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Graph Search and its Application in Building Extraction from High Resolution Remote Sensing Imagery

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1. Introduction

Man-made object recognition from remotely sensed imagery is not only scientifically challenging but also of significant practical importance for spatial data acquisition and update of geographic information system databases, mapping, cartography, image interpretation, military activities and other applications, etc. In the literature, a large amount of work that has been done in the field of high resolution image understanding focuses on the development of efficient and robust algorithms to detect and extract typical man-made objects, such as buildings and roads. Most methods for building extraction can be classified into two categories: edge-driven approaches and region-driven approaches. The edge-driven approaches usually involve a procedure of bottom-up processing of image primitive features, trying to link or group the linear features corresponding to a building to obtain building boundary. In a region-driven strategy, various methods, such as artificial neural networks, support vector machines, machine learning strategies and other traditional classification schemes in pattern recognition are employed to categorize the regions derived by segmentation based on region features. The following section briefly reviews the methodologies of these two categories available in the literature.

Edge-driven methods, such as perceptual grouping and contour tracing, are widely used for building extraction in the literature. Perceptual organization (Mohan and Nevatia 1989) was used to detect and describe buildings in aerial images. There, linear features are firstly extracted and grouped into parallel lines. Parallel lines with aligned endpoints trigger the formation of a U structure. Two U structures trigger the formation of a rectangle hypothesis which is further filtered. Katartzis and Sahli (2008) proposed a method based on a stochastic image interpretation model, using a novel contour-based grouping hierarchy under the principles of perceptual organization. The BABE (Buildup Area Building Extraction) system (McKeown 1990) performed perceptual organization of lines and orthogonal corners into chains and rectangles to form building hypotheses that were further verified using shadow information. Lin and Nevatia (1998) derived the geometric relationship between building margin lines and building shadows analytically according to a general illumination model.

Zheltov et al. (2001) used the line extraction method proposed by Burns et al. (1986) and combined it with a rectangular building model to extract buildings from aerial images. Karantzalos and Paragios (2009) introduced a recognition-driven variational framework which facilitates automatic and relatively accurate multiple building extraction from aerial and satellite images.

Region-driven methods are also widely used for building extraction in the literature. Fua and Hanson (1987) first segment an image into regions, and extract edges corresponding to region boundaries, and then determine any if there was evidence of geometric structures among the edges to classify a region as a man-made object. Lee et al. (2003) proposed an approach using classification results of IKONOS multi-spectral images to provide approximate locations and shapes for candidate buildings. A fine extraction is then carried out in the corresponding panchromatic image by segmentation and squaring. Baatz and Schäpe (2000) proposed a method that combines multi-scale region segmentation with an object-oriented decision tree classifier to classify target by analysing the spectral, texture and context information. In (Matsuyama and Hwang 1985) a region segmentation method was used and the relationships between objects such as roads and houses are used to improve detection performance. Segl and Kaufmann (2001) combined supervised shape classification with unsupervised image segmentation for the detection of small buildings in suburban areas.

Although many techniques have been proposed to address the task of building detection and mapping using high resolution imagery, there are still many challenges resulting from the complexity of a scene. Most of the edge-driven approaches lack a well-founded formulation of the grouping process to derive the relationship among randomly distributed and fragmented linear features. Although many endeavors (Matsuyama and Hwang 1985, Huertas and Nevatia 1988, Venkateswar and Chellapa 1986, Mohan and Nevatia 1989, Irvin and McKeown 1989) have been made to link or group the line segments corresponding to buildings to obtain a desired building boundariy, this problem can still not be addressed robustly. Region-driven building extraction strategies, also encounter the problem of fragmentation as the region of a building may not be homogenous. There are also a number of strategies reported in the literature which combine linear feature extraction and image segmentation. These strategies offer a better solution compared to approaches that rely merely on edges or regions as the integration of complementary methods helps to overcome the drawbacks of individual methods. However, this category of methods usually can not fully utilize the complementary information of edges and regions. Therefore, most of these methods are not able to extract buildings robustly and efficiently in the presence of noise and interfering structures and it remains impossible to extract small structures.

Therefore, based on the robustness of the Hough transformation and the capabilities of graph in shape representation, we propose a robust approach for building description and extraction from high resolution remotely sensed imagery. In the literature, although there are also some graph-based approaches, most of them can not extract the exact building boundary robustly and the graph construction procedures are usually complex. Jaynes et al. (1994) proposed a method to represent feature relationships by a weighted feature relation graph. However, the construction of this relation graph requires a complex grouping strategy. Kim and Muller (1999) utilized a graph to describe the relationship of the lines, followed by the extraction of the cheapest cost in a function. Yet, their graph construction is still based on a complex grouping process. Croitoru and Doytsher (2004) used a graph approach to express building structures. A search algorithm is used to extract node sequences corresponding to a building model. However, as a model based approach, it is restricted to certain types of buildings. Sirmaçek and Ünsalan (2009) employed a scale invariant feature transformation (SIFT) and graph theoretical tools, which may fail in dense urban areas and is also restricted by building models.

2. Methodology

In practice, most building roofs in urban areas and industrial centers are rectangular or combinations of several rectangles. Therefore the extracted building polygon should be dominated by rectangles. In this sense, Hough transformation is an efficient strategy to extract perpendicular and parallel lines which comprise the structure of a building. To be more efficient and robust, the extraction scheme should incorporate region information of the building since the integration of edges and regions provides complementary information. Therefore, we propose the scheme demonstrated in Fig.1 to address the problem of building extraction with four main steps as described below.

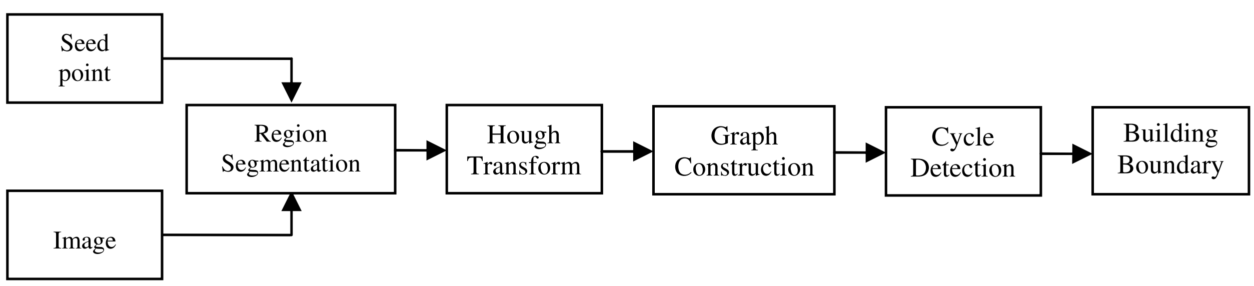


Fig. 1. Extraction workflow

2.1 Building region segmentation

In the first step, a region growing method is employed to derive the approximate building region due to its simplicity and low computational complexity, but could be replaced by other sophisticated image segmentation algorithms at a local neighborhood as used in the first experiment, such as mean shift image segmentation (Comaniciu and Meer 2002). For region growing segmentation, the user has to determine the building manually by selecting the position of the building in the image, and define a threshold used for the stop criterion. After derivation of the building region, edge detection or contour tracing is applied to get the approximate outline, which is usually needed as the input for the following Hough transformation.

