COMPUTER-AIDED DESIGN & APPLICATIONS, 2018
VOL. 15, NO. 1, 147–155
https://doi.org/10.1080/16864360.2017.1353746

The assessments of hierarchical 3D spatial data in an urban environment

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ABSTRACT
Urban fabric usually specifies the physical presence of existing structures. Examination of both permanent and temporary structures helps to understand the specific inconsistency occurring within the framework. This study applied the methodology in reverse engineering to verify the dynamic nature of urban fabric by the progress of development in Taipei, Taiwan. As-built urban fabric scans were used to identify inconsistencies from urban scale to building façade and street lamps for quantitative analysis purpose. An assessment to spatial data hierarchy is achieved through the comparison to a detailed level. The methodology was approached using different hierarchies of scan data as organized in terms of general scans of the entire site from roof level and focused scans on selected façade on street level. The data include the point clouds retrieved in Leica's scan worlds and Faro's scans, with selected regions using Asus Xtion Pro. A systematic approach was made for such inspections, in BIM 500 level, using a publicly accessible CAD platform. By referring to the original BIM or GIS, the identification of different parts is outlined for measurement or evaluation. The cross-reference base is created, and can refer to urban chronological development, local update information, construction quality or the misalignment of objects or facilities like street lamps.

KEYWORDS
Urban fabric; 3D scan; BIM; LOD 500; as-built data; buildings

1. Introduction

Urban fabric, which is a summation of urban artifact configuration, features inconsistent appearance and structure. The changes illustrate the flexibility of what an urban space framework can achieve, and interpret the cross-relationship between buildings and temporary fixtures in macro and micro forms [10,11]. Identifying the changes requires, first, the representation of urban fabric, and the second, the collection of related data to verify the relationship between space and new modifications. City models can be created by at least three main geometric approaches: conventional techniques, high resolution satellite images with laser scanning, and terrestrial images by photogrammetry [2,13], nevertheless, different levels of precision apply. The concerns are if the details are feasible for practical inspection to certain smaller scale. 3D city models using a digital map and panoramic images are straightforward [5], but more details are required for architectural practice. 3D objects from point clouds are also developed with success [6], the model details are good for conceptual study, not quite sufficient for architectural representation. For the test of detailed urban data, utility Information is important [7]. But the correctness remains to be verified, since field modifications have to be updated.

The abstraction of fabric is usually represented in diagrams, maps, or virtual models. Virtual 3D city models are becoming more widely implemented by governments and city planning services; this requires highly detailed 3D models that reflect the complexity of city objects and their interrelations [14]. Nowadays, city modeling has reached a new standard in which 3D point cloud models have been treated with rich geometric properties and rich details, which enable the clouds to be integrated with other city model types [12]. Since the cloud models are as-built data, the integration with old environmental data leads to a specific application in showing the most current status of the environment, or in contrasting changes.

2. Consistency among hierarchies

The dynamic nature of urban fabric comes from the constant changes of environment, and as a result, causes inconsistency between maps and scans. In order to keep up with urban life-cycle as-built data updates, the contents among hierarchies must be identified. The digit map or aerial photos, which may be used as legal documents, do not necessary provide sufficient details of buildings' as-built configuration for design reference and practice.

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Few government-certified drawing documents are able to offer such detail.

Consistencies found among hierarchies enable the comparison made in this study, and illustrates the dynamic nature of urban development over many decades. Inconsistencies between different periods of time not only show the nature of development, but also cover various versions of maps or drawings across different departments. This consistency study is part of a series of efforts in scanning Taipei's urban environments subject to people's daily living experiences. In order to illustrate different versions of a digital city, the scans were conducted at downtown areas and specific open spaces. The former consist of a mixture of office buildings and residential apartments, while the latter includes the Shan-Ti Boulevard, which is located among a series of department stores.

The assessments of hierarchical 3D spatial data in an urban environment have to deal with problems as follows.

- Inconsistency occurs between different hierarchies. The dynamic nature of urban fabric comes from decades of development. In urban environment, the hierarchy varies from the location of a single facility to regional map. Each level of hierarchy inherits records subject to different versions, periods, and formats.
- The interaction between scans and hierarchies creates even more complicated situation in assessment. The factors include the evolving nature and segmental representation of urban fabric. The interaction can be case-dependent, upon to different scales and subjects.

The proposed solution to the interaction with inconsistent hierarchies has two parts: reference creation and reverse engineering. The former refers to the database in relating the new design to the existing environment, with the numeric check of modification. As the data are usually presented in varies types, this study applies as-built scan data for reference. Scan data come in two hierarchies, general scans and focused scans, which were used to verify inconsistent data under different formats (images, drawings) and versions. Different sets of scan also have individual set of registration which was used to confirm the existence of temporary fabric.

The reverse-engineering-based assessment of inconsistency was made to different versions, periods, and formats of urban fabric representation. The methodology was applied to maps from historical maps, geographic maps, to lamp maps for consistency checks. For installations not on map, on-field scans were made to mark the difference. As a quantitative study, the displacements of real object were measured after projecting 3D point cloud model on maps. As a qualitative study, the integration of scan hierarchies before the data were applied to other hierarchies was explored in order to make comparisons.

