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OVERVIEW OF TRAJECTORY DATA MINING AND THE TECHNIQUES USED

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ABSTRACT

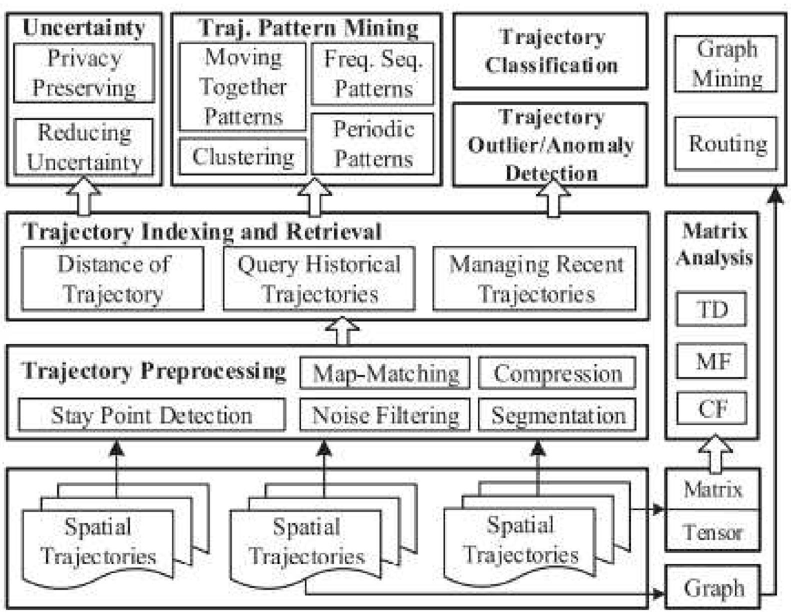
The advances in location-acquisition and mobile computing techniques have generated massive spatial trajectory data, which represent the mobility of a diversity of moving objects, such as people, vehicles, and animals. Many techniques have been proposed for processing, managing, and mining trajectory data in the past decade, fostering a broad range of applications. In this article, we present a systematic approach on the major research into trajectory data mining, providing a panorama of the field as well as the scope of its research topics. This paper also introduces the methods that transform trajectories into other data formats, such as graphs, matrices, and tensors, to which more data mining and machine learning techniques can be applied. Finally, some public trajectory datasets are presented.

KEYWORDS
stay point detection, noisy filtering, segmentation, compression, map matching, tensor, clustering, patterns.

1. INTRODUCTION

A spatial trajectory is a trace generated by a moving object in geographical spaces, usually represented by a series of chronologically ordered points, for example, p1 → p2 → ··· → pn, where each point consists of a geospatial coordinate set and a time stamp such as p = (x, y,t). The advance in location-acquisition technologies has generated a myriad of spatial trajectories representing the mobility of various moving objects, such as people, vehicles, and animals. Such trajectories offer us unprecedented information to understand moving objects and locations, fostering a broad range of applications in location-based social networks [1], intelligent transportation systems, and urban computing [2]. The prevalence of these applications in turn calls for systematic research on new computing technologies for discovering knowledge from trajectory data. Under the circumstances, trajectory data mining has become an increasingly important research theme, attracting the attention from numerous areas, including computer science, sociology, and geography.

FIG. 1: PARADIGM OF TRAJECTORY DATA MINING



Intensive and extensive individual research has been done in the field of trajectory data mining. However, we are lack of a systematic review that can well shape the field and position existing research. Facing a huge volume of publications, the community is still not very clear about the connections, correlations and difference among these existing techniques. To this end, a comprehensive survey that thoroughly explores the field of trajectory data mining, according to the paradigm is shown in Figure 1.

