Spatial Trajectory Prediction Using a Matrix Representation

Wen-Chen Hu
Department of Computer Science, University of North Dakota
Grand Forks, ND 58202-9015, USA

Naima Kaabouch
Department of Electrical Engineering, University of North Dakota
Grand Forks, ND 58202-7165, USA

Hung-Jen Yang
Department of Industrial Technology Education, National Kaohsiung Normal University
Kaohsiung City 80201, Taiwan

and

Lei Chen
Department of Computer Science, Sam Houston State University
Huntsville, TX 77341, USA

ABSTRACT

Inertia has a moving object follow a path or trajectory that resists any change in its motion. Human travel patterns normally have the similar inertia feature. For example, the vehicles on a highway usually stay on the highway or people tend to walk towards a popular destination such as a mall or park. This research tries to predict a spatial trajectory based on the current and previous trajectories. Spatial trajectory prediction requires a complicated processing of trajectories (lists of locations) such as trajectory collection, storage, indexing, transmission, and matching. This research makes trajectory prediction simple and effective by using an innovative matrix representation for trajectories. At the same time, user privacy is fully protected because the matrix representation allows the trajectories to be predicted at the mobile clients instead of the servers. By using our method, trajectory processing becomes matrix processing, which is well documented and includes a variety of tools and methods. This research is useful and popular and is related to a couple of subjects such as mobile computing and security, location-based services, and human behavior recognition.

Keywords: Location-Based Services, Spatial Trajectory Prediction, Privacy Preservation, Matrices, and Mobile Computing.

1. INTRODUCTION

A location-based service is a service based on the geographical position of a mobile handheld device. LBS are extremely popular these days; e.g., one of the LBS examples is to find a nearby ethnic restaurant by using a smartphone. The future of LBS is bright according to the following observations:

- The number of location-based service users worldwide would reach to almost 800 million by the end of 2012 according to Gartner [1], which also forecasted the revenue generated by consumer location-based services will reach $13.5 billion in 2015, of which advertising will be the dominant contributor.
- According to Research and Markets [2], the global location-based services market is forecasted to nearly triple over the eight years from 2013-2020, with a cumulative CAGR (Compound Annual Growth Rate) of more than 12%.
- During the period 2011-2016, the CAGR for worldwide location-based learning products and services is 26.3% based on a report from Ambient Insight, LLC [3], which also predicted revenues would rise from $212.38 million in 2011 to $682.13 million by 2016.

This research proposes a kind of location-based research, spatial trajectory prediction, which is based on the fact that inertia has a moving object follow a path or trajectory that resists any change in its motion; e.g., people are attracted by interesting locations or landmarks such as parks and malls. It is useful and can be applied to a variety of subjects such as traffic control and planning and travel recommendations. The proposed method is simple and effective by using an innovative matrix representation to represent spatial trajectories. Trajectory processing then becomes matrix processing, which is well documented and includes plenty of tools and software. At the same time, user privacy is rigorously preserved because the simplicity of the proposed method allows the prediction to be carried out on the client, instead of the server. The rest of this article is organized as follows. Section 2 gives the background information of this research including two themes: location-based services and spatial trajectory prediction. The proposed system and its structure and method are introduced in Section 3. Section 4 shows some experimental results step by step. The last section summarizes this research.

2. BACKGROUND AND LITERATURE REVIEW

Two themes related to this research, location-based services and spatial trajectory prediction, are discussed in this section.

Location-Based Services (LBS)

A location-based service is a service based on the geographical position of a mobile handheld device [4]. Popular LBS include mapping and navigation, search and information, social networking, entertainment, and tracking [5]. A nice introduction of LBS technologies and standards can be found from an article by Wang, Min, and Yi [6]. A generic system structure of location-based services, shown in Figure 1, includes five major components [7]:

a) *Mobile handheld devices*, which are small computers that can be held in one hand. For most cases, they are smartphones.
b) *Positioning system*, which is a navigation satellite system that provides location and time information to anyone with a receiver.
c) *Mobile and wireless networks*, which relay the query and location information from devices to service providers and send the results from the providers to devices.
d) *Service providers*, which provide the location-based services.
e) *Geographical data providers*, which are databases storing a huge amount of geographical data such as information about restaurants and gas stations.

