Developing methods for GIS-based terrain path planning

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Abstract: This research addresses the subject of cross-country terrain path finding using forest inventory route planning as a case study. Although the subject is closely related to the key concepts of geography, so far it has not been studied in academic geography in any significant extent. Accordingly, an additional motive for the research is to attempt to raise the importance of terrain path finding within the domain of academic geography and GIS. The research also strives to develop GIS-based methods that would be particularly useful in applications related to the environment, conditions and industries of the North and periphery.

Background of the study

The past decade has witnessed tremendous advances in geographic information technology, most notably in positioning and navigation technologies. Navigation applications that only ten or fifteen years ago were very expensive and restricted to professional use, have now become affordable and available for the general public. The most prominent example of these are car navigation systems, which enable finding the best driving route between locations with the help of positioning capability.

The proliferation of the opportunities provided by geographic information technology has raised a lot of interest also in the scientific community. As a manifestation of this, an interdisciplinary research project concerning "mobile environmental information systems and services" was launched in 2002 as a collaborative effort between the Departments of Geography, Information Processing Science and Biology at the University of Oulu. The project was inspired by the prospects of novel applications attainable by combining new mobile information technology having a positioning capability with environmental information in the context of Geographic Information Systems (GIS). One of the concrete objectives of the project was to investigate and develop methods for cross-country terrain navigation, which was to be implemented as a mobile nature guide to be run on a handheld device (Antikainen et al. 2004, Keronen et al. 2004). Unfortunately, the project was somewhat ahead of its time, suffering from hindrances associated with immature technology and troubles raising the necessary funds. Even the interdisciplinary research cooperation was plagued with many difficulties. As a result, after a couple of years of preliminary work, the project was suspended. Nevertheless, the ideas conceived in the project were never completely abandoned; rather they were put on hold to wait for better times and new application opportunities.

It was several years later that the idea of automated terrain path planning re-emerged, this time as part of a joint research effort with the Finnish Forest Research Institute (Metla). The project with Metla was motivated by the currently ongoing changes in the forest management planning system in Finland concerning privately owned forests. There is a purpose to move from the traditional, extensive compartment-wise field inventories carried out periodically by field personnel to a more comprehensive utilization of information provided by modern remote sensing technologies, including airborne laser scans, aerial photographs, and satellite imagery (Hyvönen 2007). Although the objective of the new practice is to significantly decrease the need for data collection in the field, it will not lead into complete abolition of field inventories. There still remains a need to inventory a certain subset of forest compartments for which the information provided by remote sensing techniques is inaccurate, or that need to be inventoried just for the sake of data validation.

Although the fact that fewer compartments need to be visited in the new data collection practice might be thought of as making inventory route planning a much easier task than before, the effect is actually the opposite. In contrast to the traditional inventory setting, where each compartment in a region subject to management planning was to be inventoried in any case, the compartments to be inventoried are now scattered sparsely over the region. As a consequence, relatively more time will be spent on traversing between the compartments, effectively making the inventory route planning an increasingly critical aspect of the entire inventory process. As traversing between compartments is both time consuming and unproductive by itself, GIS-assisted planning capable of taking into account the effect of obstacles and different terrain types on traversability may be expected to bring significant savings in terms of effort and working hours. This research challenge provided an ideal real-world case study for the doctoral thesis addressing the subject of cross-country terrain path planning methods.

The research process

At the beginning of the study, the intention was to carry out the research by applying only those methods and tools that can be found in the literature and that had also been made available as part of GIS software packages, particularly the ArcGIS software developed by ESRI. According to the literature survey, there is an abundance of studies pertaining to road-based path planning and navigation in the urban context, just as could be expected, but unfortunately the situation is much worse for the cross-country context. This observation made it necessary to rethink the preconditions for the research, because it possibly implied the need to develop customized tools in order to realize the objectives of the case study.

Even though it turned out to be difficult to find existing solutions for terrain path planning, an important realization was that certain theoretical principles hold true for any kind of spatial path planning problem. In general, spatial path planning is essentially about determining an optimum path between interconnected locations. The notion of optimality may be associated with the physical distance separating the locations or a function of it, such as traversal time, effort, risk, or any other measure of impedance, that the path attempts to minimize (Longley et al. 2005). The connections between locations and the associated impedance can be modeled using the concepts of the so-called *graph theory* (Mainguenaud 1995), which serves as the framework for an abstract network model consisting of a set of *nodes* and weighted, possibly directed *edges*. In the road network context, the nodes would correspond to the intersections of roads, while the edges would stand for road segments connecting the intersections. The edges are assigned a positive weight, or "cost", derived from the measure of impedance (Chou 1997). Once this is accomplished, an optimal, impedance-minimizing path can be found between any locations within the graph using a path-finding algorithm, such as the well-known Dijkstra algorithm or some of its many variations (Cormen et al. 1997).

