Bending the axial line:

Smoothly continuous road centre-line segments as a basis for road network analysis

50

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Abstract

This paper presents the use of smoothly continuous road centre-line segments – which are here termed strokes – as a useful basis for the analysis of street and road networks. The decomposition of networks into linear strokes, which show good continuation of direction and continuity of character (width or type), has been found to provide a basis for robust, effective, and efficient automatic generalisation of road networks. Network generalisation and space syntax are shown to have similar requirements for understanding the importance of individual elements in the network structure. Stroke-based network generalisation employs structural analyses based on space syntax methods. The idea of replacing axial lines with strokes as the basic spatial representation in space syntax is presented. It is suggested that in spaces where linearity is dominant, in certain contexts such as traffic flow studies or when curved routes must be handled, stroke-based space syntax could offer definite computational and modelling advantages over the conventional use of axial lines.

1. Introduction

This paper is concerned with techniques of space syntax and network generalisation, and the idea of introducing into space syntax a spatial representation originally developed to facilitate generalisation. The two discipline areas will be introduced, noting some common requirements. The idea of "strokes", how they can be used to describe networks, and their role in the generalisation of networks will be discussed. Finally, the idea of using strokes in space syntax is introduced, and possible advantages this new representation could bring are considered.

1.1. Space syntax

Space syntax is a method for measuring the relative accessibility of different locations in a spatial system (Hillier & Hanson, 1984; Batty & Rana, 2001). In space syntax the convex spaces in the system under study are first identified and then approximated by straight line segments called axial lines. The axial lines represent what would be the principal lines of sight for any humans in the system, with implied unobstructed movement. The axial map is a minimal set of axial lines covering all the convex spaces and their connections (Klarqvist, 1993). The analysis of the space is then achieved by an analysis of the properties and relations of the axial map.

Space syntax has proven to be a valuable tool for modelling and analysing urban patterns with respect to some human activity (e.g. pedestrian movement, traffic flow, burglary). This success would seem to confirm the effectiveness of axial lines in capturing essential aspects of how visibility and freedom of movement influence human behaviour in spatial systems.

It is recognised, however, that the definition of axial lines is a controversial issue, both with respect to their precise definition and the methodology for recognition, and their suitability for the modelling of certain spatial configurations. For example, there are recognised problems of reproducibility of methodology (Dalton, 2001; Batty & Rana, 2002), and in the modelling of curved routes (Dalton, 2001). These issues will be considered again below.

1.2. Generalisation

Slightly modifying one standard definition (ICA, 1973) to reflect the new importance of spatial databases and GIS, generalisation could be described as the selection of detail appropriate to the scale and/or purpose of a dataset. Generalisation is a fundamental procedure in cartography and spatial data analysis and integration (Weibel, 1997; AGENT, 1998).

Generalisation may be understood as a process of controlled distribution refinement affecting both thematic and geometric domains (DeLucia & Black, 1987): attenuating a spatial pattern while retaining the most important elements for a given context and, moreover, preserving the character of the pattern where possible. Generalisation is most clearly entailed in map scale reduction. It may be relatively easy to judge how much detail should be eliminated for a given scale change, but the question of which particular elements to eliminate is entirely different. To address this question the cartographer must judge the relative contribution of map elements to the message of the map.

Road networks present a specific instance of this general requirement: effective generalisation requires a means of understanding – or at least estimating – the relative importance of the elements of a network, on the basis of their spatial (geometric and topological) properties. This requirement of network generalisation is shared with space syntax. As part of broader research in automated generalisation undertaken at Canada Centre for Remote Sensing (Richardson, 1993; 1994), first attempts at such analyses of road networks were made through the consideration of optimal paths between designated locations, and other graph theoretic methods (Thomson & Richardson, 1995; Richardson & Thomson, 1996). These analyses were computationally intensive and did not provide completely satisfactory solutions.

