Robertsson, J., Von-Schwerin, J., Girardi, G., 2012: Kinect and 3D GIS in archaeology. Proc. 18th IEEE Intern. Conference on Virtual Systems and MultiMedia (VSMM), G. Guidi / L. Addison (Eds.), pp. 331-338. Milan, Italy.

- Rives, V., Talegon, J. G., 2006: Decay and conservation of building stones on Cultural Heritage monuments. Materials Science Forum, 514-516, pp. 1689-1694.

- Rodríguez-Gonzálvez, P., Muñoz-Nieto, A. L., del Pozo, S., Sanchez-Aparicio, L. J., Gonzalez-Aguilera,

D., Micoli, L., Gonizzi Barsanti, S., Guidi, G., Mills, J., Fieber, K., Haynes, I., Hejmanowska, B., 2017: 4D reconstruction and visualization of Cultural Heritage: analyzing our legacy through time, ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W3, pp. 609-616.

- Sánchez-Aparicio, L. J., Villarino, A., García-Gago, J., González-Aguilera, D., 2016: Photogrammetric, geometrical, and numerical strategies to evaluate initial and current conditions in historical constructions: a test case in the church of San Lorenzo (Zamora, Spain). Remote Sensing, 8, pp. 1–20.

- Sidiropoulou-Velidou D., Georgopoulos A., Lerma J.L., 2012: Exploitation of thermal imagery for the detection of pathologies in monuments. Progress in Cultural Heritage Preservation EuroMed. Lecture Notes in Computer Science, 7616.

- Stefani C., Busayarat C., Lombardo J., De Luca L., 2013: A web platform for the consultation of spatialized and semantically enriched iconographic sources on cultural heritage buildings. JOCCH International Journal on Computing and Cultural Heritage, 6 (3).

- Sterflinger, K., Piñar, G., 2013: Microbial deterioration of cultural heritage and works of art — tilting at windmills? Applied Microbiology and Biotechnology, 97(22), pp. 9637–9646.

- Stylianidis, E., Remondino, F., 2016: 3D Recording, Documentation and Management of Cultural Heritage. Whittles Publishing, ISBN 978-184995-168-5, 388 pages.

- Torres-Martínez, J.A., Seddaiu, M., Rodríguez-González, P., Hernández-López, D., González-Aguilera, D., 2016: A multi-data source and multi-sensor approach for the 3d reconstruction and web visualization of a complex archaeological site: the case study of “Tolmo De Minateda”. Remote Sensing, 8(7), 550:1-550:25.

- Von Schwerin, J., Richards-Rissetto, H., Remondino, F., Agugiaro, G., Girardi, G., 2013: The MayaArch3D project: A 3D WebGIS for analyzing ancient architecture and landscapes. Literary and Linguistic Computing, doi: 10.1093/lilc/fqt059.

- Vosselman, G., Maas, H., 2010: Airborne and Terrestrial Laser Scanning, CRC, BocaRaton, ISBN 978-1904445-87-6.

- Wahbeh, W., Nebiker, S., Fangi, G., 2016: Combining public domain and professional panoramic imagery for the accurate and dense 3d reconstruction of the destroyed Bel temple in Palmyra. ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, III-5, pp. 81–88.

- Watt, J., Tidblad, J., Kucera, V., Hamilton, R., 2009: The effects of air pollution on cultural heritage New York: Springer, 6, 10-12. ISBN 9780387848921.

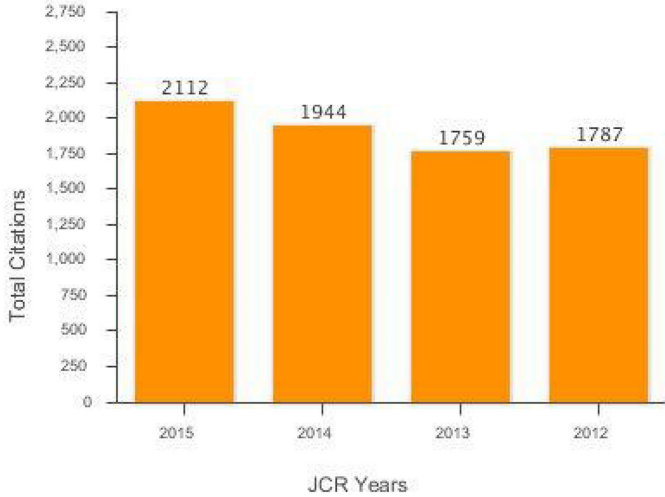
Annex I: Quality indexes and impact factor of the international journals

The scientific articles that compose this Doctoral Thesis have been published by impact journals indexed in the Journal Citation Reports®. The statistical and biometric parameters are presented below.

Article I - ARCube - The augmented reality cube for archaeology

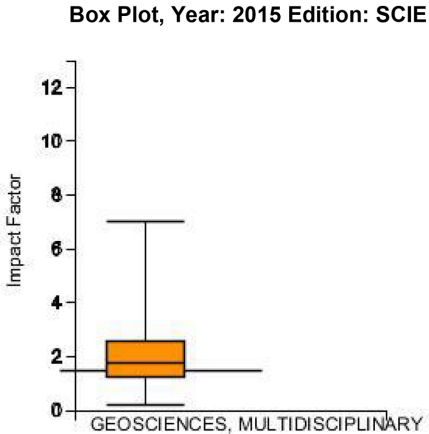
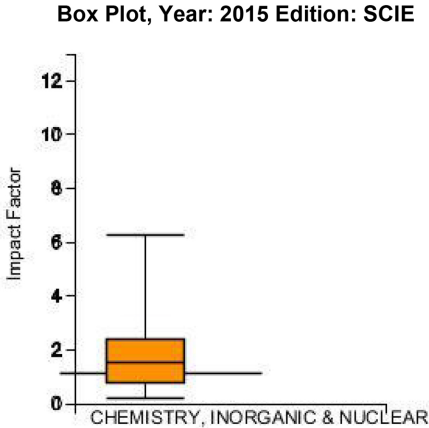
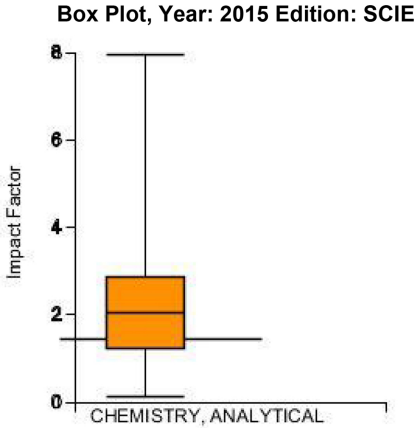
Journal	Archaeometry
Editorial	Wiley
ISSN	1475-4754
Impact factor (2015)	1.364
Ranking	115/184
Quartile	Q3

