SHAPE ANALYSIS IN GIS

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ABSTRACT

The essential objectives in the analysis and subsequent understanding of geographical phenomena involves searching for spatial patterns, followed by evaluating possible causes and effects of patterns, and predicting future patterns. On a human level, the visual identification and comparison of areal shapes is a fundamental and integral component of this process. Scientists and practitioners across a variety of fields have recently turned to GIS technology as a central component to manage and analyze observational data. Despite a rich heritage of techniques for describing and analyzing shape within geography as well as other fields, such capabilities generally remain quite primitive within GIS. A general purpose shape analysis capability that even approaches the level of sophistication of other current GIS capabilities is still not part of the GIS toolkit. This paper examines the need for a shape analysis capability and examines potential approaches to extend GIS for handling more powerful shape analysis techniques.

INTRODUCTION

Imagine that you are a field biologist interested in habitat areas for primates in Costa Rica. Through various techniques, including radio telemetry, field mapping, and a GIS, you have identified two regions that are possible habitats for large monkey troops. The GIS component consists of using overlay techniques, distance measurements, area calculations, and a shape function, to extract common physical variables including: slope, vegetation type, distance to streams, area, and an irregular lobed shape. One of your goals is to protect the species; consequently, your objective is to understand how and why these regions are suitable habitats so that you can search for other similar regions. You extract from your GIS all other regions with the identical physical conditions and then ask additional questions regarding the shape of these areas such as: 1) How has departure from a specified "ideal" shape and size changed the behavior of the different troops? 2) What is the juxtaposition of these particular shapes with other land characteristics (e.g., nearness to water)? 3) Can changes to the shape of habitats be projected into the future based on the underlying processes of soils, geology, and current vegetation? With existing GIS software, these questions would be difficult to answer because they require a shape analysis capability. Extracting all regions with similar irregular lobed shapes would require a manual, visual examination of each polygon to determine if they match your idea of a habitat shape.

The gains in ecology from a shape measure are evident in the analysis of habitat delineation (Eason 1992; Gutzwiller and Anderson 1992). Eason (1992) claims that scarcity of resources is forcing the optimization of territories and this requires knowledge beyond the size, vegetation, and topography of a given region. It was once believed that a round territory was ideal within a homogenous region, yet these assumptions are beginning to be proved incorrect. The geometry of the area is now considered a critical factor in defining and analyzing habitat regions.

There is a continued interest and need for shape analysis in many fields of study; the ecology example given above being only one of many potential applications. In other contexts, scientists are concerned about characterizing and comparing spatial shape when studying the effects of urban growth, analyzing the effects of earthquakes, determining the impact of deforestation, and measuring the parameters of drainage basins. Specifically, urban geographers have used shape indices to quantify the shape of political districts to explain spatial patterns and studied the organization of transportation to assess the changing shape of cities over time (Gibbs 1961; Simons 1974; Lo 1980; Austin 1981; Rhind, Armstrong et al. 1988). As a result of these applications and many more, numerous attempts have been made to quantify shape for the identification and subsequent comparison of geographic regions (Boyce and Clark 1964; Lee and Sallee 1970; Moellering and Rayner 1982).

Given the impact that identifying shapes has in understanding spatial processes, and the use of GIS in geographical research, improved GIS analytical capabilities includes the quantitative characterization of the form of regions. Visually identifying and comparing regions on the basis of shape is easy and intuitive for humans to do. Our visual/cognitive system is well-attuned to this kind of task. Given the increasing frequency of large volumes of data in GIS and the need for analysis over large geographical areas, make the visual approach impractical. The goal of this paper is to suggest a method for improving the ability to compare the shape of regions in a GIS environment that is less dependent on direct human intervention.

WHAT IS SHAPE ANALYSIS?

Pattern identification is critical in understanding spatial relations, and pattern and shape are closely linked. Consequently, for clarity in this research, an explicit definition of pattern and shape is given. This discussion provides the basis for a detailed description of shape analysis and definition of shape indices in the context of studying geographic scale phenomena.

