DOI:10.1068/b31128c

Encoding geometric information in road networks extracted from binary images

Rui Carvalho

The Bartlett School of Graduate Studies, University College London, 1–19 Torrington Place, London WCIE 6BT, England; e-mail: rui.carvalho@ucl.ac.uk

Michael Batty

Centre for Advanced Spatial Analysis, University College London, 1–19 Torrington Place, London WC1E 6BT, England; e-mail: m.batty@ucl.ac.uk Received 14 November 2003; in revised form 20 October 2004

Abstract. The authors discuss recent progress in extracting road networks from digital imagery. We briefly review recent developments in methods for the automatic extraction of road centre line networks and propose a related algorithm aimed at encoding the geometry of road networks with line segments. Our algorithm is inspired by 'axial lines', which have been defined as lines of uninterrupted movement within urban streetscapes or buildings. We show that axial lines appear as ridges in isovist fields. These are formed from the maximum diametric lengths of the individual isovists, sometimes called viewsheds, which make up these fields. We present an image-processing technique for the identification of lines from ridges, discuss current strengths and weaknesses of the method, and show how it can be implemented easily and effectively.

As Ratti and Richens recently pointed out in this journal (Ratti and Richens, 2004), image-processing techniques have rarely been used in urban analysis, despite the quite widespread construction and exploitation of low-cost geospatial databases from a variety of image sources. This has been one of the most active areas in computer vision and photogrammetry, in which techniques for extracting buildings and roads from images have made extensive progress towards operational use (see Baltsavias et al, 2001; EuroSDR Working Group; Gruen et al, 1997; Mena, 2003; Zhang, 2003). There is thus a strong case for urban planners and designers to become involved in these fields, as recently pointed out by Steadman (2004) in an editorial in this journal. In particular, we believe that algorithms for the automatic extraction of road networks offer considerable potential for significantly improving the analysis, understanding, representation, and modelling of urban dynamics and urban growth. Whereas the challenge in developing countries is to build the road network from scratch, in developed countries the purpose of such algorithms is to detect changes and to adapt existing map bases accordingly.

Although progress in extracting roads from digital imagery has drawn considerable attention recently (Gruen et al, 1997; Mena, 2003; Zhang, 2003), there is as yet no unifying theory behind all these techniques. The approaches developed are quite distinct because of the differences in strategies, type, and resolution of input images, the primitives employed for road identification, experimental configurations, ways of processing, and even in the general assumptions adopted. Road-extraction approaches are generally classified according to their degree of automation. A typical automatic system for road extraction consists of road finding, road following/tracking/tracing, and then road linking. A semiautomatic approach requires the interaction between the algorithm and an operator. In contrast to automatic methods, road initialisation is given by a human operator; therefore the algorithm does not have to consider the problem of road finding. Most of the methods currently in use are semiautomatic and

would presumably fail, or at best be very limited, in their applicability to images taken over very dense built-up areas (Hinz et al, 2001).

In this paper we propose an automatic method of road-network reconstruction from binary images. In contrast to currently existing methods of road extraction, this one will allow for the efficient encoding of geometric information as straight-line segments. An economic encoding of geometric information into automatically extracted road networks might assist in the characterisation of the growth and spatiotemporal dynamics of the road network. Nevertheless, parsimony comes at the expense of information loss: the method we propose is economic in that it encodes the road network as a set of line segments, but there is a loss of morphological information (that is, one cannot recover the full detail of the original morphology from the network). Here we focus on an algorithm to extract lines from urban open space (that is, a binary map based on built/not built) and therefore leave more complex situations (for example, road-network extraction from satellite imagery) for future work. We also note that our method is a first-order approximation to the encoding of geometric information; one could derive higher order approaches by fitting polynomials along the curves of road-centre lines, instead of limiting these to straight-line segments.