Essential Science Indicators : Total Citations Graph

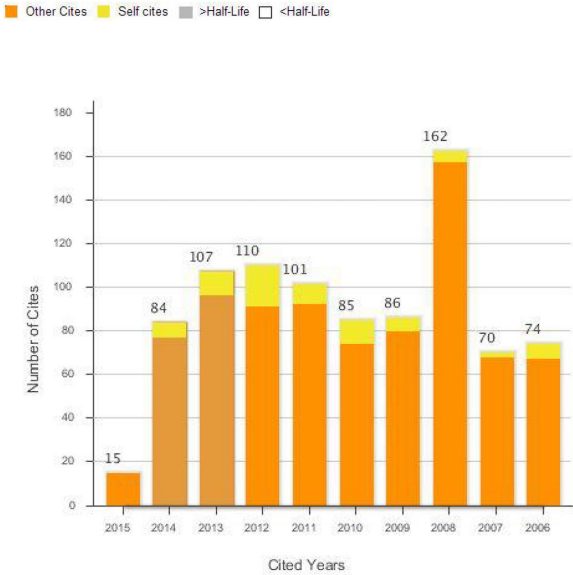


Journal Citation Report : Impact factor

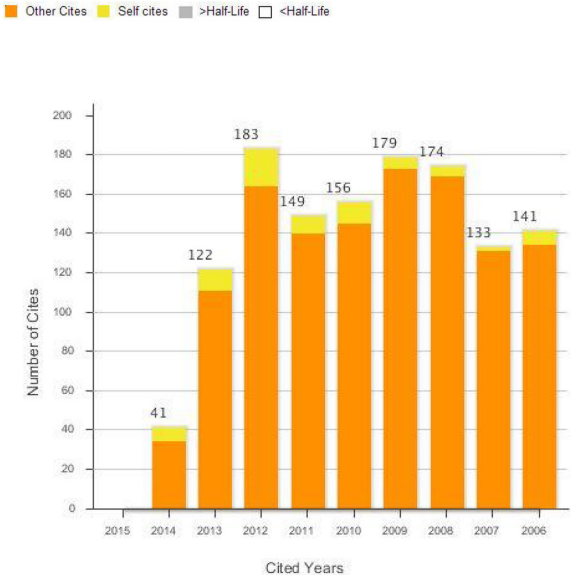
JCR Year	CHEMISTRY, ANALYTICAL			CHEMISTRY, INORGANIC & NUCLEAR			GEOSCIENCES, MULTIDISCIPLINARY		
	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2015	51/75	Q3	32.667	30/46	Q3	35.870	115/184	Q3	37.772
2014	48/74	Q3	35.811	27/45	Q3	41.111	94/175	Q3	46.571
2013	50/76	Q3	34.868	32/45	Q3	30.000	104/174	Q3	40.517
2012	51/75	Q3	32.667	28/44	Q3	37.500	96/172	Q3	44.477
2011	50/73	Q3	32.192	28/44	Q3	37.500	93/170	Q3	45.588
2010	40/73	Q3	45.890	24/43	Q3	45.349	68/167	Q2	59.581



Cited Journal Graph



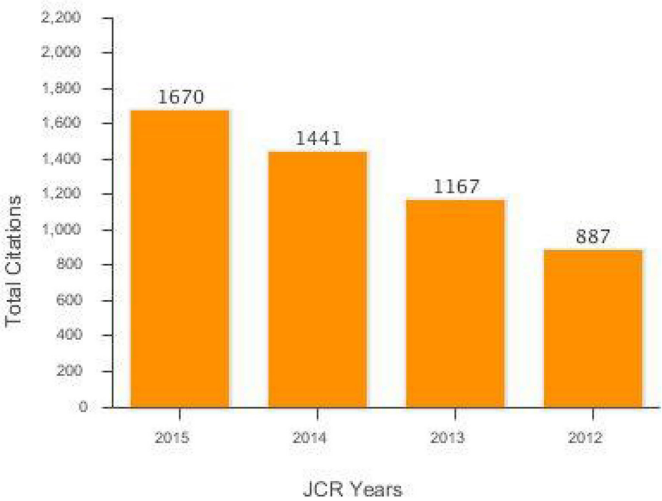
Citing Journal Graph



Article II - Access to complex reality-based 3D models using virtual reality solutions

Journal	Cultural Heritage
Editorial	Elsevier
ISSN	1296-2074
Impact factor (2015)	1.533
Ranking	104/184
Quartile	Q3

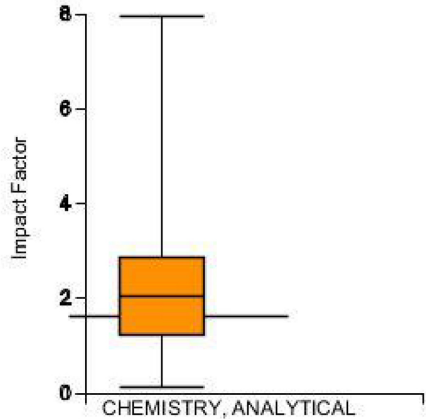
Essential Science Indicators : Total Citations Graph