Merging two different sources of data are proved better for visualization [3]. Merging two different platforms of 3D scanners are now proved even better to support multiple hierarchical assessments of various comparisons. The vast amount of data actually opens up opportunities in various fields of study, especially when showing the complexity of city objects and their interrelations. To solve this, this study starts from collecting the data on ordinary days and during festivals, and applies a reverse engineering approach to process the difference.

3. Scan planning

The downtown areas have been the focus of scans for years. Recent efforts include two main streets running north-south, a main street running east-west, three commercial districts, and a number of individual buildings. These scans were made mainly on ground and roof levels for clearer capture of as-built data to be integrated in the BIM 500 level. The exemplification was made to Taipei Konkung district, which refers to the region located next to the National Taiwan University at the center of Taipei. To be more specific, Konkung is the commercial district surrounding the university campus, in which a rich urban development history can be verified and illustrated from a collection of maps by the changes on a macro scale.

This study used a Leica HDS 3000® and a Faro Focus 3D® laser scanner (Fig. 1.). The former was for map-based comparisons over and area of about 250000 sq. meters under a scan range of 250 m. In a range of 80–120 m, a region of about 150000 sq. meters was retrieved by Focus 3D® for more detailed comparison. The scans in different hierarchies is represented by general scans (Leica®), focused scans (Faro®), and hand-held scans (Asus Xtion Pro®) at selected areas (Fig. 2). The result is a set of cloud models of about 1.5 billion points each. To view the model, other than by the scanner's host platform, the data was exported under different resolutions to 3D Reshaper®, Meshlab®, CloudCompare® and Geomagic Studio® for visualization purposes.

As BIM LOD 500 data are usually not available along a street, a field 3D scan is the only way to retrieve the geometric configuration of building enclosures. The identification of newly modified parts requires the two compared clouds to be perfectly aligned. The algorithmic computation can be time-consuming, depending on the number of points and the size of the sample to be identified. Since

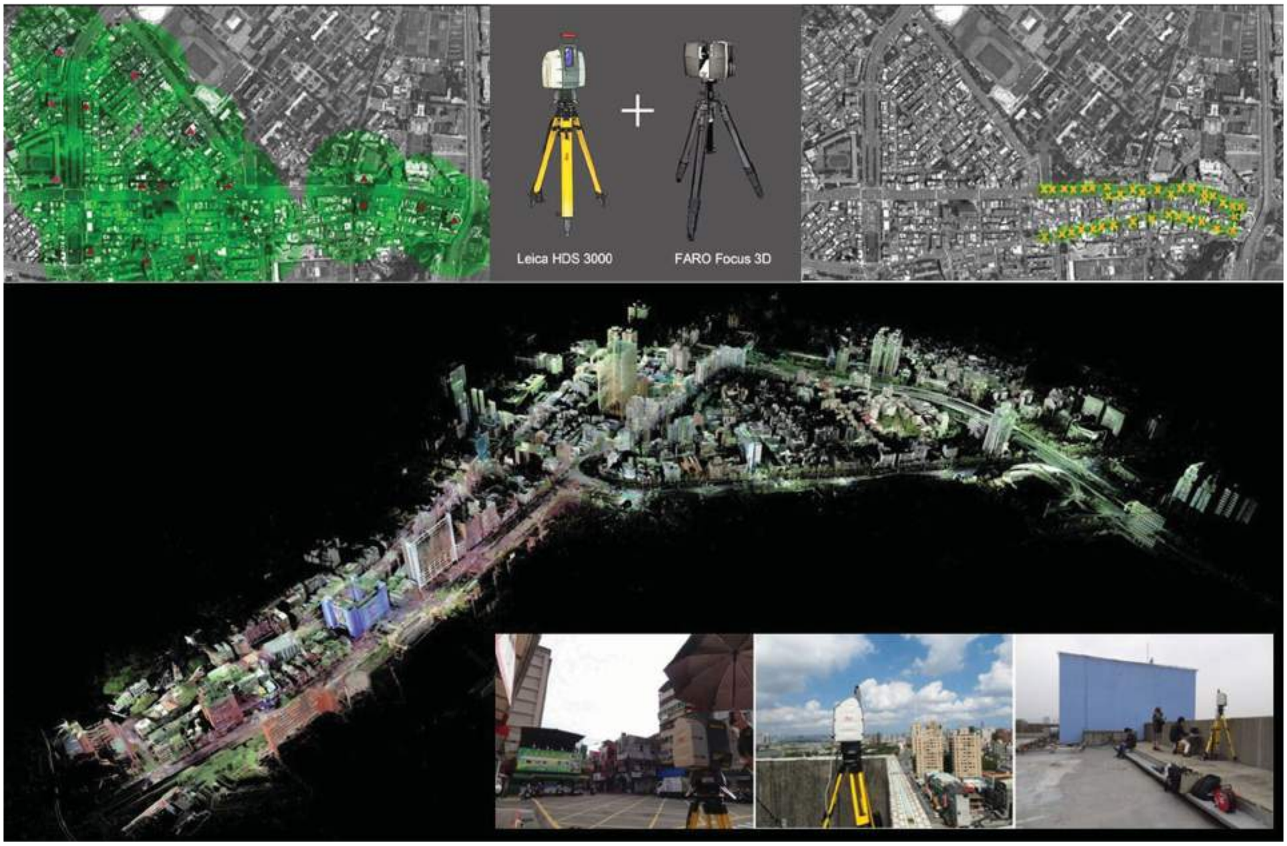

Figure 1. The scan scope and the corresponding systems for Konkung, Taipei.