Axial lines are used in space syntax to simplify connections between spaces that make up an urban or architectural morphology. Usually, they are defined manually by partitioning the space into the smallest number of largest convex subdivisions and defining these lines as those that link these spaces together. Subsequent analysis of the resulting set of lines (which is called an 'axial map') enables the relative nearness, or accessibility, of these lines to be computed. These can then form the basis for ranking the relative importance of the underlying spatial subdivisions. Peponis et al (1990) proposed that space-syntax measures may be relevant in understanding the relation between building layout and spatial cognition, and presented a case study of Homey Hospital. Hillier et al (1993) suggested that links between streets, squares, alleys, and so on can have effects on movement patterns which are independent of 'attractors', and presented case studies of Kings Cross and the City of London, in London (United Kingdom). Peponis et al (1997) argued that space-syntax measures may help explain patterns of pedestrian and vehicular movement in Buckhead and Downtown Atlanta (both in Atlanta, Georgia, USA).

To date, progress has been slow in the automatic generation of axial lines. Lack of agreement on their definition (Batty and Rana, 2004; Carvalho and Batty, 2004; Penn et al, 1997; Peponis et al, 1998; Turner et al, 2005), and lack of awareness of how similar problems have been treated in fields such as pattern recognition and computer vision, have inhibited explorations of the problem, and only very recently have there been any attempts to evolve methods for the automated generation of such lines (Batty and Rana, 2004; Peponis et al, 1998; Ratti, 2002).

Our approach stems from the observation that Hillier and Hanson's original definition can be decomposed into two independent parts: the first is a ranking process which states that one can draw the axial map by "first finding the longest straight line that can be drawn ..., then the second longest, and so on"; the second states that the process should be repeated "until all convex spaces are crossed and all axial lines that can be linked to other axial lines without repetition are so linked" (1984, page 99). Here, we show that the fundamental part of Hillier and Hanson's definition is the ranking process and that, apart from unconnected lines on the periphery of the space, one can arrive at axial maps without consideration either of convex partitions or of "all axial links" (1984, page 92). We also show that Hillier and Hanson's intuition can be captured with a simple and parsimonious image-processing algorithm, similar to existing procedures used to extract road-centre lines.

A definition of axial lines (global entities) with neighbourhood methods (local entities) implies that the transition from small-scale to large-scale urban environments will carry no new theoretical assumptions, and that the computational effort will grow linearly with the number of mesh points used. Our main goal is to gain insight into urban networks in general, and axial lines in particular. Therefore, we leave algorithm optimisations for future work. It is, however, beyond the scope of the present paper to address generalisations of axial maps, or to integrate current theories with geographical information systems (GISs) (but, see Batty and Rana, 2004; Jiang et al, 2000).

Automatic extraction of road networks from binary images: simple algorithms

Typically, the extraction of road-centre line data from digital images involves the identification of the road edges and then the application of a morphological image analysis operation, such as thinning, to reduce the road to its centre line. Morphological image analysis is a field of applied mathematics that concentrates on the geometric structure within a raster image. The basic idea is to probe the image with a structuring element. The structuring element is normally a 3×3 matrix which is displaced along the pixels of the image, and either matches the original image in the local neighbourhood or not. This process allows for the construction of formal algorithms that are compositions of two canonical operations: morphological dilation and erosion. Morphological operations are the algorithms of choice to describe the *shape* of raster images, such as boundaries, skeletons, and the convex hull, as well as to implement preprocessing techniques, such as filtering, segmentation, thinning, and pruning. It is beyond the scope of this paper to review the field, but the interested reader is referred to chapter 9 of Gonzalez and Woods (2002) for a comprehensive introduction to thinning and skeletons; to Soille (2003, pages 56, 158) for a discussion of homotopy and the set of structuring elements used in thinning; to chapter 9 of Gonzalez et al (2004) for a hands-on approach to morphological image processing in MATLAB; and to Soille and Pesaresi (2002) for an introduction to the use of morphological image processing in spatial analysis. Figure 1 (over) shows the extraction of the road-centre line network for the French town of Gassin [see figure 1(d)]. Road-centre lines are extracted by using the morphological image processing technique of thinning.