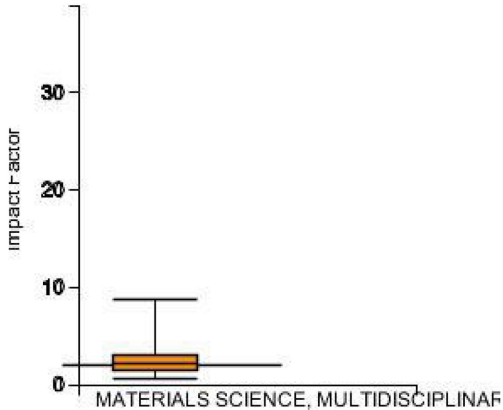
Journal Citation Report : Impact factor

JCR Year	CHEMISTRY, ANALYTICAL			GEOSCIENCES, MULTIDISCIPLINARY			MATERIALS SCIENCE, MULTIDISCIPLINARY			SPECTROSCOPY		
2015	48/75	Q3	39.333	104/184	Q3	43.750	148/271	Q3	45.572	26/43	Q3	40.698
2014	46/74	Q3	38.514	93/175	Q3	47.143	130/260	Q2	50.192	24/44	Q3	46.591
2013	54/76	Q3	29.605	117/174	Q3	33.046	154/251	Q3	38.845	32/44	Q3	28.409
2012	55/75	Q3	27.333	105/172	Q3	39.244	131/241	Q3	45.851	31/43	Q3	29.070
2011	52/73	Q3	29.452	105/170	Q3	38.529	121/232	Q3	48.060	31/42	Q3	27.381
2010	48/73	Q3	34.932	92/167	Q3	45.210	108/225	Q2	52.222	28/42	Q3	34.524

