Construction and Visualization of Photo-Realistic Three-Dimensional Digital City

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***Abstract*—This paper presents systematic approaches to create photo-realistic three-dimensional (3D) digital city systems. In the created 3D digital city systems, prismatic and polyhedral building models are constructed from assorted remote sensing and spatial datasets, including topographic maps, aerial and satellite images, airborne and ground-based LIDAR point clouds. Close-ranged digital photographs and video sequences are used to generate facade texture images for photo-realistic texture mapping of the constructed building models. High performance visualization algorithms based on Level of Detail (LOD) processes are also implemented for real-time, interactive exploration and applications. A few applications of the constructed 3D digital cities to urban development evaluation, environmental simulation, hazard mitigation and crime scene reconstruction are presented to demonstrate the usability of the developed 3D digital city system.**

I. Introduction

Three-dimensional (3D) digital city or cyber city is one of the emerging and fast-growing topics in the research and applications of spatial information science and geoinformatics. Among the various subjects in 3D geoinformatics, cyber city probably has the most sophisticated extent. A cyber city is a virtual replica of a real city in a computer-generated environment. It not only resembles the layouts and geometry of various city objects, but also should contain the activities and functionality of a real city. The implementation of a cyber city requires the integration of remote sensing, geographic information systems (GIS), information and network technologies. As the technologies in remote sensing advance, new types of data from assorted sensors and with different characteristics have become available for the reconstruction of important objects that constitute a city. Similarly, the new technology developments in geoinformatics have enabled cyber city systems with advanced designs and implementions as well as more powerful processing and analysis capabilities for sophisticated applications that are difficult to achieve previously. On the other hand, the integration of visualization and 3D geoinformatics provides an intuitive platform for effective analysis and decision support, especially for users not familiar with technical issues and operations.

The applications of cyber city range from simple mapping and information display to complicated tasks such as city and regional planning, virtual tourism, intelligent transportation systems, and decision support for disaster management, hazard mitigation and other activities. This research developed a sophisticated 3D digital city system fore real-time and interactive cyber city applications. The developed system comprised of photo-realistic terrain and building models reconstructed from remote sensing data and associated attributes in GIS layers. The constructed 3D prismatic and polyhedral building models conform to the OGC (Open Geospatial Consortium) Level-2 CityGML standard and have photo-realistic facade texture attributes generated from close-ranged digital photographs and video sequences. Advanced visualization algorithms were also developed to provide high rendering performance for real-time applications. A few applications of the developed systems to urban development planing, environmental simulation, hazard mitigation and crime scene reconstruction are also presented to demonstrate the usability of 3D digital city systems.

II. Construction of 3D Digital City

Terrain, buildings and roads are probably the most important objects in a digital city. Three-dimensional models of these objects can be constructed from different remote sensing and spatial data sources. For example, digital terrain models (DTM) can be reconstructed from LIDAR (Light Detection and Ranging) survey or stereo aerial photographs. However, different datasets have different characteristics. For instance, optical airborne and satellite images provide good spectral information of ground targets but with little geometric properties. On the other hand, LIDAR point clouds are accurate in range measurement but they are discrete and without topological relationship. Consequently effective strategies and algorithms must be employed to fully utilize the advantages of different data. As buildings are the most ubiquitous objects in

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a city, building modeling is a critical factor in the construction of 3D digital city. Therefore, issues of generating 3D building models with photo-realistic texture attributes are the focus of this section.

A. *Bare Bone Building Models*

The building models used in the developed 3D digital city are primary prismatic and polyhedral models with flat or complicated roof structures, which are conforming to the Level-2 model of OGC CityGML standards. These models are constructed from topographic maps, aerial photos and LIDAR surveys. These datasets can be used independently or by data fusion.

The procedure of constructing building models with topographic maps is illustrated in Fig. 1. Topographic maps provide accurate 2D outlines of buildings but only annotate the number of floors of each building. Therefore, they can be used to quickly construct block-based building models but without roof structures.