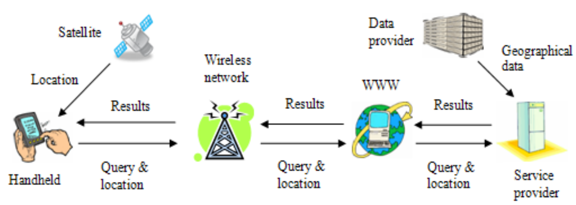


Figure 1. A generic system structure of location-based services.

An example of location-based services using our research is given step by step as follows:

1) The smartphone (a) includes the application of spatial trajectory prediction.
2) The mobile user submits a query of predicting a trajectory by submitting his/her current location information from a positioning system (b) along with several dummy locations to the server.
3) The application program calls the server-side programs (d) located at the Aerospace School of the University of North Dakota along with the location information via mobile or wireless networks (c).
4) The programs at the servers send 3D trajectory matrices, encoding many trajectories, to the user by using an Oracle database (e) which stores trajectory data.
5) The client-side programs then predict a trajectory based on the 3D matrix they received.

Spatial Trajectory Prediction

Trajectory prediction has been applied to a variety of areas such as location-based services, traffic control, and networks. There are roughly two approaches to trajectory prediction: probability-based approach and learning-based approach. This subsection discusses major methods of each approach. Some related trajectory research, but not trajectory prediction, can be found from the articles [8].

Probability-based approach: This approach predicts trajectories based on probabilistic information. For example, Liu & Karimi [9] calculates the probability of taking each road segment at each intersection. The probability parameters are stored in a conditional probability matrix for each intersection. Based on the matrix, they build a decision model and a trajectory search tree and use them to predict the user's road choice intersection by intersection until an exit point is reached. Not only trajectory prediction can be applied to ground traffic, but also it can be used by other applications. Related approach can be found in the articles [10].

Learning-based approach: This approach characterizes trajectory features and adopts machine learning algorithms for trajectory prediction. Choi & Hebert [11] present an approach to predict future motion of a moving object based on its past movement. Their approach exploits the similarities of short-term movement behaviors by modeling a trajectory as concatenation of short segments, which are assumed to be noisy realizations of latent segments. The transitions between the underlying latent segments are assumed to follow a Markov model. Liu & Karimi [9] also propose a learning-based model that incorporates context information in trajectory prediction. One advantage of their learning-based model is that mobile contexts can be quantitatively measured and mapped into a feature space for prediction.

3. THE PROPOSED SYSTEM

One of the location-based services, spatial trajectory prediction, receives a great attention these days because of its usefulness and popularity. For example, spatial trajectory prediction can be used to send location-based advertisements/announcements or find better network routes. However, it also suffers the privacy problem of most location-based services. This research proposes a privacy-preserving spatial trajectory prediction, so users can use this function without concerns. This section introduces (i) the structure of the proposed system, (ii) the map tile system, and (iii) the proposed algorithm.

The System Structure

Spatial trajectories provide useful information to mobile users. For example, based on the user's travel routes, spatial trajectory prediction is able to show the distant gas stations or interesting places such as shopping malls and landmarks. This research predicts spatial trajectories by sending a mobile user's current location along with several dummy locations to the LBS server. Instead of finding the trajectories at the LBS server, the server sends a 3D trajectory matrix, which encodes multiple trajectories, to the user to predict a trajectory. By doing this, user privacy is preserved because only current location with several dummy locations instead of the whole trajectory are sent to the server. Figure 2 shows the system structure of the proposed system consisting of two parts: server-side and client-side subsystems. The former collects and saves sets of trajectories and the later predicts trajectories based on the saved trajectories. The server-side subsystem includes the following components:

- *Trajectory data collection*: The first step is to collect trajectory data. This step can be done before the app is put to use or it continues collecting and updating the trajectories while the app is used.
- *Trajectory data preparation*: Not all collected trajectories are usable for this research and the trajectories may need to be processed before being put to use [12]. Also, the GPS data is usually not stable or consistent. This step may include noise removal, deletion of rarely-used trajectories, or trajectory completion.
- *Trajectory pattern analysis and discovery*: Before the trajectories are entered to the database, the system may try to find useful trajectory patterns such as the most popular trajectories or likely destinations of the trajectories.
- *LBS Database*: The trajectories, lists of locations, are then saved in the LBS Database including two tables: Trajectories and Locations.
- *LBS Manager*: It receives locations from users. For each location it receives, the LBS Manager will send a 3D trajectory matrix back to the user for trajectory prediction. The 3D matrix stores the trajectories passing through the location submitted by the user.