2.2 Parallel and perpendicular line detection by hough transformation

The commonly used methods for straight lines extraction are based on various edge detection techniques followed by a chain code extraction process, such as the Douglas-Peuker algorithm (Douglas and Peuker 1973). Then the chain codes are segmented into line segments. Although such algorithms are straightforward for line extraction, they are of low robustness in the presence of noise or occlusions which are common in remotely sensed imagery.

To retrieve the parallel and perpendicular lines corresponding to a building efficiently, the Hough transformation provides a robust solution especially in the presence of noise. Straight line candidates are identified as local maxima in a parameter space derived by transforming each pixel in the image into a parameter space according to the following formula

$$x = \rho \cos\theta, y = \rho \sin\theta \quad (1)$$

where x and $\rho \geq 0$ are the coordinates of the pixels in image space. After transforming, each straight line parameterized by (θ, ρ) in the image space is associated with a point (θ, ρ) in the parameter space, where $\rho \geq 0$ is the distance between the line and the origin and θ $\theta \in [0, 2\pi)$ [0, 2π) is the angle of the line as can be seen in figure 2(a). Pixels lying on the same straight line in the image space correspond to curves through a common point in the parameter space. Similarly, points lying on the same curve in the parameter space correspond to lines through the same pixel in the image space. Consequently, peaks corresponding to parallel lines in the image space align vertically in the parameter space, and the distance along the horizontal axis in the parameter space between peaks corresponding to perpendicular lines in the image space is about π/2, as can be seen from figure 2(b) and figure 2(c). Parallel lines in the image space can be detected by retrieval of all the peaks with the same θ and simultaneously surpassing a threshold value which is about 30% of the maximum value in the parameter space. Lines which are perpendicular to a set of parallel lines can also be detected in the same way along the column with the horizontal coordinate $\theta_2 = \theta_1 \pm \pi/2$, where θ1 represents horizontal coordinate of these parallel lines and θ_2 is the horizontal coordinate of the lines to be detected.

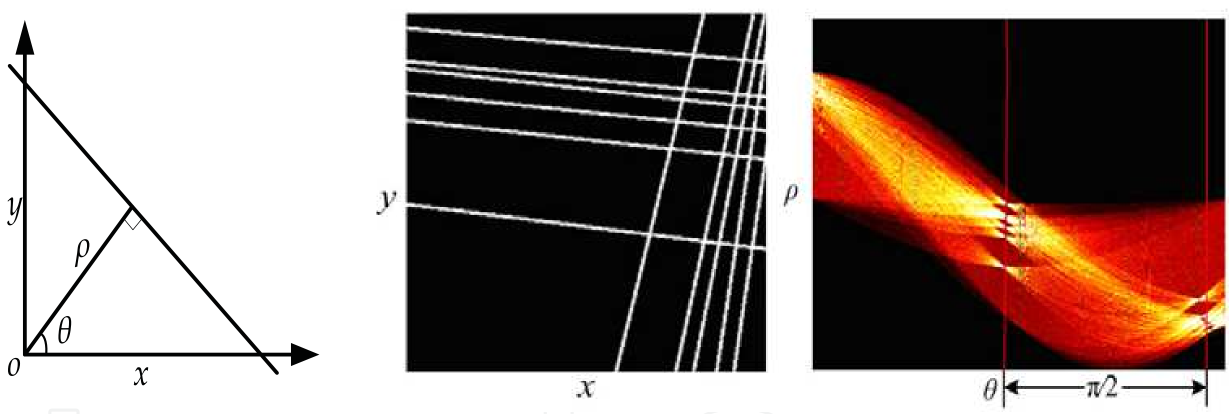


Fig. 2. Hough transformation: (a) Straight line representation in image space; (b) Test image with straight lines; (c) Parameter space, the distance between the two red lines is $\pi/2$, the horizontal coordinates of the two red lines are θ_1 and θ_2 respectively.

2.3 Construction of a building structural graph construction

The structure of a building can be intuitively represented by an undirected graph, the vertices of which represent a building corner, while the edges of the graph represent building edges connecting two corners. If all the intersections of the dominant line sets comprising the building outline are used to create an undirected graph, it will become expensive. To reduce the computational complexity, we have to eliminate certain edges which are not related to the building. It is reasonable to assume that there should be certainly a difference in the grey values between the two sides of the building edges. The average grey value of pixels within two rectangles on both sides of an edge is used to remove false edges. If the difference of the average grey value is smaller than a predefined threshold, the edge can be safely removed. According to this criterion, irrelevant edges will be eliminated. After the filtering of irrelevant edges, the remaining edges are used to construct the building structural graph.

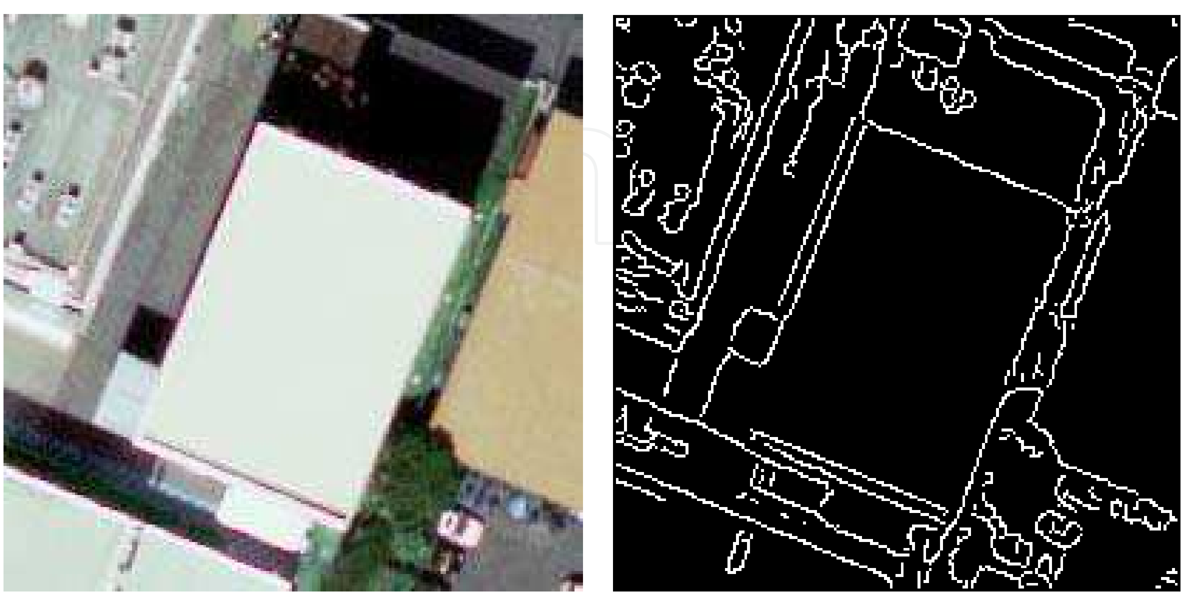
2.4 Cycle detection

Based on the building structural graph, cycle detection is needed to derive the desired cycle corresponding to the building polygon. In the literature, the most widely used method is the backtrack algorithm. However, this category of backtrack algorithm may not be suitable for an undirected graph. We therefore adopted an effective scheme which is preferable for an undirected graph and composed of the following three steps.