Axial maps can be regarded as members of a larger family of axial representations (often called 'skeletons') of two-dimensional images. There is a vast literature on this, originating with the work of Blum on the medial axis transform (MAT) (Blum, 1973; Blum and Nagel, 1978), which operates on the object rather than on its boundary [see Tonder et al (2002) for a link between visual science and the MAT applied to a Japanese Zen garden]. Geometrically, the MAT uses a circular primitive. Objects are described by the collection of the maximal discs, ones which fit inside the object but into no other disc inside the object. The object is the logical union of all of these maximal discs. The description is in two parts: the locus of centres, called the symmetric axis; and the radius at each point, called the radius function, R (Blum and Nagel, 1978). The MAT employs an analogy to a grassfire. Imagine an object whose border is set on fire. The subsequent internal convergence points of the fire represent the symmetric axis, the time of convergence for unity velocity propagation being the radius function (Blum and Nagel, 1978).

For binary data, the related notion of skeletons can be derived from the medial axis and be computed by (grassfire-like) distance transforms. It is, however, well known that features extracted in this way can be highly sensitive to small perturbations of the boundary. Figure 1(b) shows the medial axis transform for the open space of the French town of Gassin, where the sensitivity to perturbations of the boundary is apparent. The reader is referred to chapter 9 of Gonzalez and Woods (2002) and



Figure 1. (a) Layout of the French town of Gassin. (b) Medial axis transform of the open space in (a). (c) Thinning of the plan in (a). (d) Layout of Gassin, overlaid with thinning of the open space, the road-centre line network appears on the open space and intersections (nodes) are highlighted in red in the online version of the journal.

chapter 9 of Gonzalez et al (2004) for a discussion on morphological image-processing algorithms to extract the medial axis transform.

An isovist is the space defined around a point (or centroid) from which an object can move in any direction before the object encounters some obstacle (Benedickt, 1979). In space syntax, this space is often regarded as a viewshed, and a measure of how far one can move or see is the maximum line of sight through the point at which the isovist is defined. We shall see that the paradigm shift from the set of maximal discs inside the object (as in the MAT) to the maximal straight line that can be fit inside its isovists, holds a key to understanding what axial lines are.

As in space syntax, we simplify the problem by eliminating terrain elevation and associate each isovist centroid with a pair of horizontal coordinates (i, j) and a third coordinate, $\Delta_{i,j}^{\max}$, which we define as the length of the longest line segment that crosses the observation point (i, j) and whose points are all in the isovist of (i, j). Our hypothesis states that axial lines are equivalent to ridges on the $\Delta_{i,j}^{\max}$ surface. The reader can absorb the concept by 'embodying' himself or herself in the $\Delta_{i,j}^{\max}$ landscape.

To show that all axial lines are ridges on the $\Delta_{i,j}^{\max}$ surface, we note that movement along the direction perpendicular to an axial line implies a decrease along the $\Delta_{i,j}^{\max}$ surface; and that $\Delta_{i,j}^{\max}$ is an invariant, both along the axial line and along the ridge. As we will show later [see figure 4(a)], there are simple examples where the ridge is not defined along the full length of the axial line. In these situations, the above argument applies only to the region where both the ridge and the axial line are locally defined and the axial line is generated from the ridge by extracting a line segment that crosses the open space until the border (built form). We establish an arbitrary threshold, and consider only ridges with length larger than the street width; smaller ridges are not associated with axial lines. Showing that, up to an issue of scale, all ridges on the $\Delta_{i,j}^{\max}$ landscape are axial lines is more difficult, and it is easy to understand that one may not be able to trace axial lines even for very simple geometries (how does one draw axial lines in a circle?) Therefore, we rely on numerical simulations to verify the second part of the argument, but are aware that, in general, the algorithm will extract curves and not lines.