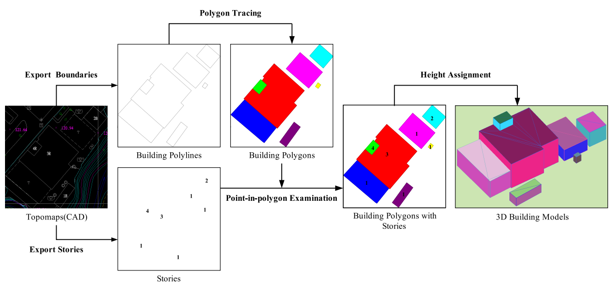


Figure 1. Building modeling from topographic maps.

Stereo aerial photographs, on the other hand, provide better information about building roof structures. However, traditional photo-synthesis procedures for constructing 3D models from aerial images require intensive human interactions to extract point and line features from images. A procedure was developed to extract 3D line segments from aerial photos and to shape them to polyhedral building models as illustrated in [1] and Fig. 2. Similarly, LIDAR surveys provide accurate and more complete roof structures, but they are discrete point clouds. A procedure as displayed in Fig. 3 was developed to construct 3D building models from LIDAR point clouds.

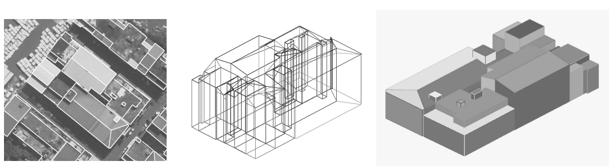


Figure 2. Building reconstruction from aerial photographs.

As mentioned previously, these data sets can be used independently or by data fusion for building reconstruction to increase the efficiency and provide better results. For example, coupling the vector topographic maps and LIDAR data is an effective approach for efficient building reconstruction because

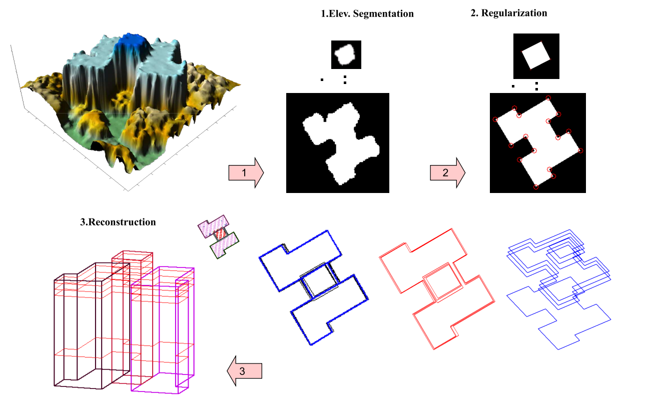


Figure 3. Building reconstruction from LIDAR data.

topographic maps have accurate building outlines but without real building heights and roof information while LIDAR data are excellent for extracting building heights and roof structures but original LIDAR point clouds provide no topological information. A split-merge-shape algorithm as demonstrated in Fig. 4 was developed to fully utilize the advantages of both datasets for the reconstruction of complex building models [2][3]. Similar techniques can also be applied to the reconstruction of 3D road models [4].

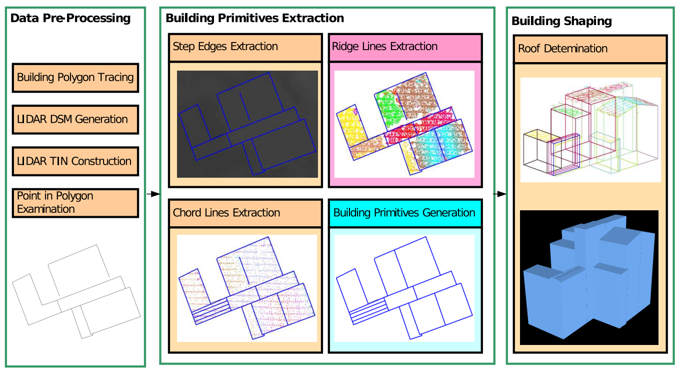


Figure 4. Fusion of LIDAR and vector map for building models.

B. *Photo-realistic Digital City*

The algorithms described above create only “bare-bone” models, i.e., only geometric properties of buildings are constructed. For a photo-realistic digital city, another important task is to provide realistic textures of terrains and facades of building models. Terrain texturing can be achieved by draping aerial or satellite images onto terrain meshes. Building facade texturing is a more complicated issue. Shading building models with pseudo or generic textures is a commonly adopted technique in visualization. However, this only produces attractive visual effects of generated scenes instead of representing true texture attributes of buildings.