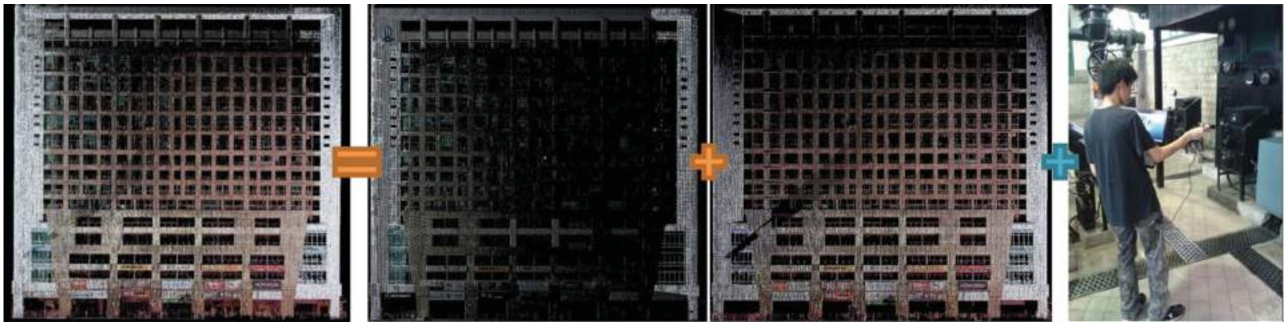

Figure 2. The the scans made by general scans, focused scans, and hand-held scans.

the efficiency of Boolean operation is of concern, this study chose pair-based comparison when a detailed study of a particular façade was needed.

4. Verification through comparisons

Urban fabric usually specifies the physical presence of existing structures. Examination of both permanent and temporary structures helps to understand the specific activity occurring within the framework. Urban studies are usually easier with a clearly documented boundary. However, records seldom illustrate the facilities that appear temporarily in a void space and, consequently, a relevant investigation can hardly be made to occasional settings. A gray zone should be added to a traditional figure-ground diagram accompanied by the facilities to be identified and measured. Two types of comparisons were conducted in this study: by decades and by details, followed by a more detailed verification of a temporary setting. For the comparison by decades, long-range plus middle-range scans were used to show that scans in different resolutions and hardware systems could be integrated for a better or on-demand data quality. For the comparison by details, a dedicated scan region was used to prove that any part of an urban scan could be focused to identify the different settings in an occasion.

To prove the study is feasible, verifications must be applicable to any subject. The scan data enables 5 levels of comparison, from the urban scale to the block level, street level, building level, and detailed level. The methodology of comparison starts from several procedures with the methods as follows.

- Algorithmic calculation: software-based identification of subject for a small region.
- Overlay: visual-based inspection by orthogonal overlapping layers of point models and maps.

4.1. Quantitative measurements for facility

For update status in BIM 500, concept of reverse engineering was applied to compare the difference between the real locations and the drawn location of street lamps on geographic maps and lamp maps (Fig. 3). Measurements indicated displacement did exist in a range between 0.55 m (minimum) and 8.49 m (maximum) on a lamp map, comparing to 1.35 m and 6.53 m on a geographic map. Two marks were missing on lamp map, comparing to 26 missing marks on geographic map. When the inspection was extended to the entire street beyond the scope of this study, only 11.6% are located within 1 m of range, among 640 street lamps on lamp map. For 597 street lamps on geographic map, only 3.8% are located within 1 m. The assessments of 3D spatial data comparisons in an urban district were also made to the entire model, the simulated flood was visualized at the level of 12, 25, and 35 m (Fig. 4).

4.2. Quantitative measurements for temporary installation

An urban environment is constantly evolving as a result of occasional building remodeling, which often does not necessarily keep to the originally licensed design. On many special occasions, temporary constructions are made only for a certain period of time, and are removed or demolished afterward. Traditionally, any remodeling requires approval from government before construction