Before using trajectory data, we need to deal with a number of issues, such as noise filtering, segmentation, and map matching. This stage is called trajectory preprocessing, which is a fundamental step of many trajectory data mining tasks. The goal of noise filtering is to remove from a trajectory some noise points that may be caused by the poor signal of location positioning systems (e.g., when traveling in a city canyon). Trajectory compression is to compress the size of a trajectory while maintaining the utility of the trajectory. A stay point detection algorithm identifies the location where a moving object has stayed for a while within a certain distance threshold. A stay point could stand for a restaurant or a shopping mall that a user has been to, carrying more semantic meanings than other points in a trajectory. Trajectory segmentation divides a trajectory into fragments by time interval, spatial shape, or semantic meanings, for a further process like clustering and classification. Map matching aims to project each point of a trajectory onto a corresponding road segment where the point was truly generated.

Many online applications require instantly mining trajectory data (e.g., detecting traffic anomalies), calling for effective data management algorithms that can quickly retrieve particular trajectories satisfying certain criteria (such as spatiotemporal constraints) from a big trajectory corpus. There are usually two major types of queries: the nearest neighbors and range queries. The former is also associated with a distance metric.

2. TRAJECTORY DATA

In this section, we classify the derivation of trajectories into four major categories, briefly introducing a few application scenarios in each category. Trajectory data representing human mobility can help build a better social network [3] and travel recommendation [4].

2.1. Mobility of people: People have been recording their real-world movements in the form of spatial trajectories, passively and actively, for a long time.

- **Active Recording:** Travelers log their travel routes with GPS trajectories for the purpose of memorizing a journey and sharing experiences with friends. Bicyclers and joggers record their trails for sports analysis.
- **Passive Recording:** A user carrying a mobile phone unintentionally generates many spatial trajectories represented by a sequence of cell tower IDs with corresponding transition times.

2.2 Mobility of transportation vehicles: A large number of GPS-equipped vehicles (such as taxis, buses, vessels, and aircrafts) have appeared in our daily life. For instance, many taxis in major cities have been equipped with a GPS sensor, which enables them to report a time-stamped location with a certain frequency. Such reports formulate a large amount of spatial trajectories that can be used for resource allocation [5], traffic analysis [6], and improving transportation networks [7].

2.3. Mobility of animals: Biologists have been collecting the moving trajectories of animals like tigers and birds, for the purpose of studying animals' migratory traces, behavior, and living situations.

2.4. Mobility of natural phenomena: Meteorologists, environmentalists, climatologists, and oceanographers are busy collecting the trajectories of some natural phenomena, such as hurricanes, tornados, and ocean currents. These trajectories capture the change of the environment and climate, helping scientists deal with natural disasters and protect the natural environment we live in.

3. TRAJECTORY DATA PREPROCESSING

This section introduces a fourfold of basic techniques that we need to process a trajectory before starting a mining task, consisting of noise filtering, stay point detection, trajectory compression, and trajectory segmentation.

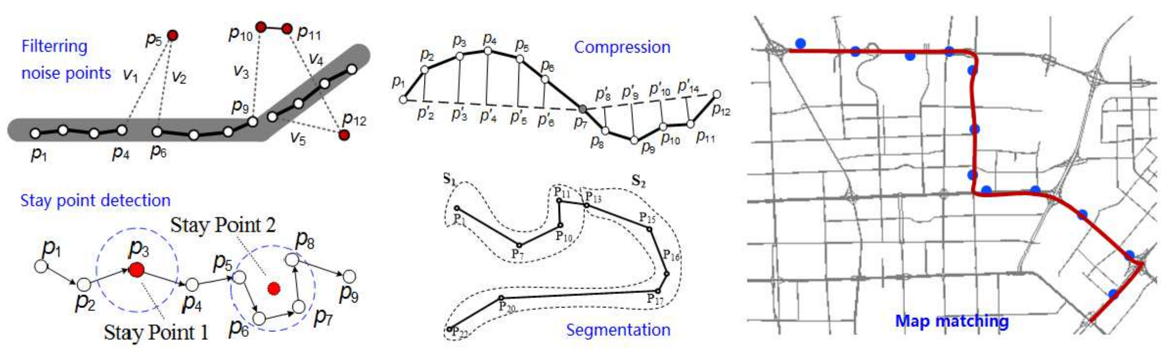
3.1. Noise Filtering: Spatial trajectories are never perfectly accurate, due to sensor noise and other factors, such as receiving poor positioning signals in urban canyons. Sometimes, the error is acceptable (e.g., a few GPS points of a vehicle fall out of the road the vehicle was actually driven), which can be fixed by map-matching algorithms (discussed in Section 3.5). In other situations, as shown in Figure 2, the error of a noise point like p5 is too big (e.g., several hundred meters away from its true location) to derive useful information, such as travel speed. So, we need to filter such noise points from trajectories before starting a mining task.