Our method follows a procedure similar to MAT. Indeed, the MAT approach to skeletonisation first calculates a scalar field for the object (the distance map) and then identifies a set of ridge points, or generalised local maxima, in this scalar map. In a discretised representation the final skeleton consists of such ridge points, with the possible addition of a set of points necessary to form a connected structure (Simmons and Séquin, 1998). Our method is also inspired by the generalisations of axial maps proposed by Batty and Rana (2004), and we use the same measure, $\Delta_{i,j}^{max}$, albeit with the more restricted goal of arriving at a definition of the axial map.

Here, we sample isovist fields by generating isovists for the set of points on a regular lattice (Batty, 2001; Ratti, 2002; Turner et al, 2001). This procedure is standard practice in spatial modelling (Burrough and McDonnell, 1998). Specifically, we are interested in the isovist field defined by the length of the longest straight line across the isovist at each mesh point (i, j). This measure is denoted the maximum diametric length, $\Delta_{i,j}^{\max}$ (Batty and Rana, 2004), or the maximum of the sum of the length of the lines of sight in two opposite directions (Ratti, 2002, page 204). To simplify notation, we prefer the first term.

First, we generate a digital elevation model (DEM) (Burrough and McDonnell, 1998) of the isovist field, where $\Delta_{i,j}^{\max}$ is associated with mesh point (i, j) (Batty, 2001; Ratti, 2002). Next, we use a point algorithm to locate the ridges on the DEM. Our algorithm detects ridges by extracting the local maxima of the discrete DEM. Next, we use an image-processing transformation (the Hough transform, HT) on a binary image containing the local maxima points which lets us rank the detected lines in the Hough parameter space. We then invert the HT to find the location of axial lines on the original image.

The HT is used in computer vision and pattern recognition for detecting geometric shapes that can be defined by parametric equations. Related applications of the HT include detection of road-lane markers (Kamat-Sadekar and Ganesan, 1998; Pomerleau and Jochem, 1996) and the determination of the directionality of urban texture (Habib and Kelley, 2001; Ratti, 2002). There are two major difficulties with the Hough method: it does not yield any information as to the location of the line segment being considered; and it responds equally to a line segment composed of connected points and a set of collinear, but nonconnected, points.

The HT converts a difficult detection problem in image space into a more easily solved, local peak detection problem in parameter space (Illingworth and Kittler, 1988). The basic concept involved in locating lines is point-line duality. In an influential paper, Duda and Hart (1972) suggested that straight lines might be usefully parameterised by the length, ρ , and orientation, θ , of the normal vector to the line from the image origin. This is illustrated in figure 2 (over), where we show the relationship between Cartesian and polar coordinates for a line:

$$\begin{aligned} \rho &= \frac{x}{\cos\theta} + (y - x \tan\theta) \sin\theta \\ &= \frac{x}{\cos\theta} + y \sin\theta - x \frac{\sin^2 \theta}{\cos\theta} \\ &= x \left(\frac{1 - \sin^2 \theta}{\cos\theta} \right) + y \sin\theta = x \cos\theta + y \sin\theta . \end{aligned}$$

1



Figure 2. Relationship between the definition of a line by Cartesian and by polar coordinates.

The HT proceeds as follows. First, for each pixel value, (x, y), vary θ from 0° to 180° and calculate $\rho = x \cos \theta + y \sin \theta$. Second, given an accumulator array (ρ, θ) of size (N_{ρ}, N_{θ}) , where N_{ρ} and N_{θ} are the number of cell elements along the ρ and the θ coordinates, respectively, increment the element in the array that lies in the box with centre (ρ, θ) . Third, look for the highest values in the accumulator array (ρ, θ) and thus identify the pair (ρ, θ) that is most likely to indicate a line in (x, y) space. In short, each point p, P = (x, y), in the image space is mapped into a sinusoidal curve in the (ρ, θ) space, $\rho = x \cos \theta + y \sin \theta$, and points lying on the same straight line in the image plane correspond to curves through a common point in the parameter plane—see figure 3. The HT specifies a line as follows. Imagine yourself standing on the image plane at the origin of the coordinates, facing the positive y direction—see figure 3(c). Turn a specified angle, θ_L , to your right, and then walk a specified number of pixels, ρ_L , forward. Turn through 90° and go forward; you are now walking along the required line in the image.