Pattern can be described as the organization of phenomena in geographic space that has taken on some "specific regularity, which in turn is taken as a sign of the workings of a regular process" (Ebdon 1988). Shape on the other hand is more basic; shape describes the geometric form of individual spatial objects (MacEachren 1985). An object in geographical terms is defined as a foreground placed on some type of background. Examples include lakes, common soil types, political boundaries, or any area defined to be homogeneous with regard to some characteristic or combination of characteristics. The regular or irregular organization and juxtaposition of these individual areas provides the building blocks for describing spatial pattern. Pattern alone is highly complex, but the measurement of shape in the context of pattern provides a mechanism to simplify pattern into basic units.

Shape analysis is the process of building fundamental units for identifying and describing patterns in the landscape. The requirements for this process are to describe shape, including a distinction between regular and irregular shapes, and to answer questions regarding shape (Pavlidis 1978; Moellering and Rayner 1982; Ehler, Cowen et al. 1996; Xia 1996). Describing shape involves identifying the outside boundary of an object in space. Another component to the description of shape involves the description of both regular and irregular shapes. Regular geometric shapes, such as circles, squares, and triangles can be described simply. Irregular shapes, however, can be highly complex with infinite variations and are more likely to appear in a geographical context. The second step in the process involves addressing shape comparisons. Distinguishing between areas that have holes (such as an island within a lake) and areas with different edge roughness, where the overall geometric configuration does not vary, is part of the geographical analysis.

An index to describe shape and allow for comparisons must meet several specific criteria. MacEachren states that "the first [criterion] is to develop a measure of shape uniqueness by which any shape can be distinguished from all other shapes and similar shapes result in similar descriptions" (MacEachren 1985). The list of criteria for a shape index for this research are: 1) each unique shape be represented with a unique number; 2) independent under translation, rotation, size, and scale change; 3) match human intuition; 4) deals with regions that contain holes; 5) easy to calculate and interpret the results. The ideal shape index would meet all these criteria.

The primary reason that shape analysis is not currently part of the GIS toolkit is that no single satisfactory method has been developed (Lee and Sallee 1970; Ehler, Cowen et al. 1996). Nevertheless, numerous indices have been suggested varying from simple area and perimeter calculations, to complex indices using sophisticated mathematical functions. The evidence that no method exists is suggested in a review of "successful" implementations of shape indices. For example, in geography Frolov (1974/5) and later, MacEachren (1985) summarized techniques to measure the compactness of regions. Frolov focuses on the history of the various approaches, but MacEachren summarized and categorized the indices. MacEachren provides a systematic comparisons of the various methods but never suggested any single approach as the best method for measuring shape.

RESEARCH ON SHAPE IN OTHER FIELDS

The field of geography and the geographical context is only one of a range of areas where shape is important. Computer science, mathematics, computational geometry, statistics, and cognitive science also participate in the search for shape description and representation. Nevertheless, the application, and therefore the goals and definitions in each discipline, are different. This section briefly describes the approach taken by each field and suggests possible commonalties and contributions.

Within computer science, shape analysis is studied in the context of graphics and visualization including three dimensional graphics, animation, and character recognition. Much of the research on shape analysis within these areas has used a decomposition and construction approach. For example, Marr (1982) derives a technique to represent shape with collections of small cubes packed together in arrangements to approximate the shape of the given object. Marr's techniques, as are others for similar applications, are based on the need to recognize and represent shapes graphically rather than forming a unique descriptor that can be used to compare them. Consequently, the techniques developed by Marr and others in computer science have the objective of shape identification and depiction.

The literature available within mathematics, computational geometry, and statistics is extensive (Smith 1966; Davis 1977; Lord and Wilson 1984; Grenander 1996). Unlike computer science, the research in these disciplines is not directed by an application context. Instead, shape analysis is viewed more as an interesting problem to solve in the abstract, such as use of Delaunay triangles or convex hulls (Preparata and Shamos 1985). These methods do not present a method for extracting a single number to describe shapes, which can subsequently be used as a shape measure in a geographic context.