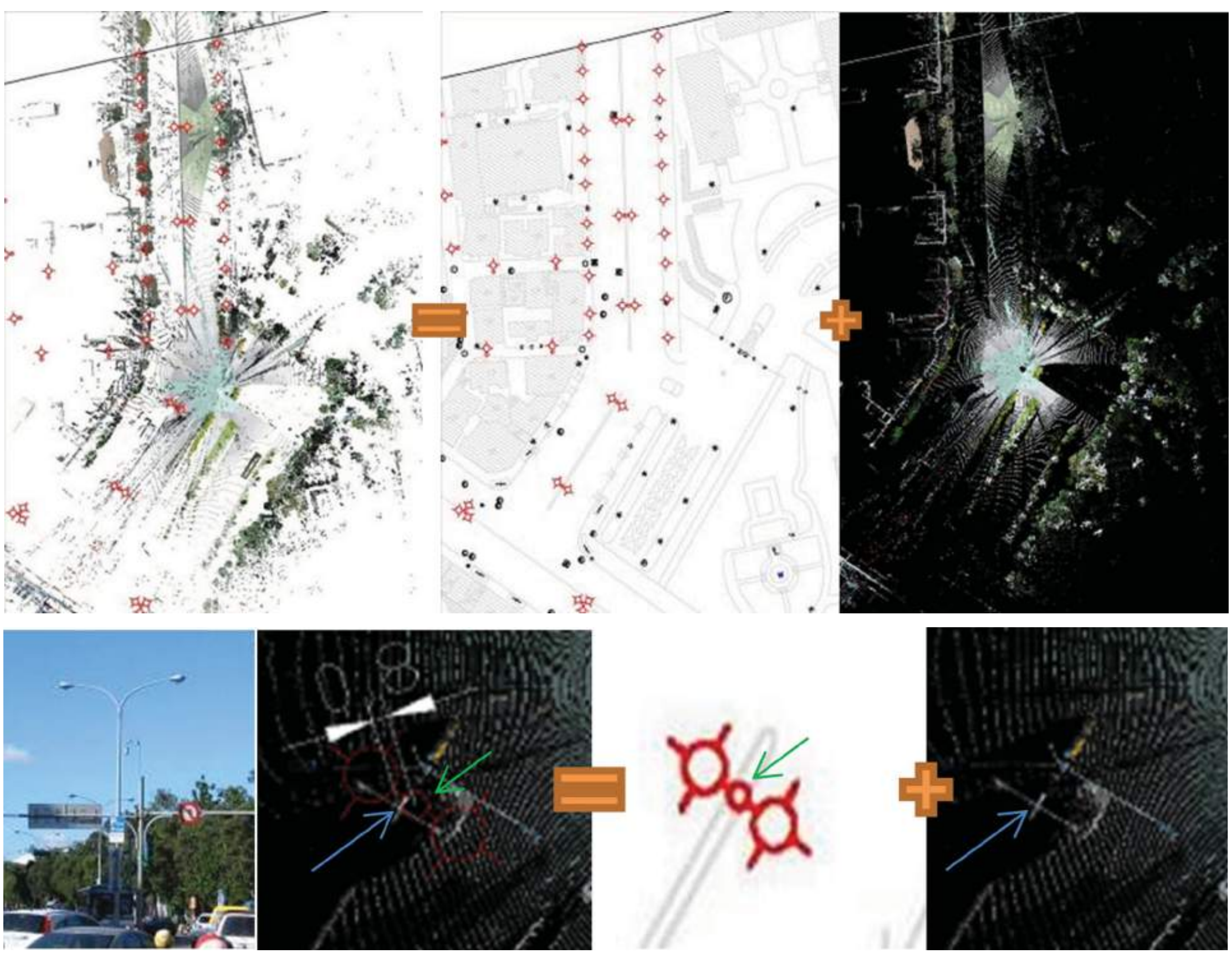

Figure 3. The integration of map and scan data (top) and a 0.8 m displacement exists between the map mark and point model (bottom).

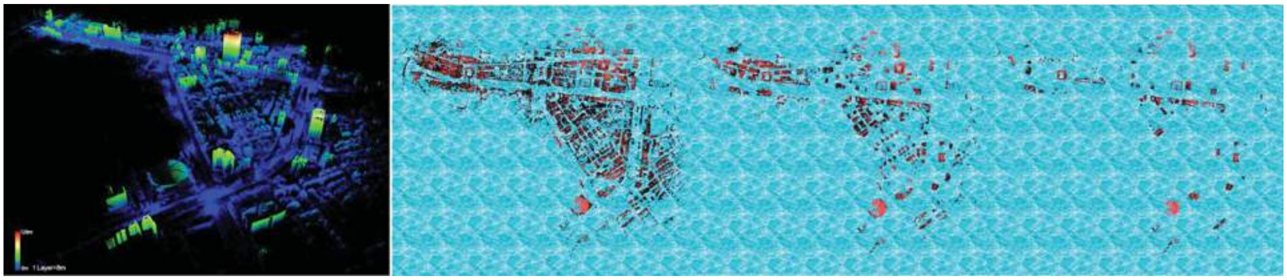

Figure 4. A simulated flood is visualized at the level of 12, 25, and 35 m.

can proceed. Filing of permanent construction can be regulated by building codes with records to be referred in the future. Temporary constructions, however, which still require license applications, have become very common recently. As a result, it has become difficult to conduct inspections if construction has been performed according to regulations or the demolition has been completed. In order to determine if the surroundings have returned to their original setting, a more dynamic and prompt checking procedure is required for this situation.

3D scans are feasible for conducting measurements at BIM LOD 500, with/out the festival-specific temporary settings [9]. For comparison at a micro scale, a scan was made at the Shin-I district (Fig. 5.). The Shan-Ti Boulevard is for pedestrian use only. The Boulevard attracts many visitors from the stores with well-planned landscape and urban furniture, especially during national holidays or festivals, with beautiful seasonal decorations. The visiting experience is a pleasant experience for both local residents and tourists. As part of the famous commercial district, the Boulevard features specific urban fabric which changes according to occasions or seasons on a micro scale. The scanned subject includes the open space decorated during festivals, and the space during Christmas 2014. A plaza around the main seasonal scene was selected for illustration. The scans have three versions: night scenes, daytime scenes and scenes outside the Christmas period. The difference indicates the relationship between temporary structures and the urban fabric (Fig. 5.).

