# Rectilinear building roof contour extraction based on snakes and dynamic programming 

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#### Abstract

This paper presents a method for extracting building roof contours from digital images collected over urban landscapes. The proposed method utilizes an energy function based on snakes that represents building roof contours in digital images and is optimized with a dynamic programming (DP) algorithm. Because most building roof contours are characterized by rectilinear sides that intercept at right angles, appropriate geometric constraints are enforced in the previously reported snake-based energy function. The main advantage of using the DP algorithm for optimizing the proposed snake-based energy function is its better radius of convergence compared to that typically obtained in the original solution based on variational approaches. Experimental evaluation, which included visual inspections and numerical analyses, was performed using real data, and the obtained results demonstrated that the proposed method has significant potential for successfully extracting building roof contours from digital images.


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## 1. Introduction

The extraction of features from digital images has been a subject of intense research since the 1970s and has been of great interest in the areas of computer vision and image analysis. In the context of collecting spatial data for mapping applications, new methods have been developed to extract man-made objects, such as buildings (Lee et al., 2003; Liu et al., 2005, 2008; Sohn et al., 2005; Lafarge et al., 2006; Xiong and Zhang, 2006; Guercke et al., 2011) and roads (Gruen and Li, 1995; Dal Poz and Vale, 2003; Peng et al., 2005; Poullis and You, 2010; Dal Poz et al., 2010), from aerial and satellite images.

The concepts of snakes and dynamic programming (DP) have been widely exploited in applications involving the extraction of road networks from digital images, such as those described by Gruen and Li (1995), Agouris et al. (2001), Dal Poz and Vale (2003) and Dal Poz et al. (2010). However, few approaches have been developed for extracting buildings from digital images using snakes. Rüther et al. (2002) used snakes to model building contours in informal settlement areas and employed a DP algorithm as its optimization method; this algorithm was initialized using approximate contours obtained by the thresholding of a digital surface model followed by the projection of the contours onto the

[^0]image space. Guo and Yasuoka (2003) proposed an approach based on snakes for extracting buildings from a combination of IKONOS images and elevation data; in this approach, multiple cues, derived from both data sources, are integrated into the snakes model to precisely extract the building roof contours. Oriot (2003) presented a statistical snakes model for the extraction of buildings from stereoscopic pairs of aerial images. This approach separates buildings from other regions by segmenting a disparity image and is accomplished by finding the polygon that minimizes the energy defined by the correlation coefficient of the area of interest. Considering the radiometric and geometric properties of buildings, Peng et al. (2005) modified the traditional snakes model to enable a more stable convergence for building contours.

Here, we propose a method for extracting building roof contours from digital images that uses snakes as the basis for developing a mathematical model of these objects, and the solution is obtained through DP optimization. The basic assumption of our method is that buildings are projected onto an image space as rectilinear structures and that their adjacent sides intercept at approximately right angles. We chose to use the DP algorithm to solve the optimization problem based on snakes instead of using the variational method (Kass et al., 1988) because of the possibility of having a larger radius of convergence. This article is organized as follows. Section 2 presents the proposed method. The experimental assessment and analysis of the obtained results are presented in Section 3. Finally, conclusions from an analysis of the results obtained in our experiments are presented in Section 4.

## 2. Method

The process of extracting features from images may be appropriately formulated in terms of an optimization problem, which may, in turn, be solved by the use of specific techniques. The basic requirement for this process is the formulation of a mathematical model of the object to be extracted. In this study, snakes are used as the basis for constructing a mathematical model that represents the building roof contours that are to be extracted from digital images. The resulting model structure is then ready to be solved by the DP algorithm. The optimal solutions for the model are polygons that represent the contours of the building roof.