This study developed several algorithms to generate true facade texture images interactively or semi-automatically from close-ranged digital images and video sequences and to map them onto corresponding building model facets. The textured city models not only have photo-realistic look and feel, but also can provide accurate texture attributes that are critical in certain applications. A polygon-based algorithm was developed to merge multiple texture blocks from overlaped close-ranged digital images for generating complete facade textures and mapping them onto corresponding model facets [5]. However, this method requires interactive operations to select areas of interest from individual texture images. This study further developed an interest-point-based image mosaicking algorithm to automatically merge overlapped images or video sequences in order to generate complete facade textures more efficiently.

First, possible interest points on overlapped images or video frames are identified using the Harris Corner Detector [6]. A corner is determined by the local maximum of cornerness function:

$$C = \det M - k\,(traceM)^2 \tag{1}$$

where k is a constant set to 0.04. The M matrix measures gradient changes of an image, I, with a window weighting factor, $w_{u,v}$:

$$M = \begin{bmatrix} \left(\frac{\partial I}{\partial x}\right)^2 \otimes w_{u,v} & \left(\frac{\partial I}{\partial x}\right)\left(\frac{\partial I}{\partial y}\right) \otimes w_{u,v} \\ \left(\frac{\partial I}{\partial x}\right)\left(\frac{\partial I}{\partial y}\right) \otimes w_{u,v} & \left(\frac{\partial I}{\partial y}\right)^2 \otimes w_{u,v} \end{bmatrix} \tag{2}$$

and $w_{u,v}$ can be specified as a Gaussian filter to reduce noise:

$$w_{u,v} = e^{-\left(u^2+v^2\right)/2\sigma^2} \tag{3}$$

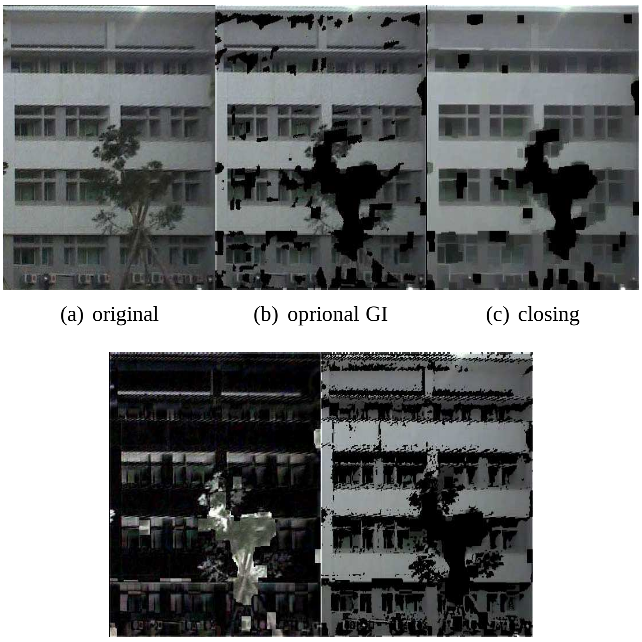
The identified corner points are filtered with non-maximum suppression and matched according to the "relative image displacement" and two iterations of Normalized Cross-Correlation (NCC) defined as:

$$r_{uv} = \frac{\sum_{u,v}\left[G_t(u,v) - \bar{t}\right]\left[G_s(u,v) - \bar{s}\right]}{\sqrt{\sum_{u,v}\left[G_t(u,v) - \bar{t}\right]^2}\sqrt{\sum_{u,v}\left[G_s(u,v) - \bar{s}\right]^2}} \tag{4}$$

where $\bar{t}$ and $\bar{s}$ are means in the target and search windows.

