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FAST QUALITY CONTROL OF 3D CITY MODELS

Devrim Akca[1], Armin Gruen[1], Mark Freeman[2], Isabel Sargent[2]

[1] Institute of Geodesy and Photogrammetry, ETH Zurich, CH-8093 Zurich, Switzerland
Tel: +41 44 633 3063, Fax: +41 44 633 1101, E-mail: (akca, agruen)@geod.baug.ethz.ch
www.photogrammetry.ethz.ch

[2] Ordnance Survey Research, C530, Romsey Road, Southampton, SO16 4GU, United Kingdom
Tel: +44 23 8079 2190, Fax: +44 23 8030 5072, Email: (Mark.Freeman, Isabel.Sargent)@ordnancesurvey.co.uk
www.ordnancesurvey.co.uk

Abstract
A method for the fast quality control of 3D city models is presented. The input model (3D building data) is co-registered to the verification data using a 3D surface matching method. The 3D surface matching evaluates the Euclidean distances between the verification and input data sets. The Euclidean distances give appropriate metrics for the 3D model quality. This metric is independent of the method of data capture. The proposed method can favourably address the reference system accuracy, positional accuracy and completeness.

Keywords
Quality assessment, 3D city model, LiDAR, point cloud, surface co-registration.

1. INTRODUCTION

For about 20 years 3D city modelling has been an important issue in R&D. Many different techniques have been proposed especially for reality-based concepts. Reviews can be found in Mayer (1999), Gruen (2000), Baltsavias et al. (2001), Baltsavias and Gruen (2003) and Baltsavias (2004). 3D city models have become one of the most relevant products of the geospatial business and many new applications are requesting this kind of data (Gruen, 2001). Reality-based models are nowadays produced with a variety of different source data and sensors (maps, GIS data, cameras of different types, LiDAR), operating from various platforms (satellites, aerial – surveying airplanes, UAVs, terrestrial – mobile mapping, street images).

While the methods for generating virgin databases efficiently and reliably are still under development and optimization, little has been done with respect to the quality control of this data and the updating/maintenance of these models.

As the performance of the data acquisition methods is improving, the quality evaluation of 3D building data has become an important issue in particular for the professional practice. So far the quality was assessed by calculating metrics either using pixels based on 2D projections (Henricsson and Baltsavias, 1997; Ameri, 2000; Suveg and Vosselman, 2002; Boudet et al., 2006), or using voxels, considering buildings as volumetric data (McKeown et al., 2000; Schuster and Weidner, 2003; Meidow and Schuster, 2005). Also, qualitative and visual evaluation based methods were used (Rottensteiner and Schulze, 2003; Durupt, Taillandier, 2006). Recently, Elberink and Vosselman (2007) introduced an end-to-end quality analysis (of 3D reconstructed roads) using error propagation applied to the stochastic properties of input data. Detailed reviews can be found in McKeown et al. (2000) and Sargent et al. (2007).

In 2007, a cooperative project was started between the Chair of Photogrammetry and Remote Sensing of ETH Zurich and the Research department of Ordnance Survey, called 'Quality Assessment of 3D Building Data'. The project aims to derive methods to calculate metrics for the quantitative evaluation of 3D buildings, which are assumed to be the basic elements of a given 3D city model. The metrics and methods should correspond to customers' requirements (of Ordnance Survey) and should be independent of the method of data capture.

Over the last few years, Ordnance Survey has initiated several projects to look into how the quality of 3D data, particularly building models, can be assessed. This work designs quality assessment measures that have meaning to users, so as to ensure that data is captured according to users' requirements and that users understand the usefulness of the 3D data for their purposes. Ordnance Survey is also testing assumptions made in 3D modelling research about how best to represent real-world detail from the point of view of user requirements (Sargent et al., 2007).

The input data to be assessed are 3D building models provided in CC-Modeler (CyberCity 3D, Inc., El Segundo, CA, USA) format. The verification (reference) data is either airborne laser scanning (ALS) point cloud data and/or another 3D model that is given at a presumably higher quality level.

Usually 3D building data is in surface model form. For that the pixel or voxel based representations are only indirect approaches and thus sub-optimal. This work proposes a method, which directly works on 3D surface elements (surfels). The input model is co-registered to the verification data by use of the Least Squares 3D surface matching method (Gruen and Akca, 2005). The LS3D method evaluates the Euclidean distances between the verification and input data sets. The Euclidean distances give appropriate metrics for the 3D model quality.