The festival-settings, which don't appear during the rest of the year, were registered and computed using scan data. In order to compare two point clouds, two sets were well-aligned to contrast differing elements. Most of the comparison can end here, because the non-overlapped parts usually stand out from the rest, and can be visualized with properly colored clouds. To avoid potential mistakes in visual comparison, non-overlapping parts from each cloud have to be identified or isolated. An algorithmic approach is applied to eliminate or turn off the overlapped parts in terms of locations adjacent to old shape. Three empirical methods were applied and illustrated. Geomagic Studio® was used as an indirect identification approach. It has a well-controlled registration interface to facilitate the registration of one, three, or multiple reference points. Deviation analysis was illustrated in different color ranges, and was used to identify non-overlapping parts. Leica Cyclone® is similar to Geomagic Studio®, and a "compare" option can be selected in "analysis" after two clouds are registered. CloudCompare® is the most direct approach, in which a point cloud was divided into overlapped and non-overlapped parts with the deviation analysis illustrated in different color ranges (Fig. 5.).

Data collaboration was enabled cross platform in which the non-overlapped part of the cloud was imported to Geomagic Studio® for area estimation. The largest element was the Christmas tree, surrounded by many smaller objects like people or landscape elements. The area was 208 sq. meters, because there were many small differences, and the Christams tree featured a complicated configuration. The comparison can also be used to identify illegal construction, which commonly occurs at roof level. The volume can be defined, as shown in Fig. 6.

4.3. Qualitative comparison for urban historical development

A place can remain in peoples' memories by relating place identity and self-identity [4]. 2D Maps of a certain era are usually used to symbolize a memory shared by local people and visitors. For the integration of cultural characteristics and as-built 3D city models, 2D information should be extended to be registered with 3D properties [8]. The comparison between as-built urban environments and maps was conducted in two manners: 2D overlapping and 3D overlapping. The former combined 3D point projection images and map coordinates to reveal the possible trails of urban renewals. The comparisons were made to the maps by decade, starting with the Japanese rule period (Fig. 7.). The integrations with 3D scan data were made to the maps from the Japanese rule period and 1980 (Fig. 8.). In order to illustrate the changes made to a local area, partial images were enlarged to indicate where major changes occurred, and how the new buildings were