### 2.1. Mathematical model of building roof contours

In an image, a snake is described by a curve that moves in the $x$ and $y$ directions under the influence of internal and external forces (Xu and Prince, 1998a,b). Originally, a snake was formulated based on a continuous parametric curve, although the parametric curve should be replaced by a discrete curve when computational implementation is involved, which is given by a polygonal line or by a polygon defined by a sequence of $n$ vertices, as follows:
$v_{i}=\left[\begin{array}{ll}x_{i} & y_{i}\end{array}\right], \quad i=0, \ldots, n-1$.
The energy function of snakes may be expressed in the following manner (Kass et al., 1988):
$E_{2}(v)=\sum_{i=1}^{n-1}\left(\alpha_{i}\left|v_{i+1}-v_{i}\right|^{2}+\beta_{i}\left|v_{i-1}-2 v_{i}+v_{i+1}\right|^{2}\right)+E_{\text {ext }}(v)$,
where the expression under the sum is known as the internal energy of the snakes, the first and second terms of the internal energy are first and second order terms, the constants $\alpha_{i}$ and $\beta_{i}$ are weights that control the terms of the first and second orders, and $E_{\text {ext }}(v)$ is the external energy.

In general, the internal energy term permits the geometric control of curve $v$, and the external energy term is responsible for moving the contour $v$ toward the feature of interest in the image. Specifically, the constant $\beta_{i}$ permits the smoothness of the curve to be controlled. In general, a higher value of constant $\beta_{i}$ corresponds to a smoother curve $v$; when $\beta_{i}=0$, the curve $v$ develops a corner at the vertex $v_{i}$. The optimal curve $v$ must minimize the energy function $E(v)$.

In terms of the object 'roof contour', curve $v$ is a polygon that represents the roof contour. An important feature of building roof contours in digital images is that they are typically delimited by step edges, which permits the external energy function to be defined as follows:
$E_{\text {edge }}(v)=\sum_{i=0}^{n-1} \gamma_{i}\left|\nabla G\left(v_{i}\right)\right|^{2}$,
where $\gamma_{i}$ is a negative constant and $\left|\nabla G\left(v_{i}\right)\right|$ is the image gradient magnitude at the vertex $v_{i}$ of the contour.

In most images, buildings are represented by rectilinear structures that are defined by consecutive edge segments forming right angles at their corners. Thus, an additional external energy term may be defined by the following equation:
$E_{\text {corner }}(v)=\sum_{i=0}^{k-1} \eta_{i}\left[\left(1-\cos \left(\delta_{i}\right)\right) \cdot \operatorname{CS}\left(v_{i}\right)\right]^{2}$,
where $\eta_{i}$ is a positive constant, $\operatorname{CS}\left(v_{i}\right)$ is the response of a corner detection operator, and $\delta_{i}$ is the deflection angle at the corner represented by the vertex $v_{i}$. Note that the term $\left(1-\cos \left(\delta_{i}\right)\right)$ is a weighting function that favors right-angles at corners $\left(\left(\delta_{i} \sim 90^{\circ}\right)\right)$.

The mathematical model of building roof contours based on snakes may thus be expressed by incorporating Eqs. (3) and (4) into Eq. (2), resulting in the following:

$$
\begin{align*}
E_{2}(v)= & \sum_{i=0}^{n-1}\left[\alpha_{i}\left|v_{i+1}-v_{i}\right|^{2}+\beta_{i}\left|v_{i-1}-2 v_{i}+v_{i+1}\right|^{2}\right. \\
& \left.-\gamma_{i}\left|\nabla G\left(v_{i}\right)\right|^{2}-\eta_{i}\left[\left(1-\cos \left(\delta_{i}\right)\right) \operatorname{CS}\left(v_{i}\right)\right]^{2}\right] \tag{5}
\end{align*}
$$

