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3D MODELLING OF HISTORIC URBAN CENTRES AND ITS APPLICABILITY TO THE FIELDS OF SECURITY AND DEFENCE

Abstract

Historical cities (or centers) show a value which goes beyond the properly historical or cultural, being considered as milestones for the own collective memory of its inhabitants. Because their strategic value, it is of paramount importance to develop research lines for increasing our knowledge about them.

In this article, we propose a proper methodology for the generation of three-dimensional digital models considering the characteristics of historical urban centers. This methodology is based on the combined and complementary use of photogrammetry and laser scanner. The models finally obtained for each building are geometrically precise and visually aesthetic. These models can be integrated into virtual environments, and used for safety of historical cities, which are especially vulnerable against war or terrorist actions.

Keywords

3D virtual models, historical cities, military defence, photogrammetry, laser scanner, memoricide, safety, urbicide.

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3D MODELLING OF HISTORIC URBAN CENTRES AND ITS APPLICABILITY TO THE FIELDS OF SECURITY AND DEFENCE

INTRODUCTION

From a quantitative perspective, the world's population is becoming increasingly concentrated in urban areas. According to recent statistics published by the United Nations, more than half of the world's population currently lives in urban areas. Although major differences become apparent if we take into account the distribution of this percentage by region, the fact is that this trend is on the increase at global level. According to forecasts provided by the UN, approximately two thirds of the world's population will be living in cities by the year 2050¹. Therefore it is becoming increasingly necessary to develop research methodologies that will allow for greater in-depth knowledge of urban areas, prompted by dynamism and the concentration of activities (and interests) within them.

For some years now the generation of *3D digital models* in urban areas has been a topic of great interest². A number of studies have been focused on different aspects including, among others, the techniques applied for data collection, the different methodologies employed in data processing, the type of models generated and/or the relationship between the quality of the digital model and its final application³. The majority of previous studies presented methodologies involving large-scale monitoring of study areas in a recurring basis, selecting for that purpose massive data collection methods (generally based on airborne systems) and recommending final models that are low on detail⁴.

1 UN: «Más de la mitad de la población vive en áreas urbanas y seguirá creciendo», *UN Department of Economic and Social Affairs*, 10 July, 2014, <http://www.un.org/es/development/desa/news/population/world-urbanization-prospects-2014.html> (Date accessed: 15 March 2017).

2 *Ibid.*

3 BALSA-BARREIRO, José, y LERMA, José L. «Aplicación de la tecnología del láser escáner aerotransportado (ALS) a la generación de modelos digitales urbanos», *Topografía y cartografía*, n.º 23(136), 2006, pp. 3-8.

SHIODE, Narushige. «3D urban models: Recent developments in the digital modelling of urban environments in three-dimensions», *GeoJournal*, n.º 52(3), 2000, pp. 263-269.

4 BILJECKI, Filip; SOTER, Jantien; LEDOUX, H.; ZLATANOVA, Sisi and ÇÖLTEKIN, Arzu: «Applications of 3D city models: State of the art review», *ISPRS International Journal of Geo-Information*, n.º 4(4), 2015, pp. 2842-2889.

5 HU, Jinhui; YOU, Suya and NEUMANN, Ulrich. «Approaches to large-scale urban modeling», *IEEE Computer Graphics and Applications*, n.º 23(6), 2003, pp. 62-69.

FRÜH, Christian, and ZAKHOR, Avideh. «Fast 3D model generation in urban environments», in: *IEEE Conf. on Multisensor Fusion and Integration for Intelligent Systems*, 2001, Baden-Baden, Germany, pp. 165-170.

However, an alternative working methodology could be proposed for historic urban areas such as «historic city centers» or «old cities». Such areas have a particular urban physiognomy determined by the great cultural value of their buildings, some of which are perceived as landmarks by their inhabitants and their urban fabric that has remained largely unchanged for centuries.

The generation of three-dimensional digital models in historic urban areas requires specific work methodologies in order to obtain final models with a high level of detail and considerable level of realism, which permit us to find out more about these areas. To that end, techniques are required during the phase of data acquisition for the collection of accurate information on buildings from points located at ground level, which similarly take into account the inherent difficulties facing these areas. The possible applications of the digital models obtained are many and various, including the cataloguing and preservation of historic buildings, urban planning and urban safety, as well as navigation and tourist entertainment programmes, etc.

In this article we are presenting our own work methodology and with this in mind we will recount our work experience within the framework of the European research project *4D-CH World*. We will also discuss the value of the generation of three-dimensional models for the security of historic urban areas.

ANALYSIS FROM THE PERSPECTIVE OF SECURITY AND DEFENCE

Of special significance within urban environments are their *historic city centres*, around which the present-day city has been articulated and expanded. These historic city centres bear more qualitative than quantitative weight, with a historical value that transcends their own cultural and economic value (derived from their own exploitation as a resource), as they become perceived as milestones that are part of the collective memory of its people. For this reason, the authorities allocate large resources to the conservation and preservation of these areas, considered of *fundamental strategic value*. Recent proof of the strategic nature of these historical environments is the media interest that cultural terrorism has attracted during the wars in Afghanistan (2001-2014), Iraq (2003-2011) and *Syria* (2011-today), despite the fact that devastation has been widespread in large regions of these countries.

In addition and simultaneously, the vulnerability of a large part of the heritage features present in these historic areas must be considered, for which the authorities propose their own security policies in terms of conservation and maintenance.

The natural threats to which our architectural heritage is subjected on a daily basis are familiar and close to us. In 2015, part of the roof of the church of *Castronuevo*

6 DANTI, Michael D. «Ground-Based Observations of Cultural Heritage Incidents in Syria and Iraq», *Near Eastern Archaeology*, n.º 78(3), 2015, pp. 132-141.

de los Arcos (Zamora) was detached due to the weight of the storks nests on top of them. This particular example is by no means an isolated case, as this has become an increasingly frequent threat due to the changing habits of these birds⁷. In 2013, the interior of the sanctuary of *A Virxe da Barca* in Muxía (A Coruña), one of the most emblematic in Galicia, was struck by lightning and badly damaged by fire. The result of the rehabilitation works, at an estimated cost of € 750,000⁸, was widely rejected by the local inhabitants⁹.

But in addition to threats due to natural causes, there are other direct anthropic threats or disturbances related in particular to situations of conflict. Some authors refer to the concept of *urbicide* (killing of the city), understood as the intensification of attacks on cities and/or their destruction. This concept was popularised by the former mayor of *Belgrade* (Serbia), *Bogdan Bogdanovic*, when referring to the constant siege and destruction of some of the main Balkan cities (*Vukovar*, *Sarajevo*, *Mostar* and *Dubrovnik*) during the *Bosnian War* (1992-1995)¹⁰. Mazzucchelli¹¹ points out that in this war the objectives were more symbolic than strategic in nature, in a context of confrontation between the rural world, representing the country's own identity, and the urban world, representing the cosmopolitan and multicultural space of that same country. It is estimated that in Bosnian territory alone around 180 villages and 560 mosques were destroyed during this war¹².

