New developments in Geographical Information Technology for Urban and Spatial Planning

José António Tenedório[1], Carla Rebelo[1], Rossana Estanqueiro[1], Cristina Delgado Henriques[2], Luís Marques[3], José Alberto Gonçalves[4]

[1] e-GEO, Research Centre for Geography and Regional Planning, Faculdade de Ciências Sociais e Humanas, Universidade NOVA de Lisboa, Portugal

[2] CIAUD, Faculdade de Arquitectura, Universidade de Lisboa, and e-GEO, Research Centre for Geography and Regional Planning, Faculdade de Ciências Sociais e Humanas, Universidade NOVA de Lisboa, Portugal

[3] CPSV, Research Centre of Land Policy and Valuations, Polytechnic University of Catalonia – BarcelonaTech, Spain and e-Geo, Research Centre for Geography and Regional Planning, Faculdade de Ciências Sociais e Humanas, Universidade NOVA de Lisboa, Portugal

[4] CIIMAR, Interdisciplinary Centre for Marine and Environmental Research, and Department of Geosciences, Environment and Land Planning, Science Faculty, Universidade do Porto, Portugal

ABSTRACT

Measuring urban form, modelling 3D point clouds and visualizing data within an (augmented) mixed reality environment through mobile devices are three of the new developments in Geographical Information Technology for urban and spatial planning. New geographical information technology supports data representation for urban and spatial planning. This chapter has two main objectives: (i) to demonstrate that geographical information technology supports every stage of urban and spatial planning, and (ii) to argue that technologies are a means for the external representation of cities and territories. The chapter sections include measuring urban form (quantitative analysis of urban shape), modelling 3D point clouds for the extraction of urban parameters, and the visualization of virtual models through mobile devices.

1. INTRODUCTION

What if John Snow had not analyzed, back in 1854, the spatial relationship between deaths by cholera and the location of water wells in a neighborhood in London? What if the assessment of potential locations for urban expansion was based solely on non-geographical data? What if information on the potential of solar energy was not introduced in urban planning models?

These issues reveal the many applications of Geographic Information Systems (GIS) and particularly three degrees of such systems (in the general sense of the term): spatial analysis, location assessment, and data modelling. Spatial analysis translates the zero degree of GIS work targeted at planning decisions since decision making is “outside data”; location assessment incorporates *a priori* criteria and therefore the spatial intelligence that results from the criteria certified by institutions; data modelling reduces the forecast of determinants for the simulation of future spatial situations.

Studies on planning are believed to need these three GIS degrees. GIS technology has been consolidated and its most recent advances correspond to 3D data modelling and the incorporation of time into modelling processes.

The consolidation of GIS has enabled the dematerialization of processes that imply the virtual organization of geoinformation. Shanon’s information theory has laid the foundations for the virtualization of territories as we know them today. Geoinformation feeds the *external representation* of the territory, namely through computational modelling (2D, 3D, 4D). The full range of GIS consolidation has allowed for: (i) the digital transcription of information that must favor the acceleration of public access; (ii) the digital transcription of information that must favor the transparency of processes (of debate, decision, assessment, etc.); (iii) the digital transcription of information that promotes public participation in the planning process; and (iv) the transcription of digital information that recreates the collaborative construction of knowledge and a culture of permanent assessment. It seems that we can accept that GIS *technology* has contributed to the “dematerialization” and that it allows for the virtual organization of geoinformation over a network.

On the one hand, Remote Sensing has become a public service in the age of the information society, to which States, public and private institutions and companies contribute. This service has reached a high maturity level, directly related to the increase in geometric and spectral sensor resolution, the performance of scientific investigation as regards the construction of new algorithms designed to digitally process images, and the development of applications, the communalization of added-value services, and a, albeit timid, decrease in the rates for orbital data, and fundamentally the already mentioned growing "democratization" of GIS platforms. On the other hand, the operational interest of digital image processing is enabling us to obtain semantically significant classes from the classification of spectral data – i.e., grouping pixels into classes or obtaining image segments based on pixel oriented approaches (in the first case) or object oriented approaches (in the second case) can present, from the geometric point of view, a good definition of border (in agreement with the demands for cartographic quality; positional accuracy) and, from the semantic point of view, an interesting content (with high levels of thematic accuracy). Regarding these subjects, the automatic extraction of vector-based geographic information from digital images has not fully answered either the operational and formal needs (those that stem from the law) or the actual urban and spatial planning needs.

The aforementioned developments place the question: What are the new developments in terms of Geographical Information Technology applied to urban and spatial planning? The general scope of this chapter is precisely to introduce some new developments in Geographical Information Technology for Urban and Spatial Planning.

This chapter was guided, therefore, by the following ideas: (i) measuring urban shape demands algorithms that have not yet been implemented and therefore open source programming is one of the most recent developments as regards geographic information technologies applied to urban and spatial planning; (ii) 3D point cloud modelling from LiDAR data and UAV data enable the extraction of urban parameters and the creation of models for 3D visualization; (iii) UAV technology is emergent; and (iv) visualizing data within an (augmented) mixed reality environment through mobile devices allows for the virtualization of urban form.

2. MEASURING URBAN FORM

Sustainable development and the urban forms that should underlie it occupy a substantial place in current research trends, namely in discourses that foster discussions on the "compact cities" versus "disperse cities" debate. The research gap regarding this subject is conceptual and relates to the operationalization of methods that can help identifying what is determinant in terms of form and urban form content. In view of the literature review carried out, the physical and spatial dimensions of urban form, materialized in what Anglo-Saxon research terms “urban shape”, may translate a primary (and/or primitive) dimension, i.e., one of the dimensions of sustainability discourses. We can state that Kevin Lynch (1999) by pronouncing the “spatial, physical city” was referring to that conceptual order without, however, electing it as determinant in the production of the good urban form of the city. Urban shape and its content emerge in the reference literature, produced by different Schools, as an object of study, i.e., as the object of conceptual research before they are revealed as concepts that embody discourses on sustainable urban form.

Current research, inspired by the work developed by authors affiliated with several Schools and with different academic backgrounds – namely French, Anglo-Saxon, Italian, and Spanish – allows us to argue that the issue of urban form may be analyzed under different perspectives. In this context, we have chosen the idea of the pertinence of spatial metrics of the urban form (quantification and analysis) at the service of intervention mechanisms and tools that support action policies, whose aim is to monitor and intervene regarding changes that occur in the urban space. Therefore, we have focused, on the one hand, (i) on the perspective that we may call “physical and spatial”; a perspective that discusses the pertinence and possibility of measuring forms. This view implies quantification and modelling using methods that we may consider classic (gradient analysis, shape indexes, *inter alia*) based on shape analysis (a set of techniques targeted at the analysis of the geometry of form) and more recent methods, such as the case of factor analysis or cellular automata. A large part of the studies carried out following this perspective uses the urban sprawl phenomenon as an analysis referential. On the other hand, (ii) on the perspective of the importance of form for the future configuration of urban expansion and its control. Presently, the dominant discourse is backed by the concept of sustainable urban development, and much has been said on the discussion of “compact city” models as opposed to “sprawled city” models (considering the intra-urban scale), as well as on the ideas and policies that promote urban polycentrism as opposed to urban monocentrism (considering the inter-urban scale, particularly at the European level), a supposed cause for the dysfunctional character of the metropolis. From this thought emerges the need to analyze, in detail, the notions of urban density and contiguity and the changes that their meaning may introduce in how a city is made.