The next chapter briefly introduces the surface matcher and the quality assessment strategy. When the ALS point clouds are used as the reference, irrelevant points (points belong to terrain, vegetation, etc.) should be excluded. Details of a filtering process using the SCOP++ LiDAR software are given in the third chapter. The results of the experiments conducted at two test sites are shown in the fourth chapter.

2. QUALITY ASSESSMENT BY SURFACE MATCHING

2.1. Least Squares 3D surface matching

Our quality evaluation is done by co-registering the reference data and the input 3D building data by use of the Least Squares 3D surface matching (LS3D) method.

The LS3D method is a rigorous algorithm for the matching of overlapping 3D surfaces and/or point clouds. The mathematical model is a generalization of the Least Squares 2D image matching method (Ackermann, 1984; Pertl, 1984; Gruen, 1985). It estimates the transformation parameters of one or more fully 3D surfaces with respect to a template surface, using the Generalized Gauss-Markov model, minimizing the sum of the squares of the Euclidean distances between the surfaces. This formulation gives the opportunity to simultaneously match arbitrarily oriented 3D surfaces, without using explicit tie points. A correspondence operator searches the surface-to-surface correspondences. The geometric relationship between these conjugate surface correspondences is defined as a 7-parameter 3D similarity transformation. This parameter space can be extended or reduced, as the situation demands it.

This method provides mechanisms for internal quality control and the capability of matching of multi-resolution and multi-quality data sets. More details are given in Gruen and Akca (2005). The method was originally developed for the co-registration of point clouds and surfaces. Recently, it has also been used for 3D comparison, change detection, quality inspection and validation studies (Akca, 2007).

2.2. Quality assessment strategy

For quality assessment three procedural steps are used as follows. Without restricting the generality of the approaches it is assumed that the reference surface has been generated from LiDAR.

First, the LS3D software is run without any 3D transformation calculation with only one iteration. The 3D spatial distances (Euclidean distances) from LiDAR points to the corresponding 3D building triangles are calculated. This step is to show the initial (spatial) disagreement of both data sets before applying a 3D similarity transformation. At this stage, the errors are composed of at least two components: errors due to the reference system and the positional errors of individual buildings. These errors are factorized in the subsequent second step.

At the second step, a full LS3D surface matching is performed. It calculates any translational, rotational and scale difference between the validation and test data sets. According to our preliminary tests (done with the experimental data presented here), there are only translational differences (spatial shifts) between both data sets. The rotational and the scale differences are not significant. Then, the LS3D software is run in the 3 degrees of freedom (DOF) mode. This step shows the reference system accuracy of the building models with respect to the coordinate system of the LiDAR data. The estimated 3D transformation parameters (held as a translation vector) are applied to the test data sets. Thus, the reference system errors are isolated from the individual building errors.

At the third step, the last LS3D run is applied, but again without any 3D transformation calculation. Only the correspondences are computed. This final step shows the positional accuracy of individual buildings and the completeness.

The proposed method can address the following quality criteria:

• **Reference system accuracy**: Due to differences in production techniques, the reference frames of the input and verification data sets may differ, leading e.g. to positional shifts and angular tilts. The LS3D algorithm calculates any translational, rotational and scale differences between the two data sets with their associated theoretical precision values.

• **Positional accuracy**: The LS3D surface matcher establishes the 3D correspondences for every point or surfel element of the verification data with respect to the surfels of the input data. In fact, every correspondence is a 3D Euclidean distance vector. Assuming that the verification data are available at a higher quality level and in an appropriate point density, the Euclidean distances show the positional accuracy of the individual surfels of the input surface.

• **Completeness**: The non-measured/missed points/features/building parts are the real problem. Currently, there is no practical way to check fully automatically for this deficiency. Only through comparison with the verification data or through visual checks can one get quality measures. Assuming that the verification data set is complete, accurate and dense enough, the LS3D surface matcher can provide the completeness criteria, which are equivalent to the omission type of gross errors. In statistics, there are two sorts of gross errors (or outliers), which are the omission (type I or false positive or probability of rejecting a correct null hypothesis) and commission (type II or false negative or probability of accepting a false alternative hypothesis) errors. For the 3D building case, the omission error describes the rejected or missing buildings (partially or entirely). This means that some elements of the verification data will not have a correspondence with the input data. The commission error is the acceptance of non-building objects as buildings. They appear as some surfels of the input data, but will not receive a correspondence from the verification data. Specifically for the 3D building case, the omission errors are more likely to occur than the commission errors.