7 GENER, Mari P. «Un nido de cigüeña hunde el tejado y cae sobre la bóveda de la iglesia de Andosilla», *Diario de Navarra*, 20 January 2012, http://www.diariodenavarra.es/noticias/navarra/tierra_estella_valdizarbe/un_nido_ciguenas_hunde_tejado_cae_sobre_boveda_iglesia_andosilla_65848_1006.html (Date accessed: 15 March, 2017). -: «Un nido pone en peligro el tejado de la iglesia de las Carmelitas de Peñaranda», *La Gaceta de Salamanca*, 20 January, 2017, <http://www.lagacetadesalamanca.es/viva-mi-pueblo/penaranda-de-bracamonte/2017/01/20/nido-pone-peligro-tejado-iglesia-carmelitas/194892.html> (Date accessed: 15 March, 2017).

8 REJON, Raúl. «La Iglesia declara a las cigüeñas una amenaza patrimonial para sus edificios», *Eldiario*, 18 February, 2016, http://www.eldiario.es/sociedad/iglesia-considera-ciguenas-amenaza-patrimonial_o_485751680.html (Date accessed: 15 March, 2017).

9 -: «Un rayo incendia el emblemático santuario de Muxía, en A Coruña», *El País*, 25 December, 2013, http://elpais.com/elpais/2013/12/25/actualidad/1387984741_525895.html (Date accessed: 15 March, 2017).

10 A.M. «El santuario de Muxía estrena su nueva imagen ante la indignación de los vecinos», *La Opinión de A Coruña*, 26 December, 2015, <http://www.laopinioncoruna.es/galicia/2015/03/26/santuario-muxia-estrena-nueva-imagen/940636.html> (Date accessed: 15 March, 2017). LADO, J. V.: «El naufragio de las obras de A Barca», *La Voz de Galicia*, 28 March, 2015, http://www.lavozdegalicia.es/noticia/carballo/muxia/2015/03/28/naufragio-obras-barca/0003_201503G28P16991.htm (Date accessed: 15 March, 2017).

11 FERNANDEZ-GALIANO, Luis. «Urbicidio balcánico», *El País*, 23 July, 1993, http://elpais.com/diario/1993/07/23/cultura/743378408_850215.html (Date accessed: 15 March, 2017).

12 MAZZUCHELLI, Francesco. «Cuando la guerra mata a la ciudad», *Esglobal*, 11 April, 2012, <https://www.esglobal.org/cuando-la-guerra-mata-a-la-ciudad> (Date accessed: 15 March, 2017).

13 *Ibid.*

Despite the recent popularisation of the concept of *urbicide*, the truth is that such destructive attacks on cities are not new. Mazzucchelli¹⁴ enumerates a series of examples of cities plundered and destroyed throughout ancient history (Carthage in the first century BC, Jerusalem in the first century AD and *Milan* in the twelfth century AD) and our more recent past (Guernica, Dresden, London, Warsaw and Hiroshima in the twentieth century).

The warlike conflicts of recent years in *Iraq* (2003-2011) and *Syria* (2011-the present day) have shown this same *urbicide* logic. In fact, attacks against cities and densely populated areas have become more commonplace since World War II due to the deployment of new military strategies based on the progressive upgrading of air strike technology and the use of increasingly destructive weapons. All this has placed cities in the firing line of attacks, despite theoretical attempts such as the *Geneva Convention* (1977), to stem the massive destruction of urban heritage and the death of civilians.

In addition to armed conflicts, most of the recent acts of terrorism in the Western world show similar patterns of behaviour, although within a context of asymmetric confrontation in which a *lone wolf* or minority group tries to spread terror on a large scale and make a strong media impact. Examples of this are the jihadist attacks in New York (2001), Madrid (2004), London (2005) and Brussels (2016), which all took place in different urban scenarios.

Attacks against the identity values embodied in the city acquire their maximum expression when the objective of the attacks is the *obliteration* of the urban landscape and the annihilation of its past (memoricide). Álvarez¹⁵, advised by a group of experts, analysed the strategies and military objectives of destruction of the five worst-hit cities since the end of the twentieth century. The city of *Sarajevo* (*Bosnia-Herzegovina*), considered the most paradigmatic example of *urbicide* and *memoricide* experienced during the *Balkan War* (1991-2001), was one of them. Among the many symbolic buildings destroyed were the *National Museum*, the *City Hall*, the mosques of *Ferhadija* and *Ali Pasha*, the *Clock Tower* and the *Brusa Market*. However, the Serbian attack on the *National Library* (1992), in which more than 1.5 million volumes were lost, was the most important attack on the collective memory in Europe since the end of World War II. On the other hand, the continuous siege of the city of *Homs* (*Syria*) in recent years has led to the enclosure, isolation and programmed destruction of a large part of its districts by the Army of *Bashar al-Assad*. The strategy in *Grozny* (*Chechnya*) followed by *Russia* (1994-1996 and 1999-2009) was the devastation of the city¹⁶ in order to diminish the enemy and discourage resistance. The Palestinian territories, mainly those located in the *Gaza Strip*, were destroyed and rapidly replaced with

14 *Ibid.*

15 ALVAREZ, Cristina. «Las 5 ciudades con más urbicidio», *Esglobal*, 09 April, 2012, <https://www.esglobal.org/las-5-ciudades-con-mas-urbicidio> (Date accessed: 15 March, 2017).

16 COWARD, Martin. «Urbicide. The Politics of Urban Destruction». Routledge: London (United Kingdom) and New York (USA), 2009, pp. 176.

Israeli housing developments in a bid to destabilise *Hamas*. Finally, several areas along the N-S line crossing *Beirut (Lebanon)* were completely destroyed during the *Civil War* (1975-1991), taking advantage of a political-military strategy in which foreign, cosmopolitan values that characterised certain parts of the city were demonised.

The constant threat to urban environments and, in particular, to their most representative historic buildings justifies the need to develop strategies designed to further our knowledge of them from a civil and military perspective. The high building density, the superposition of elements, the arrangement of houses at different levels and/or heights, the presence of abrupt changes, etc. are some of the factors that underscore the complexity of cities¹⁷.

In addition, in the case of historic city centres, other factors must be considered, such as the irregularity of the urban fabric, the presence of numerous narrow streets and areas of restricted access, etc., all of which make these environments into very complex scenarios for the development of military strategies such as the establishment of sight lines, the design of evacuation routes, the positioning of strategic enclaves, the evaluation of possible threat points, the location of transmissions and communication systems, etc.

Military operations in urban terrain (UO¹⁸ or MOUT¹⁹) are very complex from a tactical and operational point of view due to the concentration of civilians and the presence of buildings. The battlefield becomes a very complicated three-dimensional scenario for all types of military makeovers, where freedom of movement is reduced and risks are exponentially increased. From a tactical point of view, urban environments facilitate defence and hinder attack, limiting the effectiveness of heavy weapons and favouring *close quarters combat* (CQC).