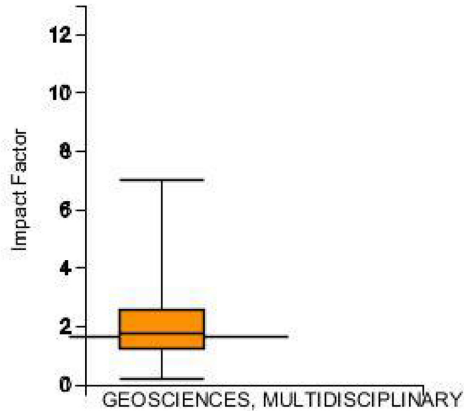
Box Plot, Year: 2015 Edition: SCIE



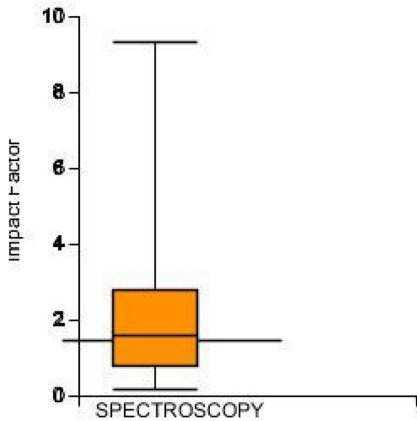
Box Plot, Year: 2015 Edition: SCIE



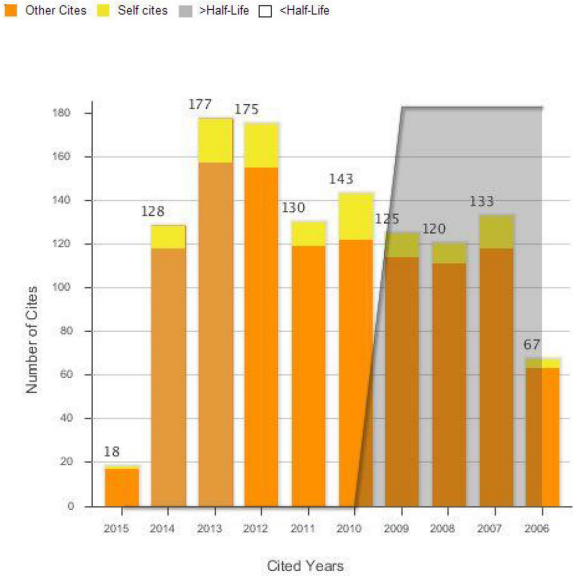
Box Plot, Year: 2015 Edition: SCIE



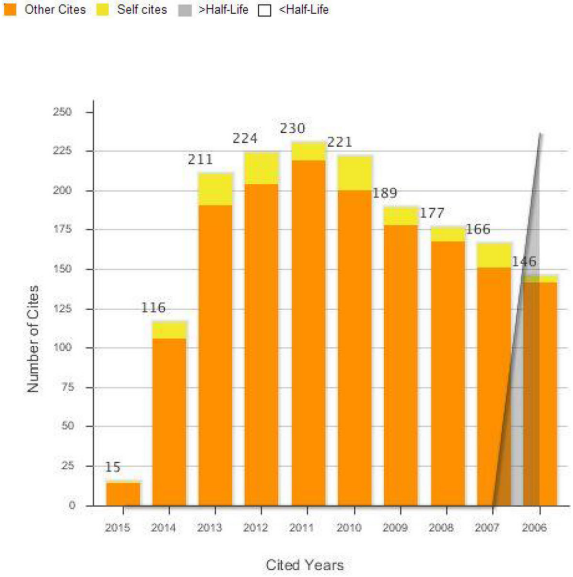
Box Plot, Year: 2015 Edition: SCIE



Cited Journal Graph



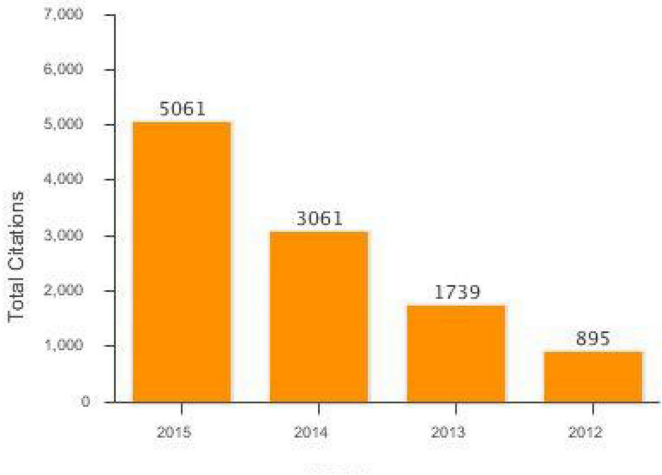
Citing Journal Graph



Article III - Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites

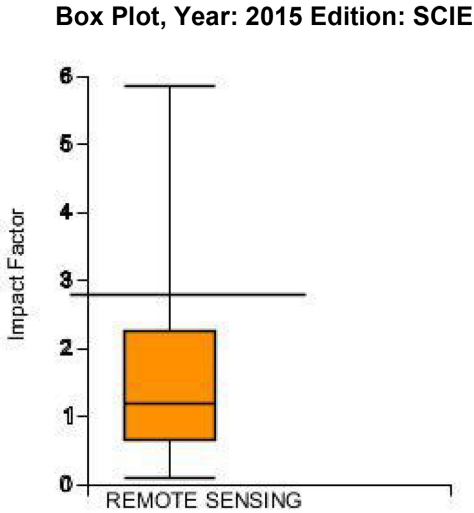
Journal	Remote Sensing
Editorial	MDPI AG
ISSN	2072-4292
Impact factor (2015)	3.036
Ranking	5/28
Quartile	Q1

Essential Science Indicators : Total Citations Graph

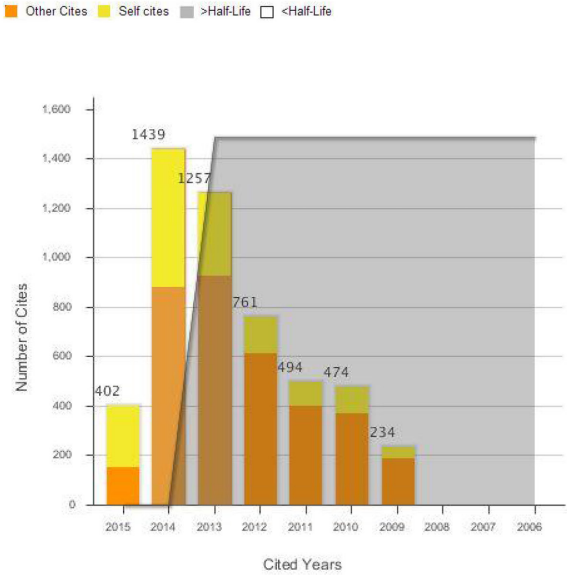


Journal Citation Report : Impact factor

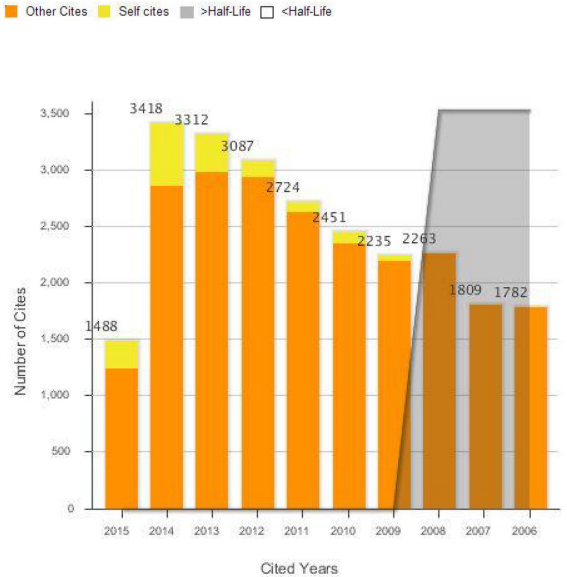
JCR Year	REMOTE SENSING		
	Rank	Quartile	JIF Percentile
2015	5/28	Q1	83.929
2014	5/28	Q1	83.929
2013	6/27	Q1	79.630
2012	7/27	Q2	75.926



Cited Journal Graph



Citing Journal Graph



Anexo II: Otros méritos

El artículo *“Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage”* presenta el trabajo de digitalización, modelación y visualización 3D para el proyecto Etruscans in 3D. El objetivo es documentar, estudiar, analizar y conservar el Patrimonio Etrusco, Tarquinia y Cerveteri entre otros (Patrimonio Mundial de la UNESCO desde 2014), así como ofrecer un mejor acceso a la información, creando contenidos digitales para exposiciones y visitas virtuales. Diferentes modelos 3D resultantes han sido utilizados para verificar la validez de las metodologías propuestas por la presente Tesis Doctoral, tanto en la escala artefacto⁶ como en la escala arquitectura⁷.

- Jiménez Fernández-Palacios, B., Rizzi, A., Remondino, F., 2013: Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage. Virtual Archaeology Review, Vol. 4(8), pp.85-89. ISSN: 1989-9947.

El artículo *“3D Surveying and modelling of the archaeological area of Paestum, Italy”* presenta un trabajo sobre la integración de técnicas de levantamiento 3D para reproducir digitalmente las principales estructuras y templos del yacimiento arqueológico de Paestum (Patrimonio Mundial desde 1998), (Italia). La fotogrametría terrestre, aérea (UAV) y el láser escáner terrestre (TLS) son integrados para explotar las ventajas intrínsecas de cada una de ellas. Además, se desarrolla un tour virtual que permite visitar el área arqueológica, vía Web. El virtual tour ha sido recreado por medio de realidad virtual, verificando la eficacia de la metodología implementada por la Tesis Doctoral y creando un nuevo enfoque para la escala arquitectura y paisaje, a través de imágenes panorámicas¹³.