Much of the understanding of what shape is, regardless of the computational or mathematical application, is derived from the human visual sense. In a context different from the development of algorithms and formulas for shape descriptions, understanding of the visual aspect of shape comes from cognitive science through shape recognition, the creation of shape categories, and the language of shape. Landau et al. (1988) conclude that for perception and categorization of objects, shape recognition (other topics considered were size and texture) is significant for children who are learning words. Consequently, shape recognition is a skill that people acquire in the first few years of life. Without any additional proof, it is logical to assume that this skill is carried through life as a natural and intuitive process for identifying objects. This method of examining the world can be applied to the identification and categorization of regions with similar geometric form in the human and physical landscape.

The objectives for shape analysis from computer science, mathematics, statistics, and cognitive science are different. Nevertheless, there are overlapping agendas that contribute to meeting goals for shape analysis in GIS context. Shape analysis can be extended from the creation of a shape index to include shape extraction, as derived from computer science. This technique could be applied to remote sensing applications, where the objective is to classify homogeneous regions, such as the extent of lava flows (Xia 1996). Mathematics and statistics strive for a method to define and represent shape, which in the context of geographical analysis could be then developed into an index. Cognitive science contributes to the human-oriented needs for a shape capability through the creation of categories of similar shapes. In a GIS context, the index represents a method for comparing geographic regions so that an oblong object can be categorized with another oblong object, and jointly categorized as "potentially similar wildlife habitats". As a direct consequence of the numerous approaches to shape, there are many possible types of shape indices. In order to evaluate these as possible shape indices in the context of GIS, they can be categorized and assessed based on similar qualities.

CATEGORIES OF SHAPE INDICES

Applying the approaches from research in other fields combined with a geographic definition of shape analysis, three general categories of existing shape indices can be identified. These categories are in contrast to the ones suggested by Pavlidis (1978), or MacEachren (1985). The Pavlidis categories were limited to measures for shape recognition (e.g., character recognition). He defined two categories based on whether they examine only the boundary or the whole area and whether they describe objects based on scalar measurements or through structural descriptions. MacEachren evaluated only measures that were based on compactness, which have been combined into one category for this research and will be described in this section. The categories presented here, on the other hand, include the types of indices Pavlidis describes for shape recognition and the compactness measures described by MacEachren plus a broader range of indices. These categories are compactness measures, boundary measures, and components measures. This section defines each category and evaluates generally how well the indices in the category meet the criteria for an index.

Compactness Measures

In a geographic context, shape is often characterized through a compactness indicator, which describes the form of a given region based on how far it deviates from a specified norm (e.g., circle, square, or triangle). The regular shape (normally a circle) is given the value 1.0 and less compact regions are typically less than 1.0 (e.g., 0.54343), where the smaller the number it is, the further it is from a non-circular region. The method for calculating this number utilizes one or more of the geometric parameters of the region being measured, such as area or perimeter. The parameters used and the mathematical equation depend on the feature of shape being measured, such as elongation or indentation.

With compactness measures, differently shaped regions produce different numbers, consistent with the criteria for a shape measure. Nevertheless, these measures do not represent true measures for shape because the number depends on the scale and size of the object, which does not meet the criteria defined in this research. Compactness indices are useful, however, in some contexts and are important to geographers because "compactness is often considered to be indicative of homogeneity within units. The more compact a unit is, the shorter the average distance between any two locations, therefore, the more similar characteristics of those locations are likely to be" (MacEachren 1985).

Boundary Measures

Boundary measures describe shapes by outlining the perimeter of a region. The index is assigned based on the technique, mathematical or otherwise, used to outline it. Several of these approaches have been applied to geographic examples, but many have not. One of the critical limitations with these indices is that they do not take holes in the region into account in an explicit manner. Some of the boundary measures that have been applied in a geographic applications include Fourier series, fractal analysis, Hough transforms, and Freeman chain codes.