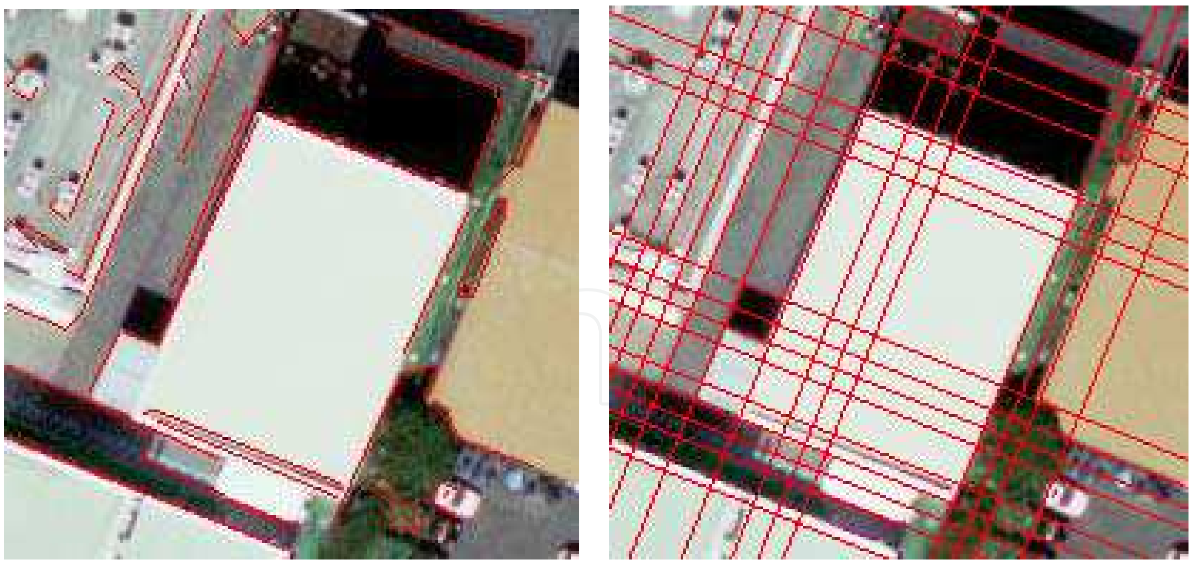
Step 1. Detect a spanning tree of the graph. One approach is to initially remove all edges of the graph. Then each edge of the graph is incrementally put back to the graph. If the graph contains cycles after the return of an edge, the edge is assumed to be a chord which is defined as an edge connecting two not-adjacent nodes in a cycle. In this way, all the chords of the graph can be derived. It is worth noting that the result depends on the initial spanning tree and therefore may not be unique..

Step 2. Find fundamental cycles of the graph. Each chord derived in the previous step is associated with a fundamental cycle. If there are k chords, there will be k fundamental cycles. Each cycle contains a chord which does not exist in all the other k-1 cycles. These cycles constitute a series of fundamental cycles.

Step 3. List all the feasible unions of the fundamental cycles. All the feasible combinations of 1, 2 … k-1 fundamental cycles are enumerated. There may be certain cases where the closed path is composed of two or more cycles. For a graph, the maximum number of cycles and chords is $G(V,E),|V|=n,|E|=e$, where n and e are the numbers of edges and vertices respectively. Accordingly, there will be $C_k^1 + C_k^2 + \cdots + C_k^k = 2^k - 1$ feasible combinations of all the cycles at most. After cycle detection, areas of all polygons corresponding to cycles are computed. The polygon with maximum area is selected as the building boundary.



(a) (b)



(c) (d)

Fig. 3. Comparison of line extraction results: (a) Original image; (b) Edges detected by Canny detector; (c) Straight lines extracted by chain code splitting; (d) Straight lines extracted by Hough transformation.

3. Experiments and discussion

Three experiments were carried out in the following section in a Microsoft Visual C++ 6.0 environment to validate the proposed approach using real world imagery acquired by a Leica ADS40 digital sensor in the north part of Chiba in Japan with a ground sampling distance of 0.2 meter. In that region, most buildings are flat and rectangular. The first experiment was carried out on a simple subset of this large image to demonstrate our approach and the second deals with a more complex subset. Red, green, blue bands are used as a color image in the subsequent experiments. The third experiment was carried out to evaluate the ability to extract small building structures. In the first experiment, the region segmentation of a building is achieved by mean shift image segmentation. In the second and the third experiment, the user needs to pick a seed pixel within the building, and the scheme is then carried out automatically.

3.1 First experiment

The test image shown in Fig. 3(a) has dimensions of 203 pixels $\times$ 198 pixels. This simple scene comprises one salient building with two subordinate wings.

The two line extraction schemes described in section 2.2 are illustrated and compared in Fig. 3. The edges shown in Fig. 3 (b) were detected by the Canny edge detector with a variance of 0.4 for the Gaussian filter. After linking of all the edge pixels into edge chains, the Douglas-Peuker algorithm with threshold of 2.5 was applied to split each chain code into approximately straight line segments followed by least square fitting to obtain straight lines shown in Fig. 3(c). The straight lines in Fig. 3(d) were detected by applying Hough transformation to the edge map in Fig. 3(b). As can be seen from the resulting straight lines, the lines extracted by the Hough transformation are much better than those extracted by the

Douglas-Peuker algorithm as there are too many spurious short line segments which not only raise computational complexity but also decrease the efficiency. However, there are still many irrelevant straight lines not corresponding to any building edges, which is the main reason to incorporate the region information as described in section 2.1.