- Fiorillo, F., Jiménez Fernández-Palacios, B., Remondino, F., Barba, S., 2013: 3D Surveying and modelling of the archaeological area of Paestum, Italy. Virtual Archaeology Review, Vol. 4(8), pp. 55-60. ISSN: 1989-9947.

Annex II: Other merits

The article *“Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage”* presents the work of 3D recording, modeling and visualization for the Etruscans in 3D project. The aim is to document, study, analyse and preserve the Etruscan Heritage - Tarquinia and Cerveteri among others (UNESCO World Heritage since 2014) - as well as to provide better access to information and to create digital content for exhibitions and virtual visits. Some of the resulting complex 3D models have been used to verify the validity of the methodologies proposed by this Doctoral Thesis, both in the artefact scale⁶ and in the architecture scale⁷.

- Jiménez Fernández-Palacios, B., Rizzi, A., Remondino, F., 2013: Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage. Virtual Archaeology Review, Vol. 4(8), pp.85-89. ISSN: 1989-9947.

The article *“3D Surveying and modelling of the archaeological area of Paestum, Italy”* presents an integration work of 3D surveying techniques to digitally reproduce the main structures and temples of the archaeological site of Paestum (World Heritage since 1998). Terrestrial and aerial photogrammetry (UAV) as well Terrestrial Laser Scanning (TLS) have been integrated to exploit the intrinsic advantages of each. In addition, a web-based virtual tour has been developed which allows visits to the archaeological area. The virtual tour has been recreated using the developed virtual reality application, verifying the effectiveness of the methodology implemented by the Doctoral Thesis and creating a new approach for the architecture and landscape scale through the use of panoramic images¹³.

- Fiorillo, F., Jiménez Fernández-Palacios, B., Remondino, F., Barba, S., 2013: 3D Surveying and modelling of the archaeological area of Paestum, Italy. Virtual Archaeology Review, Vol. 4(8), pp. 55-60. ISSN: 1989-9947.

El artículo “*Web visualization of complex reality-based 3D models with NUBES*” trata los problemas fundamentales de la visualización Web a través de NUBES, una plataforma semántica para documentar, analizar y compartir digitalmente el Patrimonio Arquitectónico. Se presenta un nuevo procedimiento automático para la carga de escenas complejas, verificando su validez con pesados modelos digitales basados en la realidad. Debido al enorme tamaño de las escenas 3D se apuesta por un enfoque de optimización geométrica y radiométrica que posibilite la visualización en tiempo real de los grandes conjuntos de datos.

- Jiménez Fernández-Palacios, B., Stefani, C., Lombardo, J., De Luca, L., Remondino, F., 2013: Web visualization of complex reality-based 3D models with NUBES. Proc. IEEE Conference “Digital Heritage 2013”, Vol. 1, pp. 701-704, Marseille, France.

Además, han sido realizados diferentes estudios y trabajos explotando los recursos online para el desarrollo Web de navegadores y tours virtuales. Conjuntos de datos heterogéneos, tanto 2D como 3D, han sido integrados tanto para visualizar, analizar y comparar datos provenientes de diferentes sensores como para promover y divulgar el Patrimonio Cultural. Tales metodologías son válidas para cualquier escala. Algunos ejemplos de ello son:

- El navegador “*Chrysanthemums in a Green Vase*” para la escala artefacto, donde datos láser escáner, de alta resolución, son integrados con conjuntos de datos provenientes de otros sensores, como información RGB, infrarroja y rayos X, para la visualización y el análisis de la información del Patrimonio Cultural. Página Web: http://www.highres.factum-arte.org/Chrysanthemums_in_a_Green_Vase/index.html

- El “*Copán Virtual Tour*” del proyecto MayaArch3D donde la escala arquitectura, representada por modelos 3D foto-realísticos, es integrada con la escala paisaje, representada por imágenes panorámicas, para la visualización y la divulgación del patrimonio. Página Web: http://3dom.fbk.eu/repository/files/vt_copan/index.html

The article “*Web visualization of complex reality-based 3D models with NUBES*” addresses the fundamental problems of web visualization through NUBES, a semantic platform for the digital documentation, analysis and sharing of Architectural Heritage. A new automatic procedure for loading complex scenes is presented, verifying the validity of the methodology with huge reality-based digital models. Due to the enormous size of the 3D scenes, a geometric and radiometric optimization approach is used to enable real-time visualization of large data sets.

- Jiménez Fernández-Palacios, B., Stefani, C., Lombardo, J., De Luca, L., Remondino, F., 2013: Web visualization of complex reality-based 3D models with NUBES. Proc. IEEE Conference “Digital Heritage 2013”, Vol. 1, pp. 701-704, Marseille, France.