The values of weights $\beta_{i}, \gamma_{i}$, and $g=g\left(x_{1}, \ldots, x_{n}\right)=$ $g_{1}\left(x_{1}, x_{2}, x_{3}\right)+\cdots+g_{n-2}\left(x_{n-2}, x_{n-1}, x_{n}\right)=\sum_{i=1}^{n-2} g_{i}\left(x_{i}, x_{i+1}, x_{i+2}\right)$, depend on whether the type of discontinuity at the vertex $v_{i}$ is a step edge or corner. All weights (including $\alpha_{i}$ ) are positive; at a corner, there must be an abrupt change of direction at vertex $v_{i}$ of the polygon. This change of direction implies the need to nullify $\beta_{i}$ to allow a second-order discontinuity at vertex $v_{i}$. Moreover, the edge energy term (Eq. (3)) does not have any discriminatory power regarding the discontinuity at vertex $v_{i}$, which implies the requirement that $\gamma_{i}=0$. Conversely, when there is a step-edge discontinuity in $v_{i}$, the corner energy term (Eq. (4)) will have no discriminatory power, and it is necessary to nullify the weight $\eta_{i}$.

### 2.2. DP optimization of the building roof contour model

If the variables of an energy function in an optimization problem are not simultaneously interrelated, then the DP technique is an efficient way to solve this problem (Ballard and Brown, 1982). Suppose a problem of finding the optimal set of values ( $\bar{x}_{1}, \ldots, \bar{x}_{n}$ ) that minimize the energy function $g=g\left(x_{1}, \ldots, x_{n}\right)$. If the energy function $g$ may be written as a sum of sub-functions that depend on the variables ( $x_{1}, \ldots, x_{k}$ ), with $k \ll n$, such that:

$$
\begin{align*}
g=g\left(x_{1}, \ldots, x_{n}\right)= & g_{1}\left(x_{1}, x_{2}, x_{3}\right)+\cdots+g_{n-2}\left(x_{n-2}, x_{n-1}, x_{n}\right) \\
& =\sum_{i=1}^{n-2} g_{i}\left(x_{i}, x_{i+1}, x_{i+2}\right), \tag{6}
\end{align*}
$$

then a multistage procedure such as the DP algorithm may be applied. Additional details regarding this algorithm may be found in numerous publications, including in Gruen and Li (1995) and Ballard and Brown (1982).

A simple analysis of the energy function provided in Eq. (5) indicates that only three consecutive vertices ( $v_{i-1}, v_{i}, v_{i+1}$ ) of the polygon $v$ are simultaneously interrelated; thus, the energy function may be decomposed into a sum of $n-1$ sub-functions $E_{i}\left(v_{i-1}, v_{i}, v_{i+1}\right)$ such that:
$E_{2}(v)=\sum_{i=0}^{n-1} E_{i}\left(v_{i-1}, v_{i}, v_{i+1}\right)$.
The structure of Eq. (7) resembles the structure of Eq. (6) and, consequently, the optimization algorithm for DP can be effectively applied in the optimization of the energy function denoted in Eq. (5). Note that six variables, two for each vertex, are simultaneously interrelated.

To begin the extraction process, several seed points that approximately describe the contour to be extracted should be provided by an operator. In general, the seed points should be positioned in the vicinity of the corners of the roof contour. There is no need to provide seed points along the building contour sides; these can be predicted because these sides are rectilinear.

The initial polygon given at the beginning of the extraction process is described by straight-line segments defined by pairs of


Fig. 1. Illustrative example of the extraction process: (a) initial polygon defined by seed points; (b) sampling of the search space.
consecutive seed points, as shown in Fig. 1(a). Fig. 1(b) illustrates how the search space is configured.

Two types of points generate the candidate polygons for the optimal polygon: points representing the sides and corresponding to the step-edge discontinuity; and points representing the corners and corresponding to the corner discontinuity. The process of determining the corners and organizing them to form the corresponding building roof contour polygon may, at first glance, appear simple. However, false corners may be detected, or true corners for a given roof contour may be missing. As a result, it is important to include side points of the building roof contour to provide better support in determining the correct corners.