A consideration of sample road and street networks made it clear, however, that generalisation is usually possible (by a human cartographer) in the absence of such a site selection process: satisfactory generalisation is achievable purely on the basis of the network's geometric, topological, and thematic properties (i.e. the road classification information). In fact it may be noted that it is usually possible to infer the relative importance of road segments in a network even in the absence of all thematic information.

It was hypothesised (Thomson & Richardson, 1999) that this generalisation capability follows from the human visual system's ability to spontaneously perceive certain groupings of image features as 'natural' units – i.e. figure-ground discrimination (Wertheimer, 1938). When the abstraction process used to represent a network as a map preserves enough descriptive geometric detail, then the salient perceptual units make sense as 'natural' road or river segments. Further, the relative perceptual significance of these elements correlates closely with their relative functional importance in the network.

This viewpoint led to a novel method of network analysis based on the decomposition of the network into linear elements found by following the principles of perceptual grouping – most clearly the principle of good continuation, that "elements that appear to follow in the same direction … tend to be grouped together" (Cohen & Ward, 1989). This principle describes the tendency for smoothly connected elements to be naturally "grouped" and perceived as single objects, perhaps intersected by others. In the network analysis context these objects were termed strokes, prompted by the notion of a curve segment drawn in one smooth movement.

2. Strokes

If a road network is viewed as the diagram of a planar graph, with junctions and dead ends representing nodes and the corresponding connective road segments representing arcs, then a stroke is a set of one or more arcs in a non-branching, connected chain. In the arc-node topology, for example, the network shown in Figure 1 would have eight arcs and nine nodes. These elements form four intersecting strokes, where each stroke shows a good continuation of direction and of character (width or line-type).

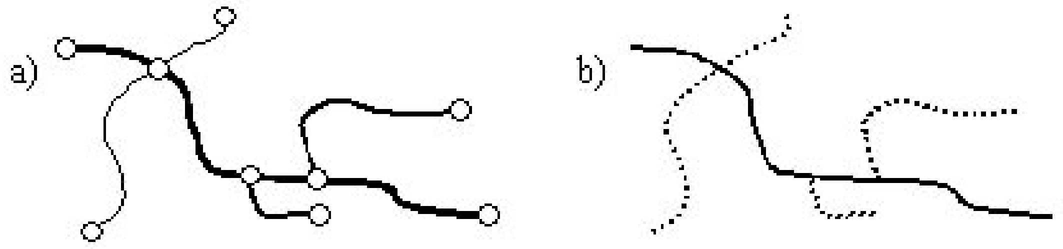

Figure 1: A simple network with 8 arcs and 9 nodes (a) resolves into 4 strokes (b)
Source: Thomson & Brooks, 2002

In this data model, a stroke comprises a set of arcs and nodes. This set represents a path through the network from one terminal node to another (possibly the same) that uses all the arcs in the set, without repetition – although the path may self-intersect and so nodes may repeat. This path is the stroke.

In the implementation used at the National Atlas of Canada, the stroke extraction (or building) process assumes that a proper planar graph data structure has been created for the given dataset, with appropriate attributes and geometric data associated with each arc. The arc will have an associated polygonal line segment, i.e. a polyline, that is an abstraction of the road segment that the arc represents, and which may be thought of as the road centre-line. Being linear, this representation cannot capture much shape detail about the navigable surface of the road: such information is usually limited to attributes such as number of lanes, or road class, or perhaps a road width or surface category.

Thus stroke extraction has not been attempted directly from an aerial representation of the road space, and has only been used in the analysis of smaller-scale map databases, for which centre-lines adequately capture the relevant structure.

2.1. Stroke extraction

For each node, the stroke building process decides which arcs (if any) incident on the node should be connected together. A number of criteria may be applied at this point. The simplest criterion is the angle of deflection that the join would imply: concatenate the pair of arcs with the best continuity of direction, if that continuity is good enough. Once all decisions have been made at each node the strokes are assembled by accumulating sets of arcs that connect to each other. When all arcs have been assigned to some such set, the stroke construction process is complete.