Some studies consider the importance of developing 3D models in urban areas as a basis for strategic defence actions, which go beyond strictly military activities, such as the evacuation of people in the case of disasters or the provision of humanitarian aid²⁰. However, none of these previous studies focus especially on historic city centres and/or old cities despite their very particular inherent characteristics and constraints. Moreover, most former studies focus on applications based only on airborne LiDAR systems, which allow the precise geometry of the entire urban fabric to be accurately

17 LIVINGSTON, Mark A; ROSENBLUM, Lawrence J.; JULIER, Simon J.; BROWN, Dennis; BAILLOT, Yohan; SWAN II, J. Edward; GABBARD, Joseph L., and HIX, Deborah. «An Augmented Reality System for Military Operations in Urban Terrain». In: *National Training and Simulation Association*, 2002, Arlington, USA, pp. 868-875.

18 *Urban Operations*.

19 *Military Operations in Urban Terrain*.

20 LETORNEAU, François. «Different Approaches for the Creation and Exploitation of 3D Urban Models», En: *7th International Command and Control Research Technology Symposium*, 2002, Quebec City, Canada. NATO: «3D Modelling of Urban Terrain». RTO Technical Report (RTO-TR-SET-118). North Atlantic Treaty Organisation: Neuilly sur Seine (France), 2011, pp. 118.

defined²¹. However, these systems do not permit to collect clear information on the facades of buildings, which from a military point of view rules out significant and pertinent information such as the position of exit doors and windows and the materials used in them.

GENERATION OF 3D DIGITAL MODELS. STUDY OF A SPECIFIC CASE

In the following points, we present our study which focused on the generation of three-dimensional digital models in historic urban areas, in which we will include the most noteworthy aspects of the study area (3.1), the European project within the framework of which our study belongs (3.2), as well as the methodology and complete work flow that was followed (3.3) in generating these models.

Area of study

The city of *Calw* is located on the northern edge of the *Black Forest* and relatively close (approximately 50 km) to the city of *Stuttgart*, the present-day capital of the federal state of *Baden-Württemberg* (Figure 1). At the present time the city has about 23,000 inhabitants and is the most representative nucleus of its district or *Landkreis* (797.5 km²), which includes fifteen municipalities and a total of around 155,000 inhabitants²².

At present, *Calw* has a large collection of traces of its past. Among these are the ruins of the monastery of *Hirsau* or the historic city centre itself. The *old Calw* today features a very considerable number of traditional houses (typical of the architecture of its region) in a good state of conservation. In addition, contributing to the historic and symbolic value of this city is the fact that it is the birthplace of the writer *Herman Hesse* (1877-1962), *Nobel Prize for Literature* in 1946 and one of the great exponents of modern-day German literature.

The historic city occupies an approximate area of about 100,000 m² and is located on the right bank of the *Nagold River*. It serves as a commercial and service center for the surrounding municipalities and to a certain extent survives thanks to the influx of tourists attracted by landmarks such as the church of *St. Peter and Paul*, the house

21 PFEIFLE, Sam. «Using lidar in Afghanistan», *Spar3d*, 28 July, 2011, <http://www.spar3d.com/blogs/head-in-the-point-clouds/using-lidar-in-afghanistan> (Date accessed: 15 March, 2017).
WALSH, David. «Warfighters reap benefits of LIDAR mapping technology», *Defence Systems*, 26 July, 2011, <https://defencesystems.com/ARTICLES/2011/07/18/TECH-WATCH-GEOINT-LIDAR.ASPX?PAGE=1> (Date accessed: 15 March, 2017).

22 The city of *Stuttgart* is the present-day capital of the region of *Baden-Württemberg*. This region is the third most populated city in Germany with a population of some 10.8 million inhabitants.

in which *Herman Hesse* was born and the museum dedicated to him, as well as by the historic-architectural ensemble of its old town center (Figures 1 and 2).

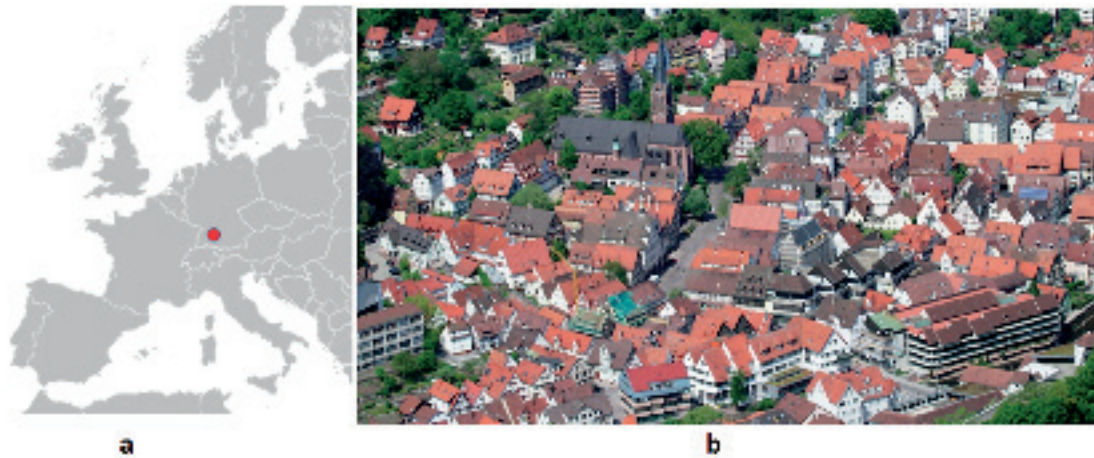


Image 1: (a) geographic localisation of the area studied. (b) Aerial image of the historic city of Calw²³



Image 2: (a) general perspective of the Marktplatz area and (b-e) of some historic buildings of the old city of Calw

The four dimensional cultural heritage world (4D-ch world)

The *4D-CH World project*²⁴ aims to analyse, research, develop and validate an innovative system integrating the latest advances in *computer vision* for the generation of 3D modelling and virtual reality aimed at generating 3D and 4D

23 Stadt Calw, 2017. Official website of the City Council of Calw (*city portrait* section): <http://www.calw.de/city-portrait> (Date accessed: 15 March, 2017).

24 4D-CH World, 2017. Website of the European project *Four Dimensional Cultural Heritage World*: <http://www.4d-ch-world.eu> (Date accessed: 15 March, 2017).

models²⁵ from personal images in a fast and effective way. This project supports the aims of the *European Commons* and the *EUROPEANA*²⁶ digital bookstores and *UNESCO Memory of the World* (MoW)²⁷ to build a sense of a shared European cultural history and identity.

The main goal of this project is to allow historians, architects, archaeologists, urban planners, and any other scientists to reconstruct, study, understand, preserve and document urban environments from data stored on repositories. For this, the project must carry out a complete organisation of extensive collections of historical images, spatially and temporally, which serve as the basis for the generation of *digital 4D models*, which allow the user to clearly visualise the influence of the passage of time on the cultural heritage. In addition to understanding the past, the system deployed in this project allows the analysis of certain factors and the simulation of scenarios adapted to future demands. Other specific applications can be considered on the basis of a different and integral view of history, leading to more harmonious and sustainable policies of renewal and preservation.