This approach stems from the conceptual base – without which it is impossible to carry a comprehensible discussion on the pertinence of shape indexes (the tangible dimension of the city) – of the classification and qualification of what is, or should be, a sustainable urban form. The concept of urban shape is considered a structural concept of the spatial expression of cities and it is intrinsically tied to the concept of shape, a basic notion in the framework of the approach oriented towards the operationalization of the concept of urban form, understood according to Boots and Lamoureux (1972) as: "(...) a set of properties possessed by a closed figure of at least two dimensions, which has a planar representation and which possesses precise boundaries: the figure outlined may be geographical, such as the delta of a river or the territory of a town or a country, or represent any object such as an egg, a carrot, etc." (Bachi and Samuel-Cahn, 1976: 206). From the concept of urban shape stems the system of metrics of the form based on shape analysis geared towards a quantitative approach to the fundamental geometric properties of the analysis of urban form. In this case, the analysis of the shape itself is oriented towards the extraction of the geometric properties of spatial form, i.e., the geometric properties that are inherent to the characteristics or descriptive parameters of the "external appearance or outward form" (the macro-urban scale), and does not consider the characteristics of the internal structure of the urban form or the intra-urban form (termed internal form centered on structural form).

The translation of the concept into metrics (what we have termed the operationalization of the concept) integrated two fundamental procedural stages: (i) the approach to the operationalization of the concept of urban form itself, which resorts to the implementation of a methodology used to delimit urban areas adjusted to Continental Portugal, based on the technical procedures of a European methodology for delimiting Urban Morphological Zones (UAB/ETC-TE, 2004) from the reclassification of the Corine Land Cover (CLC1990 and CLC2000) nomenclature; and (ii) the operationalization of the spatial analysis of urban shape in Geographic Informations Systems, by quantitatively exploring the association of urban form and geometric form supported by the calculation of form metrics.

Generation of Urban Form Data: Methodology and Results

Obtaining geographic information for the study of the urban form has resulted from the application of a methodological approach to the delimitation of Urban Morphological Areas

(UMA), based on the extraction procedures of UMZ (UAB/ETC-ET, 2004) adjusted to Continental Portugal, from the reclassification of the CLC nomenclature (1990 and 2000) in Geographic Informations Systems. This operating methodology entailed a series of procedures for data extraction and selection from two final layers (1990 and 2000) in a vector-based format.

The definition of pertinent spatial boundaries taking into consideration the fundamental theoretical scale of analysis – urban macro-form (based on the meaning of Allain, 2004) – and the morphological and statistical criteria adopted in its spatial delimitation have allowed for the definition of the minimum unit of analysis – the Morphological Polygon of the City (MPC). The MPC considers the possibility that a city, defined by the official limits of “statistical city” (INE, 2002), may not be composed of one or more UMA polygons in order to guarantee (or not) one of the pre-defined morphological criteria – spatial continuity (Urban areas less than 200 m apart are considered to belong to the same Urban Morphological Area (UMA)) between classes of land use and occupation according to the UMA methodology.

The extraction of MPC for both dates has served as the basis for the calculation of shape indexes and also for the selection of two information levels according to the spatial limits of the “statistical city” (INE, 2002): (i) composition of CLC land uses by UMA class; and (ii) socio-demographic content from census data (1991 and 2001 census).

The second stage of the general procedures is targeted at the operationalization of the spatial analysis of urban shape in Geographic Information Systems, by quantitative exploration of the association of urban form and geometric form supported by the calculation of form metrics.

In the technical and scientific context, specialized literature emphasizes the lack of software in a SIG environment and extended to the end user with an adequate set of tools for the analysis of shape. This lack is probably due to “classic” difficulties in conceptualizing and in the way to mediate form, as well as the computation of the geometric properties that are inherent to the calculation of such measures (Wentz, 1997). The lack of applications or software that can integrate the totality of shape indexes and the need to know the algorithms that underlie their calculation has led to the need to resort to computational programming. In this context, the translation of the concept into metrics (which we have termed operationalization of the concept) resorts to the creation of algorithms and the implementation of a library – libTestIndexes – dedicated to exploring metrics to support the analysis of urban form geometry, developed in C++ using solely FOSS (Free and Open Source Software). We would like to highlight that part of the geographical data input/output algorithm was supported by already existing libraries that are freely available (GDAL, GEOS, CGAL) (Fig. 1).

Fig.1. Schematic structure of the "shapeIndexes" package oriented towards the calculation of shape indexes.

The development of an application – shapeIndexes – based on this library (libTestIndexes) has allowed us to calculate a variety of shape indexes (in a total of nineteen shape indexes based on the works of Horton, 1932; Miller, 1953; Schumm, 1956; Boyce and Clark, 1964; Lee and Sallee, 1970; Clark and Gaile, 1973; Blair and Biss, 1973; Frolov, 1975; Haggett et al., 1977; MacEachrenc, 1985) that integrate a set of geometrical shape parameters: the area and the perimeter of the polygon, the centroid, the length of the main major axis of the polygon (major axis) and the length of the second major axis that is perpendicular to the major axis (secondary axis or minor axis), the area of the inscribed circle and the circumscribed circle, among others. The calculation of the set of shape indexes supports the analysis of six fundamental geometrical properties of the urban form, namely: the degree of compactness, circularity, ellipticity, length, linearity according to axis-vector and (ir)regularity of perimeters.

Indexes are used to create urban form typologies based on the statistical combination of their values, having been tested for the MPC (1990 and 2000) of continental Portuguese cities (Estanqueiro, 2011). The classification of MPC by applying descriptive and classifying statistical methods and by developing an exploratory multivariate data analysis, based on the determination of Pearson correlation coefficients, by applying namely the Principal Components Analysis (PCA) and the experimentation of techniques for the classification of data by cluster analysis, enabled the creation of five types of UMA of cities, associating the socio-demographic content and the characteristics of the buildings.

Evaluation of Urban Form Data for Urban Planning

The quantitative approach to urban form by applying form metrics has proven to be a fundamental contribution to the discursive framework of urban sustainability, supporting namely the disambiguation of spatial concepts often used subjectively and not very clearly or accurately.

Examples are the notions of compact and sprawl, widely used in the discussion on the dialectics between the compact urban growth model and the disperse growth model. These spatial concepts that incorporate the geometric properties of form thus appeal to a conceptual formalization that encompasses a quantitative approach to urban form. It is in this reference context that we argue for the introduction of shape metrics for the analysis of urban form, extending the pertinence of this approach to urban planning. This statement is based on the idea that conceptual disambiguation increases improvement in terms of design, implementation and assessment of the instruments for territorial development and management, in the sense that a greater accuracy of the geographic information coupled with quantifiable spatial concepts can serve as an instrument for the assessment and optimization of geographic information aimed at supporting public urban planning policies. Thus, the transparency and conceptual accuracy based on the quality of the generated geographic information not only allows us to restate the efficiency but also to strengthen the efficacy of public territorial planning policies. The diffusion of geographic information, with correctness and accuracy, supports the democratic character of the process at its different stages of conception, implementation and assessment, strengthening the value of spatial analysis

Discussion

This approach to measuring urban form combines the theoretical and conceptual component and its methodological or operating character revealing two fundamental topics for reflection that we have systematized according to the following synthesis.

The pertinence of urban form spatial analysis is based on the role of quantifying the definition of spatial concepts. The relevance of the quantification for the definition of urban form as a spatial concept is, from the start, observed due to the need to define spatial limits. This element has proven to be indispensable to broadly qualify and quantify urban shape.

The spatial analysis of the urban shape in GIS by applying shape indexes enables the description of urban macro-forms and supports the quantified translation of concepts whose physical and spatial dimensions are strongly associated. The results obtained from the creation of typologies for Continental Portuguese cities have revealed the absence of “spatial clusters” of the urban macro-forms and their temporal permanence. The analysis of the changes between the five types of MPC considering the two dates (1990 and 2000) has revealed that over half of the MPC maintain their geometrical characteristics regarding shape. This trend may be due to the fact that a ten-year timeframe does not suffice for the spatial analysis of urban form. On the other hand, the case study has revealed the inexistence of an MPC spatial pattern of distribution, which strengthens the need for: (i) associating the physical and spatial dimensions to the geographic dimension of form, i.e., the incorporation of location and situation as elements that support the spatial analysis of urban form; and (ii) incorporating 3D representations associated with the roughness of the urban surface, as well as the consideration of the large scale.