The decisions on arc concatenation at nodes (i.e. junctions) are controlled by a small set of rules. The rule sets can be varied according to context, and so different rules may be used in urban and non-urban junctions, for example. Thus stroke building in this manner is a local process, considering each node in turn and dependent completely on the properties of the network at that node neighbourhood. This implies that strokes can be locally adjusted, with the update requiring only small processing time. Further, the stroke-building method is consistent and symmetric – the order in which the nodes are considered is irrelevant to the final set of strokes produced.

The stroke construction process is robust, in that there are no degenerate cases that cause the algorithm to fail. However, if faulty data is used as input, strokes will still be defined, although they may not accurately correspond to any meaningful real world objects. To achieve meaningful results it is essential that the dataset have correct connectivity. Better results can be achieved by using additional attribute information to guide the stroke building process. For example, in both road and river networks, constraining the process so that arcs with the same name attribute (e.g. Mackenzie River; Bank Street) are connected into a stroke yields good results. Where this information is incomplete, the strokes will be built according to geometric considerations, and possibly other available attributes.

The decomposition of road, street and river networks into strokes has been found to be extremely useful, providing the basis for a good generalisation, in an efficient manner. The method has been used in production at the National Atlas of Canada (Brooks 1999; 2000), and has been taken up by other organisations.

2.2. Generalisation using strokes

Once the strokes are constructed the networks must still be generalised. First an ordering of relative importance must be found for the strokes in the network. It is comparatively straightforward to define a salience value for each stroke based on length and weighted by a factor derived from the road quality data, if available (e.g. width, number of lanes, surface type). The ordering of strokes found purely on the basis of these salience measures is usually then adjusted to avoid disconnecting the network during generalisation, and this remodelling procedure employs measures of stroke connectivity and relative depth (as defined for axial lines in space syntax studies (Hillier & Hanson, 1984)). (The relevance of such measures to network generalisation was first recognised by Mackaness (1995).)

The result of this procedure is an ordered list from which strokes can be removed in sequence without fragmenting the network, and where the reduced set at each stage gives a useful generalisation of the network, hopefully retaining the salient features of the network, even though in a necessarily attenuated form.

Figures 2 and 3 together provide an example of the method for the Ottawa-Hull conurbation, Canada.

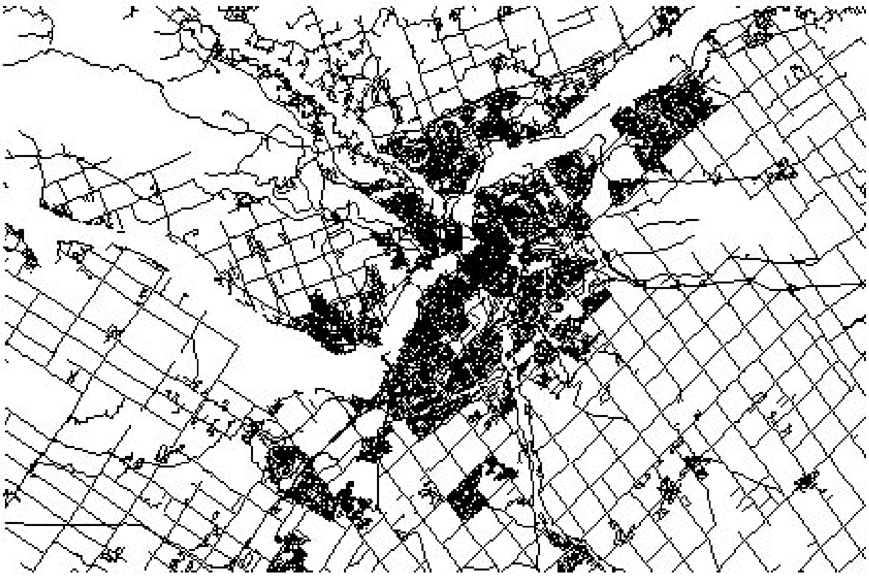

Figure 2: Raw road data for Ottawa and surrounding area
Source: Thomson & Brooks, 2000