In recent years, the *Institut für Photogrammetrie*²⁸ (hereafter IFP) has focused part of its scientific interest on the development of work methodologies for the digital preservation of historic buildings. As a partner in the *4D-CH World* project, the IFP has carried out a pilot study in the old town centre of *Calw* centred on the research and development of this project.²⁹ The research projects of several students on the international *Master of Science Program GeoEngine*³⁰ involved certain areas of the old quarters of the city including the *Marktplatz*, the *Alburgerstrasse*, *Lederstrasse* and *Im-Zwinger*³¹. To date the surface area studied comprises approximately 50.000 m², which includes a nucleus of numerous historic buildings-over a hundred (Figure 3). Among the most representative buildings and landmarks, digital models of which have already been generated, are the evangelical church of *St. Peter and Paul*, the

25 4D modelling is similar to 3D, but also taking into account the time variable.

26 EUROPEANA, 2017. Website of *EUROPEANA Collections*: <http://www.europeana.eu> (Date accessed: 15 March, 2017).

27 UNESCO MoW, 2017. *UNESCO Memory of the World* website: <http://www.unesco.org/new/en/communication-and-information/memory-of-the-world> (Date accessed: 15 March, 2017).

28 IFP, 2017. Website of the *Institut für Photogrammetrie* of the *University of Stuttgart* (Germany): <http://www.ifp.uni-stuttgart.de> (Date of access: 15 March, 2017).

29 Balsa-Barreiro, José, and Fritsch, Dieter: «Generation of 3D/4D photorealistic building models. The testbed area for the 4D Cultural Heritage World Project: The historical centre of Calw (Germany)», *Lecture Notes in Computer Science*, n.º 9474, 2015, pp. 361-372.

30 Master of Science Program GeoEngine, 2017. Website of the *Master of Science Programme GeoEngine* of the *University of Stuttgart*: <http://www.geoengine.uni-stuttgart.de> (Date of access: 15 March, 2017).

31 References to all the *Master Theses (Master of Science Program GeoEngine)* presented within the project are included in the bibliography.

City Hall and the house where *Herman Hesse* was born, as well as the bridge of *Sankt Nikolaus*.



Image 3: delimitation of the area currently studied within this project

Methodology

The main aspects of the methodology employed in this pilot study can be explained and encompassed within two main work phases, relating to the acquisition and processing of the data.

Data acquisition phase

For the data collection, two independent systems were used. On the one hand, a *Leica* ground scanner laser, as well as a semi-professional camera, the *Ricoh GXR* model.

The IFP's *Leica Scan-Station P20* system was used for the laser scanning of the study area. This system permits a 360-degree horizontal scan and a 270-degree vertical scan as a fixed point as reference. The maximum range for measuring distances with this system is about 120 metres, emitting frequencies of up to one million points per second³². One of the various criteria considered during the selection phase prior to choosing this system was that the beam of light emitted was safe for the human eye, which was rather important considering that the area studied is quite crowded.

32 Leica Geosystems AG, 2014. *Leica ScanStation P20 Product Specifications*: http://www.leica-geosystems.com/downloads123/hds/hds/ScanStation_P20/brochures-datasheet/Leica_ScanStation_P20_DAT_en.pdf (Date accessed: 15 March, 2017).

Medium-high resolution and precision levels were chosen for the system's data entry process, which permitted us to achieve an efficient ratio between the time required for scanning and the density of points obtained.

A *Ricoh GXR* digital camera, also owned by the IFP, was used to capture the images. This model of camera is a compact system that allows for different units to be interchanged. The lens used was a *Carl Zeiss Lens Biogon 2.8/21 ZM*. In terms of imaging, *aperture priority* and *infinite focal distance* were the chosen options. In addition, a tripod and a monopod were used to stabilise the camera during imaging.

Apart from the images taken on the ground, several aerial images of the whole of the historic city of *Calw* were used. These images were used to reconstruct the roofs and upper parts of the buildings, from which it was not possible to extract information from the ground.

During the data collection phase, two information acquisition systems were used, based on the principles of (a) laser telemetry and (b) photogrammetry. The measurement or laser telemetry systems currently employed comprise a wide range of equipment that can be classified according to multiple criteria³³, one of the most common is the platform on which the measurement equipment is mounted, thus permitting the differentiation between airborne (a) and (b) terrestrial systems.

The technical specifications of these systems vary according to the main purpose for which they are designed. However, although much of the equipment used may appear somewhat complex and unwieldy, the operating principle is quite straightforward³⁴. These systems emit a beam of continuous laser light, usually in the form of pulses, which are reflected by a system of mirrors inside the device. These mirrors can be arranged in different shapes and positions, thus determining different *scan patterns*³⁵. Finally, these systems enable us to obtain three-dimensional information on the surface of an object in the form of point clouds, which offer both geometric and radiometric information (Figure 4). The estimated distance values for each point allow us to determine their three-dimensional coordinates (XYZ) with respect to a local coordinate system, whose origin is located at the parking point of the equipment itself.

Scanner laser equipment permits the sweeping of very large areas for short periods of time. In this way, the position and concrete geometry of any element within the three-dimensional space can be determined. If we refer in particular to the *terrestrial laser scanner systems* (TLS), these are used mainly in sweeps from different static positions at ground level. Equipment of this type is typically used in archaeology, architecture

33 BALSABARREIRO, José and LERMA, José L. «La tecnología LiDAR: una visión general», *Topografía y cartografía*, n.º 23(135), 2006, pp. 28-32.

34 BALTSAVIAS, Emmanuel P. «Airborne laser scanning: basic relations and formulas», *ISPRS Journal of Photogrammetry & Remote Sensing*, n.º 54, 1999, pp. 199-214.

35 BALSABARREIRO, José, and LERMA, José L. «La tecnología LiDAR: una visión general», *Topografía y cartografía*, n.º 23(135), 2006, pp. 28-32.

and civil engineering, as well as in certain industrial applications such as equipment maintenance, as well as for the analysis of pipelines and similar uses³⁶.

In the project carried out in *Calw*, the goal of this first phase was the complete acquisition of data relating to the facade of all the historic buildings of the city. For this reason, a complete sweep (360 °) was envisaged from different static positions, whose locations were previously analysed in a desk-based study. However, certain characteristics of the area studied and the eventual environment around the station at the time of scanning could influence and/or partially limit the data collection process. In fact, the appearance of noise derived from the continuous passage of people or vehicles, together with the presence of certain habitual elements in urban areas (trees, signs, etc.), hampered the equipment's field of vision and/or degraded the quality of the scanned data. For this reason, depending on the area and the moment at which the sweep took place, the number of stations and their specific location may have turned out to be different from what had been originally planned.

