GAP CLOSURE IN (ROAD) NETWORKS USING HIGHER-ORDER ACTIVE CONTOURS

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ABSTRACT

We present a new model for the extraction of networks from images in the presence of occlusions. Such occlusions cause gaps in the extracted network that need to be closed. Using higher-order active contours, which allow the incorporation of sophisticated geometric information, we introduce a new, non-local, 'gap closure' force that causes pairs of network extremities that are close together to extend towards one another and join, thus closing the gap between them. We demonstrate the benefits of the model using the problem of road network extraction, presenting results on aerial images.

1. INTRODUCTION

The need to extract networks from images arises in various fields, including cartography, medicine, and biology. It is a difficult problem because the configuration space of networks is both large and complicated. Networks possess strongly constrained geometric properties (*e.g.* narrow arms with roughly parallel sides), but cannot be defined, for example, as variations around a mean shape. We will focus on the extraction of road networks from remote sensing images, but the same problems occur in other applications, and the work herein can be applied to these as well.

The presence of trees or other 'geometric noise' close to a road network can obscure its appearance in remote sensing images, directly and via cast shadows. (We will call all such phenomena 'occlusions'.) The result is that the extracted network is interrupted by gaps. Different methods deal with this in different ways, often without addressing it explicitly. Semi-automatic methods require user-defined endpoints, which must be connected. Since topology change is not allowed, gaps cannot exist, but the price is that the volume explored in network configuration space is very limited, leading to errors. This class includes methods minimizing the optimal path between endpoints [1, 2, 3], and active contour models such as 'ribbon snakes' [4, 5] and 'ziplock snakes' [6]. Methods using marked point processes [7, 8] penalize isolated extremities, but not gaps *qua* gaps. One road tracking method [9] uses an 'inertia' term that allows the estimated road to extend a short distance despite unsupportive data. In contrast to the above methods, we introduce a method that specifically concentrates on the closure of gaps by making pairs of network extremities in proximity extend towards one another and join.

We work within the framework of higher-order active contours [10, 11]. Conventional active contours [12, 13] are defined by linear functionals, expressible as single integrals over the contour or its interior. In contrast, higher-order active contours are defined by polynomial functionals, expressible as multiple integrals over the contour. They lead to non-local forces, which are themselves integrals over the contour. Polynomial energies define interactions between the contour and itself, and allow the incorporation of complex shape information, as well as more sophisticated descriptions of the data. Because they incorporate more specific information, higher-order active contours are more robust to noise than conventional active contours, and permit a generic initialization that renders them automatic.

A particular choice of quadratic functional produces contours with network geometries, and in conjunction with a data term, itself quadratic, has proved effective for road network extraction [10]. We describe this model in section 2. Then, based on the geometry of gaps in networks, we design a non-local gap closure force, to be described in section 3, that makes pairs of points on the contour attract one another if they have high curvatures, lie outside the contour with respect to one another, and are closer than a certain distance. The effect is that network extremities that are close attract, extend towards one another, and join, thus closing the gap between them. In section 4, we present results on real aerial images showing the benefits of the new force. We conclude in section 5.

2. A MODEL FOR NETWORK EXTRACTION

In [10], a particular example of a quadratic active contour was proposed as a model for road networks. In this section, we review it. Let Ω be a bounded subset of $\mathbb{R}^2$, and $I : \Omega \to$

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$\mathbb{R}$ be an image. Define a region by its boundary, denoted C, and called a contour. We define a functional on the space of boundaries of the following form:

$$E(C) = E_g(C) + \lambda E_i(C; I) \tag{1}$$

where λ balances the contributions of the geometric part E_g and the data part E_i. The geometric part E_g is the sum of three terms: two linear (length and area), and one *quadratic*, which defines an interaction between points:

$$\begin{aligned} E_g(C) = &\int dp \;\; |\vec{\mathbf{t}}| + \alpha\, \mathcal{A}(C) \\ &- \beta \int\!\!\int dp \;\; dp' \;\; (\vec{\mathbf{t}} \cdot \vec{\mathbf{t}}')\Psi(R(p,p')) \;\; , \end{aligned} \tag{2}$$

where $\mathcal{A}(C)$ is the area inside the contour; the integrals are over the contour, parameterized by p; $\vec{\mathbf{t}}$ is the tangent vector to the contour; Ψ is a function with the form of a smoothed hard-core potential; and $R(p,p')$ is the Euclidean distance from $C(p)$ to $C(p')$. (Unprimed variables are supposed evaluated at p or $C(p)$; primed variables at p' or $C(p')$.)