Another important issue in generating facade textures from close-ranged images is the identification and correction of occlusions commonly seen on the original texture images. A morphological based procedure was developed to automatically identify occlusions effectively. As displayed in Fig. 5, if the occlusion is caused by road trees or other plants, a Greenness Index (GI) filtering, as listed in (5), can be applied; then morphological closing and bottom-hat operations are performed consequently to remove occluded pixels. One thing to note is that the GI filtering is useful for quickly identifying plant occlusions, but it is not critical. Image morphology is the primary engine of occlusion removal, with or without GI filtering.

$$GI = (Green - Red)/(Green + Red) \tag{5}$$



(a) original (b) oprional GI (c) closing

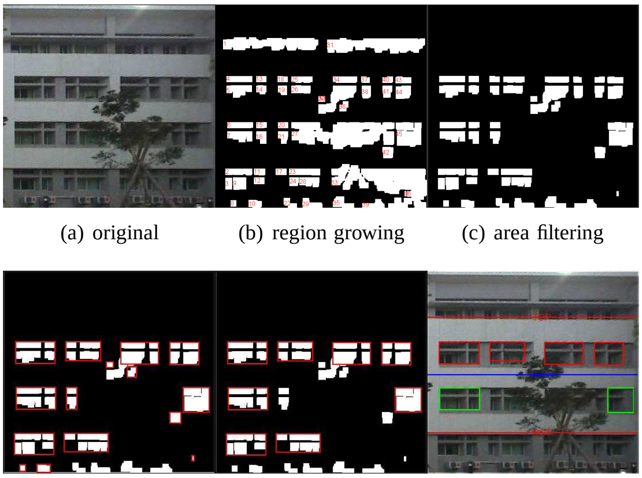
(d) bottom hat (e) result

Figure 5. Occlusion removal by image morphology.

After removing occlusions, the blanks need to be filled with reasonable information to generate complete textures. This was done automatically with a self-mending algorithm developed in this study. Because most building facades have symmetric appearances, if the axis and range of symmetry can be correctly identified, the occlusions can be corrected by a mirroring operation. As displayed in Fig. .6, the process consists of region growing, (first) histogram area filtering, homogeneity test, (second) area filtering and location filtering, consecutively. With this algorithm, most of the occlusions can be corrected efficiently, as displayed in Fig. 7. Finally, the generated facade texture mosaics are mapped onto corresponding building model faces by linear or parametric transformations [5] to create photo-realistic 3D building models with complete and accurate texture attributes.

III. LOD for Visualization

A photo-realistic 3D digital city may consist of large terrain meshes, hundreds to thousands of building models and other objects as well as numerous images. The vast amount of data of a 3D digital city poses a great challenge to the visualization and analysis, especially for real-time applications. Therefore, it is necessary to develop high performance visualization and analysis algorithms for efficient real-time, interactive applications. To this regard, level of detail (LOD) is a commonly adopted technique to increase the system performance. This study utilizes a tile-based view-dependent approach for data transmission and graphical rendering. The idea is that only visible tiles need to be processed and only changed data need to be processed. As a result, the reconstructed 3D digital city is divided into several tile blocks and multiple LOD datasets



(a) original (b) region growing (c) area filtering

(d) homogeneity test (e) area filtering (f) location filtering

Figure 6. Procedure of self-mending facade occlusions.

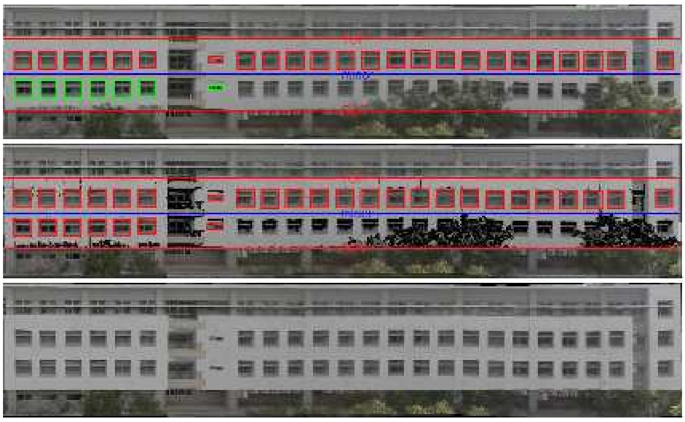


Figure 7. Result of occlusion removal and mending.

are prepared for terrain meshes and building models in each tile. In a real-time application, the scene is rendered from coarse to fine according to viewing parameters to provide high performance and smooth visualization.