3. MODELLING 3D POINT CLOUDS

3D Point Cloud Technology

3D point cloud data are very useful to generate automatically 3D models of the earth's surface including: (a) Digital Terrain Model (DTM), which represents the bare earth terrain; (b) Digital Surface Model (DSM), similar to DTM but including the elevations of buildings, vegetation and other objects (natural or manmade features) above the ground; and (c) thematic 3D models, such as 3D city models and 3D urban buildings. Nowadays, we can obtain a 3D point cloud in at least two ways: (i) directly, from Airborne Laser Scanning (ALS); (ii) indirectly, from stereo image matching algorithms implemented in digital photogrammetric stations; and (iii) from full stereo processing based on Unmanned Aerial Vehicle (UAV) imagery.

The newest automated mapping technologies, such as Airborne Laser Scanning (ALS) or Unmanned Aerial Systems (also known as UAVs) have allowed us to acquire 3D points in a less time-consuming manner than the usual photogrammetric methods. The comparison between photogrammetry and ALS can be found in Baltsavias (1999).

The ALS, also known as LiDAR *(Light Detection And Ranging)* System, is an active remote sensing technology that provides its own lighting (where no shadows are generated) and records range measurements. The LiDAR system was introduced at the end of the 1990s. The basic principle is to collect a georeferenced and dense 3D point clouds, where the irregular distribution of these points depends on scanning method, flight height and flight speed. 3D point cloud acquisition during the flight is performed by a laser scanning and a direct georeferencing system that integrates GNSS (Global Navigation Satellite Systems) and IMU (Inertial Measurement Unit). Operationally, the laser sensor transmits laser light pulses to the earth's surface, GNSS provides the position of the aircraft (Xo,Yo,Zo) and IMU provides the sensor's attitude (*roll* around x-axis, *pitch* around y-axis and *yaw* around z-axis) for each laser beam. Subsequently, these six parameters are used to transform range measurements and scan angles into a terrain coordinate system (Lemmens, 2011) either expressed as map projection coordinates *XY* (easting, northing) and *Z* the elevation above the geoid, also known as orthometric height, or ellipsoidal geographic coordinates (ϕ, λ, h), where *h* is the elevation above reference ellipsoid.

Fig. 2 - Data collection from Airborne Laser Scanning.

Each laser beam emitted to the earth's surface can record one or several portions of a light beam that hits the surface of an object (building, terrain, tree foliage, etc.), also called first or last returns (Fig. 2). The ability of the pulse laser to record some details of the objects depends on the size of the footprint laser. If the objective is surveying an urban area for the 3D modelling of buildings, a small footprint is convenient together with the high density point (Lemmens, 2011:159). Typically the footprint laser size can range between 0.2-1.1 meters at a flying height of 1000 m.

Nevertheless, another alternative is to generate the 3D point cloud automatically by digital image matching algorithms, available in the digital photogrammetry workstation. The stereo image-matching technique consists in finding corresponding pixels on the left and right image (within the overlap area of the stereo pair), which enables 3D geometry reconstruction by aerial triangulation, through the use of six elements of exterior orientation parameters (ω,φ,κ), photogrammetric angles and (X_0, Y_0, Z_0), and object space coordinates of the exposure station of the camera for each exposed image. In this case, in order to obtain a dense 3D point cloud we need stereo pairs of aerial images with high resolution and higher overlap, between approximately 80% and 90% along flight strips. More recently, various authors have demonstrated that image matching can be an alternative to LiDAR, such as Haala *et al.* (2010), Haala and Kada (2010) and Leberl et al. (2010). Haala (2011) showed that it is possible to generate a 3D point cloud by a dense matching of multiple overlapping aerial images with an accuracy and density very similar to a LiDAR 3D point cloud. The dense image matching allows achieving a 3D point cloud with a density equivalent to the resolution of the stereo models, i.e., there is an estimated 3D point of each corresponding pixels of the stereo model. Hirschmüller and Bucher (2010) evaluated a new algorithm, the Semi-Global Matching stereo method (developed by Hirschmüller, 2011) for the generation of DSMs of urban areas, whose results are more accurate and have more detail than LiDAR DSM.

On the other hand, the combination of Unmanned Aerial Systems (or UAVs) and automated processing that include dense image-matching techniques (including higher overlaps between aerial images) for some urban applications may be enough – such as the generation of DSMs for an early recognition of an urban area after a natural disaster and for urban characterization and analysis. The UAV's allows low-cost aerial photogrammetry surveys and a high flexibility. Some of the UAVs, such as swinglet CAM (weighing around 500 grams), enable the performance of a fast survey at low altitude over small urban areas without human intervention during the flight. This system integrates a direct georeferencing system, such as LiDAR and digital aerial camera systems, but the position and attitude parameters are less accurate. This system rarely acquires nearly vertical aerial images (the tilt value exceeds 3º), which affects the overlap area between pairs. Additionally, on a tilted image the magnitude and angular orientation of the tilt emphasizes the variations of scale on the image. However, the recent developments in computer vision aided in dealing with these weaknesses, which would be unacceptable for traditional photogrammetry. Strecha (2011) and Xie et al. (2012) wrote that UAV images ensure accurate results comparable to the ones obtained with traditional digital airborne cameras. To generate the UAV point clouds the stereo aerial image pairs must be post-processed by robust and automatic workflow that includes dense image matching (Küng et al., 2011). The UAV point cloud can record the RGB values for each point unlike LiDAR.

However, the production of DSMs using the LiDAR system has advantages when compared with these optical sensor systems. Some of the advantages of the LiDAR system are: (i) always enables the mapping of bare earth surface even in areas with dense vegetation or forest; (ii) the shadow effect dominant in urban areas does not exist in LiDAR data; and (iii) the acquisition of data in flight is independent of season and daytime.

Regarding the accuracy of these technologies, Baltsavias (1999) wrote that planimetric accuracy from ALS is 2-6 times less accurate than its vertical accuracy, while in photogrammetry it is typically 1/3 more accurate; Hyyppä (2011) refers that ALS enables 5-10 cm of vertical accuracy and 20-80 cm of horizontal accuracy depending on flight height and system characteristics; Küng et al. (2011) mention that accuracy is strongly influenced by the ground resolution of imagery and horizontal accuracy can range between 2-20 cm (not considering building boundaries or thin tree structures). In Harwin and Lucieer (2012) it is possible to read that the DSMs and DTMs generated by UAV imagery, according to several authors (Turner *et al.* 2012 and Vallet et al. 2011), can achieve a vertical accuracy of about 10 centimeters.

Usability of 3D Point Cloud Data in 3D Building Modelling

In fact, the largest application of 3D point clouds is to generate 3D urban models. The usage of these models would be useful for urban planning regulations (Isikdag and Zlatanova 2010), for a better visualization of the proposed plan in a process of participation and public discussion (Houtkamp and Junger, 2010), for monitoring illegal changes in buildings (Peng et al., 2008), and for the extraction of urban indicators (Carneiro, 2011).

Over the past few years, 3D point clouds obtained by LiDAR or automated image matching techniques have been used and tested by several authors: (i) in 3D urban models by Lafarge et al. (2012), Haala and Kada (2010), Hirschmüller and Bucher (2010), Xie et al. (2012); (ii) more specifically in the extraction of building elements by Zeng et al. (2008), Kaartinen et al. (2005) and Khoshelham et al. (2010); and (iii) in other urban applications such as mapping the buildings' solar potential by Santos et al. (2011).