To determine candidate points to represent a building corner, a reference point (seed point) must be provided by an operator; the remaining points are determined by an algorithm used to detect corners on a small sub-image surrounding the reference point (Fig. 1(b)). The dimensions of this sub-image should be sufficient to contain the correct corner of the building. The Harris corner detector is used (Harris and Stephens, 1988), and the corners with the best response are stored together with the deflection angles ( $\delta_{i}$ ) at their respective corners. The storage of multiple detected corners for each building corner is necessary for two reasons. First, there may be more than one corner in the sub-window. Second, the corner with the best response may be a false positive.

Candidate points that represent building roof margins are sampled at regular intervals along cross sections of the sides of the initial polygon defined by pairs of seed points (Fig. 1(b)). It is important to emphasize that the cross sections are also sampled regularly along the sides of the initial polygon. Because the cross sections are centered at points along the sides of the initial polygon, there is no preference for which side of the cross sections is searched.

To estimate the size of the search space, let each corner of the building have $m$ candidates. Also assume, for the sake of simplicity, that $m$ candidate points were sampled along each cross section of the initial polygon. Next, let $n$ be the sum of the number of seed points and the number of cross sections sampled. The number of polygons in the search space will be $m^{n}$, and the optimal polygon to be obtained by the DP optimization algorithm corresponds to the minimum of the energy function provided by Eq. (5). The solution of the optimization problem determined by DP is found in the following two steps.

- Refinement of the initial polygon defined by the seed points. The strategy described above is applied to refine the initial polygon (defined by the seed points) provided at the beginning of the extraction process. The typical resolution (the distance between sampling points) adopted for the cross sections is one pixel. However, the number of elements in these sections should be compatible with the quality of the initial polygon. In the
example illustrated in Fig. 2, the points in red correspond to the set of vertices obtained by the DP optimization.
- Refinement of the initial solution. Because points obtained along the sides of the contour may be affected by local anomalies (e.g., an adjacent tree) that can cause local irregularities in the contour, a robust linear regression method may be used to obtain the polygon sides (straight lines) that better model the contour of the building sides. The robust regression method is based on the main direction of edge points to fit a straight line equation that represents a building roof contour side. The regression method is based on the following steps:
(1) The building roof contour, which was determined by the DP algorithm, is split into edge point subsets that are each connected by a corner point;
(2) For each edge point subset, the main direction mode is computed, and the points are selected with a main edge direction that matches the main direction mode value;
(3) Based on these selected points (for each edge point subset), a linear fit procedure is applied to estimate the straight-line parameters that best fit a building roof contour side;
(4) Finally, refined coordinates for the building roof contour corners are estimated from the intersection of consecutive fitted straight lines.

Our algorithm for removing outliers from a subset of points, $S$, extracted from a building roof side is implemented as follows: (1) determine the equation of straight line, $L$, fitting the subset of points


Fig. 2. Illustrative example of the extraction process showing the result of the first optimization performed using the DP optimization.


Fig. 3. Illustrative example of the extraction process: (a) refinement of the solution with restricted search space; (b) final extracted building roof contour.
$S$ using the least-squares method; (2) remove points from the set $S$ whose distances to the straight line $L$ are above the threshold $\sigma$, which is the standard-deviation of distances from points in $S$ to the straight line $L$; and (3) repeat the linear regression using the remaining points in the set $S$. Further, determine the new vertices of the refined polygon based on the intersection of straight lines obtained by the linear regression algorithm. These new vertices will act as seed points for a new DP optimization of the energy function (Eq. (5)). A new optimization is indicated for the following reasons (Fig. 3(a)): first, straight lines determined by the linear regression may still be affected by existing anomalies and not modeled along the contour sides; second, search windows (cross sections) with a better resolution ( 0.5 pixels) are utilized to improve the quality of the final straight lines representing the building roof contour sides, which also improves the final positions of the vertices (corners) of the building roof contour polygon; and third, dimensions (in pixels) of the cross sections and sub-images around the new corners are
set equal to the standard-deviation, $\sigma$ (defined above), which makes the optimization process less sensitive to existing anomalies in the vicinity of the roof contour. After the new optimization process, the straight lines representing the building roof sides are determined again according to the same robust linear regression algorithm, and the final positions of the building corners are determined based on the intersection of those straight lines. The final building roof polygon is obtained by properly arranging these corners (Fig. 3(b)).