The core challenge with terrain path planning can be reduced to the fact that there (usually) are no linear, one-dimensional structures comparable to roads or streets in the natural environment, nor is there any objective and straightforward way to measure the concept of impedance that path planning is fundamentally based on. The challenge for research is to overcome these limitations and find a solution that allows the natural environment be somehow represented by means of the weighted graph model. For this purpose, two aspects need to be considered. Firstly, natural environment, modeled and represented in a digital form in a GIS, has to be converted into a set of interconnected nodes. Secondly, the connections, or edges as they are known in the graph theory, need to be weighted to depict the movement cost between the nodes.

While the construction of the graph model is the core issue linking path planning to the theory, the edge weights in turn are important by connecting the mathematical abstraction into the real world. Certainly, the weights could be purely hypothetical, as has been the case in the few previous studies concerning this subject. In fact, in most cases even the terrain data used in the research have been either completely artificial or at least complemented by simulated data. However, in a real world case study the weights have to be determined properly based on certain criteria. Although this might appear to be very sensitive to subjective assessment, the weights, representing terrain traversability, can be expected to obey the "principle of least action". The principle of least action describes the tendency of elements in nature, humans included, to always seek the minimum effort solution (Burgess & Darken 2004). Therefore, the actual problem is to quantify this tendency in order to obtain the weights. In this case, the weights were determined by interviewing a selected group of professionals possessing hands-on experience on the subject using an evaluation method based on pair-wise comparisons. The terrain types considered relevant to traversability were ranked according to their desirability, yielding a quantitative desirability index, which could subsequently be easily inverted to weights corresponding to movement cost. Not only was the determining of the weights in this fashion necessary for the case study itself, but it also revealed some valuable aspects concerning the entire analysis that perhaps would not have been otherwise considered.

While the terrain weights could be attained quite comfortably through interviews, the construction of the mathematical graph model turned out to be a very challenging task. Fortunately the literature survey revealed some elementary ideas as to how it could be accomplished. There exists a small but relatively high-quality body of research on representing cross-country terrain as a weighted graph which can be broken down into roughly two different types of strategies, distinguished by the data model and structure used to represent the terrain. The two alternatives are obviously the field and entity data models, and their corresponding raster and vector data structures (Maguire & Dangermond 1991). The raster data structure can be considered as a more tractable option to carry out the transformation into a weighted graph, as in the raster structure each raster cell (or cell center) can be readily converted into a node, which is connected to a certain number of neighboring cell centers. In fact, this procedure serves as a foundation for a group of methods that are usually referred to as *cost surface analysis*, which is included in some advanced GIS software (McCoy & Johnston 2002). For example, the ArcGIS software includes a path optimization function based on cost surface analysis, but the function is not very well suited for real-world applications, particularly because the user is unable the control the path alignment error inherent in the raster data structure and cell connectivity pattern. As the existing ArcGIS function was deemed useless for the case study purposes, the next step in the study was to build a substitutive function carrying out the same task with certain improvements. Although the programming task was a very difficult and time-consuming process, as it took a lot of time and effort to get used to the programming tools and just to get the application working, it was a breakthrough that truly opened up a whole new dimension for the research.

The breakthrough into the world of custom functions signified that the research could now be performed totally differently. Instead of conforming to existing software solutions and their limitations, it was now possible to dig more deep into the theoretical considerations around the subject matter because of the freedom regarding the implementation in practice. For this reason, both the raster- and vector-based terrain path planning approaches were taken under scrutiny, and they were implemented in the ArcGIS programming environment using the Visual Basic and C# programming languages.

As for the raster-based alternative, different varieties of the "traditional" raster approach were implemented using different cell connectivity patterns, as well as an innovative method based on the idea of an "extended raster model" conceived by Bemmelen et al. (1993). The vector approach was more difficult to realize, because unlike the raster data model which is discrete (the amount and location of nodes is restricted), in the vector data structure the number of different location options is infinitely large. Therefore, a discretization approach was adopted using the so-called Steiner points as auxiliary nodes and employing an analogy of Snell's law in optics to find the optimal locations where the path intersects the boundary between two regions of dissimilar terrain (Werner 1968, Miller & Shaw 2001).

For reasons specific to the data model, the paths generated based on the graph model tend to deviate from true optimality, requiring the employment of a rectifying procedure. Perhaps the most important contribution of this study to terrain path planning is the actual implementation of path rectifying procedures that enable the production of high-quality paths with only negligible deviation from true optimality, in so far as "optimality" is considered with respect to the underlying data representing the terrain. Obviously, this is not a guarantee of true optimality in the real terrain, as it is dependent on the quality and accuracy of the original data and the resolution used in the analysis. Nevertheless, the results of the study signify a step forward in improving the prospects of terrain path planning by providing alternative means of generating high-quality paths.