2.3. Correspondence search

Correspondence search is the most computationally expensive part of every surface matching algorithm. There are many ways to reduce the search space, and thus the computational burden. In the basic implementation we use a 3D boxing based search algorithm. See Akca and Gruen (2005) and Akca (2007) for the details.

Searching the correspondence is guided by the 3D boxing structure, which partitions the search space into cuboids. For a given surface element, the correspondence is searched for only in the box containing this element and in the adjacent boxes. The correspondence is searched in the boxing structure during the first a few iterations, and meanwhile its evolution is tracked across the iterations. Afterwards, the search process is carried out only in an adaptive local neighbourhood according to the previous position and change of correspondence. In any step of the iteration, if the change of correspondence for a surface element exceeds a limit value, or oscillates, the search procedure for this element is returned to the boxing structure again.

For the 3D building data quality assessment case, the boxing structure is established for the 3D building polygon files. For any point of the LiDAR data, the coincident box is calculated. All buildings (entirely or partially) situated in the coincident box or in its 28-neighbourhood are listed. The correspondence is searched only on the triangles of those building.

2.4. Outlier detection

Detection of false correspondences caused by outliers and occlusions is crucial. We use the following strategy in order to localize and eliminate the outliers and the occluded parts. In the course of iterations a simple weighting scheme adapted from the robust estimation methods is used:

$$(\mathbf{P})_{ii} = \begin{cases} 1 & \text{if} \quad |(\boldsymbol{v})_i| < K\hat{\sigma}_0 \\ 0 & \text{else} \end{cases} \tag{1}$$

where vector $(\boldsymbol{v})_i$ is the Euclidean distance of the i-th correspondence and $\hat{\sigma}_0$ is the standard deviation of the Euclidean distances of the current iteration. In our experiments K is selected as ≥4. For many application cases of the robust estimation procedure, this is a fairly small number which carries the danger of exclusion of some correct inliers. On the other hand, when increasing the robust weighting factor, for example to ≥8 or 10, the computation is usually distorted by the impairing effect of the non-relevant points, i.e. points belonging to ground or trees, etc.

3. FILTERING OF GROUND AND VEGETATION POINTS IN THE VERIFICATION DATA

When using the LiDAR point clouds as verification data, handling of the non-relevant points (points which do not belong to buildings) needs an appropriate strategy. The robust weighting factor alone cannot solve the problem. In our experiments the SCOP++ LiDAR version 5.4 (Inpho GmbH, Stuttgart, Germany) software package was used for the filtering. The SCOP++ LiDAR classifies the LiDAR point clouds into 7 classes: ground, below (outlier points below the ground), building, high vegetation, medium vegetation, low vegetation, and unclassifiable. Among them the classes ground, below and low vegetation were discarded, the rest of the point clouds were merged into one file, and this merged file was used as the verification data.

4. EXPERIMENTAL WORK

We have three test sites in the United Kingdom for the verification of the procedure

- Avonmouth (AV),

- Bournemouth test area 1 (BO1),
- Bournemouth test area 2 (BO2).

The experimental results of only two test sites (AV and BO2) are given here for brevity.

Each test site has a LiDAR point cloud and 3D building polygon files. The LiDAR point clouds were acquired by Airborne 1 Corporation using a Bravo 50K ALTM system carried on a helicopter platform. They were in 25 points/m2 density and delivered in both ENZI and LAS formats. The LiDAR point clouds were used as verification data in all experiments.

The 3D buildings were captured using stereo-viewing of pairs of DMC (Intergraph) images from a nadir block with 60% overlap and sidelap. The low resolution RGB imagery was pan-sharpened with the high resolution panchromatic image resulting in imagery with a GSD of approximately 15cm (flying height around 1500-1600 m, focal length 120 cm, and pixel size 12 microns). The building measurement was done using CC-Modeler software in semi-automatic mode. The final polygon files were delivered in standard CC-Modeler V3D file format.

All experiments were carried out using the in-house developed software LS3D, which was implemented as a MS Windows application with a graphical user interface (GUI) using the C/C++ programming language.

3.1 Results of test site AV

The filtered airborne LiDAR data and the input 3D building data are shown in Figure 1a and 1b.