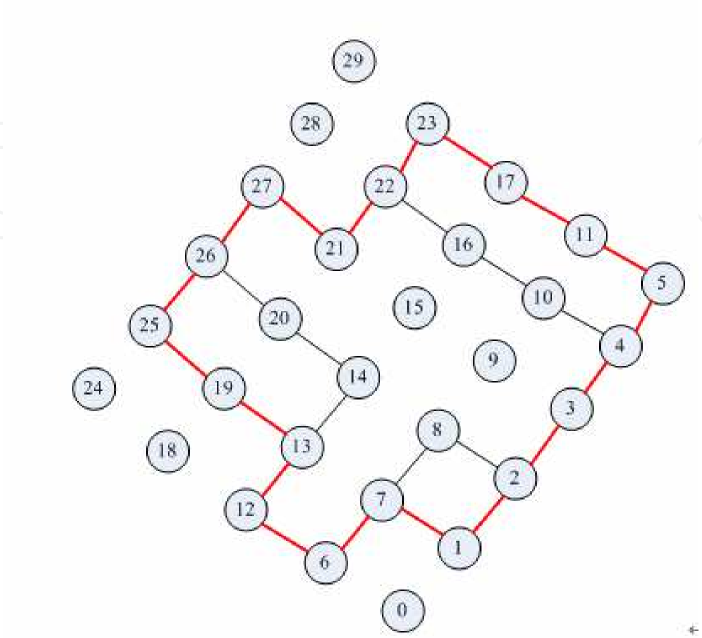
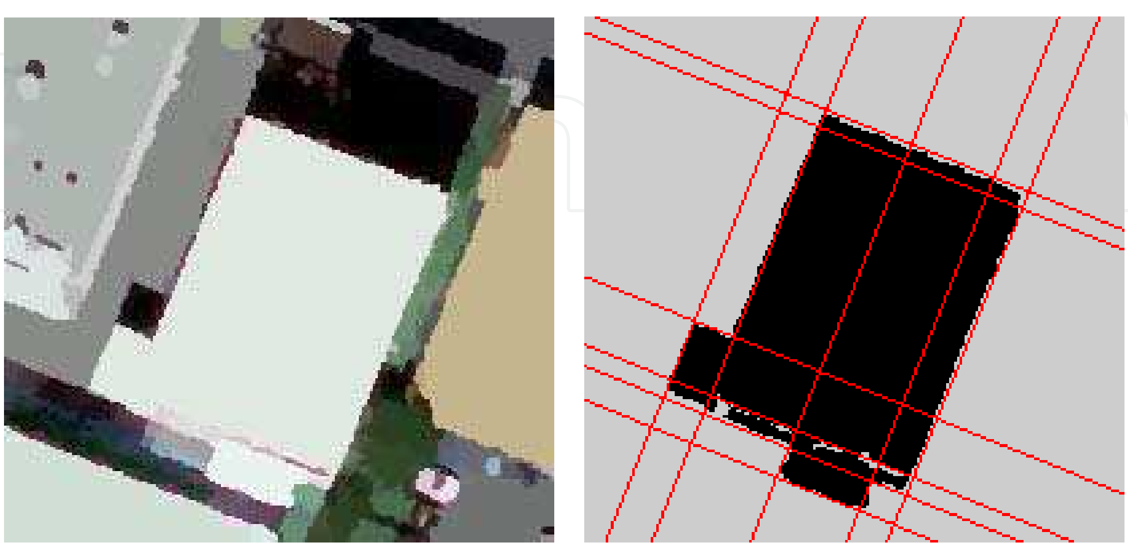
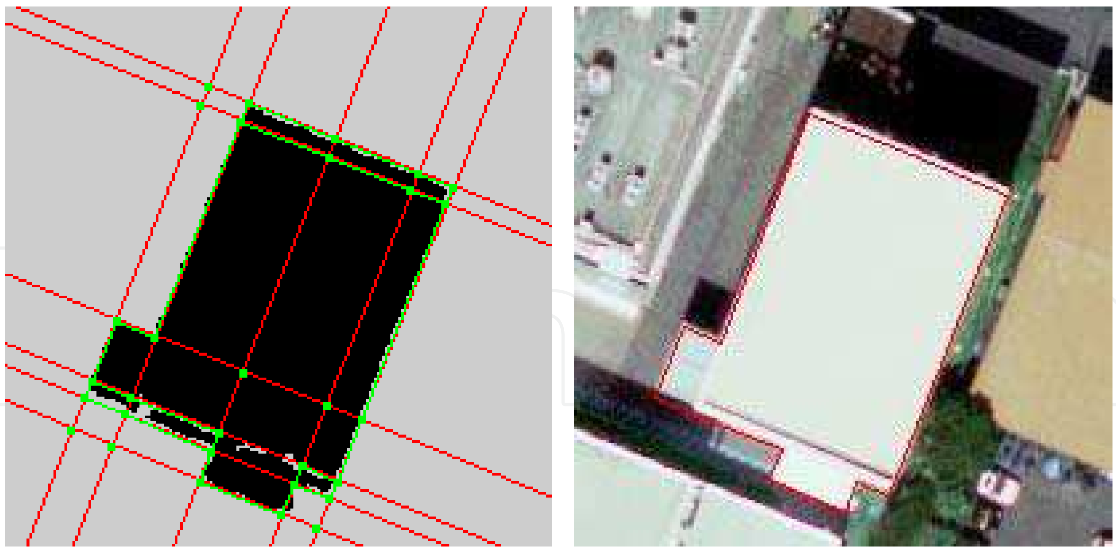


Fig. 4. Building structural graph.

To incorporate region information, image segmentation based on mean shift is applied to discriminate the building region. In this step, the building region may be segmented into different parts as a result of inhomogeneous conditions. Thus, a region merging based on grey value discrepancy is necessary when dealing with a complex scene. The result of segmentation is shown in Fig.5 (a). After segmentation, Hough transformation is applied to the boundary map of the building region to derive the straight lines corresponding to the building. As can be seen in Fig.5 (b), the resulting straight lines are much better than those in Fig. 3(d).



(a) (b)



(c) (d)

Fig. 5. (a) Segmented image using a mean shift segmentation algorithm; (b) Lines extracted using Hough transformation; (c) Green line segments are related with a building; (d) Extraction result.

To construct a building structural graph, spurious line segments which are irrelevant to any building edges have to be removed by comparing the average grey value of pixels inside two rectangles on both sides of each line segment. If the difference of the average grey value is smaller than a threshold, the edge can be safely removed. In this step, the threshold being used is 10. The width of the two rectangles perpendicular to the corresponding line segments and the threshold value are important as they determine the complexity of the graph and whether there are cycles in the graph. The remaining line segments after the removal of spurious line segments are shown and marked in green in Fig. 5(c). With these remaining line segments, a building structural graph is constructed and shown in Fig.4. The cycle marked in red in Fig.4 is the desired one and corresponds to the building outline. After