## 3. Experimental results

To evaluate the proposed method, four experiments were performed using real data. These experiments and a visual and numerical analysis of the corresponding results are described below. The numerical analysis is based on quality parameters derived from a comparison of building roof polygons extracted


Fig. 4. Experiment 1: (a)-(d): initial polygons; (e)-(h): extracted polygons; (i): reference polygon.


Fig. 5. Experiment 2: (a) and (b): initial polygons; (c) and (d): extracted polygons; (e) and (f) reference polygons.
by the computer algorithm and by an operator. The manually extracted polygons are referred to as reference polygons. We calculated completeness ( $C_{1}$ ), correctness ( $C_{2}$ ), and RMSE (root mean square error) values. Completeness and correctness parameters are estimated from the areas of the reference and extracted polygons as follows:
$C_{1}=\frac{A_{E \cap R}}{A_{R}} \cdot 100 \% ;$
$C_{2}=\frac{A_{E \cap R}}{A_{E}} \cdot 100 \% ;$
where $A_{E \cap R}$ is the area of intersection between an extracted and a reference polygon and $A_{R}$ and $A_{E}$ are the reference and corresponding extracted polygon areas, respectively.

The RMSE is calculated as a function of the distances between corresponding vertices in the extracted and reference polygons:

RMSE $=\sqrt{\frac{1}{n} \sum_{i=1}^{n} d_{i}^{2}}$,
where $d_{i}$ is the distance between vertex $i$ of the reference polygon and the corresponding vertex of the extracted polygon, and $n$ is the number of vertices in both polygons.

Table 1
Quality parameters estimated from the results of Experiment 1.

| Quality parameters | Extraction |  |  |  |
| :--- | :--- | :--- | :--- | :---: |
|  |  |  |  |  |  |
| First | Second | Third | Fourth |
| Completeness (\%) | 99.4 | 98.8 | 93.6 | 93.3 |
| Correctness (\%) | 97.3 | 97.5 | 97.7 | 97.1 |
| RMSE (pixels) | 0.916 | 1.103 | 1.761 | 2.218 |

### 3.1. Experiment 1

Fig. 4 illustrates the first experiment that was performed. The main objective of this experiment was to assess how the method performed the task of extracting the same building roof contour from different initial approximations to verify the repeatability of the results to determine the robustness of the method. To validate the method, we selected a well-defined building. Four extractions were performed using the initial contour approximation shown in Fig. 4(a)-(d), and the corresponding building roof contours extracted by the computational algorithm are presented in Fig. 4(e)-(h), respectively. In general, the repeatability of the proposed method is satisfactory. However, as indicated in Fig. 4(g) and (h), one side of the roof contour was incorrectly extracted due to a shadow from the neighboring building. These extraction problems indicate that the interaction of buildings with close shadows may affect the repeatability of the proposed method.

Table 1 summarizes the quality parameters of completeness, correctness, and the RMSE, which were estimated by numerically comparing each of the extracted polygons with its corresponding reference polygon (Fig. 4(i)).

The results presented in Table 1 indicate that both the completeness and correctness values were similar for all the extractions, which was expected because the extracted polygons were very similar to the reference polygon. However, the extraction problems noted above for the third and fourth extractions (Fig. 4(g) and (h)) clearly affected the corresponding RMSE parameters.

### 3.2. Experiment 2

In the second experiment, we selected two image segments that contained three and five buildings each. Two and four roof contours were extracted from each image segment. Fig. 5(a) and (b) shows the initial polygons, overlaid on the image segments, used to initialize the extraction process. The corresponding extracted polygons were then overlaid on the image segments (Fig. 5(c) and (d)). The reference polygons superimposed on the image segments are shown in Fig. 5(e) and (f).