Step 1. The standard deviation of the Euclidean distances (sigma naught) before the LS3D surface matching is 0.77 m. The blue colour indicates that the 3D building data is above the verification LiDAR data, while yellow-red indicates the opposite case (Figure 1c and 1e). Note that in Step 1 and Step 3, for all test sites, a 2.0 m threshold is used for the robust re-weighting. This means that all the correspondences whose Euclidean distances are greater than 2.0 m are not considered in the calculation. This is mainly done to exclude the non-relevant points, e.g. points on the terrain, trees, bushes, etc. Note that there is no coverage of LiDAR point clouds for a few houses as seen at the bottom right of Figure 1a.

Step 2. The robust weighting factor is set to 4 times sigma naught (of the current iteration). The translation parameters between the reference systems of the LiDAR point cloud and the building models were estimated as +0.06, +0.05, –0.85 m for the X, Y and Z axes, respectively.

Step 3. After correcting the reference system errors, the sigma naught dropped down to 0.30 m. The robust threshold value is 2.0 m again. The dark red points at the edges of the buildings (Figure 2a and 2b) are due to non-relevant (disturbing) terrain points that the LS3D surface matcher considers to belong to the buildings due to their proximity. Thus, the sigma naught of 0.30 m is not solely related to the building inaccuracy. It also includes the effect from those (outlier) ground points. The red arrows in Figure 2b show some missing parts of the model data which indicate a lack of completeness.