The process of use of the HT to detect lines in an image involves the computation of the HT for the entire image, accumulating evidence in an array for events by a voting, or counting, scheme (points in the parameter plane 'vote' for the parameters of the lines to which they possibly belong) and searching the accumulator array for peaks which hold information about the potential lines present in the input image. The peaks provide only the length of the normal to the line and the angle that the normal makes with the *y* axis. They do not provide any information about the length, position, or end points of the line segment in the image plane (Gonzalez and Woods, 2002). Our linedetection algorithm starts by extracting the point that has the largest number of votes in parameter space, which corresponds to the line defined by the largest number of collinear local maxima of $\Delta_{i,j}^{max}$, and proceeds by extracting lines in rank order of the number of their votes in parameter space. One of us has previously (Batty and Rana, 2004) proposed rank-order methods as a rigorous formulation of the procedure originally outlined as "first finding the longest straight line that can be drawn, then the second longest line and so on ..." (Hillier and Hanson, 1984, page 99).

To test the hypothesis that axial lines are equivalent to ridges on the $\Delta_{i,j}^{\max}$ surface, we start with a simple geometric example: an H-shaped open-space structure (see figure 4, over). As illustrated in figure 4, axial lines are equivalent to ridges for this simple geometric example if the ridges are extended until the borders on the open space. Indeed, one confirms this both in figure 4(a) and in figure 4(b) by zooming-in



Figure 3. (a) Point P = (75, 75) in the image plane. (b) The Hough transform converts P into a sinusoidal curve, $\rho = x \cos \theta + y \sin \theta$, where (x, y) = (25, 25) are the coordinates of P relative to O = (50, 50) and $\theta \in [0, 180]$. (c) Line segment between points (0, 50) and (50, 0). This segment crosses point P and is orthogonal to the segment \overline{OP} . (d) The line segment in (c) is identified in Hough space by the point at which all the sinusoids intersect— $(\rho_L, \theta_L) = (2^{1/2}x, 45) \cong (35.4, 45)$. The line defined by the segment in (c) can be rebuilt on the image plane by starting at O facing the direction of the positive y-axis, turning θ_L degrees to the right, walking forward ρ_L (until P) and finally tracing the perpendicular line to \overline{OP} .

the $\Delta_{i,j}^{\max}$ landscape. Next, we aim at developing a method to extract these ridges as lines. In figure 5(a) (over), we plot the local maxima of the discretised $\Delta_{i,j}^{\max}$ landscape. A point (i, j) is a local maximum of the $\Delta_{i,j}^{\max}$ surface iff

$$\Delta_{i,j}^{\text{localmax}} \equiv \max(\Delta_{k,j}^{\text{max}})\Big|_{\substack{k \in \{i-1, i, i+1\}\\l \in \{j-1, i, j+1\}}} = \Delta_{i,j}^{\text{max}}$$

that is, if and only if it is the maximum of the surface on a 3×3 neighbourhood. The local maxima are a discretised signature of the ridges on the $\Delta_{i,j}^{\max}$ continuous field (in our case, the ridges can be computed as the local maxima of the $\Delta_{i,j}^{\max}$ discretised surface). Figure 5(b) is the HT of figure 5(a), where θ goes from 0° to 180° in increments of 1°. The peaks on figure 5(b) are the maxima in parameter space, (ρ , θ), which are ranked by height in figure 5(c). The first four visible peaks in parameter space—figures 5(b) and 5(c)—correspond to the four symmetric lines defined by the highest number of collinear points in the original space—figure 5(a). Then, the ranked maxima in parameter space are inverted onto the coordinates of the lines in the original space, yielding the 'detected' lines which are plotted in figure 5(d), in which we have only plotted the lines corresponding to the six highest peaks in parameter space.



Figure 4. (a) Plot of the maximum diametric length $(\Delta_{i,j}^{max})$ isovist field for an H-shaped open-space structure. (b) Zoom-in (detail) of (a), showing the ridges on the longer arms of the H shape. Arrows point to the ridges on both figures.