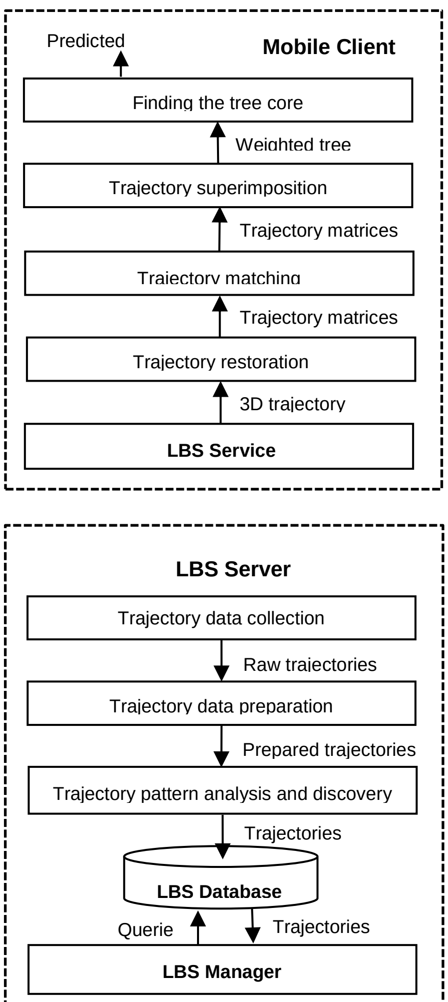


Figure 2. The structure of the proposed system including two components: (a) mobile clients and (b) the LBS server.

On the other hand, the major mission of the client-side subsystem is to predict a trajectory based on the previous stored trajectories. The LBS Service records the current trajectory and sends the current locations along with several dummy locations to the server. It then receives 3D matrices from the server and initiates the following steps: (i) restoring the trajectories from the 3D trajectory matrix, (ii) matching the current trajectory to the restored trajectories, (iii) superimposing the result matrices from the matching, and (iv) the superimposed matrix containing a weighted tree and the core of the tree being treated as the predicted trajectory. By using this approach, user privacy is preserved at the same time because the predication is performed at the client side. Spatial trajectories, lists of locations, are the major data to be processed in this research. Trajectory/list management is normally not easy and complicated. Some of trajectory indexing and retrieval methods can be found from the article by Deng, Xie, Zheng, and Zhou [13]. This research adapts the data structure, matrices, for the trajectory representation. The representation, called the trajectory matrices, facilitates the trajectory storage, indexing, transmission, and processing.

The Map Tile System

A map is usually rendered from a number of map tiles for convenience and speed. A map tile system includes many tiles of different zoom levels. By using map tiles, a map can be panned and zoomed easily and quickly. For panning, some of the map tiles instead of the whole map are replaced. For zooming, different zoom-level tiles can be retrieved more efficiently because lengthy tile searches can be avoided if map tiles are used. Several methods are used to find and display the correct maps. For example, Figure 3 shows a map using pixel coordinates [14]. The pixel at the upper-left corner of the map has pixel coordinates (0,0) and the pixel at the lower-right corner of the map has pixel coordinates (2047,2047). One of the advantages of pixel coordinates is that the specific locations can be pinpointed quickly. At the same time, using an image to represent a world map of a specific zoom level is not realistic because the image size would be huge. Therefore, a map usually consists of a number of map tiles.

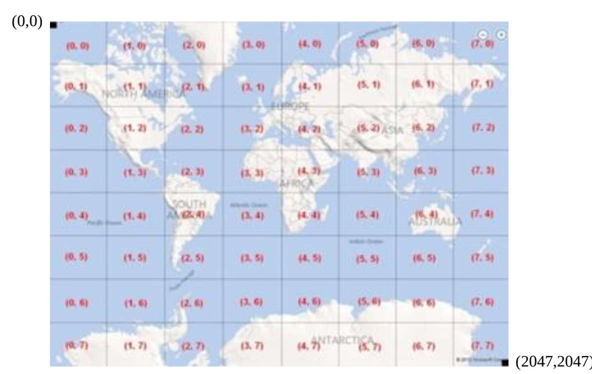


Figure 3. A world map consisting of 64 map tiles.