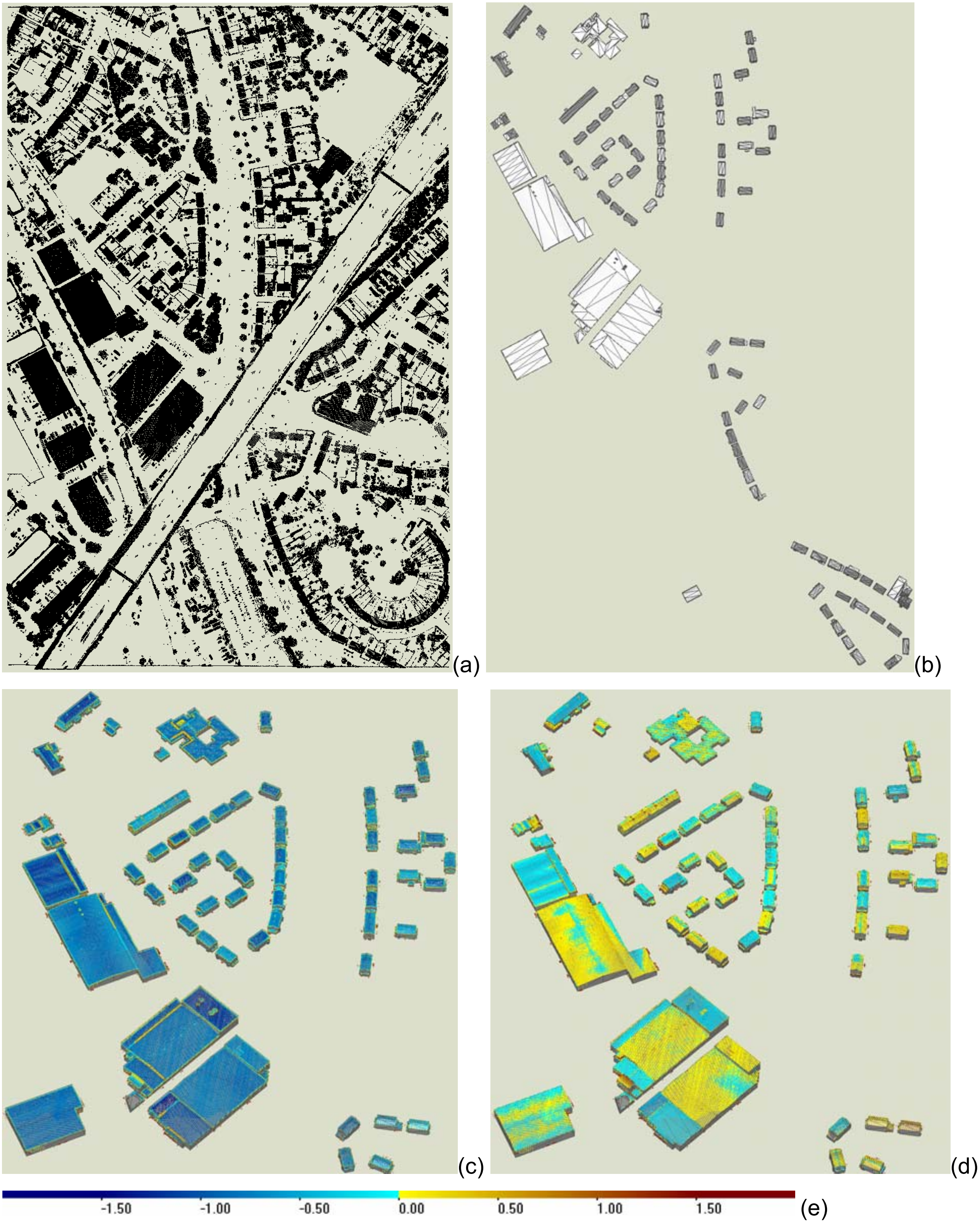

Figure 1. Test site Avonmouth. (a) Filtered LiDAR point cloud, (b) input 3D building models, (c) comparison of the reference and the input data before LS3D surface matching, (d) after LS3D surface matching, (e) residual bar in meter unit. Ordnance Survey © Crown copyright. All rights reserved.

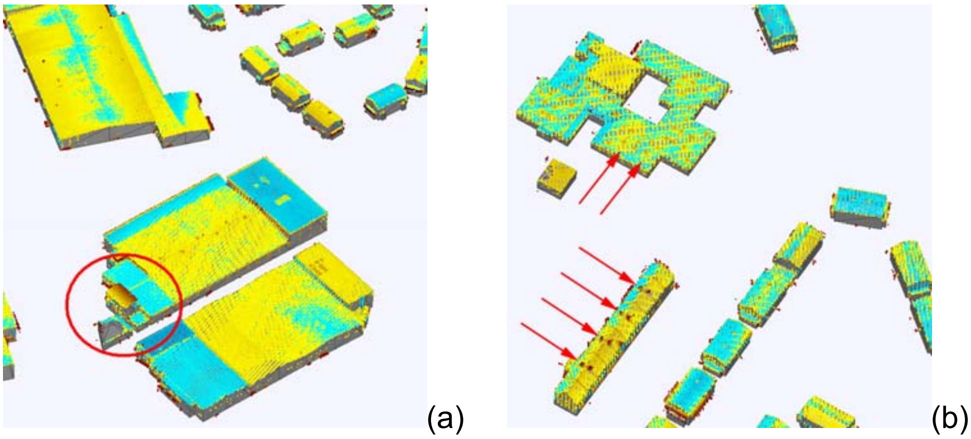

Figure 2. (a) Zoom into below-left part of Figure 1d. The red circle shows a part of a building which has large differences between the model and the reference. (b) Zoom into upper part of Figure 1d. The red arrows show the missing chimneys and dormers in the V3D model data. Ordnance Survey

3.2 Results of test site BO2

In the test site BO2 the filtered reference data is complex and highly mixed with points belonging to vegetation (Figure 3).