Now it is important to demonstrate the usability of 3D point clouds for the legislation that regulates Territorial Management Instruments at the urban level. Part of this demonstration was begun in the context of the GeoSAT project for the representation of 2D urban features at municipal scale (Santos, 2011a) by using LiDAR data. More recently, Rebelo and Tenedório (2011 a, b) also explored the LiDAR point cloud for the characterization of roof buildings through the correlation of orthometric height, slope, intensity and density of points/m2. The exploratory analysis and evaluation of UAV point cloud data for the extraction of building façade height was also explored in Rebelo et al. (2013).

The automatic extraction of urban parameters, pursuant to the Portuguese legislation, can be very useful for the planning process, where a plan should be evaluated and monitored every two years. The extraction of 3D building geometric information for the regular process of assessing and monitoring one of the two urban plans – urbanization plan or design plan – has not been demonstrated yet.

According to Decree-Law No. 9/2009, in Portugal, the building façade height parameter corresponds to the vertical dimension and should be measured from the elevation of cornice, parapets, rooftop railings or gutters to the elevation of building base (also called "elevation of the main entrance of the building" if it matches the ground level). This parameter is important to monitor: (a) illegalities in built-up areas, such as the building of new blocks or floors; (b) the distance between façades – "the 45º rule"; (c) the delimitation of consolidated planned urban areas, where the shape of neighborhoods, blocks and streets should be harmonized in terms of the visual relationships and transitions between new and older buildings; and (c) the vertical development of a building façade facing a public street or a backyard.

Building façade height is also important for the calculation of other parameters and indicators, such as building mass (or building volume). For example, the combination of building height façade and building mass enable the creation of urban pressure indicators in coastal areas.

The following sections address an overview of the usage of 3D point clouds in urban planning. Firstly, we show the usability of 3D LiDAR point clouds for the automatic generation of 3D building models with the extraction of average building height, building roof lines and type of building roof. Subsequently, we demonstrate and discuss the potential usage of this point clouds for the extraction of urban parameters that involve the third dimension, particularly building façade height and building mass in the context of the Portuguese legislation. Secondly, we demonstrate the usability of 3D UAV points for the semi-automatic extraction of building block mass and the evaluation of errors and accuracy of the estimated parameter building block mass extracted from UAV 3D point clouds.

3D LiDAR Point Cloud - Case Study

Study Area and Georeferenced Data Sources

The study area for this first case study is located in Praia de Faro, an open sandy beach in the Algarve (Southern Portugal), bounded west by the *Ria Formosa* barrier island system (Fig. 3). The area defined has an extension of 300×100 m, as shown in figure 3. In this area we are able to identify an avenue over the built-up area and some scattered vegetation, such as palm trees, and deciduous and coniferous trees. In this study area there are 30 isolated buildings, which were mostly built in the 1950s and 1970s. The majority of the buildings are single-family with two floors; and southwest there are 9 constructions used exclusively for restaurants and beach facilities. The buildings have irregular shapes, where the roofs are flat, multiple-level flat, pitched and complex (roofs with different slopes).

Fig. 3 - Location of the study area by an orthomosaic - Praia de Faro, Southern Portugal.

In this study, the 3D point cloud collected from the LiDAR system TopEye MK II was used, which has an average point density of 6 points per square meter (this means that distance between points is less than one meter). According to the flight planning report, this point cloud has a vertical accuracy of 10 cm. Table 1 shows the geographic data sources used in this study.

Table 1. *Characterization of georeferenced data sources*

Data	**Year**	**Technical acquisition**	**Details of data**
LiDAR	2009	Elliptical scanning Flight Height 500 m	171968 pts (First return) 5705 pts (Last Return)
3D vector data	2012	Reflectorless Total Station (Leica TCR 705)	Elevations of roofs, corners and main entrance of buildings (427 pts)
2D vector data	2002	Photogrammetric stereorestitution Mapping scale: 1:2000	Building outlines and road network
Orthomosaic	2009	Camera Rollei AIC P20 (16 MP) Georeferenced aerial images acquired from the same flight of LiDAR	Ground Sample Distance (GSD): 9 cm

Furthermore, orthomosaic was used in this study for visual inspection, such as to visualize and compare the building roofs extracted from LiDAR data. The large-scale 2D/3D vector data was also important for the development of the methodologies presented in following sections. For example, the 2D vector data of building outlines was used to calculate the building area and the 3D vector to calculate the building façade height reference.

Evaluation of LiDAR Data in the Extraction of Buildings for the Generation of 3D Building Models: Methodology and Results

The automatic extraction of buildings from LiDAR point clouds, using all return points, can be performed following three steps: (1) interpolating from point cloud to raster DSM; (2) creating raster DTM from DSM; and (3) extracting building features based on DSM, DTM, and a set of building parameters.

The methodology developed for building extraction was performed by LIDAR Analyst software. The flowchart for this automatic processing is shown in figure 4. The approach was designed to extract buildings using a subset of parameters, where the refining of DSM is an essential task in this workflow.

Fig. 4 - Methodological approach for building extraction based on LiDAR point cloud.

When performing building extraction, we need to ensure a great quality of the DSM and DTM. If the DSM and DTM are built without any filtering, it will be more difficult to extract accurate building roof lines (Fig. 5). Afterwards, the refining process for obtaining DTM is carried out by editing the DSM removing cars and other objects near the buildings.

The third step (Fig. 4) is the extraction of building roof lines using a set of building parameters, which can be manipulated with a combination of different parameter values. Firstly, the parameters used to define building boundaries were changed by the minimum and maximum slope values. Then, this combination was repeated with two additionally changed parameters: minimum building height and smoothing tolerance. The latter parameter defines the maximum distance a point can move in relation to its neighboring vertices. Another parameter used in the extraction was texture variance to differentiate between trees and buildings. Table 2 shows one of several combinations of these parameter values within the set of tests performed to extract building roofs, whose results are illustrated in figure 5.

Table 2. *Parameters defined for extracting isolated buildings*

Parameters	Isolated Buildings
Do Not Remove Buildings with area between	30-35000m^2
Slope for building roofs (minimum-maximum)	15-40º
Texture Variance Trees	80%
Remove Buildings with Height Less Than	2 m
Smoothing Tolerance	2.2 m

The approach used to extract isolated building roofs showed difficulties in the acquisition of accurate rooftop lines, because these did not match the highest elevation values visible in DSM ("white shaded areas" in figure 5) or the building outlines of reference data.

Fig. 5 - Visualization of isolated building roofs extracted from different building parameters with the overlap of building outlines (reference data).

This extraction process implies that there are specific building attributes that are calculated simultaneously, such as average building height, minimum/maximum building height and roof type. The generation of 3D building models without roof details, also called block model (according to Kolbe (2005), LoD1), can be easily done by extruding the footprint of each building roof to their average height as seen in figure 6.

On the other hand, it is possible to visualize rooftops classified into three types: complex, simple/flat and pitched (Fig. 6). The roof of each building was classified differently according to parameters defined along the automatic extraction process. When the roof extracted was characterized by higher slopes, it was classified as pitched, and when the slope was low, the roof was classified as flat (Fig. 6). If the building roof is not accurately extracted (or if it does not represent the "real shape of the roof"), its classification by roof type or any other attribute can also be wrong.

Fig. 6 - Visualization of 3D building models (LoD1) and reference 2D vector data of building outlines. The types of roofs extracted are showed, as well as the visualization of the classification of four buildings on the 3D model.

The generation of 3D building models from LiDAR data shows that it is difficult to extract automatically each building roof area with irregular roof size and heterogeneous surface structures. However, this approach has revealed potential for the delimitation of built-up areas. On the other hand, the automatic extraction of building heights from LiDAR data can be a great advantage for the production of 3D block models of buildings by extruding these values to vector data of building outlines.