Relationship between the research subject and academic geography

In spite of the fact that the relevance of the study with respect to geography has not at any stage been in doubt, one of the most striking observations done in the course of the study was that although there does exist a considerable amount of research into path planning problems in general, the contribution from academic geographers to it has been meager. This is quite surprising considering that path planning is essentially about assessing geographic locations, their relationships in space, and the relativity of distance; things that have generally been regarded as core characteristics of academic geography. Certainly, path planning is considered as an important research topic in geography, but the theories, data models and path-finding methods are adopted to geography from other fields of research (Wright et al. 1997). For example, graph theory, on which path planning is based, has been conceived and developed in the fields of mathematics and computer science (Harju 2007). The same holds true to most path-optimization algorithms, whose development seems nowadays to be concentrated in the fields of operations research, computer games and robotics. Although spatial dimension is intrinsically embedded also in these fields, their relevance to the context of the human scale and the physical reality of the Earth's surface is limited.

Considering that the problem of terrain path planning is intrinsically geographic by nature, it is evident that academic geography, and geographers, would have a great potential to contribute to it. The actual question is then why is such an inherently geographical subject dealing with the very key concepts of geography being neglected by geographers? This is a matter that needs to be put in a wider perspective by considering the relationship between academic geography and GIS in general.

Path planning is a process consisting of several ingredients that are commonly associated with GIS, and can therefore be undoubtedly labeled as GIS-based research. GIS can be claimed to have become an integral part of academic geography, to the extent that there has actually been a tendency to abandon the concept of GIS in favor of alternative terms underlining the scientific nature of "doing GIS", such as GIScience and geoinformatics (Goodchild 1992, Mark 2000, Longley et al. 2005). But what really is the relationship between academic geography and GIS, GIScience, geoinformatics, or whatever term is used to refer to "GIS-centered research activity"? It looks like that many geographers still have reservations about GIS, and the threshold for starting to utilize it is felt high. As a result of this, research topics focusing on or closely related to GIS are not being addressed by geographers. The situation is aggravated by the fact that many GIS analyses, terrain path planning being an illustrative example of this, cannot be carried out, at least not effectively, by contemporary GIS software packages without having to write some code at some stage. This brings us to the core of the real problem with geographers and GIS, which is that with few exceptions, academic geographers are but passive consumers of GIS technology, not the contributors to it. Therefore, geographers are utterly dependent on the GIS tools developed by people familiar more with computer science and related fields than geography. A related, and actually an even more serious problem is that geographers may have little understanding as to how GIS analyses implemented as GIS software really work, resulting in a situation where geographers do not really understand analyses they are performing and the results they are getting. This is bound to have a negative effect on the relationship between GIS and geography, and to academic geography as a whole. However, as it is not possible to demand the GIS software developers to become geographers, the only solution is for geographers to take a more active role on GIS software development. The good news is that the contemporary software packages, like ArcGIS, provide the tools that are needed to write custom functions within GIS, so in this respect there is no excuse for geographers not to become more GIS-oriented.

Implications of the results of the study

The research has many implications specifically on its application area, but also on geography and GIS in general. The main results of the research provide an insight into alternative cross-country terrain path planning methods using real terrain data – which is something that in actual fact still has a lot of novelty value even in today's world where "personal navigation technology" has become commonplace. Being of particular interest, the implementations of the methods include functionality for controlling the error inherent in the underlying data structures used to model the terrain. Certainly, the research and the tools developed in the study involve many limitations, as there are a number of generalizations and abstractions that have been applied in order to keep the research problem in hand. For the same reasons, some details regarding the modeling of the terrain may have been ignored altogether. Still, it is necessary to maintain that the study involves a lot of pioneering work at least in the context of academic geography.

Following the sucess and popularization of vehicle navigation applications, research into terrain path planning is likely to proceed in the years to come and more efficient methods will be developed. Yet, it is necessary to bear in mind that scarcity of previous studies into terrain path planning may hint to the possibility that the subject is simply not considered very important in most countries. If this is true, as it can very well be, it is unlikely that major software companies are willing to develop tools for a purpose having a potentially small user base. This is problematic concerning the circumstances of the North and periphery, where logistic problems and navigation often involve the need for path planning in off-road areas. Forest industry and nature tourism are good examples of this, and they indeed are the most important application areas of the methods investigated in this study. For the same reason, it is important for geographers familiar with the circumstances of remote regions to develop GIS-based methods that are needed to address the problems specific to these regions.

As a concluding remark, besides the actual objectives embodied in the case study, the research is an attempt to bring the topic of terrain path planning into geography, the field of research where it really belongs to. Associated with this, the study strives to serve as an example how the commercial GIS software packages with limited functionality can be extended to perform any task needed to address even complicated research problems that geographers may want to consider. This is also to emphasize that GIS (or GIScience/geoinformatics) is backed by a considerable amount of theoretical knowledge originating from several fields of research encompassing a spatial dimension. Thus far, only a fraction of this knowledge has been implemented as GIS tools, and this is a territory where the contribution by geographers will be needed.

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