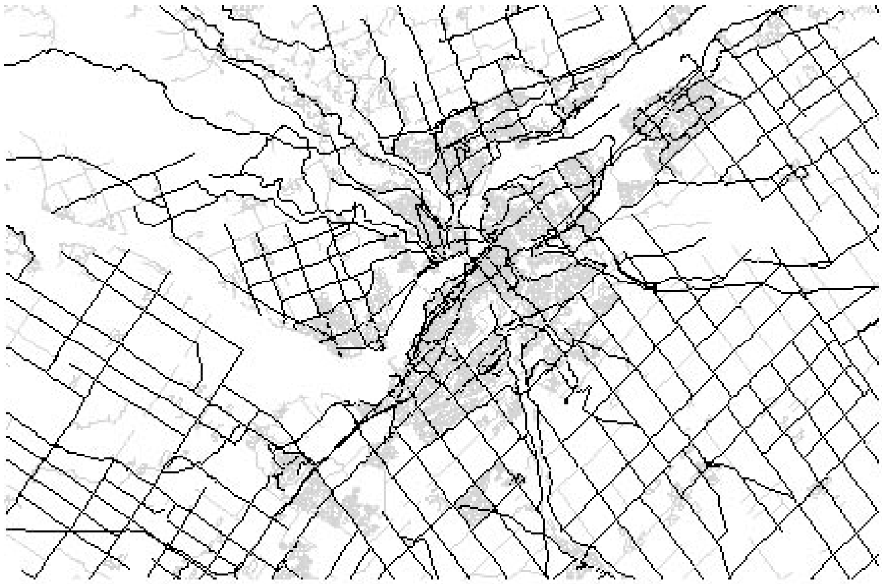

Figure 3: Generalised road network for Ottawa and surrounding area. The retained strokes are shown bold and discarded strokes are shown faint
Source: Thomson & Brooks, 2000

It appears that stroke-based generalisation is effective because strokes delineate units of a network in a manner that echoes the human perception of the network (viewed as a map or aerial image). Strokes are therefore 'meaningful' in that they are perceived as natural units of a network. However, there is a strong correlation between the perceptual salience of a stroke and its relative functional importance in a network. This means, for example, that routes on a map that look relatively important generally are relatively important. This is not simply fortuitous, but reflects the relationship between visual perception and the physical world (Pinker, 1997 (ch.4)). Perceptual grouping is central to the visual system because the sorts of generic groups or figures perceived in general do represent important phenomena in the world: as Pinker remarks, motion makes straight lines in the world.

2.3. Generalisation using named streets

It is of interest to note a similar approach to the generalisation of urban street networks. Jiang and Claramunt (2002) propose the use of named streets as the basic functional units (c.f. strokes), and a structural analysis that is again founded in space syntax principles. The authors note the similarity between named streets and strokes (but view strokes as essentially graphical representations). In fact, as noted above, the stroke extraction process is able to use road name information, where available, to guide the concatenation of road segment, resulting in any continuous, named street being wholly contained in a stroke, perhaps with further concatenated segments.

3. Strokes and axial lines

Spatial data generalisation and space syntax share similar goals in the analysis of spatial structure and functionality. Space syntax techniques have been found to provide measures suitable for controlling the generalisation of road networks (Thomson & Brooks, 2000; Jiang & Claramunt, 2002). This prompts the question of whether, conversely, experience in network generalisation can contribute to space syntax. In particular, what could the use of strokes as a spatial representation offer to space syntax?

(Note that although only axial lines have been mentioned above as descriptors of space that are used in space syntax, there are several other established descriptors in the space syntax family, such as convex spaces and isovist elements. These variants are discussed by Dalton (2001), for example.)