Evaluation of LiDAR Data for the Extraction of Two Urban Parameters

Building Façade Height and Total Building Mass

The usability of LiDAR point cloud data for the extraction of urban parameters will be demonstrated, including the calculation and evaluation of errors obtained in the estimation of these urban parameters. Firstly, we will present the methodology used for the extraction of building façade height and building mass from LiDAR point data. Secondly, we will compute and analyze the vertical errors in terms of building façade height, as well as the total error of building mass.

The methodology developed included a set of routine operations which have been automated and optimized, along geoprocessing models implemented in GIS and *R* statistical *software* environment. The reference data are also important for the development of this methodology, such as building outlines (2D-vector data) and 3D data of building rooftops (Table 2). Therefore, the extraction of a “set of LiDAR points” that defines the top or base of building façade height (Fig. 7) will be processed using reference data. The methodology for the extraction of building façade height followed two major steps, as seen in figure 7.

Fig. 7 - Summary of the methodology.

The development of this methodology (Fig. 8) was performed with LiDAR points contained within building polygons (outlines) and in the 2-meter buffer generated from building polygons.

Fig. 8 - Flowchart for the extraction of building façade height and building mass from LiDAR data.

The first part was the extraction of higher elevation of the building façade, near a cornice, parapet, rooftop railing or corner of the building façade. The following steps are taken at this stage (Fig. 8): (i) *K-Means clustering* of LiDAR points (using *clustTool* library of *R*) based on the elevation attribute. The objective is the delimitation of the rooftop's upper plan that defines the building façade by one *cluster K*; (ii) defining the boundary of LiDAR points which best defines the higher plan of the building façade by selecting the "*cluster K* and a range of slope values" condition; and (iii) computing the median values of selected LiDAR points, which are within *X* distance of the reference point value (which defines the highest point of the building façade).

The extraction of building base elevation was performed in three major steps (Fig. 8 and 9): (i) the spatial limits of the upper plan building façade points must be visualized as the convex-hull (building roof polygon); then, (ii) the LiDAR points that are outside the convex-hull polygon ("outside LiDAR points") and are one meter distant from the edge of building polygons (defined by convex-hull) should be selected by a "range elevation values and range slope values" condition ("LiDAR ground points"); and finally (iii) computing the median values of LiDAR points selected from the following spatial selection condition: "LiDAR ground points" that belong to the base building area and are at X distance value from edge road.

Fig. 9 - Results of the first and second part of the geoprocessing model – extraction of LiDAR points of building façade height and building base elevation.

The end of this process is the computation of building façade height based on the difference between higher elevation of the building façade and building base elevation.

The evaluation of the results achieved for each building in the urban parameter building façade height was based on the calculation of vertical position errors. The vertical error of the building façade height estimated corresponds to the difference between the value estimated from LiDAR point data and the reference value from 3D vector data.

Figure 10 shows the magnitude of vertical errors estimated for 19 buildings of the urban area of Praia de Faro. The urban parameter building façade height estimated a maximum vertical error of approximately 0.70 m.

Fig. 10 - Distribution of vertical error obtained from the difference between building façade height value estimated from LiDAR and the reference value from surveying.

There are two buildings whose vertical error is higher than 0.2 meters (Fig. 10). The reasons for this magnitude of error are the variations that appeared near the base of the building (vegetation, grass or other elements), or some changes that have occurred between the acquisition of reference data and flying LiDAR. About 73% of the sample buildings have a vertical error of less than 0.1 meter, where most buildings have a flat rooftop.

On the other hand, two more buildings were removed, so they are not showed in figure 10, because they have been identified as blunders.

The building mass parameter was calculated by multiplying the building façade height value by the built area outline value.

The 3D building model represented in figure 11 shows the volume of each building according to the number of stories. As we can see, the buildings with more vertical error in terms of the building façade height (Fig. 10) were removed from the sample. Afterward, the total of building mass reference (calculated using the building façade height reference) is about 20096 m^3.

Fig. 11 - Visualization of 3D building models (LoD1) that represent the distribution of buildings by stories and the visual perception of the volume of each building.

The errors made by the estimation of building façade height have contributed to a volume error of 380 m^3 in the calculation of the total building mass, which corresponds to 2% of the value of total building mass reference. If the buildings with higher vertical error were not removed from the 3D building model, the percentage of error regarding total building mass would be approximately the same.

3D UAV Point Cloud - Case Study

Study Area and Georeferenced Data Sources

The second case study was performed in a selected urban area of Amadora, located about 10 km from Lisbon city. The selected geographic area has a total area of 9 hectares, with a width of 150 m north to south and 600 m long east to west (Fig. 12). The dwelling area has 89 buildings grouped into 7 blocks and is bounded south by the railway line. The majority of the buildings have five or six stories, with tiled roofs. There are also some scattered trees near the building blocks.

Fig. 12 - Study area of Amadora city, Portugal.

This area was covered by 85 aerial images (3000 by 4000 pixels) acquired from a swinglet CAM produced by senseFly. The flight trajectory on this selected area can be seen in figure 13.

Fig. 13 – Trajectory flight lines performed by Swinglet CAM on the area selected and visualization of tilt value for each exposed image.

These stereo aerial images have a higher overlapping between each other, which is about 90% along flight and 60% cross flight overlap. Most values of tilt image ranges between 5-10 degrees and the maximum value of tilt was 23º (Fig. 13).

Table 3. Characterization of georeferenced data sources

Data	Year	Technical acquisition	Details of data
UAV data	2012	~20 min of flight 16MP camera Flying Height 100 m	1,066,700 pts (study area) Mean point Density: 11pts/m^2
2D/3D vector data	2003	Photogrammetric restitution Mapping scale: 1:2000	Building outlines, Elevations of roofs and terrain (near the buildings) for evaluation of results.
True Orthomosaic	2012	Created with DSM produced from UAV point cloud and aerial images	For visual inspection of results

The UAV point cloud was generated from the subset of stereo aerial images with a Ground Sampling Distance (GSD) of 4 centimeters. The UAV point cloud was obtained by an automatic processing workflow implemented in PiX4D software. More details about this processing and swinglet CAM system can be seen in Strecha (2011) and Vallet et al. (2011).

Evaluation of UAV Data for the Extraction of the *Building Block Mass* Parameter

In this section we will demonstrate the usability of UAV point cloud data for the extraction of the building block mass parameter. Then, in order to allow for an evaluation of the results, differences between the volume estimated for each building block and the reference volumes from 2D/3D vector data were computed.

The starting point of this study is the definition of the building block mass parameter. In this study we have defined building block mass by multiplying the mean value of building façade height and the area of building block. However, taking into consideration that a building can have different façade heights, according to its deployment on the ground, only one façade side of the building block was chosen to compute this parameter.

The methodology implemented was based on the following assumptions: (i) extracting the two parameters involved in building mass block without vector reference data; (ii) using the vector reference data only for comparing and evaluating the results; and (iii) using Free and Open Source Software (FOSS) tools for implementing a robust methodology.

The methodology developed was based on four major steps, as represented in the workflow of figure 14.

Fig. 14 - Methodological approach for building block mass extraction based on UAV point cloud.