Furthermore, different studies and works have been carried out which have exploited online resources for web development of browsers and virtual tours. Heterogeneous data sets, both 2D and 3D, have been integrated to promote and disseminate Cultural Heritage and to visualize, analyse and compare data provided by different sensors. These methodologies are valid for the different scales. Some examples of this are:

-The “*Chrysanthemums in a Green Vase*” browser for the artefact scale, where high-resolution laser scanner data is integrated with datasets provided by different sensors, such as RGB, infrared and X-ray information, to visualize and analyse Cultural Heritage information. Website: http://www.highres.factum-arte.org/Chrysanthemums_in_a_Green_Vase/index.html

- “*Copán Virtual Tour*” (MayaArch3D Project) where the architecture scale, represented by complex 3D photo-realistic models, is integrated with the landscape scale, represented by panoramic images, to visualize and disseminate Cultural Heritage Sites. Website: http://3dom.fbk.eu/repository/files/vt_copan/index.html

Curriculum Vitae

Belén Jiménez Fernández-Palacios nació en 1977 en Sevilla, España. Estudió Ingeniería Técnica en Topografía graduándose en 2008 por la Universidad de Jaén. Obtuvo dos becas de estudio para realizar estancias en el extranjero con la Universidad de Lisboa y el Politécnico de Milán, donde comenzó a colaborar en proyectos de investigación en topografía y fotogrametría. En 2009, obtuvo un Master en GIS por la Universidad La Sapienza, Roma (Italia), con especialización en Patrimonio Cultural, recibiendo el premio Maria Zevi a la mejor tesis. En 2010 recibió una beca Argo para realizar una estancia de investigación en el Instituto per le Tecnologie Applicate ai Beni Culturali, Consiglio Nazionale delle Ricerche (CNR-ITABC), Roma (Italia). De 2011 a 2014 ha trabajado como investigadora principal en la unidad de investigación 3D Optical Metrology, Fondazione Bruno Kessler (3DOM-FBK), Trento, (Italia). En 2012, y contemporáneamente a su trabajo de investigación, comienza sus estudios de doctorado por la Universidad de Salamanca. En 2013 obtuvo la beca FBK Mobility para realizar una estancia de investigación en la unidad mixta Modèles et Simulations pour L’architecture et le Patrimoine del Centre National de la Recherche Scientifique (CNRS-Map Gamsau), Marsella (Francia). En 2015 trabajó como profesora visitante para la Universidad de Salerno (Italia) en la digitalización y la modelación 3D del área arqueológica de Pompeya para el “Grande Progetto Pompei”. Desde 2016 trabaja en FACTUM Foundation (FACTUM arte), Madrid, en labores de digitalización y modelación para la conservación del Patrimonio Cultural, así como en la coordinación del departamento de 3D y fotogrametría.

A lo largo de estos años, sus principales intereses se han centrado en el campo de la digitalización, la modelización, el análisis y la visualización 3D aplicada al Patrimonio Cultural. Entre los proyectos o lugares en los cuales ha trabajado, vale la pena destacar la reconstrucción del paisaje chino de Xian en tiempos de la dinastía Han (CNR-ITABC), los templos grecorromanos de Paestum, las necrópolis etruscas de Tarquinia y Vulci, el proyecto FERNANDE 3D (sobre la primera escultura cubista de Picasso) y los templos Mayas de Copán (3DOM-

Curriculum Vitae

Belén Jiménez Fernández-Palacios graduated as a Technical Surveying Engineer at the Universidad de Jaen (Spain) in 2008. Concurrently with her studies she obtained grants to study abroad at the University of Lisbon and the “Politecnico di Milano” where she collaborated on research projects on topography and photogrammetry. In 2009 she received a master in GIS from La Sapienza University in Rome (Italy) with a specialization in Cultural Heritage, receiving the *Maria Zevi* best thesis award. In 2010 she received an Argo grant to conduct a researcher stay at the “Istituto per le Tecnologie Applicate ai Beni Culturali, Consiglio Nazionale delle Ricerche (CNR-ITABC)”, Rome (Italy). From 2011 to 2014 she worked as main researcher at the Bruno Kessler Foundation (FBK) for the 3D Optical Metrology unit (3DOM), in Trento (Italy). Since 2012, and contemporaneously to her research work, she has been carrying out her Ph.D. for the University of Salamanca. In 2013 she obtained the FBK Mobility grant to conduct a research project while visiting the mixed unit of “Modèles et Simulations pour L’architecture et le Patrimoine del Centre National de la Recherche Scientifique (CNRS-Map Gamsau)”, Marseilles (France). In 2015 she worked as a visiting professor for the University of Salerno (Italy) on the 3D surveying and modeling of the archaeological area of Pompeii for the “Grande Progetto Pompei”. Since 2016 she has been working at the FACTUM Foundation (FACTUM Arte), in Madrid (Spain), on the 3D surveying and modeling of Cultural Heritage for conservation purposes, as well as on the coordination of the 3D and photogrammetry department.

Throughout these years, her main interests have focused on the field of 3D recording, modeling, analysis and visualization techniques applied to Cultural Heritage. Among the projects or places in which he has worked, it is worth noting the reconstruction of the Chinese landscape of Xian at the time of the Han Dynasty (CNR-ITABC), the Greek-Roman Temples of Paestum, the Etruscan necropolis of Tarquinia and Vulci, the FERNANDE 3D project (concerning the first cubist sculpture by Picasso) and the Mayan Temples of Copán (3DOM-

FBK), el proyecto NUBES (CNRS-Gamsau), el área arqueológica de Pompeya (Universidad de Salerno), la reconstrucción física de la capilla Borgherini o las puertas y artefactos de Kala-Koreysh (FACTUM Foundation). Actualmente trabaja en el proyecto The Theban Necropolis Preservation Initiative, integrando sensores activos y pasivos para la reconstrucción 3D y el facsímil de la tumba egipcia de Seti I.

FBK), the NUBES project (CNRS-Gamsau), the archaeological area of Pompeii (University of Salerno), the physical reconstruction of the Borgherini Chapel and the doors and artefacts of Kala-Koreysh (FACTUM Foundation). Currently, she is working on The Theban Necropolis Preservation Initiative project, integrating active and passive sensors for the 3D digital and physical reconstruction (facsimile) of the Egyptian tomb of Seti I.