Axial lines represent straight lines of sight "possible to follow on foot" (Klarqvist, 1993). The relevance of axial lines for pedestrian movement is thus clear. However, the relevance of axial lines for vehicular traffic flow is less clear: the presence, extent and continuity of drivable surfaces could be expected to be important factors influencing the route taken by a motorist. Strokes, by definition and construction, aim to represent the lines of best continuation, and consequently could be expected to be appropriate elements for modelling and analysis in such contexts. Supportive evidence for this view may be drawn from studies such as those of Conroy Dalton (2001) who suggests that travellers appear to attempt to conserve linearity throughout their journey, avoiding unforced deflections: "the secret is to follow your nose". Thus, there is some reason to believe that for analyses of road networks on the urban scale or wider, and for traffic movement studies in particular, strokes may be suitable spatial representations.

Strokes are simple to derive automatically (although some degree of user control is usually retained in practice). The computational complexity of the stroke extraction algorithm, outlined above, has been shown to be an approximately linear function of the number of vertices in the network (Thomson & Brooks, 2000). The automatic derivation of axial lines from a cover of convex spaces – which themselves would be computationally expensive to derive – is a process that is hard if not impossible to automate (Batty & Rana, 2002). This comparison, of course, takes no account of the fact that the stroke extraction method operates on a map of road centre-lines in the form of an attributed graph, and not directly on the space representing the road surface. However, in applications concerned with, for example, traffic flow, at scales where centre-lines provide an adequate model of road configurations, the full, computationally expensive process of axial line extraction may be unnecessary and the simpler stroke-based processing may suffice. Comparative studies need to be carried out to test the conjecture.

"Straightening" important spaces (i.e. roads) so that they are represented by single axial lines in the axial map, and so become more integrated, is reported as being a common practice in analyses when handling motorways (Dalton, 2001). This is an instance of a problem with curved routes that is encountered in many contexts: should smoothly curving spaces be fractured into series of straight axial lines (and if so, what are the criteria for selecting breakpoints, and can the process be made reproducible), or should the spaces be represented as single units (and if so, how? – for example, the Axwoman software (Jiang, 1999; Jiang et al., 1999) for axial line-based space syntax analysis supports polyline axial "lines"). Since strokes can bend freely they allow turns and curving roads to be handled in a natural way. Thus the problem of curved routes may be obviated.

If curving strokes are used as basic spatial representations then it may also be possible to exploit – perhaps in a manner analogous to angular analysis (Turner, 2001) – the quantitative information that can be derived about the degree of the bending or "sinuosity" of the stroke. Many measures of line shape can be found in the image processing literature, and some have been derived specifically for use in linear feature generalisation (Buttenfield, 1991; Plazanet, 1997). This possibility has not yet been explored.

Thus, although much remains to be investigated, it does appear that for the space syntactic analysis of spaces where linear structures are dominant – such as an urban-scale road network – the use of strokes as a spatial descriptor offers the possibility of both computational and modelling advantages, particularly in the handling of curved routes.

4. Conclusions

The problem of how to derive, from the geometric and topological properties of a street or road network, an understanding of the importance of individual road elements in the structure and functioning of the network – or at least to make some useful estimation of relative importance – is common to both space syntax and automated generalisation. The utility of space syntax techniques in effecting network generalisation has been noted.

Strokes were introduced as a spatial representation that has proven to be extremely useful in the automation of road network generalisation. The technique for decomposition of a network into constituent strokes was outlined. Using strokes as a basis for analysis has brought to generalisation the advantages of a good, flexible model and efficient implementation. This prompted the question of possible contexts in which the use of strokes in place of axial lines in space syntax would be meaningful or advantageous.

It is suggested that strokes are a suitable spatial representation to employ for networks where the axiality of the space dominates convexity, such as traffic flow studies on an urban scale. In such situations both computational and modelling advantages could be expected, particularly in the handling of curved routes. Further research and experiments are required to test the hypotheses.

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