We will now describe the steps which were taken for each area (Fig. 14) following this methodology: (i) the first step (*Building Block Clusters*) was to identify the UAV points that represent building points by using the elevation attribute (Fig.15). The objective was to filter data by removing the points which are not building points using a clustering partitioning algorithm. The algorithm used was CLARA (*Clustering Large Applications*) which is suitable for large amounts of data (using *clara* library of R software). CLARA consists in the partitioning (clustering) of the data into several sub-groups (k clusters) "around k-medoids" or k representative objects that are centrally located in the cluster that they define (Kaufman and Rousseeuw, 1990). Each cluster must contain at least one object and each object should belong to a single cluster; (ii) generating "non-convex" polygons (*building block area*) that better represent the boundaries of each set of building block points (Fig.15), i.e., area occupied by each cluster. A "non-convex hull" polygon means that two points belong to the polygon, but the line segment of these points is not completely contained in the polygon. After that, we have employed the concave-hull algorithm (implemented in GRASS GIS) which allowed us to compute the envelope (non-convex or convex) of k-clusters; (iii) computing the mean value of the building block façade height, which implied the estimation of two values: elevation mean of selected UAV points that best represent the eaves of roofs $E = \left\{z_{e1,..,}z_{en}\right\}$ and the elevation mean of selected UAV terrain points $T = \left\{z_{t1,..,}z_{tn}\right\}$ that not belong to clustering (Fig.15); and (iv) computing volume by $V_{Bi} = A \cdot (\bar{E} - \bar{T}), i = 1,..,n$, where n is the number of building blocks. For the last steps we have developed an algorithm in PostgreSQL/Postgis based on spatial analysis operations for filtering UAV points.

Fig. 15 - Visualization of building block clusters (step 1), polygon (roofs outlines) and selected UAV points for building blocks on study area A (step 2 and 3).

The evaluation of estimated volume for each building block was based on the calculation of error, which corresponds to the difference between the volume value estimated from building block façade height and area parameters estimated from UAV point data and the reference volume value from 2D/3D vector data. The standard error of the estimated volume for each building block can be given by:

$$\sigma_V = \mp\sqrt{\left(\frac{\partial V}{\partial a}\right)^2 \times \sigma_a^2 + \left(\frac{\partial V}{\partial h}\right)^2 \times \sigma_h^2}$$

where σ_a corresponds to the error in the estimation of the block area and σ_h to the error in the estimation of building block height mean.

The errors computed for area and building block height mean estimated, and also the standard error of estimated volume for each building block, can be seen in figure 16. The standard error achieved for building block mass estimated from only UAV data ranged approximately from 4% to 18.7%. The magnitude of these errors is mainly due to the estimated parameter area from UAV data. Additionally, it is important to highlight that the standard error for the estimation of building block mass by using reference area value was between approximately 1% and 7%, where the maximum vertical error for building block height was about 1 meter.

Fig. 16 - Visualization of *building block mass reference values and the errors of each building block mass estimated.*

Nevertheless, the building block outlines of reference data are not enough to measure the area values estimated from UAV data for the building block roofs. The building outlines of vector reference data in some cases do not represent the building roofs that were extracted from UAV points, which explains the large error of area values estimated for the building block on the study area C (see figure 16, building block 7).

Discussion

Currently, the concept of smart cities is being thoroughly discussed. This concept has been progressively introduced in the discourse about cities and, albeit lightly, in the strategic urban planning practice. This concept involves six dimensions: smart economy, smart mobility, smart environment, smart people, smart living and smart governance. The concept has attained such popularity that nowadays cities are ranked based on the status of the aforementioned dimensions.

The concept and the practice of the smart city idea include the notion of efficiency derived from the intelligent usage of information and communication technologies. In this context, acquisition, processing and geographic information management technologies play an important role at the following levels: in terms of the quantitative and qualitative analysis of the city, regarding the characterization of the physical urban components (buildings, roads, blocks, infrastructures, etc.), and diagnosing and monitoring the physical indicators that have contributed to the promotion of a sustainable city.

One of the classic problems regarding city management is the rigorous implementation of the objectives and measures established by the plan (a plan which is understood as a formal process of city creation and management). In spite of the existence of urban planning, informal urban construction is quite common – just as the densification beyond the boundaries foreseen in the plan is also common. In this context, 3D modelling of urban data, namely data obtained by LiDAR and UAV technologies shows the required accuracy both to estimate the volume of constructed mass for urban analysis and to present planning proposals that can later be offered for public discussion, as well as to monitor informal changes that can be witnessed in the city.

The methodology employed for the measurement and representation of 3D urban buildings was evaluated for a sample of buildings as described by Rebelo et al. (2012). However, further analysis is needed regarding the usability and relevance of the data for a wider building sample, where automatic extraction of building façade height is independent from the topographic information.

The LiDAR technology has the great advantage of enabling the production of 3D block models of buildings by extruding the building polygons using the attribute of building façade height estimated from LiDAR data.

The usage of LiDAR data for the extraction of urban parameters, building façade height and building mass has revealed great potential for buildings whose higher façade plan is flat. The error value in terms of building mass is acceptable at the urban planning level, but it might be significant when it comes to urban projects.

The first approach to the usage of UAV data in urban areas has revealed potential use in the delimitation of built-up areas or the block buildings of an urban area. On the other hand, the methodology developed on free and open-source tools also enables the automatic extraction of building mass without reference vector data. This means that is possible to acquire relevant urban parameters at low-cost, from acquisition to the of 3D point cloud data to the extraction of parameters.

In view of the results reported in this chapter, we can argue for the usage of the information acquired by LiDAR and UAV technologies. In spite of the costs of LiDAR, we believe that the acquisition of both types of data should be planned for especially in the case of urban areas that are under severe urban pressure and are consequently inclined to generate very strong dynamics – both formal and informal. Following this path, LiDAR technology – as well as the blossoming technology based on UAV acquisition – suggests the permanent updating of the information needed to monitor sustainability conditions for smart cities.

4. VISUALIZING URBAN DATA WITHIN AN (AUGMENTED) MIXED REALITY ENVIRONMENT THROUGH MOBILE DEVICES

Figure 17 translates graphically the schematic approach of the procedures to develop 3D models and represent them in an augmented system.

Fig. 17 – Schematic approach and fluxes of procedures to develop an augmented reality representation.

Sequentially, the base point is related to the existence of a 3D model or multimedia data, such as text, image or video, which can be associated with an AR marker and possible to visualize through a mobile device camera (associated with other technical features, enounced further in the discussion). In the center of the scheme (Fig. 17) lays the most extended process to create the examples developed (Fig. 18).

Fig.18 – Syntheses of 3D modelling and further augmented representation over satellite imagery. Multifamily buildings in Almada municipality, within the south part of the Lisbon Metropolitan Area, Portugal: façade to Northwest (18i) and to Southwest (18ii).

Based on digital cartography, in the case of the 2D vector, we can create the volume associated with alphanumerical "z" values, while on raster documents (*e.g.* satellite imaginary or ancient cartography) the process requires 2D/3D drawing and eventually adding texture (*e.g.* building façades) or other features (*e.g.* audio or video). Considering the developed 3D model, it may be necessary to convert or adapt to other formats, compatible with the AR application to be used in the mobile device. Once imported, we can define an AR marker (*e.g.* satellite imagery as in the example used in figures 18i and 18ii) or visualized over a certain chosen surface.

Fig. 19 – 3D (built; obtained through Google catalog) augmented representation model over satellite imagery: Faculty of Social Sciences and Humanities of "Universidade Nova de Lisboa" and surrounding avenue in Lisbon (19i); the monument "Cristo Rei" in Almada (19ii), Portugal.

However, in the case of not using AR markers, the visualization in the field may be associated with real coordinates (georeferenced 3D model) and eventually enable the possibility to access more information about the object.

As a result, the images in figures 19i and 19ii exemplify the syntheses of several augmented reality approaches carried out to observe the potential of this technology, applied to several domains recurrent to geographic information and commonly associated with a strong visual perception of space.