Good planning prior to data capture allows one to optimise resources, reduce capture times, increase volume and improve the quality of the data obtained. During this same phase, those involved must also evaluate the use and location of target boards used for the assembly of point clouds obtained from the different stations. An optimal use of available resources depends to a greater or lesser extent on the technician's skill and familiarity with the area under study. In any case, good pre-planning of the laser scanning phase allows one to minimise and reduce the frequency of the appearance of gaps in the point clouds (figure 4).

The data collected from each station was recorded in a local coordinate system, whose origin corresponds to the point where the equipment is located. For the sweeping of large areas, it is necessary to take data from several locations, which allow one to obtain different geo-referenced point clouds in local coordinate systems. Subsequently, the different point clouds must be assembled to obtain a single and complete laser point cloud of the entire studied area. With this in mind, a minimum of three target boards visible from successive stations were placed in situ, which were later used as reference points for the assembly of the different point clouds.

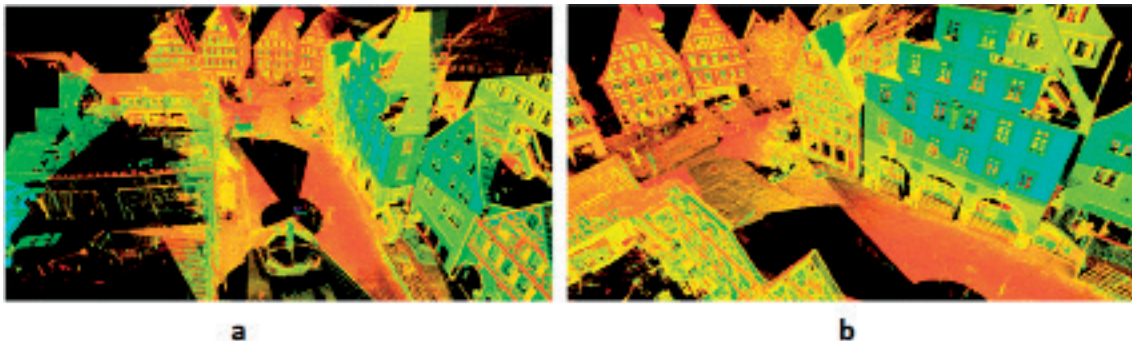


Image 4: (a-b) point clouds obtained from scanning from a specific stationary point. Note also the presence of shaded areas due to the limitations to the laser equipment's field of vision

36 GrindGIS, 2015. «LIDAR Data 50 Applications and Uses- It is important», GrindGIS, 18 August, 2015, <http://grindgis.com/data/lidar-data-50-applications> (Date accessed: 15 March, 2017).

Photogrammetric techniques

Photogrammetry allows us to determine the geometric properties of different objects from photographic images. Using photogrammetric techniques it is possible to obtain 3D information for the *object space* based on 2D information from the *image space*. For this purpose, the images must have been previously positioned, focused and rectified. Depending on the distance covered, photogrammetry can be either (a) close-up or (b) distant, the latter referring mainly to aerial photography.

The process of reconstructing 3D objects through photogrammetry is based on the generation of three-dimensional clouds of points from pairs of stereo images (*multi-view stereo*). To determine the three-dimensional coordinates of any point in space it is necessary to have a set of images for the same point captured from different positions. On a larger scale, *image-matching techniques* are applied in order to locate common points in different images.

The set-up of the images is crucial in terms of obtaining quality results. For this reason, the places from which the images are taken must be previously evaluated and analysed. A *SIFT operator* is generally used for finding homologous characteristics in the successive images³⁷, thus facilitating the identification of the orientation and specific positions from which the successive images were taken. Subsequently, block adjustment of all the images is performed, a process whereby it is possible to determine a low-density cloud of 3D points. Within this process, a *RANSAC robustness estimator* is usually used to filter errors³⁸.

Although this point cloud gives us a fair idea of the shape of the scanned object, its density is too low for a precise reconstruction. For this reason, and in a second step, *image-matching techniques* are again applied to obtain a much denser point cloud, in which the main details of the scanned object can be more clearly distinguished. The *SURE software*, developed by the IFP, is used to densify point clouds from photogrammetric pairs³⁹. The input required by the software is a set of oriented images, which are rectified as a first step. Then as a second step, SURE selects the most appropriate pairs of images to establish a matching process in a similar way as the *Semi-Global Matching* (SGM) algorithm does. Finally, the result obtained is a dense point cloud (in LAS format or similar), with resolution levels of one 3D point

37 LINGUA, Andrea; MARENCHINO, Davide and NEX, Francesco. «Performance analysis of the SIFT operator for automatic feature extraction and matching in photogrammetric applications», *Sensors*, 2009, n.º 9(5), pp. 3745-3766.

38 HAN, Lina; CHONG, Yanwen; LI, Yuanting and FRITSCH, Dieter. «3D Reconstruction by combining terrestrial laser scanner data and photogrammetric images». In: *Proceedings of the Asia Assoc. of Remote Sensing*, 2014, Nay Pyi Taw, Myanmar.

39 WENZEL, Konrad; ROTHERMEL, Mathias; HAALA, Norbert and FRITSCH, Dieter. «SURE – The IFP software for dense image matching». *Photogrammetric Week '13*, Ed. D. Fritsch, Wichmann: Berlin/Offenbach (Germany), pp. 59-70.

per pixel. This point cloud allows us to obtain a very accurate representation of the scanned object, which is perfectly valid for 3D modelling tasks.

Close-up photogrammetry

Photographs that are taken from a distance of less than 300 metres are generally considered under this technique. This photogrammetric technique is mainly used to obtain 3D renderings of small objects. Close-up photogrammetry allows for the reconstruction of small pieces in archaeology and architecture, the modelling and manufacture of industrial parts, and can even be used for the evaluation and quantification of material damages in vehicles that have been involved in accidents⁴⁰.

Close-up photogrammetry can be employed to complement the data collection process of laser systems. Thus, within the framework of this same project, Li⁴¹ used close-up photogrammetry techniques to obtain information on certain facades or specific areas, given the physical limitations encountered when parking the scanner laser equipment in certain parts of the *Nagold* riverbed in *Calw*.

Drawing from this particular experience and others of a similar nature, it was decided to take a complete picture of most of the historic buildings of the city. This imaging covers the complete extension of the facades of the buildings concerned from a large number of positions and covering a wide range of perspectives. Between the successive images there must be high levels of overlap that allow them to be linked up through a series of points, thus ensuring a three-dimensional reconstruction of the objects with photogrammetric techniques.

Distance or aerial photogrammetry

The use of terrestrial laser scanner equipment from ground points permits the acquisition of data from the facades of the buildings, although these systems have certain limitations in terms of acquiring information from the upper parts and/or roofs of these buildings (Figure 4). Aerial photogrammetry complements the terrestrial laser scanner, allowing for the collection of three-dimensional information in areas where it could not be initially obtained. The point clouds obtained by aerial photogrammetry enable a full reconstruction of the urban landscape including, in addition to the roofs, the interior areas of the urban fabric where terrestrial access is usually restricted.