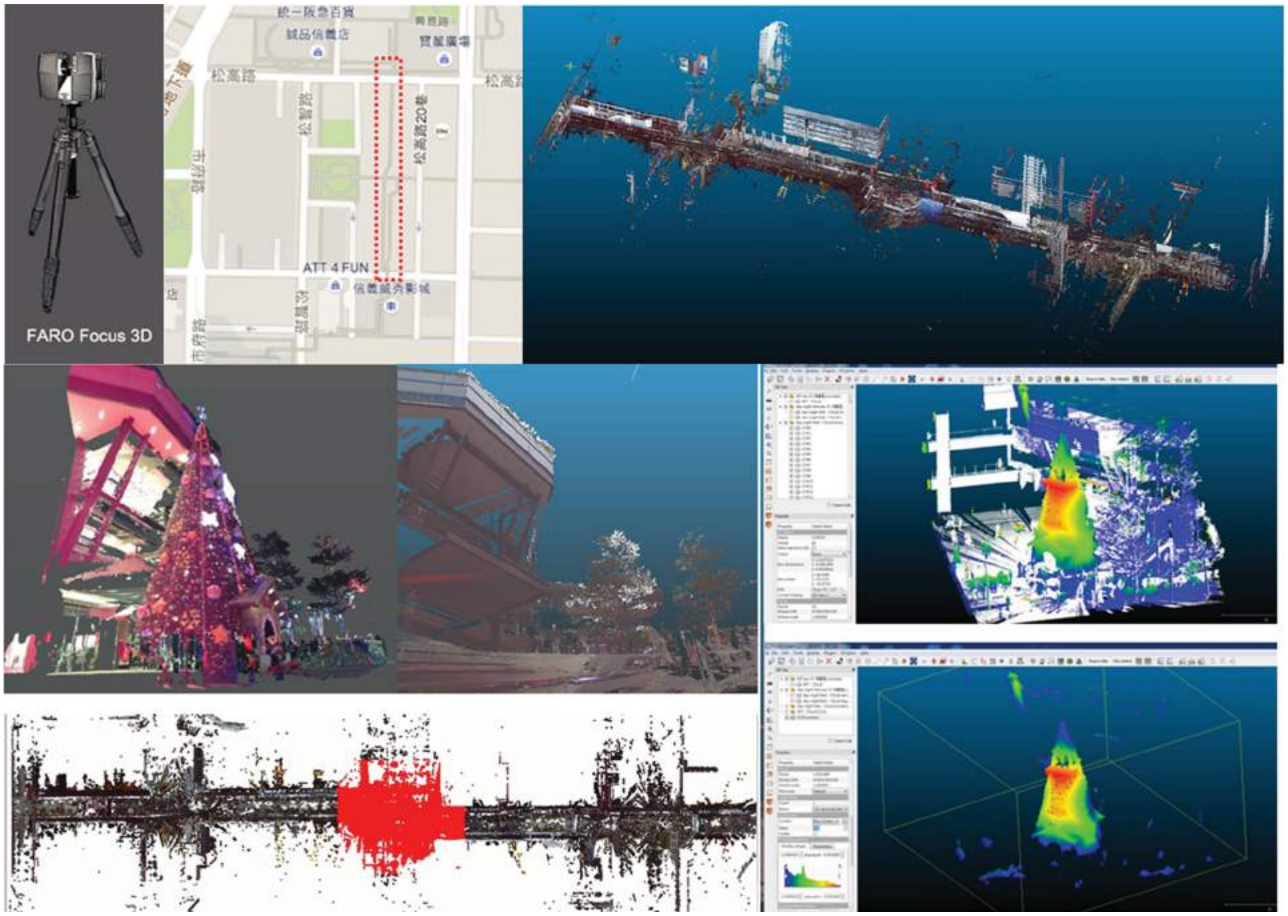

Figure 5. The illustration of temporary installation before and after Christmas.

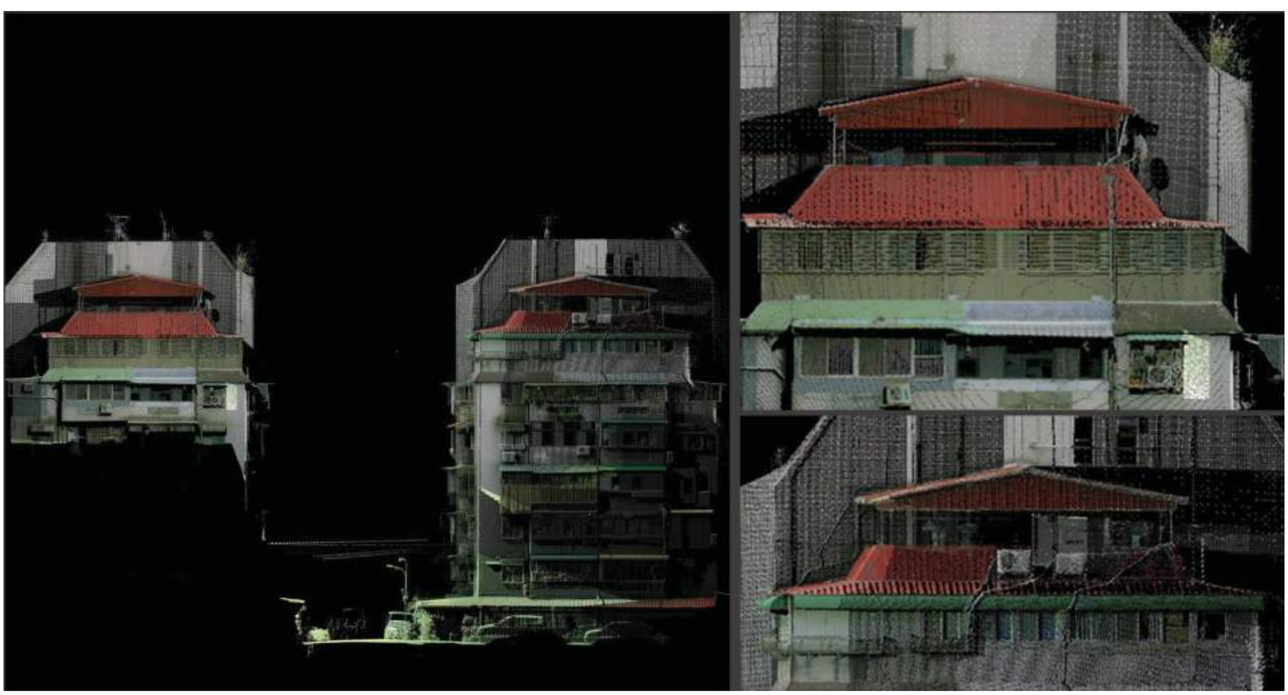

Figure 6. The point model of illegal construction.

