Taking a Systematic Look at Movement: Developing a Taxonomy of Movement Patterns

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Introduction, Objectives

Mobility is a key element of many processes and activities, and the understanding of movement is important in many areas of science and technology such as meteorology, biology, sociology, transportation engineering, to name but a few. Hence, increasing amounts of movement tracking data and other data about movement of mobile objects or agents are being collected. In most cases, moving object data sets are rather large in volume and complex in the structure of movement patterns that they contain. Therefore, it is necessary to develop efficient data mining algorithms and visual analytics techniques in order to extract useful and relevant information, regularities and structure from massive movement data sets. Hence, they can help researchers to detect movement patterns and explore movement behavior of different entity types.

By all accounts, moving objects can be categorized into two major groups of geo-referenced vs. non-geo-referenced dynamic objects. In other words, some are dynamic objects that move about in geographic space and may thus be geographically referenced such as humans, animals or vehicles, while the other group includes dynamic phenomena that move in a non-geographic space, including gaze points movements in eye movement studies or particles in a bubble chamber. Each of these dynamic objects, to a varying degree, shares some similarities but also exhibits differences to the others in terms of their data structure, dynamic behavior and nature of movement.

The proposed paper intends to contribute to the development of a toolbox of data mining algorithms for movement analysis by developing firstly a conceptual framework for movement behavior of different moving objects and secondly a comprehensive taxonomy and detailed definitions of movement patterns as well as the elements that make up movement. We argue that this is indispensable as a basis for the development of pattern recognition algorithms that are required to be efficient (i.e. usable on massive data sets), effective (i.e. capable of accurately detecting patterns not artifacts), and as generic as possible (i.e. applicable to different types of movement data).

Motivation

Generally, movement patterns include any recognizable spatial and temporal regularity or any interesting relationship in a set of movement data, whereas the proper definition (i.e. the instantiation) of “pattern interestingness” depends on the application domain. Early work on movement pattern analysis includes the simulation study of human adaptive behavior by Blythe et al. (1996) and the methods developed for the spatiotemporal analysis of wild animal movements by Imfeld (2000). Recent years have witnessed almost an explosion of research activities, triggered by the advent of cheap and ubiquitous positioning and data collection technology. Selected representatives of these more recent publications include the work by Smyth (2001) and by Lee et al. (2004) on the extraction of movement patterns from trajectories generated by individual users of location-based services; and the work on data mining of movement patterns in groups of moving objects by Laube (2005), Laube et al. (2005), Gudmundsson et al. (2004), and Benkert et al. (2006). Furthermore, visual analytics methods for exploratory analysis of movement data have been proposed by Andrienko and Andrienko (2007) that seek to exploit the analytical capacity of the human visual and cognitive system.

The above publications document significant progress of research over the past few years. These studies usually set out with fairly accurate definitions of the patterns they are looking for — as an indispensable prerequisite to data mining (Fayyad et al, 1996) — but they tend to be restricted to a selected, narrow set of patterns. Hence, we are still facing a fundamental problem and impediment to the development of a comprehensive toolbox of movement analysis techniques: There is no agreement on the relevant types of movement patterns nor any comprehensive and systematic definition of these. Therefore, there is a need to create a systematic classification of patterns in movement data. Andrienko and Andrienko (2007) probably come closest to what may be termed such a comprehensive taxonomy for this purpose. However, while their proposal forms an excellent point of departure for subsequent work, the taxonomy should be better rooted in the relevant literature and the associated definitions must become more detailed and accurate.

There are several good reasons for a comprehensive taxonomy and accurate definitions of movement patters. First, the design of efficient and effective algorithms requires accurate formalization of the movement patterns and their properties. Second, most of the quoted work departs from the assumption that generic algorithms can be developed that will be suitable for different kinds of moving object data. However, this will only be possible if we know exactly the similarities but also the differences between different types of moving object data. Third, and related to the second point, is the argument of interoperability: Movement analysis extends across diverse disciplines and hence different people should be able to gain the same understanding of the same terms. This also applies to the 'translation' of natural language descriptions of movement patterns as they may be collected in cognitive experiments (Blythe et al, 1996). Finally, an accurate definition of motion patterns and their constituents is also important for the evaluation of detected patterns by simulation (Laube and Purves, 2006).

Methodology

We started off by a review of the research conducted so far in the area of movement pattern analysis, including the above references as well as review articles such as Erwig (2004) and Gudmundsson et al. (2008) and additional application-specific references. The aim of this first step was to categorize patterns of movement proposed by other researchers and to discover commonalities and differences in terminology and pattern types. Furthermore, we wanted to avoid developing redundant, conflicting terminology. The result of this first step was a first cut at a systematic taxonomy — still incomplete but with missing patterns types or insufficient definitions identified.

While this first step essentially represents a top-down approach we also approached this problem from bottom-up, with the aim of developing a conceptual framework of movement that could 'host' the taxonomy. In order to study the movement behavior of dynamic objects, it is important to take a closer look at movement itself. In other words, it is necessary to know what exactly the *variables* are that define movement, what *constraints* and *external factors* affect movement and most importantly to understand what types of *movement patterns* can be composed from these primitives of movement. Additionally, *spatial and temporal scales* are playing an important role in producing and interpreting a specific movement pattern. By varying temporal and spatial resolution fairly similar movement behavior can be extracted in different moving object data. Finally, a difference is made between movements of *single* individuals and *multiple* individuals, with or without specific relations of group members.

Results

Two main results will be reported in the proposed paper, the conceptual framework of movement, and the taxonomy of movement patterns with associated definitions.

The conceptual framework of movement consists of the following elements:

- Basic and derived variables, organized into spatial, temporal, and spatio-temporal dimensions: For instance, *distance* and *direction* of movement are basic variables in the spatial dimension and solely a function of x, y. *Instance* and *interval* are f(t) and hence basic variables in the temporal dimension; while *speed* is the basic variable that combines both space and time dimensions. From these basic variables, several derived variables can be defined such as *acceleration* which is a function of speed.
- Number of moving objects involved: individual vs. collective (groups); functional collective vs. arbitrary collective groups.
- Constraints: spatial constraints (networks, barriers etc.); environment/background (e.g. land cover for animal movements, map/image for eye movement); other agents (e.g. competition, attraction, disturbances); other constraining factors (top speed, etc.).
- Scale/granularity: spatial, temporal resolution of the movement phenomenon; process scale; sampling rate of the data recording.

The paper will explain how these elements work together to form a framework and basis for the definition of movement patterns.

We will then propose and illustrate our taxonomy of movement patterns, and give associated, detailed definitions. The taxonomy uses individual vs. collective movement patterns as a top level dichotomy of the taxonomic tree. It then branches into similarity patterns vs. arrangement patterns. The following levels contain instances of movement patterns such as *trend, divergence,* and *convergence,* where trend is an instance of an arrangement pattern, and has divergence and convergence as sub-categories. The concepts used on the instance levels of the taxonomy have been based on terms found in the literature as far as possible, but additional pattern concepts had to be introduced to make the taxonomy comprehensive. Finally, we give detailed definitions for each pattern type using the elements of the above conceptual framework, directly informing the development of movement pattern mining algorithms. We also give application examples for each pattern.

Finally, we will use the non-typical (and non-geographic) example of eye movement data to demonstrate how the elements of the conceptual framework and the taxonomy can be used to identify to what degree eye movement data can be used as a proxy of other, geographic movement data (e.g. movements of humans or animals), and what movement patterns can be detected in such data.

Keywords

Motion pattern, moving object, spatiotemporal analysis, spatiotemporal data mining, taxonomy

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