40 LUHMANN, Thomas; ROBSON, Stuart and KYLE, Stephen. «Close range photogrammetry: principles, techniques and applications». Whittles: Dunbeath (United Kingdom), 2007, pp. 528

41 LI, Jing (supervised by, Dieter and KHOSVARANI, Ali M. «High definition modeling of Calw, Badstrasse and its Google Earth' integration», Master Thesis, Germany, Universidad de Stuttgart, 2014.

For the application of these techniques several aerial images of the *Calw* city centre are used, which were supplied by the *Landesamt für Geoinformation und Landentwicklung*⁴². These images have geo-referenced coordinates of the projection centres and orientation angles, and have a *Ground Sampling Distance* (GSD) of 10 cm.

The processing of these images in *SURE* comprises two steps. In the first, aerial images are corrected for distortion and rectified in pairs. In the second, suitable pairs of images are selected to which an algorithm similar to *Semi-Global Matching* (SGM) is applied. Finally, dense point clouds are generated with 10 cm spacing, which corresponds to a 3D point per pixel. The point cloud generated by aerial photogrammetry also serves as a reference for point clouds obtained with laser scanners.

Data processing phase

Once the information has been acquired with the different methods, a large volume of data represented in the form of *point clouds* is obtained spatially. This information is processed in two successive work steps: (a) the *registration* and (b) the *3D modelling/texturing* of the point clouds.

*Cyclone*⁴³ software was used for the process of registering the laser point clouds, as well as for CAD modelling in conjunction with *Autodesk 3ds Max*⁴⁴. *PhotoScan*⁴⁵ and *SURE*⁴⁶ programmes were used to generate point clouds from images. Once the models had been obtained, *Photoshop*⁴⁷ was used in the editing phase and the preparation of textures, which were then inserted into the CAD model using *Sketchup*⁴⁸. Finally, the integration of the 3D models of buildings in a virtual environment was accomplished in *Unity*⁴⁹.

42 LGL-BW, 2017. Website of *Landesamt für Geoinformation und Landentwicklung de Baden-Württemberg*: <https://www.lgl-bw.de> (Date accessed: 15 March, 2017).

43 Leica Geosystems AG, 2017. *Leica Geosystems AG* company website: <http://leicageosystems.com> (Date accessed: 15 March, 2017).

44 Autodesk Inc., 2017. *Autodesk Inc* company website: <http://www.autodesk.com> (Date accessed: 15 March, 2017).

45 Agisoft LLC, 2017. *Agisoft LLC* company website: <http://www.agisoft.com> (Date accessed: 15 March, 2017).

46 nFrames GmbH, 2017. *nFrames GmbH* company website: <http://www.nframes.com> (Date accessed: 15 March, 2017).

47 Adobe Systems Inc., 2017. *Adobe Systems Incorporated* company website: <http://www.adobe.com> (Date accessed: 15 March, 2017).

48 Trimble Inc., 2017. *Trimble Inc.* company website: <http://www.trimble.com> (Date accessed: 15 March, 2017).

49 Unity Techn., 2017. *Unity Technologie* company website: <https://unity3d.com> (Date accessed: 15 March, 2017).

Point cloud registration

The registration of point clouds is a process whereby the successive point clouds are assembled. In the case of this particular project, there are two successive stages to the assembly process: (a) merging the point clouds obtained by laser scanner to obtain a single point cloud, and (b) merging the latter with the point cloud obtained by aerial photogrammetry techniques. *Cyclone* software can perform the registration of the point clouds obtained with laser scanner.

By applying this procedure to the laser scanner information, a complete point cloud of the entire external block of buildings is obtained, which also includes the surrounding area. However, the information relating to the inner and/or top part of this entire block of buildings could not be obtained due to physical access restrictions. These data gaps are not limited exclusively to these areas, but may also appear in part of the buildings facades due to the presence of trees or other elements that could hinder the laser beam at the time of scanning. For this reason, the previous point cloud must be linked to that obtained by photogrammetry, which contains information on the upper part of the buildings (Figure 5.a).

The point cloud generated by aerial photogrammetry is geo-referenced in the *Gauss-Krueger* coordinate system, which is used as a reference system common to all point clouds by a process called *transformation*. For that purpose, the different generated clouds must be combined and fitted in position, orientation and scale, by applying a *seven-parameter 3D Helmert transformation*, comprising three translations (T), three rotations (R) and a scale factor (λ). For the calculation of these parameters, there is a requirement for more than seven equations to be presented, while in practice at least three common points are required between the different point clouds.

Generally, the location of these common points in the respective point clouds must be achieved manually, which can lead to less than ideal results. For this reason an alternative is usually chosen involving the application of the *Iterative Closest Point* (ICP) algorithm to obtain a better result⁵⁰. It is important to note that this

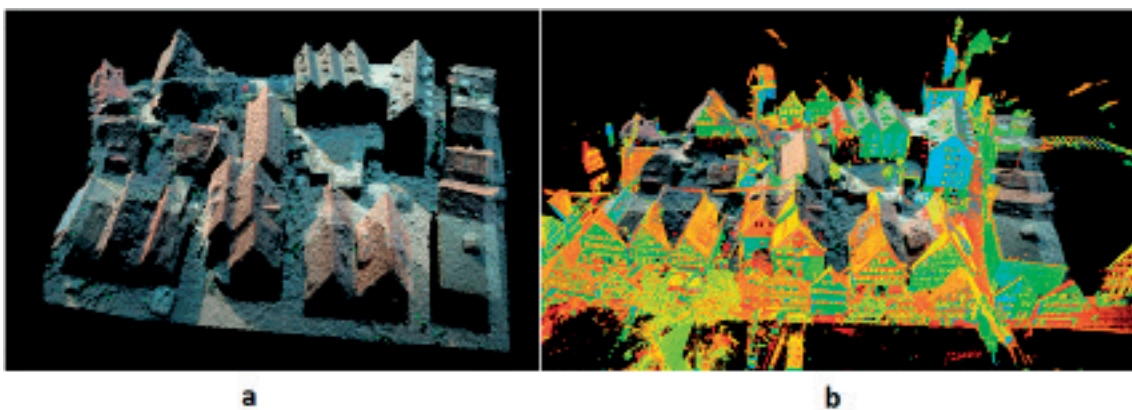


Image 5: (a) point cloud obtained from aerial photogrammetry. (b) Point cloud finally obtained after registration and transformation procedures are carried out

50 BESL, Paul J. and McKAY, Nail D.: «A method for registration of 3-D shapes», *IEEE Transactions on Pattern Analysis and Machine Intelligence*, n.º 14(2), 1992, pp. 239-256.

procedure is only valid if the point clouds have similar geometries and they are partially aligned⁵¹.

Finally, and as a result of the combination of the different point clouds, a single (and complete) point cloud of the whole area is obtained, which will be used in later steps for 3D modelling (Figure 5.b).