For example, Figure 3 shows a world map consisting of 64 map tiles from $(0,0)_t$ to $(7,7)_t$ and each tile contains $\left(\frac{2048}{8}\right) \times \left(\frac{2048}{8}\right) = 256 \times 256$ pixels. Given a pair of pixel $(x, y)_p$ coordinates, the corresponding tile coordinates $(a, b)_t$ containing that pixel is given by Equation 1.

$$a = \left\lfloor \frac{x}{256} \right\rfloor \quad and \quad b = \left\lfloor \frac{y}{256} \right\rfloor \tag{1}$$

On the other hand, most locations use latitude and longitude. Examples of how to convert latitude and longitude to tile numbers can be found from the CloudMade Web site [15]. Traditional map panning and zooming is complicated and slow because they need an algorithm to find the correct map locations. Map panning and zooming are made easy by map tiles. Figure 4 shows an example of map tiles of three zoom levels.

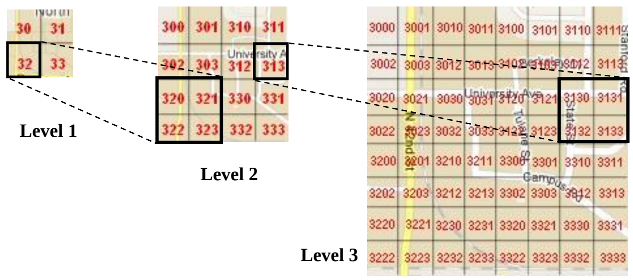


Figure 4. Map tiltes of three zone levels.

Algorithm of the Spatial Trajectory Prediction

The proposed method builds a tree (rooted at the end location of the current trajectory) from the previous trajectories. It then takes the core of the tree as the predicted trajectory. A path is a sequence of vertices connected by edges and a simple path is a path without repeated vertices. In the tree $\mathrm{T} = (\mathrm{V}, \mathrm{E})$, a core is the simple path $\mathrm{T} = (\mathrm{V}', \mathrm{E}')$ that minimizes the following function:

$$\delta(\mathrm{P}) = \sum_{\mathrm{v} \in \mathrm{V}} \mathrm{d}(\mathrm{v}, \mathrm{P}) = \sum_{\mathrm{v} \in \mathrm{V}} \min_{\mathrm{u} \in \mathrm{V}'} \mathrm{d}(\mathrm{u}, \mathrm{v}) \tag{2}$$

where $\mathrm{d}(\mathrm{u}, \mathrm{v})$ is the distance between the nodes u and v [16]. Since the matrix does not include edges, this research uses $\mathrm{d}(\mathrm{u}, \mathrm{v}) = \mathrm{w_v}$, the weight of the node v. A predicted trajectory is usually a path among a set of paths that users like to take or is the most popular one and the core is the longest critical path of a tree. It is the main reason that the core of the tree (superimposed trajectories) is treated as the predicted trajectory. Experiments or proofs may be needed to prove that this approach correctly predict the trajectory we want. The proposed algorithm is given as follows and its flowchart representation is shown in Figure 5.

Privacy-Preserving Spatial Trajectory Prediction

1. *(User) The mobile user sends his/her current location along with several dummy locations to the LBS server.*
2. *(Server) The server sends 3D trajectory matrices based on the locations it receives back to the user.*
3. *(User) Restore trajectory matrices from the 3D matrices.*
4. *(User) Match the current trajectory to each restored trajectory to generate a weighted matrix.*
5. *(User) Superimpose the matching result matrices.*
6. *(User) Find the core of the tree, the predicted trajectory, in the superimposed matrix.*

User privacy may be violated at two places in this method: (i) user sending his/her location to the server and (ii) the server sending the stored trajectories to the user. User privacy is preserved by using this simple approach because the server is not able to tell the user location among the current and dummy locations submitted. Additionally, each 3D matrix encodes many trajectories and several 3D matrices are sent, so the server is not able to associate trajectories to the user.