Having tested the hypothesis on a simple geometry, we repeated the procedure for the French town of Gassin. We scanned the open-space structure of Gassin (Hillier and Hanson, 1984, page 91) as a binary image and reduced the resolution of the scanned image to 300 dpi (see inset in figure 6, over). The resulting image has 171×300 points, and was read into a MATLAB matrix. Next we used a ray-tracing algorithm in MATLAB (angle step = 0.01°) to determine the $\Delta_{i,j}^{\text{max}}$ measure for each point in the mesh that corresponds to open space. The landscape of $\Delta_{i,j}^{\max}$ is plotted in figure 6. The next step was to extract the ridges on this landscape. To do this, as we have seen before, we determined the local maxima on the $\Delta_{i,j}^{\max}$ landscape. Next, we applied the HT, as in the H-shape example, and inverted it to determine the six axial lines for the town of Gassin (see figure 7, over). We should alert readers to the fact that, as we have not imposed any boundary conditions on our definition of lines from the HT, these lines intersect building forms-illustrating that what the technique has done is identify the dominant linear features in image space, but ignoring any obstacles which interfere with the continuity of these linear features. We consider that this is a detail that can be addressed in subsequent development of this approach.



Figure 5. (a) Local maxima of the maximum diametric length $(\Delta_{i,j}^{\max})$ for the H-shaped structure in figure 4. (b) Hough transform of (a). (c) Rank of the local maxima of the surface in (b). (d) The Hough transform is inverted and the six highest peaks in (c) define the axial lines shown.

Where do we go from here?

Figure 7 shows that the axial map encodes road-network geometry in a set of straight lines; whereas figure 1(d) suggests that the road-centre line network could provide a more detailed description of urban morphology if road-centre lines were to be interpolated with polynomial curves between the street intersections. This leads us to suggest that axial lines could be used as a first approximation to encoding geometric information in road networks, complementing existing land-use and transport models. The availability of geometric information on the network edges may also be relevant to the modelling of urban growth, as it is more precise than is information on the location of the network nodes alone. As Steadman (2004) points out, these considerations seem so far to have been peripheral to space syntax. But, as algorithms to extract road-centre lines reach maturity, how the two descriptions may complement each other is, in our opinion, a central issue.

Our hypothesis has successfully passed the test of extracting axial lines both for a simple geometry and for a traditional case study in space syntax—the town of Gassin. Indeed, $l_{2, detected}$, $l_{3, detected}$, $l_{4, detected}$, $l_{5, detected}$, and $l_{6, detected}$ in figure 7(b) all match the lines originally drawn reasonably well [figure 7(a)]; Hillier and Hanson, 1984). Differences between the original and detected lines appear for $l_{3, original}$ and $l_{3, detected}$, when the mesh we used to detect lines was not fine enough to account for the detail of the geometry, and the HT counts collinear points along a line that intersects buildings; and for $l_{5, original}$ and $l_{5, detected}$, where the original solution is clearly not the longest line through the space.



Figure 6. Plot of the maximum diametric length $(\Delta_{i,j}^{\max})$ isovist field for the town of Gassin. The inset shows the scanned image (Hillier and Hanson, 1984).



Figure 7. (a) Axial lines for the town of Gassin (Hillier and Hanson, 1984). (b) Local maxima of $\Delta_{i,j}^{\max}$ (\blacksquare) and lines detected by the proposed algorithm.

Figure 7 highlights two fundamental issues which are shared by any spatial problem, both of which are related to the issue of tracing "all lines that can be linked to other axial lines without repetition" (Hillier and Hanson, 1984, page 99). The first is that defining axial lines as the longest lines of sight may lead to unconnected lines on the urban periphery. The problem is quite evident with line $l_{1,\text{original}}$ in figure 7(a) (Hillier and Hanson, 1984, page 91), where the solution to the longest line crossing the space is $l_{1,\text{detected}}$ —see figure 7(b). Thus, the price to pay for a simple algorithm may be that not all expected connections are traced. The second problem is an issue of scale, as one could continue identifying more local ridges with increasing image resolution (see discussion in Batty and Rana, 2004). We believe that the problem is solved if the width of the narrowest street is selected as a threshold for the length of axial lines detected from the ridges. Thus, we consider only ridges longer than this threshold.