The quadratic term causes pairs of points with antiparallel tangent vectors to repel each other, and with parallel tangent vectors to attract each other. This has two effects: it prevents pairs of points with anti-parallel tangent vectors from coming too close, and it encourages the growth of arm-like structures. As a result, the minima of this purely geometric energy, rather than being circles as would be the case in the absence of the quadratic term, have a reticular structure composed of narrow arms with parallel sides. The energy thus makes a very good prior for networks. Several examples of purely geometric evolutions using this energy are given in [11].

The image part E_i is composed of two terms:

$$\begin{aligned} E_i(C; I) = &\int dp \;\; \hat{\mathbf{n}} \cdot \nabla I \\ &-\lambda \int\!\!\int dp \;\; dp' \;\; (\vec{\mathbf{t}} \cdot \vec{\mathbf{t}}')(\nabla I \cdot \nabla I')\Psi(R(p,p')) \end{aligned} \tag{3}$$

where $\hat{\mathbf{n}}$ is the unit outward normal to the contour. The first, linear term favours situations in which the outward normal is opposed to a large image gradient, or in other words, in which the road is brighter than its environment. The second, *quadratic* term favours situations in which pairs of points that are not too distant, and whose tangent vectors are antiparallel (*i.e.* points on opposite sides of the road), lie on large image gradients that point in opposite directions, something that is impossible with a linear term.

We minimize the energy in equation (1) using level set techniques adapted to the non-local forces arising from the quadratic terms. Details are given in [11]. Computing the functional derivative then gives the following descent equation:

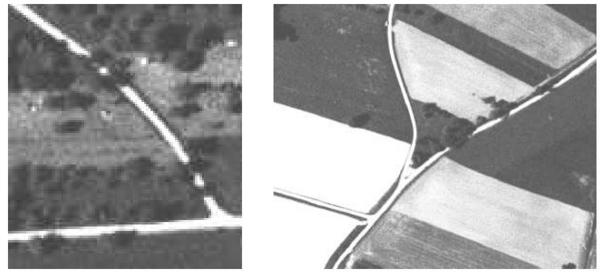

Fig. 1. Aerial images with shadows on roads.

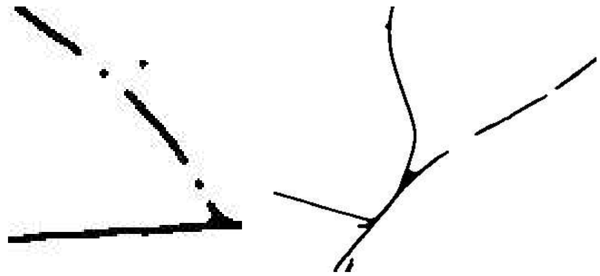

Fig. 2. Results of extraction.

$$\begin{aligned} \hat{\mathbf{n}} \cdot \frac{\partial C}{\partial t} &= -\kappa - \lambda \nabla^2 I - \alpha \\ &+2\lambda \int dp' \;\; (\nabla I' \cdot \nabla\nabla I \cdot \hat{\mathbf{n}}')\Psi(R(p,p')) \\ &-2 \int dp' \;\; (\hat{\mathbf{R}} \cdot \hat{\mathbf{n}}')(\beta + \lambda \nabla I \cdot \nabla I')\dot{\Psi}(R(p,p')) \;\; , \end{aligned} \tag{4}$$

where the dot indicates a derivative; $\hat{\mathbf{R}} = \vec{\mathbf{R}}/|\vec{\mathbf{R}}|$, where $\vec{\mathbf{R}} = C(p') - C(p)$; and κ is the curvature.