A. Terrain LOD

For large terrain meshes, an adaptive LOD algorithm based on quad-tree mesh simplification [7] was adopted to generate multiple levels of terrain meshes for individual tile blocks. A critical issue of quad-tree based process is the selection of appropriate thresholds for different levels to minimize the meshes while preserve terrain features of different resolutions. In this study, the thresholding scheme was determined from ground sampling distances (GSD) of viewing geometry as illustrated in Fig. 8. The GSD at a particular viewing distance, D, is calculated from:

$$GSD = \frac{D \times \tan(\theta)}{\cos(\gamma)} \quad (6)$$

where

$$\theta = \frac{FOV}{\text{pixels per scanline}} \quad (7)$$

The advantage of using GSD to determine appropriate quad-tree thresholds is that it can find suitable screen (pixel) resolutions adaptive to different viewing conditions, thus avoiding under-sampling or over-sampling of terrain meshes while preserving terrain features in different level of details.

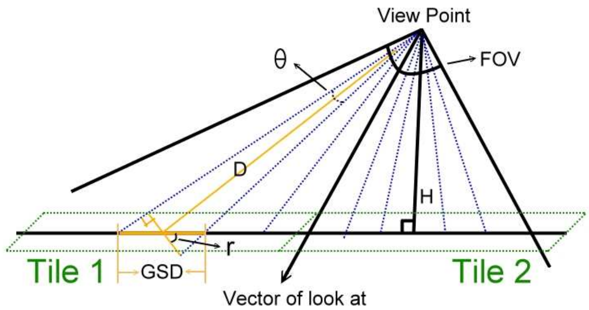


Figure 8. Ground sample distance (GSD).

To further improve the performance of large terrain rendering, instead of storing mesh data of all LOD levels, a diff-vector recording differences between each pair of adjacent LOD sets is created to reduce the data amount required for transmission and avoid redundancy. Other issues such as patching up cracks (T-junctions) caused by discontinuity between adjacent tiles were also dealt with to create seamless terrain rendering of the constructed 3D digital city systems during real-time visualization.

B. Building LOD

As buildings are the most ubiquitous object in a city, rendering all buildings would be a bottle neck for real-time visualization of a cyber city system. In addition to tile-based process, LOD for building models may also required to increase the visualization performance. In this study, building models in different LODs are generated by a divide-and-conquer strategy. The algorithm is modified from the simplification on 2D orthographic projects of 3D building models [8]. This algorithm is effective in generalizing prismatic and polyhedral building models with U-, Z- and L-shaped structures and different roof types. The general procedure is illustrated in Fig. 9.

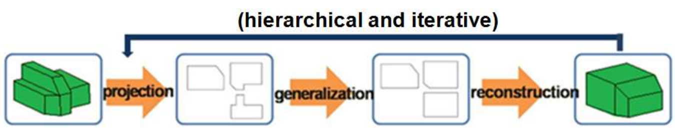


Figure 9. Building generalization by simplification of ortho-projections.

At least three orthographic projections are generated from the original building models. Individual orthographic projections are simplified according to a pre-set generalization threshold to reduce detail features. Generalized building models are then reconstructed from simplified orthographic projections. This process can be repeated with different generalization thresholds to create models in multiple levels of detail. An example of the building generalization is demonstrated in Fig. 10.

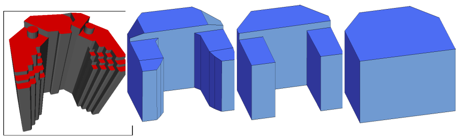


Figure 10. Building LOD example.

Combing the terrain and building LOD algorithms with image pyramid process for terrain and facade texture images, the visualization of the constructed 3D digital city can be rendered efficiently. With the developed LOD algorithms, the system can have high-performance visualization while dynamically preserve important object features according to different viewing parameters. This makes the system more suitable for real-time exploration, analysis and applications.

IV. Example Applications

The developed 3D digital city system was used in several applications to evaluate its usability and performance. Fig. 11 shows the photo-realistic reconstruction of a shoot-out event which resulted in a fatality of a suspect. The reconstruction was based on Level-2 CityGML models generated from aerial photographs and 1/1000 topographic maps and augmented with ground-based LIDAR scans to created more detail (Level-3 CityGML model) building structures for targets of interest. Investigators can interactive explore the digital crime scene to determine trajectories and possible time-stamps of all shots fired. This enables them to reconstruct the event and to ascertain whether the police had used deadly force excessively.