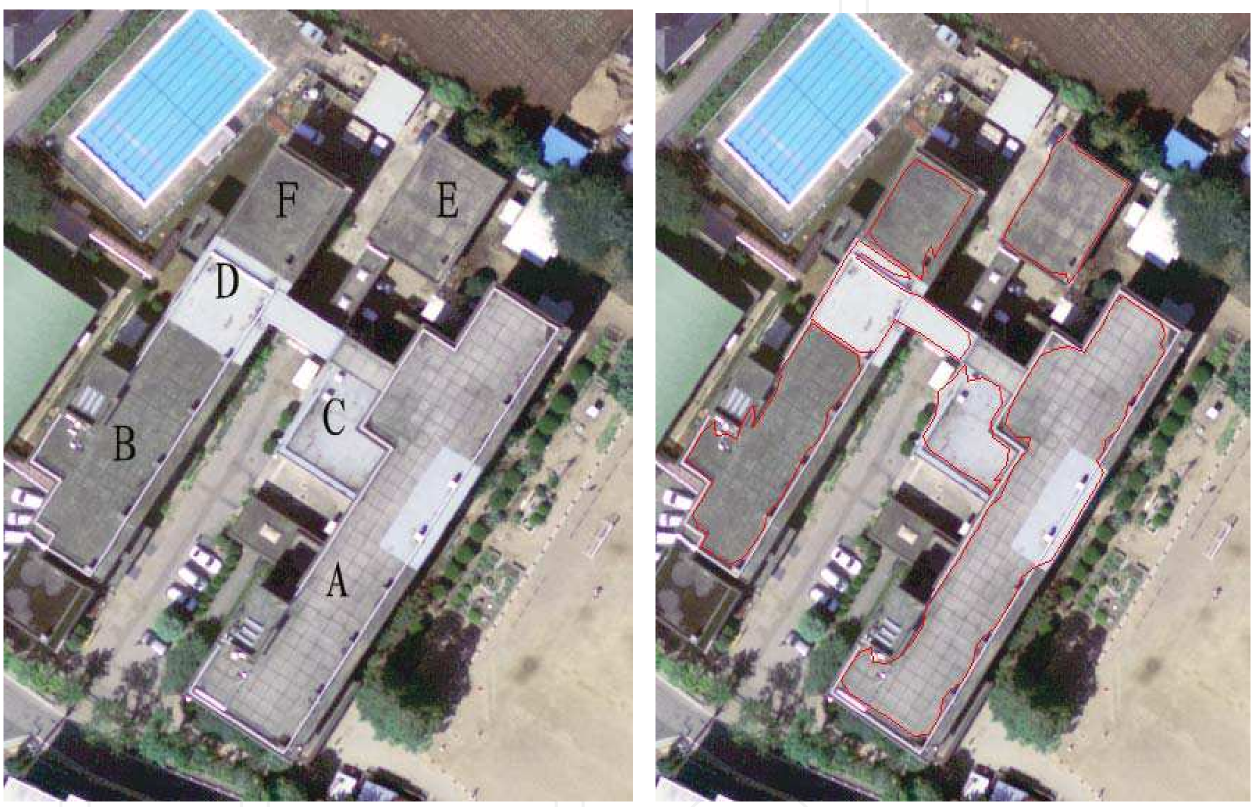
ID	Sequential vertices of each cycle	Area (m2)
1	1 2 3 4 5 11 17 23 22 21 27 26 20 14 13 12 6 7 1	10612.76
2	1 2 3 4 5 11 17 23 22 21 27 26 25 19 13 12 6 7 1	11022.41
3	1 2 3 4 10 16 22 21 27 26 20 14 13 12 6 7 1	10036.44
4	1 2 3 4 10 16 22 21 27 26 25 19 13 12 6 7 1	10446.09
5	1 2 8 7 1	112.45
6	2 3 4 5 11 17 23 22 21 27 26 20 14 13 12 6 7 8 2	10500.31
7	2 3 4 5 11 17 23 22 21 27 26 25 19 13 12 6 7 8 2	10909.96
8	2 3 4 10 16 22 21 27 26 20 14 13 12 6 7 8 2	9923.99
9	2 3 4 10 16 22 21 27 26 25 19 13 12 6 7 8 2	10333.64
10	22 23 17 11 5 4 10 16 22	576.32
11	26 25 19 13 14 20 26	409.65

Table 1. Cycles in the graph and area of each cycle

cycle detection, all the cycles contained in the building structural graph are retrieved and the sequential vertices of each cycle are listed in table 1. The cycle with maximum area was selected as the final building outline and is shown in Fig. 5(d).

3.2 Second experiment

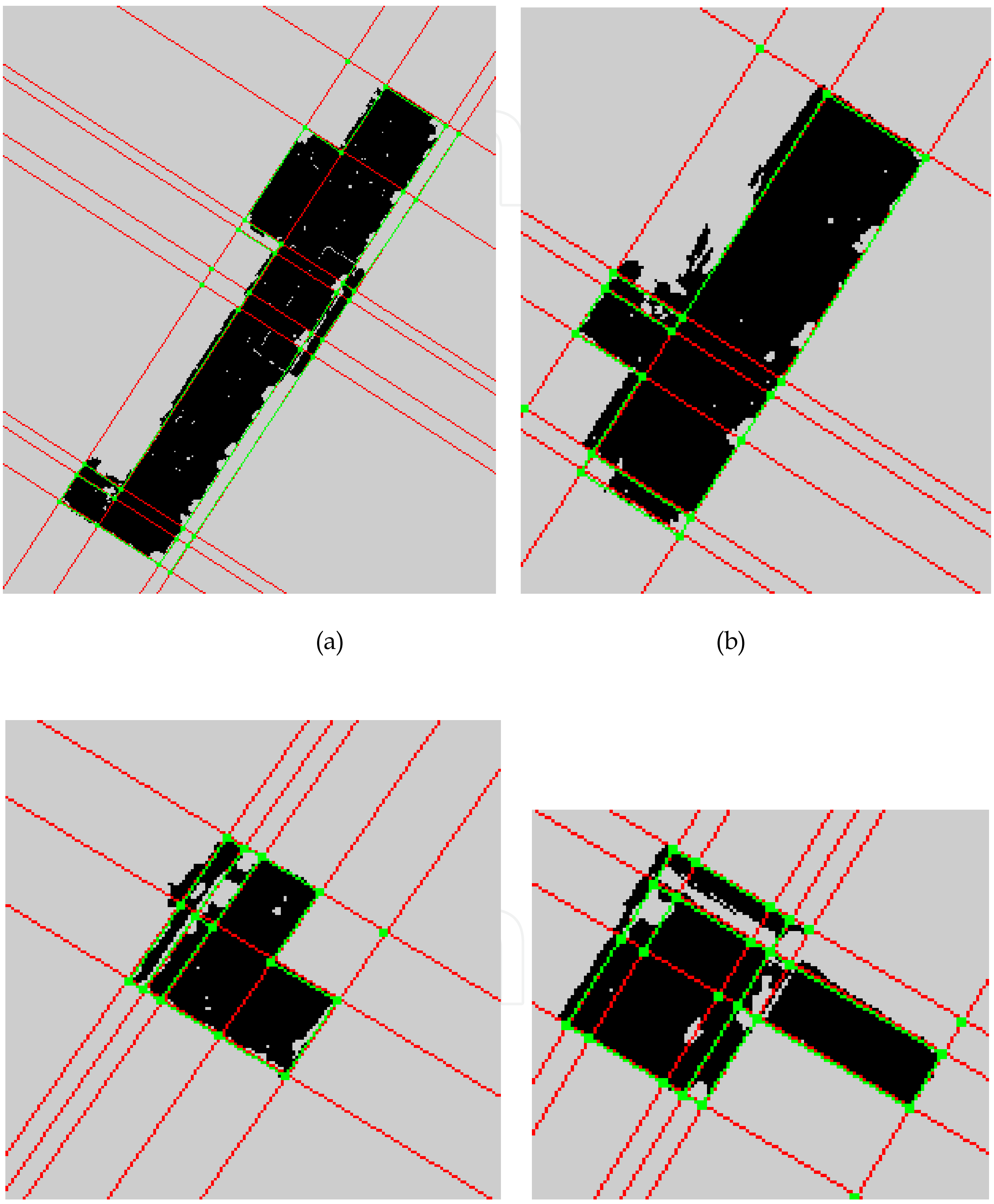
To further test this method on buildings with complex shapes, another experiment was performed on the color image shown in Fig.6 (*a*). It has dimensions of 428 pixels × 536 pixels. The geographical location of this subset is about 35°41'05.70″ N and 140°05'33.10″ E. In this scene, there are two buildings with complex shapes which increase the difficulty of extraction.