Although several of theses indices are independent of rotation, scale, and translation, and provides a technique to regenerate the region, they do not provide a single index that can be used to compare the shapes of regions. For example, the Dual Axis Fourier Shape Analysis generates several numbers that, when combined, form a representation of shape (Moellering and Rayner 1982). The numbers, however, are difficult to calculate because the method requires that the points of the polygon be digitized at fixed intervals. In GIS applications, the stored digital coordinate data usually do not meet this restriction and re-sampling would mean a time consuming extra step. Other boundary measures do exist that address these issues, but they also have limitations, such as producing an index that is complex to interpret and not identifying regions with holes.

Component Measures

The components measures is the final category of shape indices. These measures describe the form of a region by deconstructing the region into combinations of regular shapes such as squares, circles, and triangles, as suggested in the computer science literature. The number and type of regular shapes, and possibly other parameters, become the index. This is necessary if comparisons are to be made between regions because it is conceivable that two different regions could be made up of the same combination of regular shapes, but because of different organizations, the visual shape of the regions would be different.

The strength of the components measure is that it breaks irregular shapes into regular shapes, which can then be numerically defined. There are, however, many weaknesses. The primary weaknesses of the components measures are they generally do not maintain topology and consequently they do not retain the same characteristics under translation and rotation. Additionally, complex regions result in complex indices, which are difficult to interpret and tend to oversimplify the original region.

Summary

The indices just described are diverse and measure different elements of shape. Compactness measures do not distinguish between regions with holes and do not indicate edge roughness. Boundary measures are well suited for measuring edge roughness, but little can be done for identifying holes in regions and they are often complex to calculate. The components measures represent a descriptive measure for shape rather than a quantitative (thus comparable) measure for shape. This paper has identified the need for a shape analysis capability in a GIS context, and found that no suitable measure in its current form exists. Nevertheless, there is a potential approach that will allow for a more powerful shape analysis technique.

THE OUTLOOK FOR SHAPE ANALYSIS IN GIS

The basis for this research suggests that compactness measures, or any of the other indices for that matter, alone do not measure enough aspects of shape. The compactness measures, although they match our defined criteria, are not suitable measures for shape because two similar shapes can have different numerical representations and two different shapes can have similar numbers. For example, Figure 1 shows two shapes (regions A and B) that have similar numbers based on the area-perimeter compactness measure (0.489 and 0.491), but are not similar in shape. In the same figure, a third region is identified (region C) that is similar in shape to region B, but the shape index (0.429) is not as close as the index for region A. Consequently, evaluating the shape of these regions based on the compactness measure does not effectively measure shape. To examine two shapes that are different in area and perimeter, Figure 2 highlights two regions that have a similar index, but are quite obviously different in shape. Similar examples for boundary measures and components measures can be made.