The method performed well in extracting building roof contours 1, 2, 4, and 6 (Fig. 5). Regarding building roof contours 3 and 5 , the shadows cast by the adjacent buildings confused the


Fig. 6. An example of the influence of a shadow edge.

Table 2
Quality parameters estimated from the results of Experiment 2.

| Quality parameter | Building roof contour |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
|  | 1 | 2 | 3 | 4 | 5 | 6 |
| Completeness (\%) | 99.3 | 99.6 | 98.9 | 99.7 | 99.8 | 98.6 |
| Correctness (\%) | 97.7 | 98.1 | 75.8 | 96.7 | 65.5 | 98.5 |
| RMSE (pixels) | 0.769 | 1.141 | 9.315 | 0.474 | 4.877 | 0.867 |

method. For example, one extracted polygon side for each building corresponded to the shadow boundary. This type of extraction problem may occur whenever a building side and an adjacent shadow boundary are near one another and approximately parallel. As a result, the internal energy of the model provided by Eq. (5) does not assist in discriminating between the building and shadow boundaries. In addition, because the strength of the shadow edge is typically greater than that of the building roof contour, the external energy corresponding to the shadow boundary predominates upon the total energy, and the DP algorithm thus selects the shadow boundary instead of the corresponding building boundary. This effect is illustrated in Fig. 6, in which the polygon side of building roof contour 3 was not correctly extracted. The points indicated in blue belong to the building edge, and those shown in red belong to the shadow edge. Each pair of proximate points (one in red and another in blue) belongs to a cross section of the corresponding initial polygon side. As shown in Fig. 5(d), the method extracted the points in red instead of extracting the correct ones in blue.


Fig. 7. Experiment 3: (a) initial contours; (b) extracted contours; (c) reference contours.


Fig. 8. Experiment 4: initial contours.

The quality parameters summarized in Table 2 are consistent with the preceding qualitative discussion. For example, these parameters are significantly better for building roof contours 1,2 , 4 and 6 than for the other contours. The most incorrect value was estimated for contour 5 , indicating a failure in the extraction process (i.e., two of the four sides of roof contour 5 were moved toward the wrong edges).

### 3.3. Experiment 3

Fig. 7 illustrates the third experiment, in which we selected an image segment with several buildings and performed the extraction of six roof contours. The initial, extracted, and reference contours were overlaid on the image segment and are shown in Fig. 7(a)-(c). Extracted contours 1, 2, 4, and 6 present extraction problems. Although extracted contour 4 is relatively compatible with the reference polygon, this matching was accomplished manually by connecting its vertices, which resulted in a rough
approximation for the two curved sides. These sides are also roughly estimated by the proposed method, which was predicted because the method was designed to address rectilinear building roof contours. The interaction of buildings 1,2 , and 6 with neighboring buildings affected the extraction process because the corresponding extracted contours partially coincided with neighboring buildings. The reasons underlying this extraction problem are similar to those discussed above with respect to the interaction of a building roof contour with an adjacent shadow. In the present context, the method may extract the edge of a neighboring building if its strength is greater than the correct edge. The performance of the method with contours 3 and 5 is considered satisfactory.

Table 3 summarizes the values of the quality parameters. In general, the values show that the method performed well, particularly with respect to the extraction of building roof contours $3-5$. However, as discussed above, the results obtained for building roof contour 4 are uncorrected for the two curved sides. As a result, the RMSE value is relatively high because the corner

Table 3
Quality parameters estimated from the results of Experiment 3.

| Quality parameter | Building roof contour |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 1 | 2 | 3 | 4 | 5 | 6 |
| Completeness (\%) | 98.3 | 98.8 | 98.2 | 94.5 | 96.0 | 97.5 |
| Correctness (\%) | 80.3 | 80.7 | 90.3 | 94.7 | 97.0 | 64.0 |
| RMSE (pixels) | 3.152 | 3.588 | 2.687 | 4.327 | 0.756 | 5.727 |