(a) (b)

Fig. 6. Polygon approximation: (a) Experimental image subset containing six buildings; (b) Boundary derived by traditional polygon approximation.

From the results shown in Fig.6, we can see that the approximate shapes of the buildings have been identified by the region growing algorithm. Yet, the boundaries of these regions are severely fragmented. After polygon approximation illustrated in Fig. 6(b), the boundary is irregular and is not composed of straight line segments. Therefore, the Hough transformation is especially useful in such cases because it can extract straight lines even if the boundary is severely fragmented. This can be verified by the results shown in Fig. 6 and the red lines in Fig.7 are the dominant lines of the buildings, while the green line segments are the remaining lines after line filtering, which are then used to construct the structural graphs shown in Fig.8. The following step is to detect all cycles contained in the graph. The red cycles with maximum area are the final building boundaries. The sequential nodes of all cycles detected in each graph are listed in table 2. The final extraction results and some other experimental results are shown in Fig.9.



(a) (b) (c) (d)

Fig. 7. Line sets of buildings A-D attained by Hough transformation.

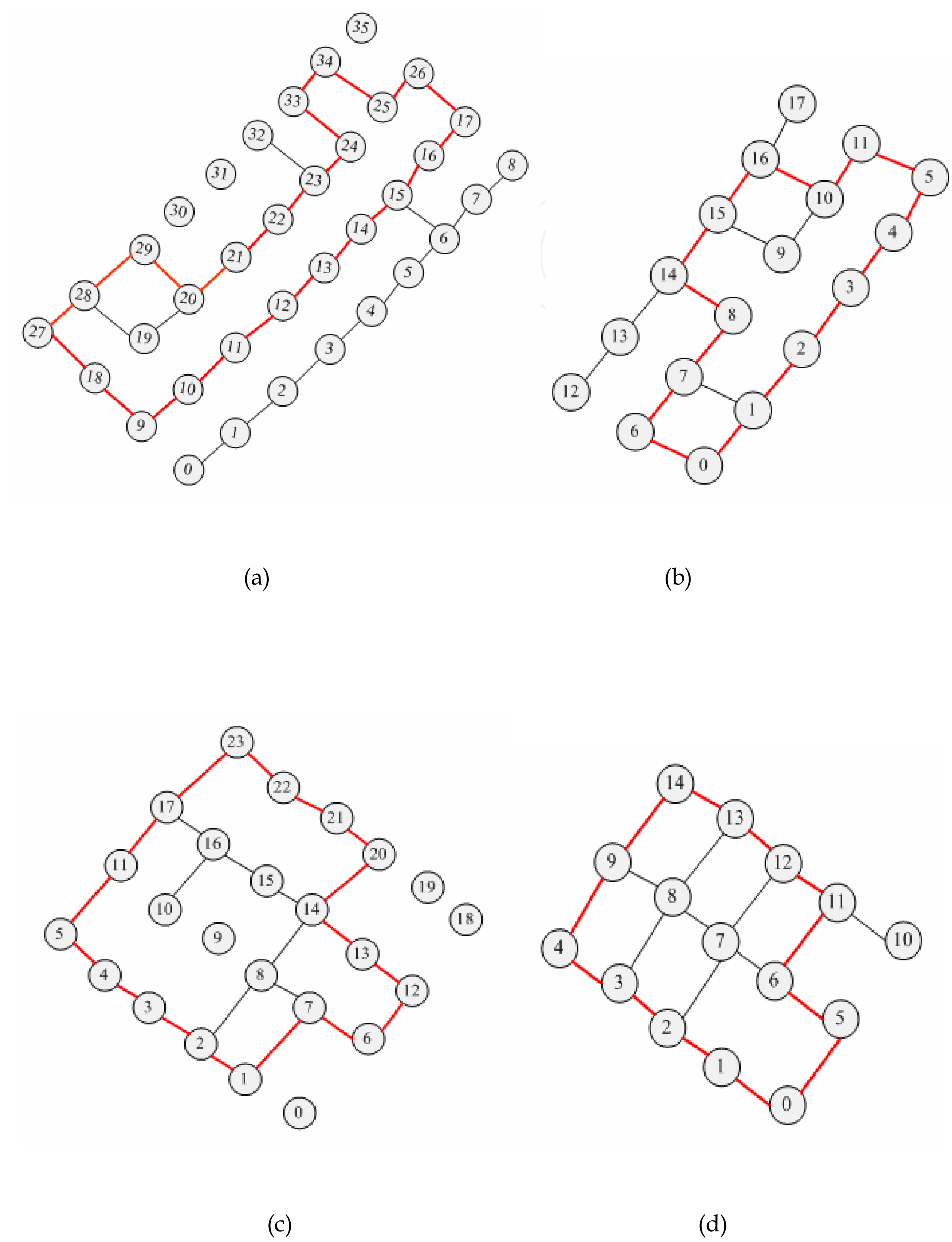


Fig. 8. Building structural graphs: (a) Building A; (b) Building B; (c) Building C; (d) Building D.