Teaching

- “Seminar on Photogrammetry”, University of Nebrija, Madrid, Spain, 09/03/2016.
- Workshop, “Training in 3D and Color Recording. Case study: Hermitage of San Baudelio,” MA in Advanced Historic Preservation, Columbia GSAPP at Factum Arte, Madrid, Spain, 10-14/10/2016.
- Visiting professor, “3D Recording Techniques. Case study: Cenador del Leon”, Departamento de Expresión Gráfica Arquitectónica, ETSA, University of Seville, Spain, 28/04/2015 & 03/05/2016.
- CIPA Summerschool “Cultural Heritage 3D Surveying & Modelling”, Paestum, Italy, 05-12/07/2014.
- Summerschool “Web Valley”, San Lorenzo in Banale, Trentino, Italy, 03/07/2014 .
- Summerschool “Rilievo e Modellazione 3D”, Paestum, Italy, 01-08/06/2014 & 03-09/06/2012.
- Coordination & Teaching “Digitalización 3D del Patrimonio”, Iverem, Madrid, Spain, 09-12/10/2012.
- Summerschool “Cultural Heritage Documentation”, Carmona, Spain, 24-28/11/2012.
- 11th Archdoc Workshop, “Architectural Heritage Documentation for Conservation & Virtual Palace Workshop”, Castle of Arenberg, Leuven, Belgium. 14-19/11/2011.
- “Italian School of Virtual Archaeology”, Monselice, Italy, 02-03/07/2010.

Publications

- Rodríguez-Gonzálvez, P., Jiménez Fernández-Palacios, B., Muñoz-Nieto, A.L., Arias-Sanchez, P., and Gonzalez-Aguilera, D., 2017. Mobile LiDAR System: New Possibilities for the Documentation and Dissemination of Large Cultural Heritage Sites. Remote Sensing, Vol 9(3), pp 189.
- Jiménez Fernández-Palacios, B., Morabito, D., Remondino, F., 2017: Access to complex reality-based 3d models using virtual reality solutions. Journal of Cultural Heritage, Vol. 23, pp. 40–48.
- Fiorillo, F., Limongiello, M., Jiménez Fernández-Palacios, B., 2016: Testing GoPro for 3D model reconstruction in narrow spaces. Acta Imeko. The Imeko Online Journal Vol 5(2), pp 64–70. ISSN: 2221-870X.
- Jiménez Fernández-Palacios, B., Nex, F., Rizzi, A., Remondino, F., 2015: ARCube – The augmented reality cube for archaeology. Archaeometry, DOI: 10.1111/arcm.12120.
- Chiabrando F., Donadio E., Fernandez-Palacios B. J., Remondino F., Spano’ A., 2015: L’ arco di Augusto a Susa: un nuovo modello digitale per rinnovate indagini Tecnologie innovative per il rilievo metrico terrestre. Segusium, pp. 217-232.
- Gonizzi-Barsanti, S., Remondino, F., Jiménez Fernández-Palacios, B., Visintini, D., 2014: Critical factors and guidelines for 3D surveying and modelling in Cultural Heritage. Int. Journal of Heritage in the Digital Era. Vol. 3(1), pp. 142-158.
- Jiménez Fernández-Palacios, B., Stefani, C., Lombardo, J., De Luca, L., Remondino, F., 2013: Web visualization of complex reality-based 3D models with NUBES. Proc. IEEE Conference “Digital Heritage 2013”, Vol. 1, pp. 701-704, 28 Oct – 1 Nov., Marseille, France.
- Jiménez Fernández-Palacios, B., Rizzi, A., Remondino, F., 2013: Etruscans in 3D - Surveying

and 3D modeling for a better access and understanding of heritage. *Virtual Archaeology Review*, Vol. 4(8), pp.85-89. ISSN: 1989-9947.

- Fiorillo, F., Jiménez Fernández-Palacios, B., Remondino, F., Barba, S., 2013: 3D Surveying and modelling of the archaeological area of Paestum, Italy. *Virtual Archaeology Review*, Vol. 4(8), pp. 55-60. ISSN: 1989-9947.

- Von Schwerin, J., Remondino, F., Richards-Rissetto, H., Jiménez Fernández-Palacios, B., Reindel, M., 2013: Collecting and structuring data for visualization and analysis in Maya archaeology. Proc. 4th “Scientific Computing and Cultural Heritage” (SCCH) Conference, 18-20 Nov., Heidelberg, Germany.

- Jiménez Fernández-Palacios, B., Rizzi, A. Nex, F., 2012: “Augmented reality for archaeological finds”. Euromed. International Conference on Cultural Heritage. Lemesos, Cyprus.

- Abate, D., Migliori, S., Pierattini, S., Jiménez Fernández-Palacios, B., Rizzi, A., Remondino, F., 2012: Remote rendering and visualization of large textured 3D models. Proc. 18th IEEE Intern. Conference on Virtual Systems and MultiMedia (VSMM), G. Guidi / L. Addison (Eds.), pp. 399-404. Milan, Italy.

- Jiménez Fernández-Palacios, B., Rizzi, A., Remondino, F., 2012: Importance of 3D models for studies and analyses of architectural structures. *Virtual Palaces I. Digitizing and Modelling Palaces*. Proceedings of the European Science Foundation Research Networking Programme PALATIUM. Leuven, 18-19 November 2011.

- Marconi, G.P., Remondino, F., Jimenez Fernandez-Palacios, B., Cozzini, M., 2012: X-Bridge Project: development of a new methodology for the monitoring of steel bridges. In “Applied Mechanics and Materials”, Vol. 256-259, pp. 1537-1541. Proc. 2nd International Conference on Civil Engineering and Transportation (ICCET 2012), Guilin, China.