3.2. Stay Point Detection: Spatial points are not equally important in a trajectory. Some points denote locations where people have stayed for a while, such as shopping malls and tourist attractions, or gas stations where a vehicle was refueled. We call this kind of points "Stay Points." As shown in Figure 2, there are two types of stay points occurring in a trajectory. One is a single point location, for example, Stay Point 1, where a user remains stationary for a while. This situation is very rare, because a user's positioning device usually generates different readings even in the same location. The second type, like Stay Points 2 shown in Figure 2, is more generally observed in trajectories.

3.3 Trajectory Compression: Basically, we can record a time-stamped geographical coordinate every second for a moving object. But, this costs a lot of battery power and the overhead for communication, computing, and data storage. In addition, many applications do not really need such a compression strategies (based on the shape of a trajectory) have been proposed, aiming to reduce the size of a trajectory while not compromising much precision in its new data representation [8]. One is the offline compression (a.k.a. batch mode), which reduces the size of trajectory after the trajectory has been fully generated. The other is online compression, compressing a trajectory instantly as an object travels.

3.4. Trajectory Segmentation: In many scenarios, such as trajectories clustering and classification, we need to divide a trajectory into segments for a further process. The segmentation not only reduces the computational complexity but also enables us to mine richer knowledge, such as sub-trajectory patterns, beyond what we can learn from an entire trajectory.

FIG 2: A) NOISE FILTERING, B) STAY POINT DETECTION, C) TRAJECTORY COMPRESSION, D) TRAJECTORY SEGMENTATION, E) MAP MATCHING



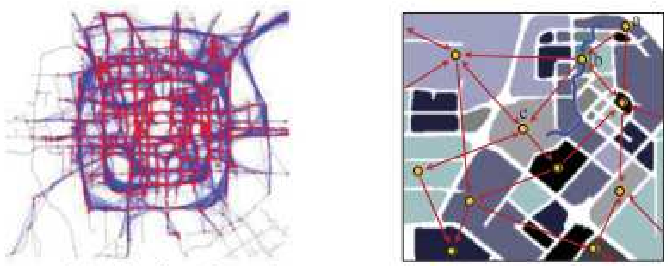
3.5. Map Matching: Map matching is a process to convert a sequence of raw latitude/longitude coordinates to a sequence of road segments. Knowledge of which road a vehicle was/is on is important for assessing traffic flow, guiding the vehicle's navigation, predicting where the vehicle is going, and detecting the most frequent travel path between an origin and a destination, and so forth. Map matching is not an easy problem, given parallel roads, overpasses, and spurs [8].

4. TRANSFER TRAJECTORY TO OTHER REPRESENTATIONS

4.1. From Trajectory to Graph: Trajectories can be transformed into other data structures, besides being processed in its original form. This enriches the methodologies that can be used to discover knowledge from trajectories. Turning trajectories into graphs is one of the representative types of transformation. When conducting such a transformation, the main effort is to define what a node and an edge is in the transformed graph. The methods for transforming trajectories into a graph differentiate between one another, depending on whether a road network is involved in the transformation.