Our approach to axial map extraction is preliminary, as the HT detects only line parameters whereas axial lines are line segments. Nevertheless, there has been considerable research effort put into line-segment detection in urban systems, generated mainly by the detection of road lane markers (Kamat-Sadekar and Ganesan, 1998; Pomerleau and Jochem, 1996), and we are confident that further improvements would only involve existing theory.

We have shown that global entities in urban morphology can be defined with a purely local approach. We have shown that there is no need to invoke the concept of convex space to define axial lines. By providing rigorous algorithms inspired by work in pattern recognition and computer vision, we have started to uncover problems implicit in the original definition (disconnected lines at boundary and scale issues), but have proposed working solutions to all of these problems which, we believe, will enrich the field of space syntax and engage other disciplines in the effort of gaining insight into urban morphology. Finally, we look forward with considerable optimism to the automatic extraction of axial lines and axial maps in the near future, and believe that automatic processing of streetscape morphologies in medium-scale to large-scale cities is only a few years away from routine implementation on desktop computers.

Acknowledgements. Rui Carvalho acknowledges generous financial support from Grant EPSRC GR/N21376/01 and is grateful to Professors Bill Hillier and Alan Penn for valuable comments. The authors are indebted to Sanjay Rana for the suggestion that axial lines appear as ridges in the MDL isovist field, and for using his Isovist Analyst Extension (Rana, 2002) to provide independent corroboration on the 'H' test problem.

References

- Baltsavias E P, Gruen A, Gool L V (Eds), 2001 Automatic Extraction of Man-made Objects from Aerial and Space Images (III) (A A Balkema, Cape Town)
- Batty M, 2001, "Exploring isovist fields: space and shape in architectural and urban morphology" Environment and Planning B: Planning and Design 28 123-150
- Batty M, Rana S, 2004, "The automatic definition and generation of axial lines and axial maps" Environment and Planning B: Planning and Design **31** 615–640
- Benedikt M L, 1979, "To take hold of space: isovists and isovist fields" *Environment and Planning B: Planning and Design* **6** 47–65
- Blum H, 1973, "Biological shape and visual science (part 1)" Journal of Theoretical Biology 38 205-287
- Blum H, Nagel R N, 1978, "Shape description using weighted symmetric features" *Pattern Recognition* **10** 167–180
- Burrough P A, McDonnell R A, 1998 *Principles of Geographical Information Systems* (Oxford University Press, Oxford)
- Carvalho R, Batty M, 2004, "Automatic extraction of hierarchical urban networks: a micro-spatial approach", in *Computational Science—ICCS 2004: 4th International Conference* Eds M Bubak, G D van Albada, P M A Sloot, J J Dongarra (Springer, Berlin) pp 1109–1116
- Duda R O, Hart P E, 1972, "Use of the Hough transformation to detect lines and curves in pictures" Communications of the ACM 15 11 – 15

EuroSDR Working Group, http://www.bauv.unibw-muenchen.de/institute/inst10/oeepe/

Gonzalez R C, Woods R E, 2002 Digital Image Processing (Addison-Wesley, Reading, MA)