We use this model to extract line networks from remote sensing images, recovering not just the 1d network topology, but the region occupied by the network in the image. The results are good [11], but some errors remain. Consider the two images in figure 1. The luminance of the road changes abruptly in places due to the presence of trees on the roadside. The corresponding results obtained with the above model are shown in figure 2. Due to the occlusions, there are gaps in the extracted networks that cannot be overcome by the existing geometric prior. Clearly we have to include more sophisticated geometric information in order to successfully close such gaps.

3. A FORCE FOR GAP CLOSURE

Consider figure 3, showing two roughly co-linear bars representing an interrupted arm of the network. To solve the

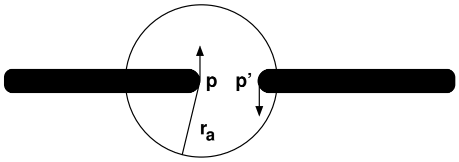

Fig. 3. Gap in a network.

problem created by occlusions or shadows, we would like our model to connect the two pieces of this configuration. However, the points on the tips of the bars have antiparallel tangent vectors, and thus, due to the quadratic term in equation (2), cannot get closer than a certain distance. The upper part of figure 5 shows the evolution of the bars using equation (2). They repel each other and hence remain separated.

The relevant contour configurations can be characterized as having two intervals of high curvature that are quite close, and such that the vector $\hat{\mathbf{R}}$ linking them is outside the contour. We thus modify the evolution equation (4) by adding a new force to make these regions attract one other:

$$F_a(p) = \beta \int dp' \ (\hat{\mathbf{R}}' \cdot \hat{\mathbf{n}}') \dot{\Psi}_2(R(p,p')) H(\kappa, \kappa') \times \left(f(\hat{\mathbf{R}} \cdot \hat{\mathbf{n}}) + f(\hat{\mathbf{R}}' \cdot \hat{\mathbf{n}}') \right) \quad . \tag{5}$$

The functions $H(\kappa_1, \kappa_2)$ and $f(x)$ are simple thresholds:

$$H(\kappa_1, \kappa_2) = \begin{cases} 1 & \text{if } \kappa_1 \text{ and } \kappa_2 > \kappa_{\text{thresh}} \ , \\ 0 & \text{otherwise} \ ; \end{cases}$$
$$f(x) = \begin{cases} 1 & \text{if } x > 0 \ , \\ 0 & \text{otherwise} \ . \end{cases} \tag{6}$$

The new force is thus zero unless the curvatures at both p and p' are high, and one of $\hat{\mathbf{R}} \cdot \hat{\mathbf{n}}$ and $\hat{\mathbf{R}}' \cdot \hat{\mathbf{n}}'$ is positive. The latter conditions amount to saying that p' is in a direction exterior to the contour at p and vice-versa.

When the new force is non-zero, it should cancel the existing, repulsive force in equation (4) and replace it with an attractive force. We thus set $\Psi_2 = \Psi_a - \Psi$, and define the attractive potential Ψ_a by:

$$\Psi_a(x) = \begin{cases} 2(\frac{x}{r_a} + \frac{1}{\pi}\sin(\frac{\pi x}{r_a}) - 1) & \text{if } x < r_a \ , \\ 0 & \text{otherwise} \ , \end{cases} \tag{7}$$

The parameter r_a determines the range of the attractive force. This function is depicted in figure 4 for $r_a = 4$.

The lower part of figure 5 shows the purely geometric evolution of two bars, as before, but with the new force added. The two bars now attract one other and fuse, thus closing the gap. Note that this type of force is only possible in the context of higher-order contours, where two points can interact with each other.