FIG. 3: TRANSFORMING TRAJECTORIES INTO GRAPHS

A) A LAND MARK GRAPH B) A REGION GRAPH

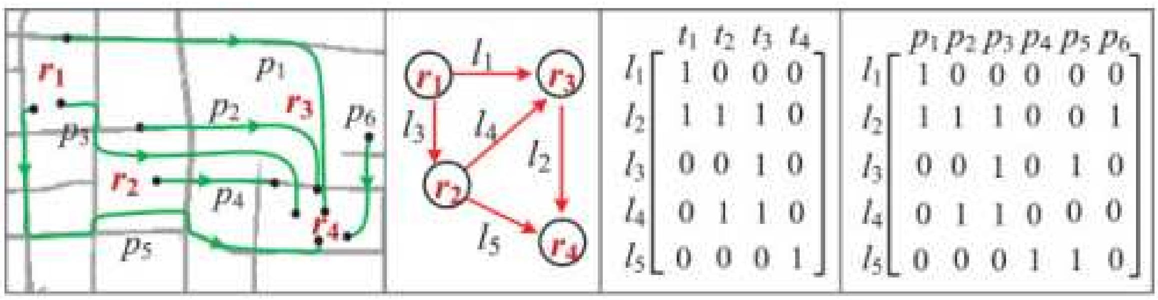


4.2. From Trajectory to Matrix: Another form that we can transform trajectories into is a matrix. Using existing techniques, such as CF and MF, a matrix can help complement missing observations. A matrix can also be used as an input to identify anomalies. The key of the transformation lies in three aspects: (1) what does a row mean, (2) what is a column, and (3) what does an entry denote?

4.3. From Trajectory to Tensor: A nature extension of the matrix-based transformation is turning trajectories into a (3D) tensor, where the third dimension is added to a matrix so as to accommodate additional information.

FIG. 3: TRANSFORMING TRAJECTORIES INTO MATRIX

A) TRAJECTORIES TO PATH B) LINKS C) LINKS TRAFFIC MATRIX D) LINK-PATH MATRIX



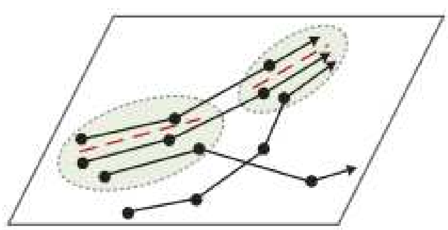
The goal of the transformation is usually to fill the missing entries (in a tensor) or find the correlation between two objects, like two road segments or gas stations. A common approach to solving this problem is to decompose a tensor into the multiplication of a few (low-rank) matrices and a core tensor (or just a few vectors), based on the tensor's nonzero entries. When a tensor is very sparse, in order to achieve a better performance, the tensor is usually decomposed with other (context) matrices in a framework of CF.

5. TRAJECTORY CLUSTERING

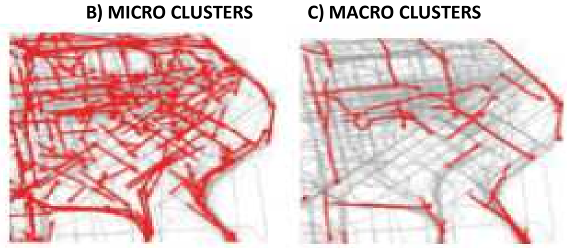
To find representative paths or common trends shared by different moving objects, we usually need to group similar trajectories into clusters. A general clustering approach is to represent a trajectory with a feature vector, denoting the similarity between two trajectories by the distance between their feature vectors. However, it is not easy to generate a feature vector with a uniform length for different trajectories, as different trajectories contain different and complex properties, such as length, shape, sampling rate, number of points, and their orders. In addition, it is difficult to encode the sequential and spatial properties of points in a trajectory into its feature vector.

FIG. 4: TRAJECTORY CLUSTERING BASED ON PARTIAL SEGMENTS [Li et al. 2010b]

A) CLUSTERS OF SEGMENTS



B) MICRO CLUSTERS C) MACRO CLUSTERS



Gaffney and Smyth [1999] [9] and Cadez et al. [2000] [10] proposed to group similar trajectories into clusters by using a regression mixture model and the Expectation Maximization (EM) algorithm. This algorithm clusters trajectories with respect to the overall distance between two entire trajectories. However, moving objects rarely travel together for an entire path in the real world. To this end, Lee et al. [2007] [11] proposed to partition trajectories into line segments and to build groups of close trajectory segments using the Trajectory-Hausdorff Distance, as illustrated in Figure 4(a).