Figure 1

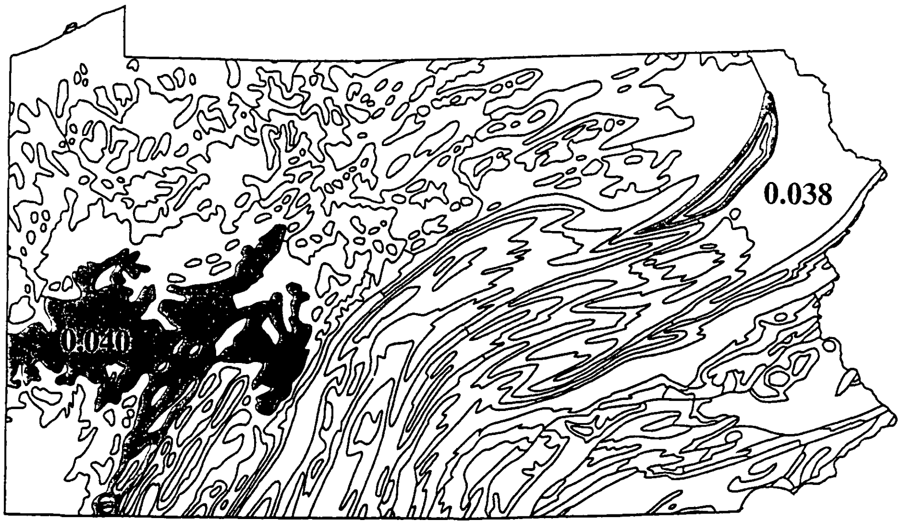

Figure 2

The problem with evaluating the indices based on this list of criteria is that the original definition of a shape index is too simplistic. Understanding the geometric form of a region may require something that does not simply match human intuition, consequently these criteria are too narrowly and defined. Ease of calculation, another one of the defined criteria, is important in the implementation phase, but should not be a deterrent if the interpretation is easy and it describes geometric form.

Intuitively, shape seems like a simple concept, although in actuality, the human visual/perceptual mechanism for distinguishing and recognizing shape is complex. Consequently, in a mathematical context, shape is also complex. Unlike measurements for area or perimeter, the definition of shape is based on linguistic expressions and human intuition. Presently, mathematics and statistics are not in a position where shape can be reduced to a single number. Due to complexity of the concept, a single numerical representation of shape may be impossible to achieve.

The results from the present assessment of shape analysis in GIS could be taken in several directions. One possibility is to redefine shape. This research is proposing a new means of characterizing shape involving deconstructing shape into components, where each component can be represented with a number. This method is similar to the way color (also visually and conceptually simple) is separated into hue, saturation, and value. In the case of shape, the properties proposed are edge roughness, compactness, and geometric form. Existing indices, from each of the three categories of existing shape indices, could be applied to quantify the different properties of shape. Boundary measures are the best at assessing edge complexity, compactness measures, as the name implies, evaluates most effectively the closeness to a compact form such as a circle, and geometric form (including whether the region contains holes) is best evaluated with the components measures. For example, fractals appear suitable to measuring edge roughness, area-perimeter measures could measure compactness, and a Triangulated Irregular Network (TIN) could represent geometric form. Each region could have three shape indices assigned to it, each based on a different property. The deconstruction of shape into these constituent components is in its early stages. The next phase of the research is to re-examine the indices to determine which would best represent a particular property of shape. Viewing each index as representing a property of shape has given a new definition to shape.

CONCLUSION

A new definition of shape could allow for several different types of analysis in a GIS context to take place. Extraction and comparison of regions with "similar shape" could utilize indices individually or in conjunction with one another. For example, in the case of a solid waste landfill siting project, compactness and geometric form are important properties. Suitable landfills are not long and skinny and do not contain holes (e.g., a new landfill would not be situated with a residential development contained within it). Compactness measures and a measure describing geometric form could identify a suitable region. Edge roughness, however, is not critical for the siting of a landfill. In the case of a habitat delineation project, edge roughness is the important component. It has been suggested that certain species prefer habitat boundaries that are non-linear because they provide protection against predators that smooth boundaries do not provide.

Using existing measures to identify distinct properties of shape rather than expect any single measure to capture all aspect of shape is a better approach because these individual properties are important in themselves. In this way, it may be possible to identify similar regions that may not be classified as similar had they been evaluated visually. For example, two shapes with similar edge roughness may be classified "similar", even though their geometric form or compactness may be quite different. Similar processes, for example in geomorphology, could be at work. Holes in regions along with different areas or perimeters may mask the similarity of geometric form that compactness indices may extract.

This research presented here fits into a broader research project that investigates a theoretical approach to advancing GIS analytical capabilities. This theoretical framework suggests that improving the analytical capabilities of GIS requires more than simply the design and implementation of advanced numerical procedures. Rather, the research suggests alternative uses of computer technology that enhance human senses in place of replicating existing manual techniques. It is expected that future research will involve exploring cognitive approaches to shape analysis within the suggested framework.

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