3D Modelling and texturisation

3D modelling procedures in *Cyclone* provides a simplified reconstruction of each of the buildings. In order to homogenise criteria and requirements, the *Open Geospatial Consortium* (OGC) has defined its own data model called *CityGML* that defines five increasing levels of representation of 3D models ranging from *LoD-0* to *LoD-4* (both included) depending on the level of detail represented⁵². The software programmes *SketchUp* and *Autodesk 3ds Max*, which features modelling tools for redefining and incorporating details, are used in the reconstruction and enhancement of the models obtained with *Cyclone*.

Once the geometry of the models is defined, the next step is the incorporation of textures, for which both geometrically and radiometrically rectified images are used. Any image editing software, such as *Photoshop*, allows one to select the area of interest of the photographs with respect to each of the defined geometric principles, in addition to rectifying the geometry and adjusting the radiometry of the parameters and/or elements of interest. Once the textures are prepared, they are carefully pasted and adjusted on each of the faces of the CAD model, and finally a photorealistic 3D model of each of the buildings is obtained.

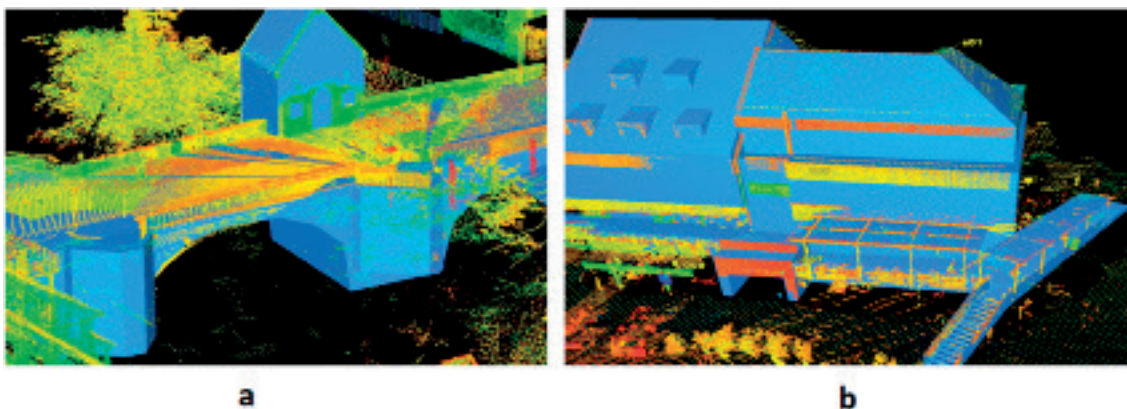


Image 6: (a-b) process of CAD modelling from point clouds

51 HAN, Lina; CHONG, Yanwen; LI, Yuanting and FRITSCH, Dieter: «3D Reconstruction by combining terrestrial laser scanner data and photogrammetric images». In: *Proceedings of the Asia Assoc. of Remote Sensing*, 2014, Nay Pyi Taw, Myanmar.

52 KOLBE, Thomas H.; GRÖGER, Gerhard and PLÜMER, Lutz: «CityGML - Interoperable access to 3D city models», in: *International Symposium on Geo-Information for Disaster Management GI4DM*, 2005, Delft, Netherlands, pp. 21-23.

RESULTS

As a result of the previous step, a textured 3D model of each of the buildings in the study area is obtained. Specific examples are displayed in Figure 7 a-c. These individual models are grouped together and integrated into a virtual environment that represents the whole of the historic city of *Calw*. This is obtained with *Unity* software, providing a realistic and dynamic visualisation of the whole set (Figure 8). An optimal execution of the virtual model finally obtained requires a good resolution and low levels of computational weight. Evidence of this is that the weight of the file obtained for the whole area studied so far is below 25 MB.

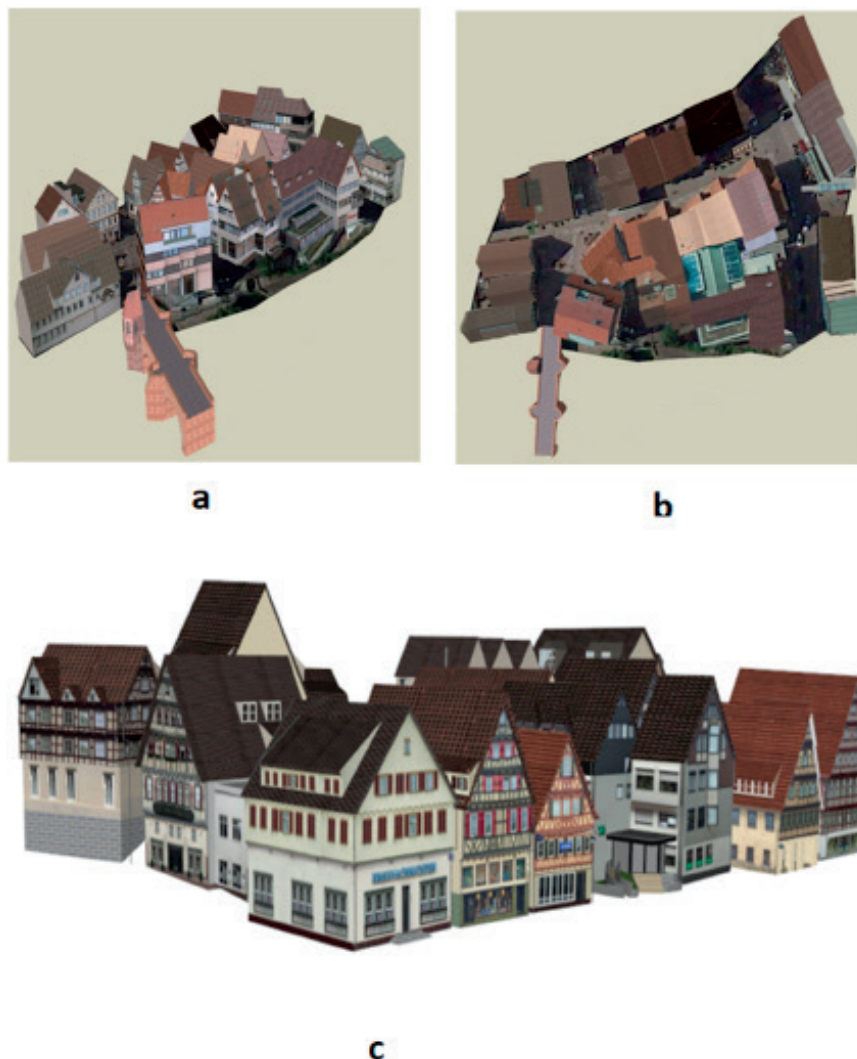


Image 7: (a-b) models obtained in certain areas of the historic city of Calw, such as (a-b) the Badstrasse sector and (c) the sector defined by Calw Market Square and Lederstrasse. Source: a-b⁵³, c⁵⁴

53 LI, Jing (supervised by FRITSCH, Dieter and KHOSVARANI, Ali M. «High definition modeling of Calw, Badstrasse and its Google Earth' integration», Master Thesis, Germany, Stuttgart University, 2014.