A representative path is later found for each cluster of segments. Since trajectory data are often received incrementally, Li et al. [2010b] further proposed an incremental clustering algorithm, aiming to reduce the computational cost and storage of received trajectories. Both Lee [2007] and Li [2010] adopted a Micro-and-Macroclustering framework, which was proposed by Aggarwal et al. [2003] to cluster data streams. That is, their methods first find mircoclusters of trajectory segments (as demonstrated in Figure 4 (b)), and then group microclusters into macroclusters (as shown in Figure 4 (c)). A major insight of Li's work [Li et al. 2010b] is that new data will only affect the local area where the new data were received rather than the faraway areas.

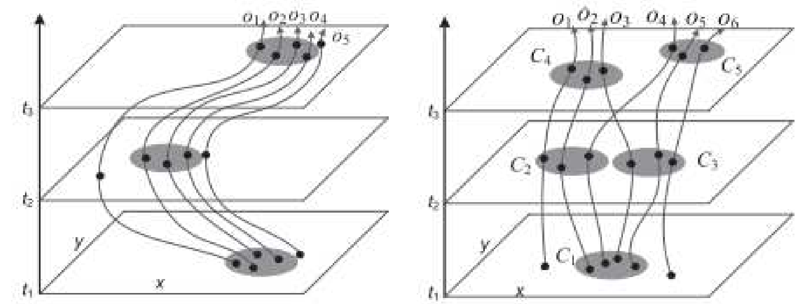
6. TRAJECTORY PATTERN MINING

In this section, we study three major categories of patterns that can be discovered from a single trajectory or a group of trajectories. They are moving together patterns, sequential patterns, and periodic patterns.

6.1. Moving Together Patterns: This branch of research is to discover a group of objects that move together for a certain time period, such as flock [Gudmundsson and Kreveld 2006; Gudmundsson et al. 2004], convoy [Jeung et al. 2008a, 2008b], swarm [Li et al. 2010a], traveling companion [Tang et al. 2012a, 2012b], and gathering [Zheng et al. 2013; Zheng et al. 2014a]. These patterns can help the study of species' migration, military surveillance, and traffic event detection, and so on. These patterns can be differentiated between each other based on the following factors: the shape or density of a group, the number of objects in a group, and the duration of a pattern.

A major concern with flock is the predefined circular shape, which may not well describe the shape of a group in reality, and therefore may result in the so-called lossy-flock problem. To avoid rigid restrictions on the size and shape of a moving group, the convoy is proposed to capture generic trajectory pattern of any shape by employing the density-based clustering. While both flock and convoy have a strict requirement on consecutive time period, Li et al. [2010a] proposed a more general type of trajectory pattern, called swarm, which is a cluster of objects lasting for at least k (possibly nonconsecutive) time stamps.

FIG. 5: EXAMPLES OF MOVING TOGETHER PATTERNS
A) FLOCK, CONVOY AND SWARM B) GATHERING



6.3. Mining Sequential Patterns from Trajectories: A branch of research is to find the sequential patterns from a single trajectory or multiple trajectories. Here, a sequential pattern means a certain number of moving objects traveling a common sequence of locations in a similar time interval. The locations in a travel sequence do not have to be consecutive.

When the occurrence of such a common sequence in a corpus, usually called support, exceeds a threshold, a sequential trajectory pattern is detected. Finding such kind of patterns can benefit travel recommendation [Zheng and Xie 2011b; Giannotti et al. 2007], life pattern understanding [Ye et al. 2009], next location prediction [Monreale et al. 2009], estimating user similarity [Xiao et al. 2014; Li et al. 2008], and trajectory compression [Song et al. 2014]. To detect the sequential patterns from trajectories, we first need to define a (common) location in a sequence. Ideally, in trajectory data, like user check-in sequences from a social net-working service, each location is tagged with a unique identity (such as the name of a restaurant). If two locations share the same identity, they are common. In many GPS trajectories, however, each point is characterized by a pair of GPS coordinates, which do not repeat themselves exactly in every pattern instance. This makes the points from two different trajectories not directly comparable. In addition, a GPS trajectory may consist of thousands of points. Without handled properly, these points will result in a huge computational cost.