Table 4
Quality parameters estimated from the results of Experiment 4.

| Quality parameter | Building roof contour |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Completeness (\%) | 99.6 | 98.4 | 96.8 | 98.3 | 99.5 | 97.0 | 92.6 | 96.8 |
| Correctness (\%) | 91.8 | 95.3 | 91.9 | 93.9 | 92.5 | 97.9 | 95.9 | 94.9 |
| RMSE (pixels) | 2.060 | 1.597 | 1.989 | 1.763 | 2.850 | 1.361 | 1.872 | 1.145 |


(a)

(b)

(c)

Fig. 9. Experiment 4: extracted contours.
determination is dependent on the quality of the extracted polygon sides. The performance of the method was only partially satisfactory for the extraction of building roof contour 2 because one of the sides was incorrectly extracted. The RMSE and correctness parameters show that the worst result was obtained in the extraction of building roof contour 6 .

### 3.4. Experiment 4

This experiment focused on the extraction of more complex roof contours, such as L- and T-shaped buildings. Fig. 8 depicts image patches that show the buildings selected for the experiment and their approximate corresponding contours that are required for the extraction method. Fig. 8(a) shows an image patch with two T-shaped buildings, whereas Fig. 8(b) shows an image patch with two T-shaped buildings and one convex building. Finally, Fig. 8(c)
shows an image patch with a large complex T -shape building that is connected to four smaller convex buildings adjacent to it.

Fig. 9 depicts the results obtained in the extraction process, in which the extracted building roof contours are overlaid on the image patches. Visual inspection of the results suggests a good performance, which may be explained in part by the use of initial contours that are close to the initial approximations required by the extraction method. Despite the apparently good results, the extracted contours had inconsistencies that are highlighted in Fig. 9. These inconsistencies mainly occurred in the concavities of the objects, indicating that the method needs improvements to address building roof contours having greater complexity.

The reference contours used for the numerical comparison of building roof contours extracted in this experiment are shown in Fig. 10, and Table 4 summarizes the quality parameters that were estimated from the numerical analysis of the extracted contours. High values obtained for all of the extracted contours (greater than


Fig. 10. Experiment 4: reference contours.
$90 \%$ of completeness and correctness) indicate that the method performed well, thereby confirming the conclusions based on visual inspection of the results. The estimated RMSE values were small and can be considered as acceptable; however, this quality parameter was not useful for identifying contours having inconsistencies. For example, contour 6 had a smaller value than did contour 7, although visual inspection indicates that contour 7 was more accurate than contour 6 . Two additional examples of the aforementioned effect are provided by contours 3 and 5; i.e., the RMSE values for these contours are small, although both presented inconsistencies.

## 4. Conclusions and future work

In this study, we proposed and evaluated a method for extracting building roof contours from digital images. To model building roof contours, we modified the snakes model proposed by Kass et al. (1988). Our underlying assumption was that buildings are projected onto the image space as rectilinear structures and that their adjacent sides intersect at approximately right angles. The resulting energy function was optimized using the dynamic programming optimization algorithm.

The results of our experiment showed that the proposed method satisfactorily performed the task of extracting different building roof contours from digital images. However, the experimental
results also showed that the main disadvantage of the method is that it cannot model the local context. For example, if a building roof contour is nearby and approximately parallel to a shadow or to another building roof boundary, the extraction process may be disturbed, decreasing the quality of the extracted polygon.

The main direction for future work is the development of strategies to circumvent the deficiencies of the method in modeling the local context. For example, shadows may be detected by an appropriate algorithm, and their edges can be removed from the image. Another possibility is to explore the fact that the gradient vectors at shadow boundary points are approximately anti-parallel to points at the corresponding building side in the circumstance discussed above in the experimental section. This property may also be exploited to help the discrimination of the roof margins of adjacent buildings. We also intend to extend the building roof contour model by adding a new energy term to address the local context related to perspective occlusions.

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