54 WANG, Yiwen (supervised by FRITSCH, Dieter and BALSA-BARREIRO, José). «Digital preservation of Calw Market Square-Lederstrasse (I) by means of automated HDS and photogrammetric texture mapping», Master Thesis, Germany, Stuttgart University, 2015.



Image 8: (a-b) integration of the 3D building models obtained in a virtual environment

APPLICABILITY OF 3D DIGITAL MODELS IN SECURITY AND DEFENCE

3D modelling can be applied in security and defence policies at different scales. When these models are integrated in virtual environments, these provide a more dynamic and realistic level of visualisation in areas of great heritage and cultural value, such as the historic centres of cities or in their most representative buildings.

With these models it is possible to provide to plan *a priori* military strategies and techniques that can be put into practice not only where manpower is required, but also in the case of robotic or autonomous teams⁵⁵, whose set-up and mission in the field demands certain route planning. In addition, the generation of high-definition photorealistic 3D models permits the evaluation of the structures and materials used in the different buildings, which is of prime importance in the implementation of military tactics such as *mouse-holing*, which consists in the creation of tunnels and spaces to further military progress. Therefore, it is possible to reduce the risk levels in the battlefield with 3D models obtained through the use of new technologies, as explicitly recommended by some of the specialised units of the *US Marine Corps* and the MCCDC⁵⁶.

In the same way, resulting 3D models are potentially useful for training of troops in order to improve their military effectiveness in this type of environments. In fact, the armies and military units of several countries have developed training zones that simulate urban areas, such as the British *Stanford Training Area* or the French *CENZUB* facilities. The US company *Archetype 3D*⁵⁷ develops real-scale models of urban areas

55 BANKS, Grant. «Squad Mission Support System set for Afghanistan», *New Atlas*, 14 December, 2010, <http://newatlas.com/squad-mission-support-system-set-for-afghanistan/17246> (Date accessed: 15 March, 2017).

56 Concepts Division, MCCDC. «A Concept for Future Military Operations on Urbanized Terrain». Department of the Navy Marine Corps Combat Development Command: Quantico, Virginia (USA), 1997. 19 pp.

57 ARCHETYPE3D, 2017. *Archetype 3D* company website (section on military models for urban assault training): <http://engineering-scale-models.com/military-model-for-urban-assault-training> (Date accessed: 15 March, 2017).

for military training. However, the generation of virtual reality scenarios and/or augmented battlefields would undoubtedly be a much cheaper and more accessible solution than those mentioned above.

3D urban models permit the evaluation of the real incidence of a hypothetical threat (pre-phase) and the possible strategies in the case of catastrophes that have already occurred (post-phase). Thus, it is possible to simulate the different levels of potential damages from a given threat by considering different scenarios. Generation of virtual scenarios in catastrophe situations presents a clear and direct application in two different stages: (a) prior to the catastrophe, during which prediction and prevention strategies are defined, and (b) immediately following the incident, when possible evacuation and action strategies must be evaluated.

These virtual scenarios also allow for setting up work teams, acquiring the necessary tools and designing potential strategies for evacuation and/or rescue depending on the different levels of risk. During the post-catastrophe (or emergency) phase, the existence of a virtual scenario also enables a more accurate quantification of the damages and the required requirements. To this effect, 3D models must be integrated into *3D-SIG environments*⁵⁸, in which the alphanumeric data must be associated to the models. *GIS-3D systems* enable geo-processing operations in three-dimensional environments that produce high levels of realism. Simulation of phenomena in these environments permits a real, reliable and easily interpretable visualisation of the different scenarios by any operator, whether or not they are experts in the use of these systems and their interaction within virtual scenarios. This favours the integration of multidisciplinary work teams, in which more factors and/or work practices can be considered.

DISCUSSION AND CONCLUSIONS

Generation of 3D digital models poses a series of future challenges such as the enhanced geometric and visual quality of 3D models in order to increase the levels of realism obtained. Another of these challenges is the improvement of the *geometry-rendering* relationship of 3D models in accordance with the possible applications for which they are designed. Thus, an inadequate strategy can generate low resolution models with a low level of detail or, at the other extreme, a very limited level of

58 DORE, Conor, and MURPHY, Maurice. «Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites», in: *Proc. 18th International Conference on Virtual Systems and Multimedia: Virtual Systems in the Information Society*, 2012, Milan, Italy, pp. 369-376. KWAN, Mei-Po, and LEE, Jiyeong. «Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments», *Computers, Environment and Urban Systems*, n.º 29(2), 2005, pp. 93-113. ZLATANOVA, Siyka; RAHMAN, Alias A., and PILOUK, M.: «3D GIS: current status and perspectives», in: *Proc. Of the Joint Conference on Geo-Spatial Theory, Processing and Applications*, 2002, Ottawa, Canada, p. 6.

interaction caused by the high computational weight of the models. Currently this type of problem can be solved in two ways: (a) by improving the methodology and achieving optimised models (accurate and light), and (b) with improvements in computer equipment and software. From a technical point of view, the main challenges consist in the reduction of modelling/texturing times and the implementation of more automated procedures.

Photorealistic 3D models with a high level of detail (*LoD-3* and *LoD-4*) and high visual quality can be used in different applications such as, for example, the preservation and maintenance of buildings of great historic value. These models also are of great interest in projects that requires *exploded views* of certain historic buildings located in protected environments where regulations prevent certain actions and restrict the use of certain materials. In these cases, high levels of accuracy in the cataloguing of the building materials and in the sizing of the different elements are required.

Optimising resources is another key point in the different phases of this project. During the data acquisition phase, the methodology shown allows for large volumes of information (and of great quality) to be captured in very short times. Thus, the data processing phase is currently more challenging on account of the difficulties of managing, analysing and interpreting the large volumes of information obtained. Optimised pre-planning means reducing the time involved in image capture and obtaining a more complete coverage of the studied area. In addition, it is possible to reduce data volumes by eliminating redundant information and therefore achieving a more efficient management of information.

Laser scanner systems are active systems for capturing data *massively* and *unobtrusively*. Thus, these systems can collect large data volumes that frequently exceed the capabilities of the tools used and the requirements of the applications for which they are designed. The development of intelligent systems for the capture of information must be focused on enhancing the procedure of data collection and its adaptation both to the real requirements of the various applications and the complexity of the element studied.

The integration of 3D models in virtual and augmented reality environments favours greater interaction from the user, providing greater knowledge of the represented reality. For its part, the integration of these models in *GIS-3D environments* enables the implementation of data geo-processing tasks leading to optimal decision-making in each possible scenario.

The techniques and methodologies adopted must take into account the particular characteristics of these areas from acquisition of the data until they are processed. The quality of the final models will depend on the application for which they are designed. The proposed work methodology allows us to obtain digital photorealistic 3D models with high definition and optimal visual quality, which are integrated into a completely virtual environment. As we have seen in this article, these 3D models offer a huge potential from a security and defence perspective.

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