- Gonzalez R C, Woods R E, Eddins S L, 2004 *Digital Image Processing using MATLAB* (Prentice-Hall, Englewood Cliffs, NJ)
- Gruen A, Baltsavias E P, Henricsson O (Eds), 1997 Automatic Extraction of Man-made objects from Aerial and Space Images (II) (Birkhäuser, Basel)
- Habib A, Kelley D, 2001, "Automatic relative orientation of large scale imagery over urban areas using modified Hough transform" *ISPRS Journal of Photogrammetry and Remote Sensing* **56** 29–41
- Hillier B, Hanson J, 1984 The Social Logic of Space (Cambridge University Press, Cambridge)
- Hillier B, Penn A, Hanson J, Grajewski T, Xu J, 1993, "Natural movement: or, configuration and attraction in urban pedestrian movement" *Environment and Planning B: Planning and Design* 20 29–66
- Hinz S, Baumgartner A, Mayer H, Wiedemann C, Ebner H, 2001, "Road extraction focusing on urban areas", in *Automatic Extraction of Man-made Objects from Aerial and Space Images (III)* Eds E P Baltsavias, A Gruen, L V Gool (A A Balkema, Rotterdam) pp 255–265
- Illingworth J, Kittler J, 1988, "A survey of the Hough transform" Computer Vision, Graphics, and Image Processing 44 87-116
- Jiang B, Claramunt C, Klarqvist B, 2000, "An integration of space syntax into GIS for modelling urban spaces" International Journal of Applied Earth Observation and Geoinformation 2 161 – 171
- Kamat-Sadekar V, Ganesan S, 1998, "Complete description of multiple line segments using the Hough transform" *Image and Vision Computing* **16** 597–613
- Mena J B, 2003, "State of the art on automatic road extraction for GIS update: a novel classification" Pattern Recognition Letters 24 3037 – 3058
- Penn A, Conroy R, Dalton N, Dekker L, Mottram C, Turner A, 1997, "Intelligent architecture: new tools for the three dimensional analysis of space and built form", in *Proceedings of the 1st International Symposium on Space Syntax, University College London, U.K.* (University College London, London) 2 30.1–30.19
- Peponis J, Zimring C, Choi Y K, 1990, "Finding the building in wayfinding" *Environment and Behavior* **22** 555–590
- Peponis J, Ross C, Rashid M, 1997, "The structure of urban space, movement and co-presence: the case of Atlanta" *Geoforum* **28** 341 – 358
- Peponis J, Wineman J, Bafna S, Rashid M, Kim S H, 1998, "On the generation of linear representations of spatial configuration" *Environment and Planning B: Planning and Design* **25** 559–576
- Pomerleau D, Jochem T, 1996, "Rapidly adapting machine vision for automated vehicle steering" IEEE Expert 11 19-27
- Rana S, 2002, "Isovist analyst extension for arcview 3.2", http://www.casa.ucl.ac.uk/sanjay/ software_isovistanalyst.htm
- Ratti C, 2002 Urban Analysis for Environmental Prediction unpublished PhD thesis, Martin Centre for Architectural and Urban Studies, University of Cambridge, Cambridge
- Ratti C, Richens P, 2004, "Raster analysis of urban form" *Environment and Planning B: Planning and Design* **31** 297 309
- Simmons M, Séquin C H, 1998, "2D shape decomposition and the automatic generation of hierarchical representations" *International Journal of Shape Modeling* **4** 63–78
- Soille P, 2003 Morphological Image Analysis (Springer, Berlin)
- Soille P, Pesaresi M, 2002, "Advances in mathematical morphology applied to geoscience and remote sensing" *IEEE Transaction on Geoscience and Remote Sensing* **40** 2042–2055
- Steadman P, 2004, "Developments in space syntax" *Environment and Planning B: Planning and Design* **31** 483–486
- Tonder G J V, Lyons M J, Ejima Y, 2002, "Visual structure of a Japanese Zen garden" *Nature* **419** 359–360
- Turner A, Doxa M, O'Sullivan D, Penn A, 2001, "From isovists to visibility graphs: a methodology for the analysis of architectural space" *Environment and Planning B: Planning and Design* 28 103 – 121
- Turner A, Penn A, Hillier B, 2005, "An algorithmic definition of the axial map" *Environment and Planning B: Planning and Design* forthcoming
- Zhang C, 2003 Updating of Cartographic Road Databases by Image Analysis Swiss Federal Institute of Technology (ETH), Zürich, http://www.photogrammetry.ethz.ch/general/persons/chunsun_pub/ chunsun_dissertation.pdf