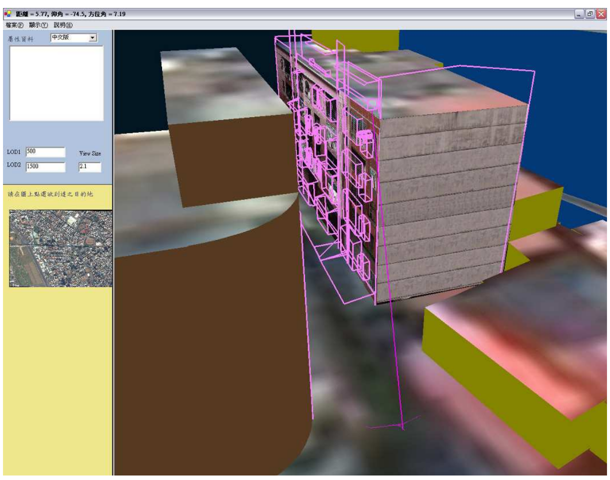
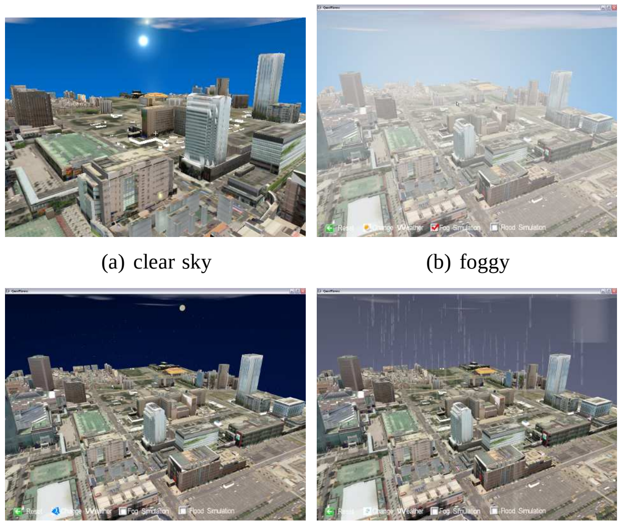


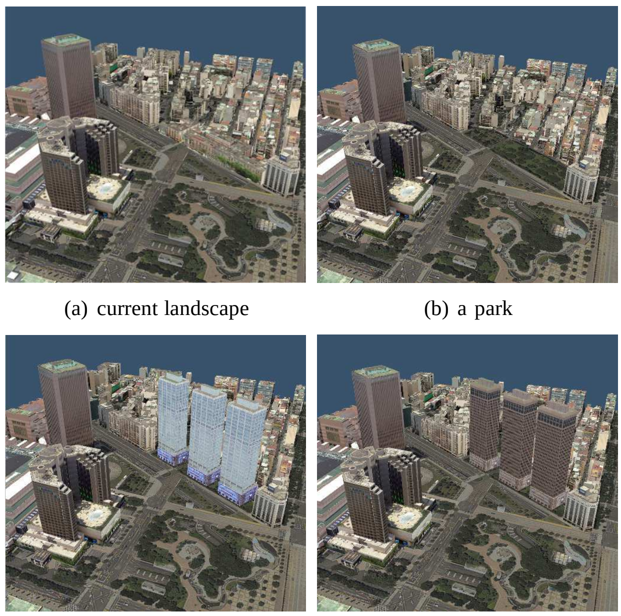
Figure 11. Crime scene reconstruction.

Fig. 12 demonstrates an example of applications to the environment simulation of a city landscape (a district in Taipei). Similar simulations can be very useful for urban development planning. For example, there is a plan to renew an old residential and commercial area in a district of Taipei. Planners can use a photo-realistic 3D digital city system to evaluate the change of landscapes and the impacts to the surrounding areas in different scenarios as displayed in Fig. 13. For this type of applications, photo-realistic 3D digital city system provides an intuitive platform for better decision support.