Evaluating Virtual Visualizations

Many entities and communities have been acquiring certain urban environment features from 2D GIS databases by representing urban characteristics in the form of points, lines or polygons, thus facing the challenge of visualizing the complex 3D (real) environment in 2D. Urban planning is intimately related to the spatial relationship between buildings, blocks, streets, neighborhoods and cities. Two-dimensional representations are considered, most of the times, inadequate to address real 3D planning problems at the scale of the modern city. Simple physical models in 3D (*e.g.* Marquette) or 3D digital representations are important tools that have been used by technicians in addition to 2D representations, thus allowing the agents involved in the design appreciation and in the planning process to participate and simulate their interactions (Goodchild, 2010; Yin, 2010; Marambio, 2012).

Digital 3D representations can be more suitable for site location, shadows (at different sun positions) and visibility analysis, as well as valuation of the built entities or urban morphology and their image or legibility (Lynch, 1960; Portugali, 1996; Golledge, 1999). 2D provides limited perspectives, while 3D representations also provide the possibility of navigating, flying over or rotating, to examine the details of a building or a space between structures at different distances, angles and scales (Lin et. al., 2008; Yin, 2010).

The Augmented Reality (AR) concept is frequently correlated with the enrichment of the real world with a complementary virtual world (mixed reality). The digital representations are merged with reality through a device that combines both views, real and virtual (Hugues et. al., 2011). An AR system expands the real world scene (requiring the user to maintain the sense of presence in that world, as opposed to a total immersive virtual world).

Discussion

AR digital representations, restitutions and simulations can offer interesting possibilities and useful applications, due to their fairly good interactive capabilities and their capacity to visually stimulate and engage the user. A mobile device, such as a smartphone or tablet, and the use of their technical features, such as the inbuilt GNSS (*e.g.* GPS and/or GLONASS), gyroscope/compass, acceleration sensors, microphone, speakers and (photo/video) camera, allow us to access virtual information, representations, simulations, reconstructions about that object or site, directly over the real environment we are looking at (Lin et. al., 2008; Marques, 2009). It is then possible to turn around in the real world and observe the representation from different perspectives and distances, and even to change the model to experiment with different colors, designs, heights, and so on (Eve, 2012). Another relevant feature is to understand the dynamics of temporal changes in the territory and their characteristics in supporting both representation and planning (regarding 3D in space and time, concerning observation, reconstruction or simulation), when compared with the spatial-temporal model aligned and merged with the real view in the device display (Zhang, 2004; Khatri, 2006; Marques, 2009; Marambio, 2012). This environment can function also as a portal to access more information on communication networks (such as the Internet), linking the real image seen in the device and accessing virtual data.

Technology is ever evolving and it might develop towards a revolutionary visualization of a projected hologram, combining the real and virtual environments more authentically.

REFERENCES

Allain, R. (2004). *Morphologie urbaine*. Paris: Armand Colin. Collection Géographie.

Bachi, R., & Samuel-Cahn, E. (1976). Applications of parameters of shape to statistical distributions. *Regional Science and Urban Economics, 6* (1976), 205-277.

Baltsavias, E. (1999). A comparison between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, *54*(2-3), 83-94. Retrieved January 22, 2014, from http://linkinghub.elsevier.com/retrieve/pii/S0924271699000143

Boyce, Ronald R., & Clark, W. A. V. (1964). The concept of shape in Geography. *Geographical Review*, *54*(4), 561-572.

Carneiro, C. (2011). *Extraction of urban environmental quality indicators using LiDAR-based Digital Surface Models*. Unpublished doctoral dissertation, École Polytechnique Fédérale de Lausanne, Switzerland.

Clark, W. A. V., & Gaile, G. L. (1973). The analysis and recognition of shapes. *Geografiska Annaler*, *Series B*, *Human Geography*, *55*(2) 153-163.

Estanqueiro, R. (2011). *Análise espacial da forma urbana em Sistemas de Informação Geográfica* [Spatial analysis of urban shape in geographical information systems] (Volume I) and Annexes (Volume II). Lisboa: UNL-FCSH. Thesis written for the completion of the Doctoral degree in Geography and Territorial Planning, specializing in Remote Sensing and Geographical Information Systems. 376p. (Vol. I) and 165p. (Vol. II). (Multicopied and PDF document) ISBN: 978-989-97821-0-5.

Eve, S. (2012). Augmenting Phenomenology: Using Augmented Reality to Aid Archaeological Phenomenology in the Landscape. *Journal of Archaeological Method and Theory*, *19*(4), 582–600. Retrieved 22 January, 2014, from http://link.springer.com/article/10.1007%2Fs10816-012-9142-7

Golledge, R. (Ed.). (1999). *Wayfinding behavior: cognitive mapping and other spatial processes*. Baltimore: Johns Hopkins University Press.

Goodchild, M., May Y., & Thomas J. (2007). Towards a General Theory of Geographic Representation in GIS. *International Journal of Geographical Information Science*, *21*(3), 239–260. Retrieved January 22, 2014, from http://www.tandfonline.com/doi/abs/10.1080/13658810600965271#.Ut_TqtLFKt8

Haala, N. (2011). Multiray Photogrammetry and Dense Image Matching. In D. Fritsch(Ed.), *53rd Photogrammetry WeeK* (pp. 185–195). Herbert Wichmann Verlag, Heidelberg.

Haala, N. & Kada, M. (2010). An update on automatic 3D building reconstruction. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(6), 570–580.

Haala, N., Hastedt, H., Wolf, K, Ressl, C. & Baltrusch, S. (2010). Digital Photogrammetric Camera Evaluation - Generation of Digital Elevation Models - Photogrammetrie - Fernerkundung - Geoinformation, 2, 99-115. Retrieved 22 January, 2014, from: http://www.ifp.uni-stuttgart.de/institut/staff/haala_publikationen.htm

Haggett, P., Cliff, A., & Frey, A. (1977). *Locational analysis in human geography*. UK: Edward Arnold.

Harwin, S. & Lucieer, A. (2012). Assessing the Accuracy of Georeferenced Point Clouds Produced via Multi-View Stereopsis from Unmanned Aerial Vehicle (UAV) Imagery. *Remote Sensing*, 4(12), 1573–1599. Retrieved from: http://www.mdpi.com/2072-4292/4/6/1573/

Hirschmüller, H. (2011). Semi-Global Matching – Motivation, Developments and Applications. In D. Fritsch(Ed.), *53rd Photogrammetry WeeK* (pp. 173–184). Herbert Wichmann Verlag, Heidelberg.

Hirschmüller, H. & Bucher, T. (2010, July). Evaluation of Digital Surface Models by Semi-Global Matching. Paper presented at the meeting of the DGPF, Vienna, Austria. Retrieved from http://elib.dlr.de/66923/

Houtkamp, J. M., & Junger, M. L. (2010). Affective Qualities of an Urban Environment on a Desktop Computer. In IEEE Computer Society (Ed.), *14th International Conference Information Visualisation*, (pp. 597-603). London, United Kingdom. Retrieved January 22, 2014, from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=5571122

Hugues, O., Jean-Marc C., & Pascal G. (2011). GIS and Augmented Reality: State of the Art and Issues. In Borko Furht (Ed.), *Handbook of Augmented Reality* (pp. 721-740). Springer

Hyyppä, J. (2011). State of the Art in Laser Scanning. In D. Fritsch(Ed.), *53rd Photogrammetry WeeK* (pp. 203-216). Herbert Wichmann Verlag, Heidelberg.

Isikdag, U**.** & Zlatanova, S. (2010). Interactive modelling of buildings in Google Earth: A 3D tool for Urban Planning. In T. Neutens & P. De Maeyer (Ed.), *Developments in 3D Geo-Information Sciences, Lecture Notes in Geoinformation and Cartography* (pp.53-70). Springer-Verlag Berlin Heidelberg.

Kaartinen, H., Hyyppä, J., Gülch, E., Vosselman, G., Hyyppä, H., Matikainen, L., Hofmann, A. D., et al. (2005). Accuracy of 3d city models : EuroSDR comparison. *ISPRS WG III/3, III/4,20, V/3 Workshop "Laser scanning 2005",* (pp. 227–232). Enschede, Netherlands.