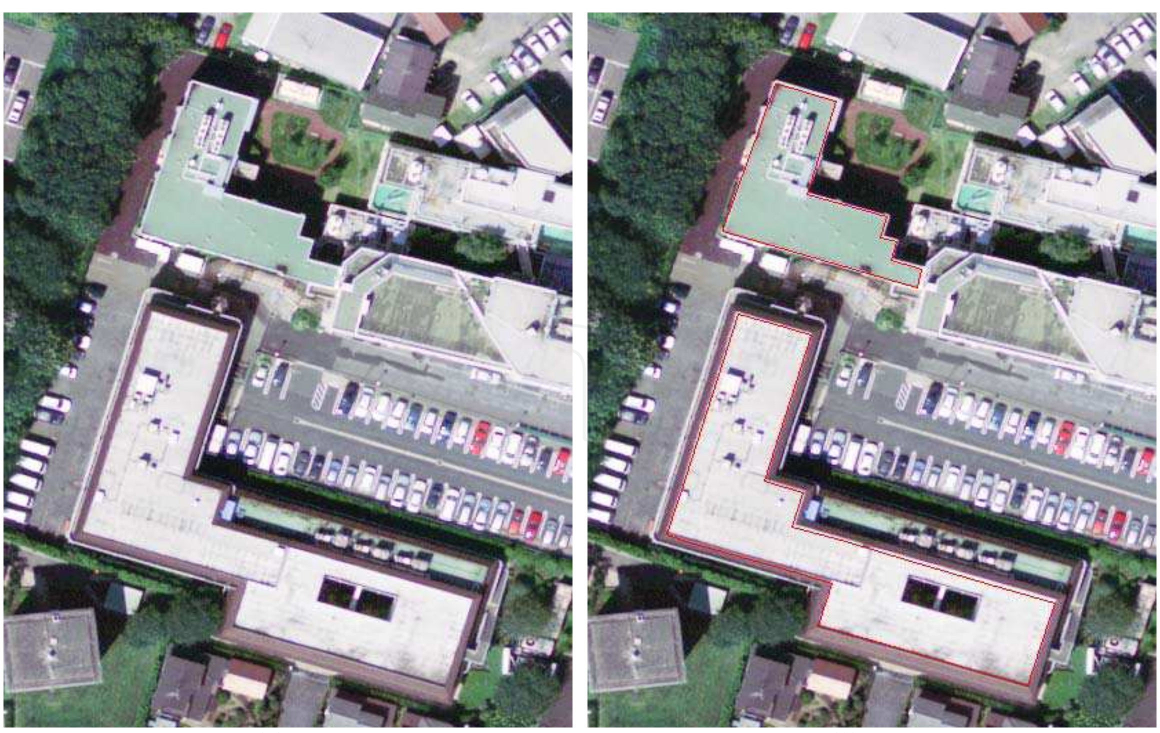
Graph	Sequential vertices of each cycles	Area (m²)
A	20 29 28 19 20	224.60
	24 33 34 25 26 17 16 15 14 13 12 11 10 9 18 27 28 19 20 21 22 23 24	17885.71
	24 33 34 25 26 17 16 15 14 13 12 11 10 9 18 27 28 29 20 21 22 23 24	*18110.31*
B	0 1 2 3 4 5 11 10 16 15 14 8 7 6 0	*8268.05*
	0 1 7 6 0	352.94
	1 2 3 4 5 11 10 16 15 14 8 7 1	7915.11
	10 16 15 9 10	210.56
	15 9 10 11 5 4 3 2 1 0 6 7 8 14 15	8057.49
	15 9 10 11 5 4 3 2 1 7 8 14 15	7704.55
C	1 2 3 4 5 11 17 16 15 14 8 7 1	2414.44
	1 2 3 4 5 11 17 16 15 14 13 12 6 7 1	3657.76
	1 2 3 4 5 11 17 23 22 21 20 14 8 7 1	2919.79
	1 2 3 4 5 11 17 23 22 21 20 14 13 12 6 7 1	*4163.11*
	1 2 8 7 1	224.60
	2 3 4 5 11 17 16 15 14 8 2	2189.84
	2 3 4 5 11 17 16 15 14 13 12 6 7 8 2	3433.16
	2 3 4 5 11 17 23 22 21 20 14 8 2	2695.19
	2 3 4 5 11 17 23 22 21 20 14 13 12 6 7 8 2	3938.51
	6 12 13 14 8 2 1 7 6	1467.92
	6 12 13 14 8 7 6	1243.32
	17 23 22 21 20 14 13 12 6 7 1 2 8 14 15 16 17	1973.26
	17 23 22 21 20 14 13 12 6 7 8 14 15 16 17	1748.66
	17 23 22 21 20 14 15 16 17	505.35
D	0 1 2 3 4 9 14 13 12 11 6 5 0	*3293.79*
	0 1 2 7 8 3 4 9 14 13 12 11 6 5 0	3062.17
	2 7 12 11 6 5 0 1 2	2409.43
	3 8 7 2 3	231.62
	4 9 14 13 8 3 4	442.18
	4 9 14 13 8 7 2 3 4	673.80
	7 12 11 6 5 0 1 2 3 8 7	2641.04
	12 13 8 3 2 7 12	442.18
	12 13 8 7 12	210.56
	12 13 14 9 4 3 2 7 12	884.36
	12 13 14 9 4 3 8 7 12	652.74
	13 8 3 2 1 0 5 6 11 12 13	2851.61
	13 8 7 2 1 0 5 6 11 12 13	2619.99
	13 8 7 12 11 6 5 0 1 2 3 4 9 14 13	3083.22

Table 2. Cycles in each graph and area of each cycle.

Fig. 9. Final extraction result

3.3 Third experiment

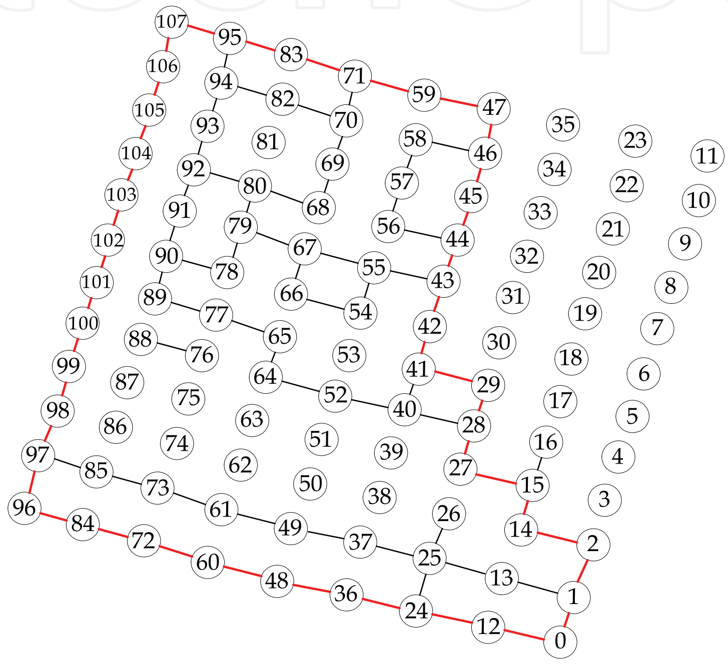
To further test this method on buildings with complex shapes, another experiment was performed on the color image shown in Fig.10 (*a*). It has dimensions of 428 pixels × 536 pixels.



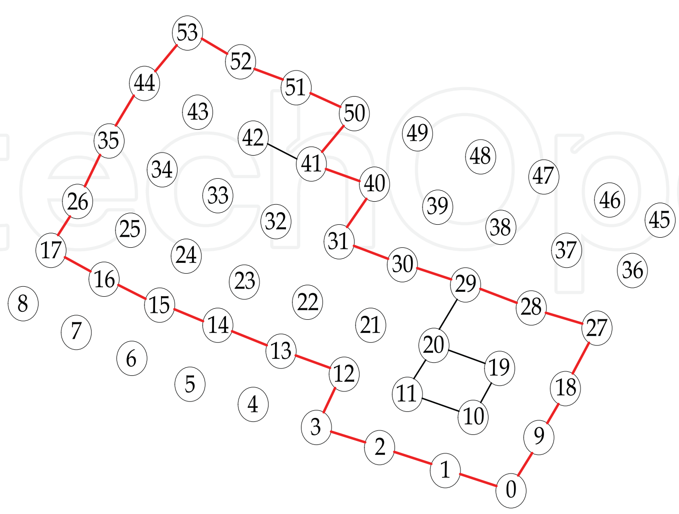
(*a*) (*b*)

Fig. 10. Polygon approximation: (*a*) Original test image with complex buildings; (*b*) Extraction results.

The geographical location of this subset is about 35°41'05.70″ N and 140°05'33.10″ E. In this scene, there are two buildings with complex shapes which increase the difficulty of extraction. Following the proposed procedure, the first step is to use region growing algorithm with a stopping threshold of 5 to identity the approximate shape of the building. Then Hough transformation is applied to detect parallel and perpendicular lines followed by graph construction. The resulting building structure graphs are shown in Fig.11. The first graph is complex because there are numerous small structures within the building. The red cycles with maximum areas are the desired cycles corresponding to building outlines. Based on the retrieved cycles, the final building outlines are extracted and shown in Fig.10 (*b*).