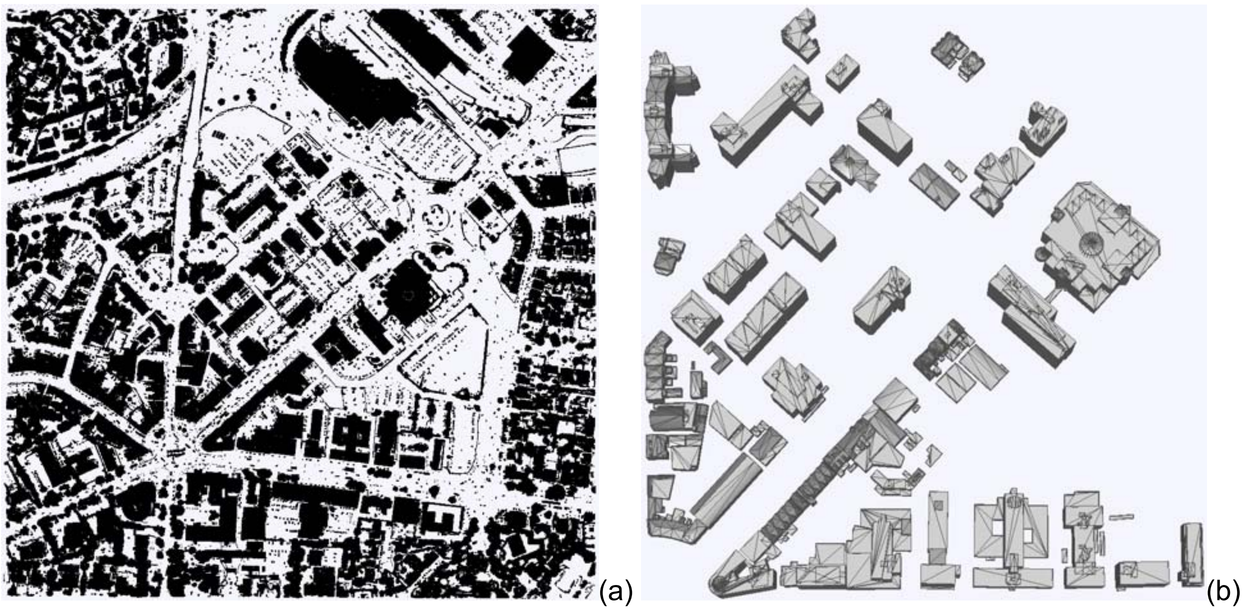

Figure 3. BO2 test site. (a) The filtered LiDAR data, (b) the 3D building data. Ordnance Survey

Step 1. Standard deviation of the Euclidean distances (sigma naught) before the LS3D surface matching is 0.65 m. See Figure 4 for the graphical representation of the results.

Step 2. The robust threshold value is set to 4 times sigma naught (of the current iteration). The translational reference system difference between the model V3D data and the reference LiDAR data is +0.24, –0.24, –0.49 m for the X, Y and Z axes, respectively.

Step 3. The sigma naught at this step is 0.54 m. The robust threshold value is 2.0 m again. See Figure 4b, 5a and 5b for the graphical results. From Step 1 to Step 3, the gain is 11 cm in terms of sigma naught. But, as mentioned before, this error budget also contains the disturbing effect of the non-building points. Their magnitude is clearly visible as red buffers at the building borders in Figure 4b and 5a. Note that the missing dormers can easily be detected by our approach (Figure 5b).

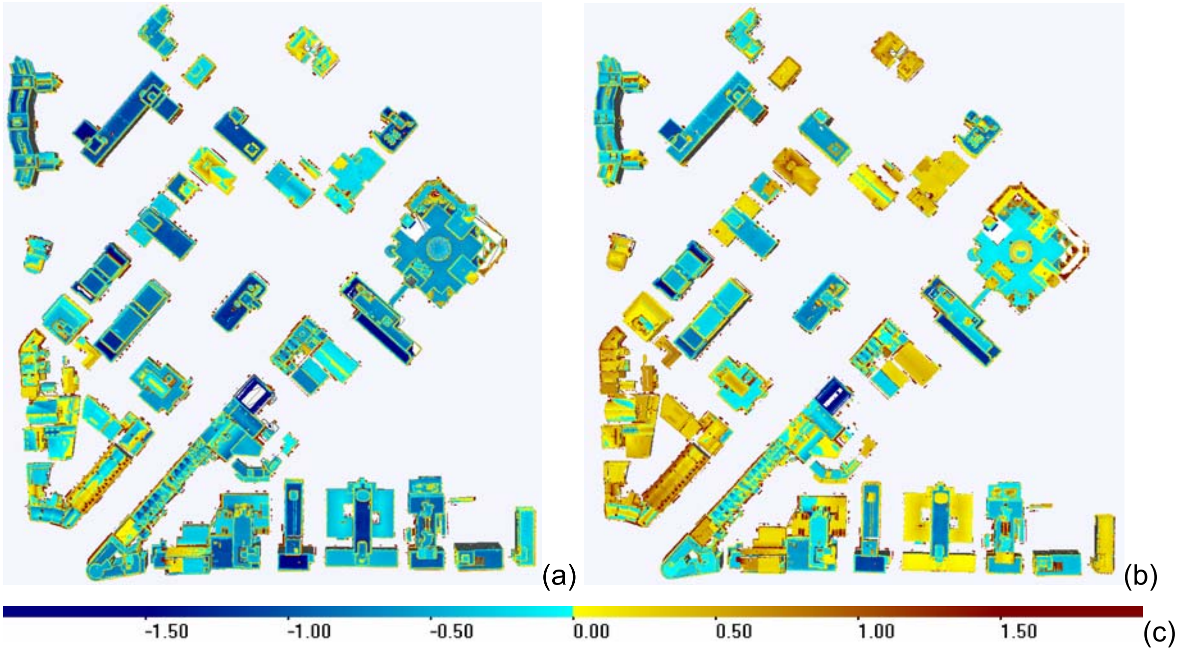

Figure 4. (a) Test site BO2 before LS3D surface matching. (b) Test site BO2 after LS3D surface matching (the errors due to the reference system differences are now corrected). (c) Residual bar in meter unit. Ordnance Survey © Crown copyright. All rights reserved.