(a) clear sky (b) foggy (c) moonlight (d) rainy

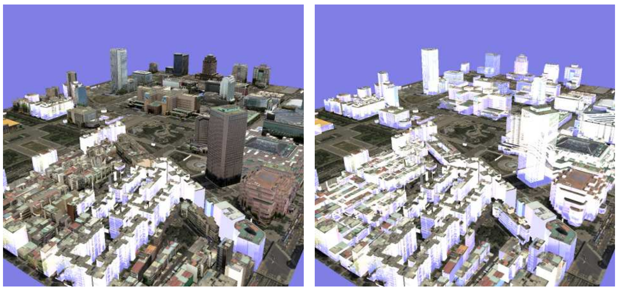
Figure 12. Simulation of cyber city environment.



(a) current landscape (b) a park (c) new buildings-1 (d) new buildings-2

Figure 13. Urban development planning application.

The developed 3D digital city system not only has a realistic look-and-feel of the real city but also provides important parameters that are difficult to obtain from traditional data for sophisticated simulation and modeling analyses. For example, solid textured buildings in Fig. 14 are the ones with 50% or higher probability of moderate damages (Fig. 14a) and with 20% or higher probability of serious damages (Fig. 14b), respectively, after a simulated severe earthquake. In this case, some important input parameters, such as building height, number of floors, centroid, volume and the like, for urban earthquake damage modeling were derived from the 3D digital city model and an advanced earthquake modeling system [9] was employed for the assessment of building damage potentials. The resultant building damage potentials were then fed back to the 3D digital system for visual-enabled exploration and analysis.



(a) 50%+ moderate damage (b) 20%+ serious damage

Figure 14. Building damage potentials of urban earthquake modeling.

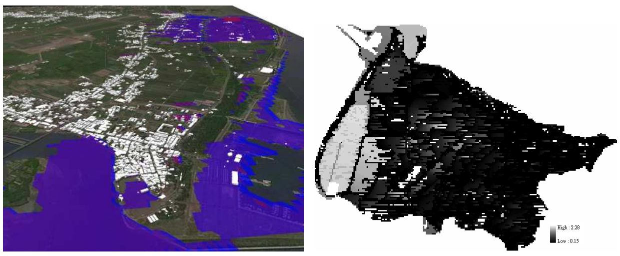


Figure 15. Potential flood perils of a 200-year frequency flood modeling.

Similar applications were also applied to the modeling of flooding potentials. Some of the required modeling parameters can also be determined more efficiently from the 3D digital city model. Combined with a sophisticated flooding modeling algorithm [10], the estimated potential flood perils were returned to the digital city system for analysis. Fig. 15 displays the potential perils of a 200-year frequency flood modeling in 3D and a conventional 2D flood map. In addition to the locations in the digital city, the potential depth of flood perils is colored from blue to red (shallow to deep). Comparing with the traditional 2D flood map, the 3D digital system not only is more intuitive, but also provides richer information as well as useful spatial information for subsequent analysis. This can be very helpful in applications such as hazard evaluation and mitigation, decision support and risk assessment. More importantly, photo-realistic 3D digital city systems may provide the opportunities to carry out more sophisticated applications that are difficult to achieve using conventional 2D datasets and methods.

V. Conclusion

This study developed systematic approaches to implement photo-realistic 3D digital city systems capable of real-time visualization and applications. Prismatic and polyhedral building models were constructed from multiple data sources, including vector topographic maps, aerial and high resolution satellite images, airborne and ground-based LIDAR surveys, independently or by data fusion. Realistic facade textures were generated from close-range digital images and video sequences interactively or with automatic feature-matching algorithms. Occlusions of facade textures were identified and rectified automatically with morphological operations and a self-mending procedure. The constructed 3D city model has not only correct geometric layouts and properties but also photo-realistic appearances with accurate texture attributes. Tile-based view-dependent rendering algorithms and LOD processes were also developed for high-performance visualization. Combined with spatial databases, the developed system can be used in real-time, interactive exploration of a 3D digital city and sophisticated applications.

Example applications presented in this paper demonstrate the usability and performance of applying the developed digital city system to a variety of applications, including crime scene reconstruction, environment simulation, urban development planning, hazard modeling for evaluation and mitigation. The developed photo-realistic 3D digital city system is a powerful, intuitive platform for presentation, analysis, decision support and other spatial applications, which should increase the social impact of remote sensing and geoinformatics technologies.

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