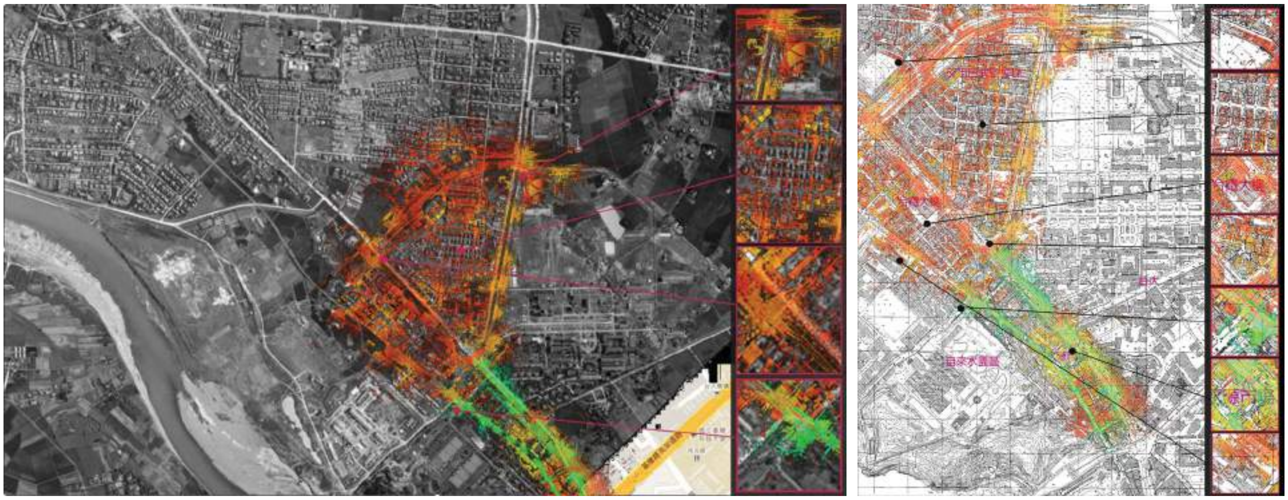

Figure 7. The comparison between the point cloud model and the aerial photos of 1945 (left) and topographic map of 1980 (right).

Figure 8. The 3D scan data integrated with the survey map in the Japanese rule period.

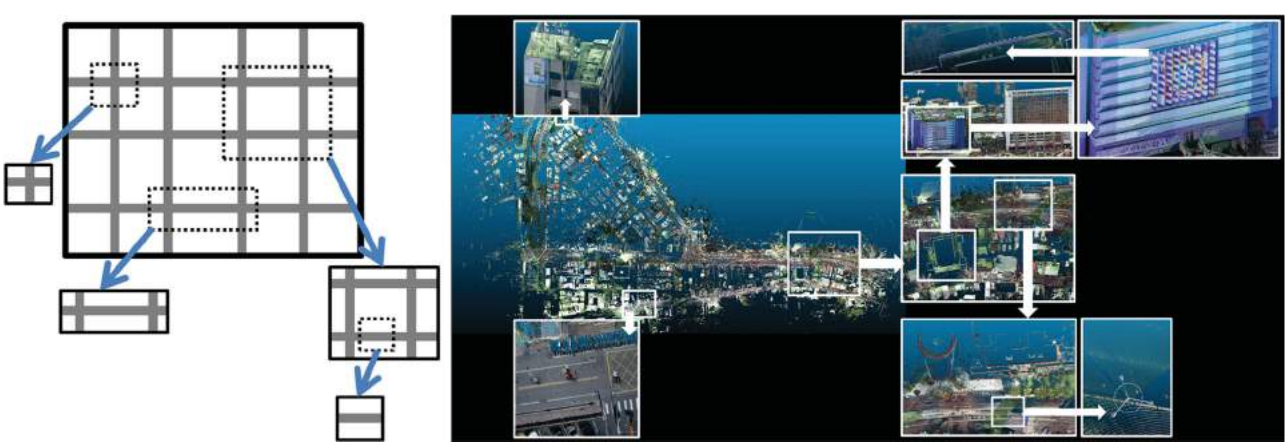

Figure 9. The conceptual map hierarchy diagram (left) and the 3D space hierarchy (right).

allocated in different colors. More information is provided with much higher accuracy than traditional 2D vector-based drawings and bitmap-based image documents. This process adds historical reference on the geographic data that enables design and practice to be aware of this chronological relationship. Although the quality of early hand-drawn maps is of concern, most of the maps are digitally regenerated by government [1].

There are 5 identified types of changes:

1. Total demolition
2. New construction after demolition
3. Renovation: Renovation with changes cannot be identified easily.
4. Deformation: Minor shape changes due to damage to existing buildings and landscape. The situation is same as above for potential difficulty in identifying the location and amount of distortion, unless as-built scans are conducted.
5. Relocation of facilities: Miscellaneous objects like electricity poles can be measured in terms of direction or distance to their previous locations.

5. Conclusion

The quantitative and qualitative comparisons were made to inconsistent data types, which were also represented in inconsistent hierarchies. This study has proved that the map hierarchy can be replaced by 3D spatial hierarchy of scan data under different scales (Fig. 9.). Instead of system-dependent exemplification, spatial data maintain details and can be applied cross different software platforms. The development of test starts from a combination of data retrieval platform in different scopes and resolutions: from Leica HDS 3000® with Faro Focus 3D® to Faro Focus 3D® only, from a larger scope of urban framework scan to the registrations with detail scans.

In order to support a study from an urban scale to a detailed level, data must be collected and carefully integrated for the most effective illustration of issues. Initially, it is the characteristics of data that distinguish different phases or scales of comparison. From there, a process enables a quantitative evaluation and allows an area of interest to be identified. As a result, a systematic structure is provided for such inspections, in BIM 500 level, using a publicly accessible CAD platform (PC and off-shelf software). By referring to the original BIM or GIS, the identification of different parts is outlined for measurement or evaluation. The cross-reference base is created, and can refer to urban chronological development, local update information, construction quality or even the misalignment of objects or facilities like street lamps.