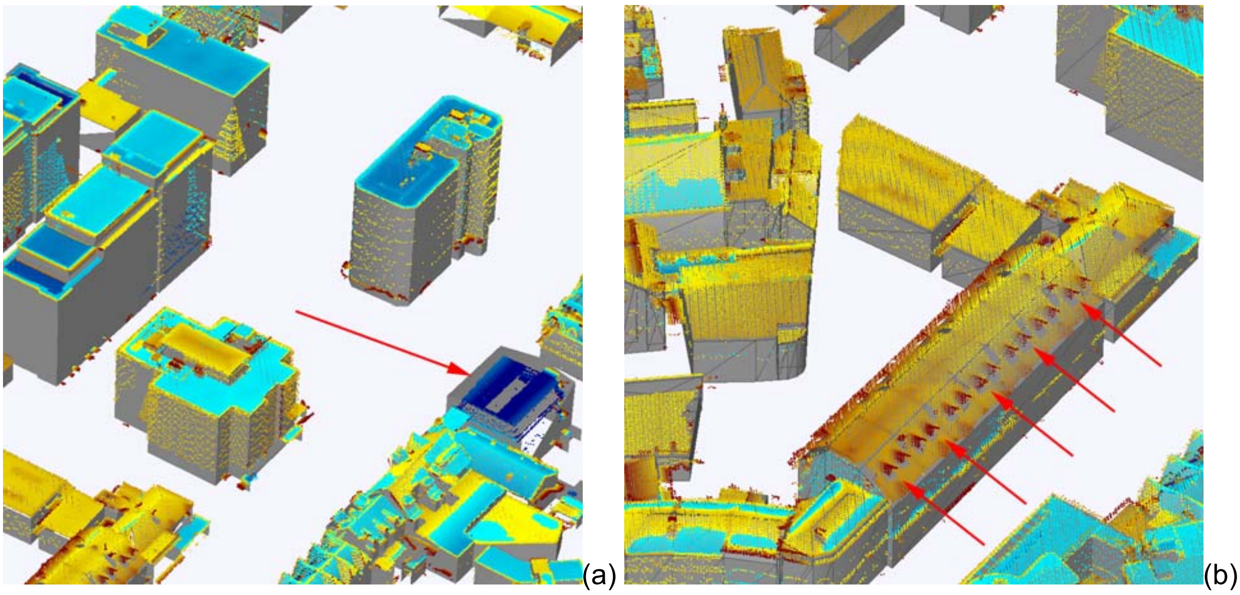

Figure 5. (a) Zoom into the central part of Figure 4b (oblique view). The red arrow shows a building with large differences between the model and the point cloud. (b) Zoom into the lower-left part of Figure 4b in oblique view. The missing dormers (indicated by the red arrows) can easily be identified by the LS3D surface matcher. Ordnance Survey © Crown copyright. All rights reserved.

4. CONCLUSIONS

2D city maps are rapidly been replaced by 3D city models. While the general emphasis has been to develop methods and tools for automatic or semi-automated generation of city models, the concept of quality evaluation has also gained high importance. The quality control is a relevant issue both from scientific and practical point of views. No standard solutions are available yet, although city models are produced world-wide at a remarkable rate.

In this project we have proposed a quality control method based on surface comparison, together with the development of a GUI-based software. Our method can successfully assess the 3D building data in terms of

a) systematic errors: errors due to difference between the coordinate systems of the input and verification data sets, systematic measurement errors of the individual buildings, and

b) gross errors: type I errors (relevant to the completeness) and type II errors.

Experiments have been carried out with two test sites in the UK. The results of our work provide measures of how well an entire building model matches reality and thus helps to identify where it differs. Together with our method of using LiDAR point clouds as verification data it allows frequent and effortless quality control of 3D city models. This also allows us to update our 3D model in order to create high quality and complete 3D city models. The same procedure can be used to detect the changes.

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