- Remondino, F., Rizzi, A., Jiménez Fernández-Palacios, B., Agugiaro, G., Baratti, G., De Amicis, R., 2011: The Etruscan in 3D: from space to underground. 23th Int. CIPA Symposium, Prague, Czech Republic (on CD-Rom).
- Remondino, F., Rizzi, A., Agugiaro, G., Jiménez Fernández-Palacios, B., Menna, F., Nex, F., Baratti, G., 2011: Rilievi e modellazione 3D. Proc. of the 15th ASITA Conference, Reggio di Colorno (Parma), Italy.
- Rizzi, A., Baratti, G., Jiménez Fernández-Palacios, B., Girardi, S., Remondino, F., 2011: 3D Recording for 2D delivering - The employment of 3D models for studies and analyses. Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 38(5/W16), on CD-ROM. 4th ISPRS International Workshop “3D-ARCH 2011: “Virtual Reconstruction and Visualization of Complex Architectures”, 2-5 March 2011, Trento, Italy.
- Jiménez Fernández-Palacios. B, 2009: “Sviluppo di un GIS in area costiera con riferimento alle emergenze storico-culturali del paesaggio” Thesis Master: “ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale”, Rome, Italy.

Notas

- 1
- Facsímil, del latín *facĕre* ‘hacer’, y simĭle ‘semejante’.
- 2
- Escala, del latín *scala*; sucesión ordenada de valores distintos de una misma cualidad; graduación empleada en diversos instrumentos para medir una magnitud; tamaño de un mapa, plano, diseño, etc., según la escala a que se ajusta; tamaño o proporción en que se desarrolla un plan o idea (RAE).
- 3
- Artefacto, del latín *arte factum* que significa ‘hecho con arte’.
- 4
- Arquitectura, etimológicamente proviene del griego antiguo. Es la conjunción de dos palabras: *arjé*, ‘el que manda, el principio, el primero’, y *tektón*, que significa ‘construir, edificar’.
- 5
- Paisaje, del francés *paysage*, derivado de *pays* ‘territorio rural, país’.
- 6
- Ver Sección I - Escala artefacto y artículo I “*ARCube - The augmented reality cube for archaeology*”.
- 7
- Ver Sección II - Escala arquitectura y artículo II “*Access to complex reality-based 3D models using virtual reality Solutions*”.
- 8
- Ver Sección III - Escala paisaje y artículo III “*Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites*”.
- 9
- Ver Anexo II - Otros méritos. Artículo “*Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage*”.
- 10
- Ver Anexo II - Otros méritos. Artículo “*3D Surveying and modelling of the archaeological area of Paestum, Italy*”.
- 11
- Ver Anexo II - Otros méritos. Artículo “*Web visualization of complex reality-based 3D models with NUBES*”, el navegador “*Chrysanthemums in a Green Vase*” y el “*Copán Virtual Tour*”.
- 12
- Ver el caso de estudio de la tumba etrusca Bettini. Sección 3.3. *Bettini Tomb*, artículo II “*Access to complex reality-based 3D models using virtual reality Solutions*”.
- 13
- Ver el caso de estudio del Virtual Tour de Paestum. Sección 3.4. *Further application*, artículo II “*Access to complex reality-based 3D models using Virtual Reality Solutions*”.

Notes

- 1
- Facsimile is derived from the Latin *facĕre* ‘to make’, and *simĭle* ‘alike’.
- 2
- Scala, originally from the Latin *scala*; ordered succession of different values of the same quality; graduation used in various instruments to measure the magnitude; size of a map, plane, design, etc., according to the scale to which it is adjusted; size or proportion in which a plan or idea is developed (RAE).
- 3
- Artefact is derived from the Latin *arte factum* which means ‘made with art’.
- 4
- Architecture, originally from Ancient Greek. It is the conjunction of two words: *arjé*, ‘the one who commands, the beginning, the first’ and *tektón*, which means ‘to build’.
- 5
- Landscape, from the French *paysage*, derived from *pays* ‘rural territory, country’.
- 6
- See Section I - Artefact scale and article I “*ARCube - The augmented reality cube for archaeology*”.
- 7
- See Section II - Architecture scale and article II “*Access to complex reality-based 3D models using virtual reality Solutions*”.
- 8
- See Section III - Landscape scale and article III “*Mobile LiDAR System: new possibilities for the documentation and dissemination of large Cultural Heritage sites*”.
- 9
- See Annex II - Other merits. Article “*Etruscans in 3D - Surveying and 3D modeling for a better access and understanding of heritage*”.
- 10
- See Annex II - Other merits. Article “*3D Surveying and modelling of the archaeological area of Paestum, Italy*”.
- 11
- See Annex II - Other merits. Article “*Web visualization of complex reality-based 3D models with NUBES*”, the “*Chrysanthemums in a Green Vase*” browser and the “*Copán Virtual Tour*”.
- 12
- See the case study of the Etruscan Bettini Tomb. Section 3.3. *Bettini Tomb*, article II “*Access to complex reality-based 3D models using Virtual Reality Solutions*”.
- 13
- See the case study of the Paestum Virtual Tour. Section 3.4. *Further application*, article II “*Access to complex reality-based 3D models using Virtual Reality Solutions*”.

Agradecimientos

- Agugiario, Giorgio
- Barba, Salvatore
- Bayod, Carlos
- De Luca, Livio
- Del Pozo Aguilera, Susana
- DICIV, Salerno
- Fdez-Palacios, Victoria
- Fiorillo, Fausta
- González-Aguilera, Diego**
- Jiménez, Agustín
- Lowe, Adam
- MAP-Gamsau, Marseille
- Nex, Francesco
- Reindel, Markus
- Remondino, Fabio**
- Richards Risetto, Heather
- Roche, Pelayo
- Rodriguez González, Pablo
- 3Dom, Trento
- Vicini, Chiara

“Tendrá trescientas páginas, o algo más. Será un tomo con el que se podrá matar a una persona tirándoselo a la cabeza.”

Federico García Lorca refiriéndose a Poeta en Nueva York, en una entrevista con Antonio Otero Seco. En el prologo de Poeta en Nueva York, Andrew A. Anderson, Galaxia Gutenberg, 2015.