6.4. Mining Periodical Patterns from Trajectories: Moving objects usually have periodic activity patterns. For example, people go shopping every month and animals migrate yearly from one place to another. Such periodic behaviors provide an insightful and concise explanation over a long moving history, helping compress trajectory data and predict the future movement of a moving object.

Periodic pattern mining has been studied extensively for time series data. For example, Yang et al. tried to discover asynchronous patterns, surprising periodic patterns [Yang et al. 2001], and patterns with gap penalties, from (categorical) time series. Due to the fuzziness of spatial locations, existing methods designed for time series data are not directly applicable to trajectories. To this end, Cao et al. [2007] proposed an efficient algorithm for retrieving maximal periodic patterns from trajectories. This algorithm follows a paradigm that is similar to frequent pattern mining, where a (global) minimum support threshold is needed. In the real world, however, periodic behaviors could be more complicated, involving multiple interleaving periods, partial time span, and spatiotemporal noises and outliers.

7. TRAJECTORY CLASSIFICATION

Trajectory classification aims to differentiate between trajectories (or its segments) of different status, such as motions, transportation modes, and human activi-ties. Tagging a raw trajectory (or its segment) with a semantic label raises the value of trajectories to the next level, which can facilitate many applications, such as trip recommendation, life experiences sharing, and context-aware computing.

In general, trajectory classification is comprised of three major steps: (1) Divide a trajectory into segments using segmentation methods. Sometimes, each single point is regarded as a minimum inference unit. (2) Extract features from each segment (or point). (3) Build a model to classify each segment (or point). As a trajectory is essentially a sequence, we can leverage existing sequence inference models, such as Dynamic Bayesian Network (DBN), HMM, and Conditional Ran-dom Field (CRF), which incorporate the information from local points (or segments) and the sequential patterns between adjacent points (or segments).

8. PUBLIC TRAJECTORY DATASETS

Collecting data is always the first priority of trajectory data mining. Thanks to researchers in this field, there are quite a few real trajectory datasets that are publicly available:

GeoLife Trajectory Dataset [GeoLife Data]: a GPS trajectory dataset from Microsoft Research GeoLife project [Zheng et al. 2010d], collected by 182 users from April 2007 to August 2012.

T-Drive Taxi Trajectories [T-Drive Data]: A sample of trajectories from Microsoft Research T-Drive project [Yuan et al. 2010a], generated by over 10,000 taxicabs in a week of 2008 in Beijing.

GPS Trajectory with Transportation Labels [Trajectory with transportation modes]: Each trajectory has a set of transportation mode labels, such as driving, taking a bus, riding a bike, and walking. The dataset can be used to evaluate trajectory classification and activity recognition [Zheng et al. 2008a, 2008b].

Check-in Data from Location-based Social Networks [User check-in data]: The dataset consists of the check-in data generated by over 49,000 users in New York City and 31,000 users in Los Angeles as well as the social structure of the users. Each check-in includes a venue ID, the category of the venue, a time stamp, and a user ID.

Hurricane Trajectories [Hurricane trajectory (HURDAT)]: This dataset is provided by the National Hurricane Service (NHS), containing 1,740 trajectories of Atlantic Hurricanes (formally defined as tropical cyclone) from 1851 to 2012. NHS also provides annotations of typical hurricane tracks for each month throughout the annual hurricane season that spans from June to November. The dataset can be used to test trajectory clustering and uncertainty.

9. CONCLUSION

The wide availability of trajectory data has fostered a diversity of applications, calling for algorithms that can discover knowledge from the data effectively and efficiently. This article shows the techniques concerned with different stages of trajectory data mining, recapping them by categories and exploring the differences between one another. This article also suggests the approaches of transforming raw trajectories into other data structures, to which more existing data mining techniques can be applied. And provides an overview on how to unlock the power of knowledge from trajectories, for researchers and professionals from not only computer sciences but also a broader range of communities dealing with trajectories. At the end of this article, a list of public trajectory datasets has been given and a few future directions have been suggested.

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