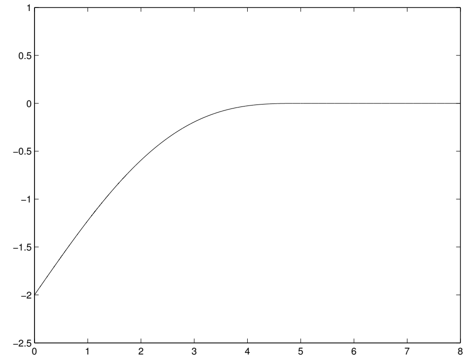

Fig. 4. The function Ψ_a for $r_a = 4$.

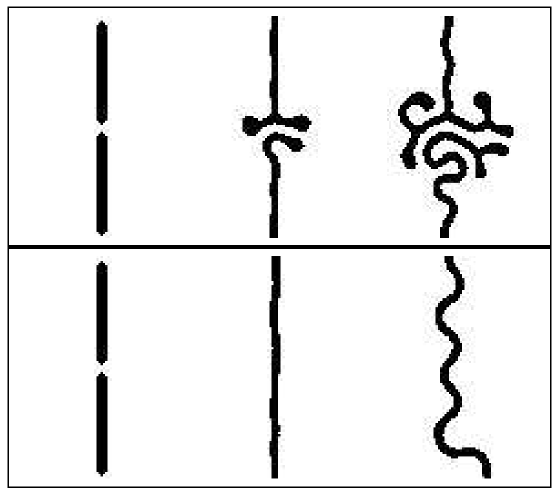

Fig. 5. Two purely geometric evolutions, one without (top) and one with (bottom) the new gap-closing force. Time runs from left to right.

4. EXPERIMENTAL RESULTS

We tested the new model on the real images of figure 1. As in the results of figure 2, the contour was initialized to a rounded square covering the whole image, without regard to the network configuration, thus rendering the method automatic. This is in contrast to many methods, which require initialization close to the true network.

The results are shown in figure 6. In the first image, the road is perfectly extracted: the gaps in figure 2 are closed. The extraction in the second image is much more difficult. There are occlusions due to the presence of trees near the road, and two junctions. In addition, the fields in the image possess a geometry and radiometry similar to that of the roads, with parallel sides and high image gradients. Nevertheless, the network is entirely recovered, with the gaps that were present in figure 2 now closed thanks to the new force.

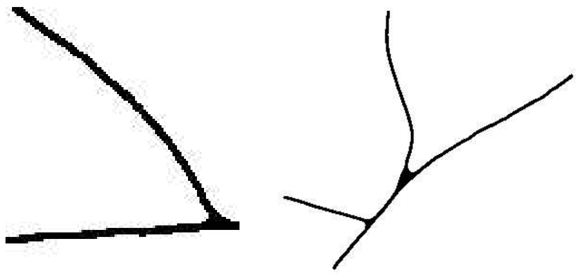

Fig. 6. Results on real images with the gap closure force.

5. CONCLUSION

Higher-order active contours offer many possibilities for describing regions in an image beyond those offered by conventional models. Since points on the contour may interact with one another, complex geometric and data information may be included. In this paper, we have proposed a new quadratic active contour model for network extraction, involving a new force term designed to overcome the problem of gaps in the network due to occlusions. The force causes network extremities that are in proximity to attract one another, thus tending to draw together two ends of a gap. The force is non-local, and can only be realized within the framework of higher-order active contours. Via experiments on road network extraction from aerial images, we have shown how higher-order active contours produce good results through the incorporation of prior shape information, reduce initialization dependence (all our initializations were generic rounded squares), and in particular how the gap closure force makes the model robust to occlusions. As we have stressed, the model is not limited to road network extraction, since the difficulties of network geometry and gap closure occur in many areas.

We proceeded by defining a force, but it would be better to include this term in the energy. Unfortunately, it is not clear that equation (5) is a gradient. Alternative energy terms pose severe technical problems because the resulting descent equations depend on second derivatives of the curvature. The numerical manipulation of such terms is very delicate, and instabilities easily arise. Our current work is focused on resolving these numerical issues.

6. REFERENCES

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