(*a*)



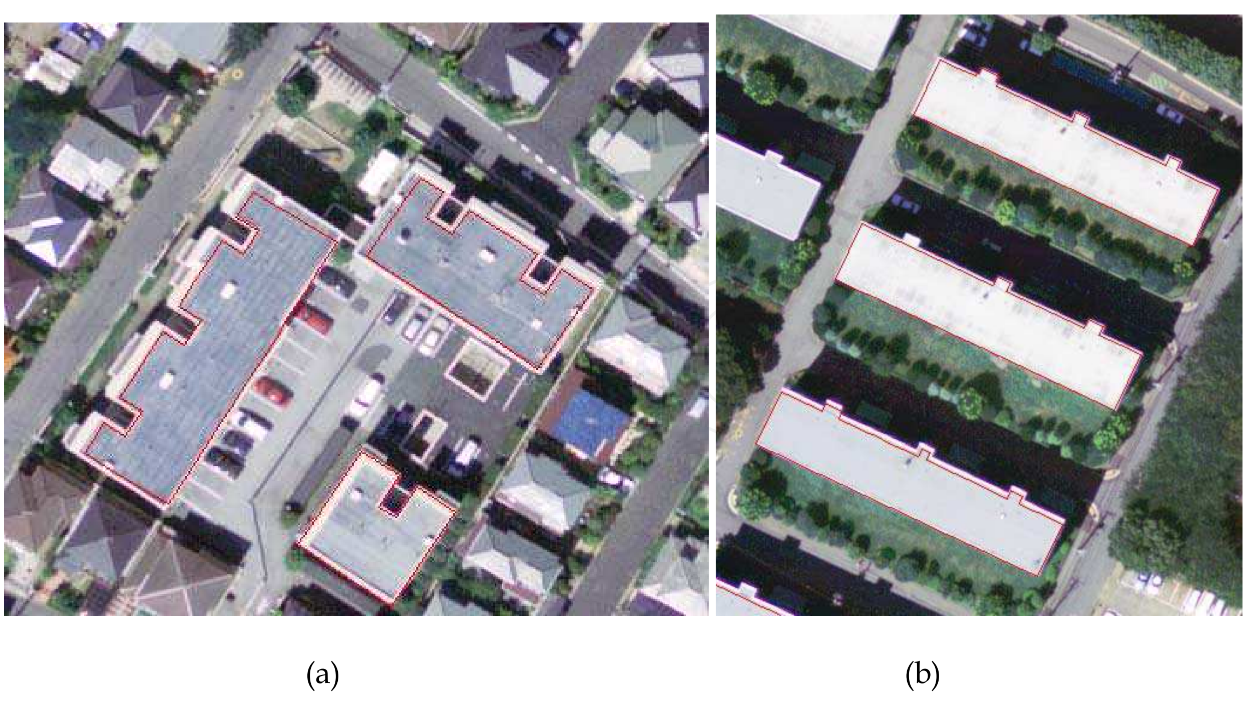
(*b*)

Fig. 11. Building structural graphs from figure 5: (*a*) Upper building; (*b*) Lower building.

3.3 Discussion

In the extraction process, two crucial steps, region growing and Hough transformation, determine directly the graph complexity and tell us whether the resulting graph contains cycles. The region growing method is carried out in RGB (red, green, blue) space because of its simplicity; it can be substituted with image segmentation in a local neighborhood. Another key point is that the Hough transformation is sensitive to the threshold and the width of the rectangle being used in the identification of the building related line segments. The threshold determines the number of lines in the two line sets. This parameter can be adjusted to extract short lines which are critical to extract small and complex structures, as can be seen in Fig.10 and Fig. 12. The small and complex structures in Fig. 10 and Fig. 12 are difficult to extract by traditional methods.

The computational complexity of this strategy depends on building region segmentation, graph construction and cycle detection. As our region growing is carried out over in a local neighborhood, it has low computational complexity, even when the image is very large. If image segmentation is used to identify the building region, we propose to apply segmentation within a local neighborhood around the building. The complexity of the graph construction is determined by the number of lines extracted by the Hough transformation. Most buildings are not extremely complex. Accordingly, the number of lines corresponding to a building is usually small. In the case of a complex structural graph, the cycle detection process may become time-consuming as the total number cycles in a planar graph can even be exponential in the number of vertices. In most cases, the search process takes one to two seconds on a PC equipped with an Intel Core2Dual processor with 2.0 GHz.



(a) (b)

Fig. 12. More results: (a) Small structures can be extracted; (b) Complex shape can also be extracted

4. Conclusion

In this chapter, we presented a simple but efficient and robust approach to address the task of building description and extraction. The experimental results confirm the effectiveness of this proposed approach, especially for flat rectangular building roofs.

Several advantages in this scheme have been confirmed. Firstly, it combines the robustness of the Hough transform with a graph search algorithm. Therefore, it improves the quality of line extraction and avoids a complex feature grouping process and boundary approximation. Secondly, this approach is not restricted by the shape of the building as long as the building is composed of orthogonal corners (and can be extended to nonrectangular buildings) and the extracted boundaries are regular as the shape of the building is derived by the graph search algorithm. If the boundary is curved, as shown in Fig. 6(b), the building polygon can not be used in subsequent applications. Finally, small building structures can also be extracted robustly, as shown in Fig. 10 and Fig. 12.

However, there are still some limitations to this approach which need to be improved in future research. The key step of this proposed method is the identification of building regions, for which region growing and mean shift segmentation were adopted in our case. Nevertheless, in the presence of noise, this step may fail; the following steps will not be able to extract the exact shape of the building. We consider that this step may be substituted with a clustering technique or accurate segmentation and this approach will be extended to nonrectangular building. Another drawback of this method may be that shadow is not considered. These two drawbacks will be overcome in future research.

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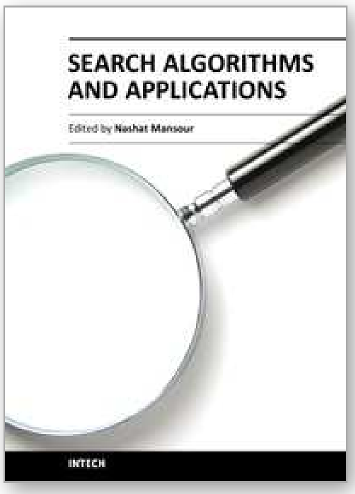

Search Algorithms and Applications

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Search algorithms aim to find solutions or objects with specified properties and constraints in a large solution search space or among a collection of objects. A solution can be a set of value assignments to variables that will satisfy the constraints or a sub-structure of a given discrete structure. In addition, there are search algorithms, mostly probabilistic, that are designed for the prospective quantum computer. This book demonstrates the wide applicability of search algorithms for the purpose of developing useful and practical solutions to problems that arise in a variety of problem domains. Although it is targeted to a wide group of readers: researchers, graduate students, and practitioners, it does not offer an exhaustive coverage of search algorithms and applications. The chapters are organized into three parts: Population-based and quantum search algorithms, Search algorithms for image and video processing, and Search algorithms for engineering applications.