The scan data collected in this study are accurate that they can be shared across government departments as the most updated digital reference for urban fabric study. A point model also has broader scope to be used as a reference for all possible future inspections. Periodic scans at the same locations are always recommended for the life cycle maintenance of building and urban data.

Acknowledgement

This research is sponsored by the Ministry of Science and Technology (former National Science Council) of ROC. The involved project numbers are NSC 101-2221-E-011-160, NSC 102-2221-E-011-118-MY2 and MOST 104-2221-E-011-131. The authors express sincere appreciation for this support.

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References

[1] Department of Urban Development: Taipei City Government: Historical maps, 2014. http://www.historygis.udd.taipei.gov.tw
[2] Dold, C.; Brenner, C.: Automatic matching of terrestrial scan data as a basis for the generation of detailed 3D city models, *International Archives of Photogrammetry and Remote Sensing, Remote Sensing and Spatial Information Sciences 35 (Part B3)*, 2004, 1091–1096. http://citeseerx.ist.psu.edu/viewdoc/summary?doi = 10.1.1.67.4419
[3] Fruh, C.; Zakhor, A.: Constructing 3D City Models by Merging Aerial and Ground Views, *3D Reconstruction and Visualization, IEEE Computer Graphics and Applications*, 23(6), 2003, 52–61. https://doi.org/10.1109/MCG.2003.1242382
[4] Hull, R. B.; Lamb, M.; Vigo, G.: Place identity: symbols of self in the urban fabric, *Landscape and Urban Planning*, 28, 1994, 109–I 20. http://doi.org/10.1016/0169-2046(94)90001-9
[5] Kim, H.; Kang, Y.; Han, S.: Automatic 3D City Modeling Using a Digital Map and Panoramic Images from a Mobile Mapping System, *Mathematical Problems in Engineering*, Vol. 2014, Article ID 383270, 2014, 10 pages. http://doi.org/10.1155/2014/383270
[6] Lafarge, F.; Mallet, C.: Creating large-scale city models from 3D-point clouds: a robust approach with hybrid representation, *International Journal of Computer Vision, Springer Verlag*, 99 (1), 2012, 69–85. http://doi.org/10.1007/s11263-012-0517-8
[7] Mali, S.; Panhalkar, S.; Pawar, C.; Das, S.: Generation of 3-D City Model for Urban Utility Information System Using Digital Photogrammetry & GIS Technology, *Global Journal of Researches in Engineering General Engineering*, 12(3), Version 1.0, 2012, 26–30. https://www.researchgate.net/publication/282002657_

Generation_of_3-D_City_Model_for_Urban_Utility_Information_System_Using_Digital_Photogrammetry_GIS_Technology

[8] Nebiker, S.; Bleisch, S.; Christen, M.: Rich Point Clouds in Virtual Globes - A New Paradigm in City Modeling? Computers, *Environment and Urban Systems*, 34, 2010, 508–517. http://doi.org/10.1016/j.compenvurbsys.2010.05.002

[9] Shih, N. J.: A Three-Dimensional As-Built Data Based Comparison of the Temporary Urban Fixtures during Special Occasions, *Proceedings of the Fifteenth International Conference on Civil, Structural and Environmental Engineering Computing*, J. Kruis, Y. Tsompanakis and B.H.V. Topping, (Eds), Prague, 2015, 1–7. http://ir.lib.ntust.edu.tw/handle/987654321/65606

[10] Shih, N. J.; Lee, C. Y.; Jhan, S. W.; Wang, G. S.; Jhao, Y. F.: Digital Preservation of a Taiwanese Historical Settlement: Using 3D post-construction scan to develop an application framework and reference for Beipu Township, *Cities*, 28, 2011, 193–205. http://doi.org/10.1016/j.cities.2010.05.003

[11] Shih, N. J.; Tzen, S. C.; Chan, T. Y.; Lee, C. Y.: Cross-Verification of As-Built Point Cloud and GIS-Related Map Data, *Open Journal of Civil Engineering*, 3, 2013, 219–227. http://doi.org/10.4236/ojce.2013.34026

[12] Shojaei, D.: Chapter 9: 3D Visualisation as a Tool to Facilitate Managing Land and Properties, In: A. Rajabifard, I. Williamson and M. Kalantari, Ed., *A National Infrastructure for Managing Land Information - Research Snapshot, The University of Melbourne, Centre for Spatial Infrastructures and Land Administration, Department of Infrastructure Engineering*, 2012, 88–94. https://minerva-access.unimelb.edu.au/bitstream/handle/11343/32729/288634_Chapter9-3DVisualisation.pdf?sequence=1

[13] Singh, S. P.; Jain, K.; Mandla. V. R.: Virtual 3D City Modeling: Techniques and Applications, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-2/W2, ISPRS 8th 3D GeoInfo Conference & WG II/2 Workshop*, 27–29 Nov. 2013, Istanbul, Turkey. http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-2-W2/73/2013/isprsarchives-XL-2-W2-73-2013.pdf

[14] Stadler, R.; Kolbe, T. H.: Spatio-semantic Coherence in the Integration of 3D City Models, Commission II, WG II/7, 2013. http://www.isprs.org/proceedings/XXXVI/2-C43/Session1/paper_Stadler.pdf