Kaufman L. K. & Rousseeuw P. J. (1990) *Finding Groups in Data: an introduction to cluster analysis*. New York: John Wiley & Sons.

Khatri, V., Sudha R., & Richard T. (2006). On Augmenting Database Design-support Environments to Capture the Geo-spatio-temporal Data Semantics. *Information Systems 31*(2), 98–133.

Khoshelham, K., Nardinocchi, C., Frontoni, E., Mancini, A. & Zingaretti, P. (2010). Performance evaluation of automated approaches to building detection in multi-source aerial data. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(1), 123-133.

Kolbe, T., Gröger, G. & Plümer, L. (2005). Citygml – interoperable access to 3d city models. In: Oosterom, Zlantanova, Fendel (Eds.), *Proceedings of the 1st International Symposium on Geoinformation for Disaster Management,* (pp. 21–23). Springer-Verlag.

Küng, O., Strecha, C., Beyeler, JC., Zufferey, D. , Floreano, Fua, P. & Gervaix, F. (2011). The accuracy of automatic photogrammetric techniques on ultra-light UAV imagery. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII*, 1–6.

Lafarge, F., & Mallet, C. (2012). Creating Large-Scale City Models from 3D-Point Clouds: A Robust Approach with Hybrid Representation. *International Journal of Computer Vision,* 69-85.

Leberl, F., Irschara, A., Pock, T., Meixner, P., Gruber, M., Scholz, S. & Wiechert, A. (2010). Point Clouds : Lidar versus 3D Vision. *Photogrammetric Engineering & Remote Sensing*, *76*(10), 1123–1134.

Lee, D., & Sallee, T. (1970). A Method of measuring shape. *Geographical Review*, *60*(4), 555-563.

Lemmens, M. (Ed.) (2011). *Geo-Information. Technologies, applications and the environment*. Springer-Verlag.

Lin, T., Yuan-Kai H., Guo-Long H., Hung-Kuo C., & Fu-Ming L. (2008). Development of a Virtual Reality GIS Using Stereo Vision. *Computers and Electronics in Agriculture, 63*(1), 38–48. Retrieved December 20, 2013, from http://www.sciencedirect.com/science/article/pii/S0168169908000446#

Lynch, K. (1960). *The Image of the City*. MIT Press.

Lynch, K. (1999). *A boa forma da cidade*. Lisboa: Edições 70.

Maceachren, A. M. (1985). Compactness of geographic shape: comparison and evaluation of measures. *Geografiska Annaler, Series B, Human Geography, 67*(1) 53-67.

Marambio A., Sarmiento J., Salas J., & Cladera J. (2010). Nuevas Formas de Accesibilidad Através de Aplicaciones Con Realidad Virtual y Aumentada En El Museo Marítimo de Barcelona: Proyecto PATRAC, Subproyecto 3. ACe Arquitectura, ciudad y entorno, 5 (13), (pp. 145-160) Retrieved December 20, 2013, from http://riberdis.cedd.net/handle/11181/3486

Marques, L. (2009). *Tecnologias de Informação Geográfica e Monitorização Ambiental em Contexto Africano*. Unpublished master dissertation, Faculty of Sciences and Technology, Universidade Nova de Lisboa. Lisboa. Retrieved December 20, 2013, from http://www.luisfilipemarques.com/tese-mestrado/

Peng, X., Liu. Z., Yin, J. & Li, Y. (2008). Applying unmanned airship to rapid detection of urban building changes. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVI*, 391–394.

Portugali, J. (1996). *The Construction of Cognitive Maps*. Dordrecht; Boston: Kluwer Academic Publishers.

Rebelo, C. & Tenedório, J.A. (2011a). Exploratory Analysis of LiDAR Data in Urban Areas: The Case of Faro Island in Southern Portugal. In N. Pinto, J. Tenedório, M.Santos, R. Deus (Ed.) *Proceedings of 7th Virtual Cities and Territories*, (pp.447-453). Lisbon, Portugal.

Rebelo, C. & Tenedório, J.A. (2011b). Avaliação de dados LiDAR para modelação 3D e caracterização dos topos dos edifícios, In *VIII Congresso da Geografia Portuguesa Repensar a Geografia para Novos Desafios*. Lisbon, Portugal.

Rebelo, C., Gonçalves, J.A. & Tenedório, J.A. (2012). Análise de dados LiDAR para a extração de parâmetros urbanísticos. *In Actas do XIII Colóquio Ibérico de Geografia Respuestas de la Geografia Ibérica a la crisis actual*,(pp.940-951). Santiago de Compostela.

Rebelo, C., Rodrigues, A. M., Neves, B., Tenedório, J. & Gonçalves, J.A. (2013, March). Extraction of urban parameters from 3d point-cloud within grass. Paper presented at the meeting VII Jornadas SIG Libre, Universitat Girona, Spain.

Santos, T. (2011). *A methodology to produce geographical information for Land planning using very-high resolution images.* Unpublished doctoral dissertation, Universidade Nova de Lisboa, Portugal.

Santos, T., Gomes, N., Brito, M., Freire, S., Fonseca, A. & Tenedório, J. A. (2011). Solar potential analysis in Lisbon using LiDAR data. In L. Halounová (Ed.), *Proceedings of 31st EARSeL Symposium: Coastal Zones* (pp. 13-19). Retrieved from http://www.earsel.org/symposia/2011-symposium-Prague/Proceedings/index.htm

Strecha, C. (2011). The Accuracy of Automatic Photogrammetric Techniques on Ultra-Light UAV Imagery. In D. Fritsch(Ed.), *53rd Photogrammetry WeeK* (pp. 289–294). Herbert Wichmann Verlag, Heidelberg.

Turner, D., Lucieer, A. & Watson, C. (2011). Development of an Unmanned Aerial Vehicle (UAV) for Hyper Resolution Vineyard Mapping Based on Visible, Multispectral, and Thermal Imagery. In *Proceedings of the 34th International Symposium on Remote Sensing of Environment* (ISRSE34).

UAB/ETC-TE (2004). *Urban Morphological Zones: Definition, methodological approach and results. Working paper*. Universitat Autònoma de Barcelona (UAB): European Topic Centre on Terrestrial Environment (ETC-TE), EEA.

Vallet, J., Panissod, F. & Strecha, C. (2011) Photogrammetric Performance of an Ultralightweight Swinglet UAV. In IAPRS (Ed.), *Proceedings of the International Conference on Unmanned Aerial Vehicle in Geomatics (UAV-g)*: Vol. 38 (pp. 14–16).

Wentz, E. A. (1997). Shape analysis in GIS. In Annual Convention & Exposition Technical Papers, *Auto-Carto 13*: Vol. 5. (pp. 204-213). Seattle, Washington: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping.

Xie, F., Lin, Z., Gui, D. & Lin, H (2012). Study on construction of 3D building based on UAV images. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XXXIX(B-1), 460-472.

Yin, L. (2010). Integrating 3D Visualization and GIS in Planning Education. *Journal of Geography in Higher Education, 34*(3), 419–438. Retrieved December 20, 2013, from http://www.tandfonline.com/doi/pdf/10.1080/03098260903556030

Zeng, Q., Lai, J., Li, X., Mao, J., & Liu, X. (2008). Simple building reconstruction from LIDAR point cloud. In IEEE (Ed.), *Proceedings of International Conference on Audio, Language and Image Processing* (pp.1040–1044).

Zhang, X. (2004). *Designing a Geographic Visual Information System (GVIS) to Support Participation in Urban Planning*. Unpublished doctoral dissertation, University of Salford, UK. Retrieved November 5, 2011, from http://usir.salford.ac.uk/2178/.