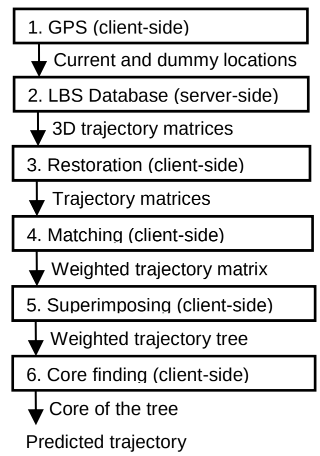


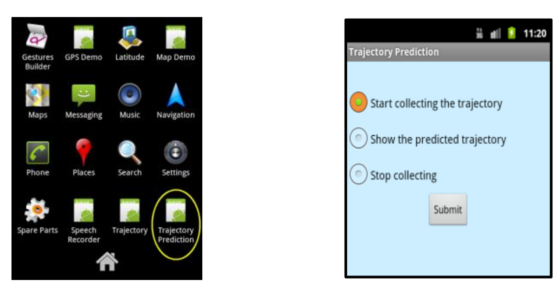
Figure 5. A flowchart of the proposed spatial trajectory prediction.

4. EXPERIMENTAL RESULTS

The proposed algorithm of spatial trajectory prediction is complicated. Details of its steps are given as follows to help readers better understand it. Except the second step, the following steps are performed at the mobile client instead of the server. Therefore, user privacy is preserved.

A Mobile User Sending Locations to the LBS Server

The user sends his/her current location, such as (latitude, longitude) = (47° 55' 31" N, 97° 01' 57" W), along with several dummy locations to the LBS server. Figure 6.a shows the application icon on a smartphone. Clicking the icon will initiate the service and display the interface as shown in Figure 6.b. Pushing the button "Start collecting the trajectory" will start recording the current trajectory. The recording will run in the background, so other smartphone functions can still work while it is recording. The user will receive a recommended trajectory if the button "Show the predicted trajectory" is pushed and the service ends when the button "Stop collecting" is clicked.



(a) (b)

Figure 6. (a) The application icon and (b) the main interface.

The LBS Server Sending 3D Trajectory Matrices to the Mobile User

This step takes the longest time among all steps, so the execution time of this algorithm is (n^3), where n is the number of trajectories or the number of row or column entries. The 3D trajectory matrix is based on the location sent by the user and the location is usually located at the center of the matrix. It encodes the stored trajectories passing through the location. A 3D matrix notation is given by Equation 3 and is listed again as follows:

$$D = \begin{bmatrix} d_{1,1} & d_{1,2} & \dots & d_{1,n} \\ d_{2,1} & d_{2,2} & \dots & d_{2,n} \\ \dots & \dots & \dots & \dots \\ d_{m,1} & d_{m,2} & \dots & d_{m,n} \end{bmatrix} \quad (3)$$

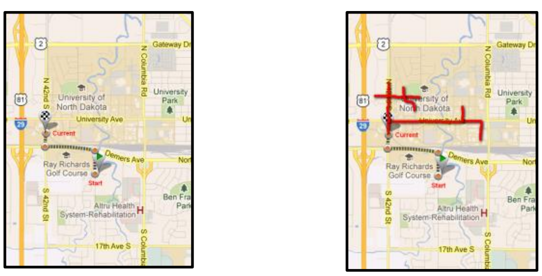
where the value of each entry $d_{i,j}$ is an array of weights of the trajectories on the map tile.

Restoring the Trajectory Matrices from the 3D Matrix

The restoration is simple because the value of the entry $d_{i,j,k}$ of the 3D matrix D is the weight of the trajectory k on the tile coordinated at $f(i,j,l)$. For example, the trajectory T_k is

$$T_k = \begin{bmatrix} t_{1,1} & t_{1,2} & \dots & t_{1,n} \\ t_{2,1} & t_{2,2} & \dots & t_{2,n} \\ \dots & \dots & \dots & \dots \\ t_{m,1} & t_{m,2} & \dots & t_{m,n} \end{bmatrix} \quad (4)$$

where $t_{i,j}$ is the value of the array element k at the entry $d_{i,j}$ of the 3D matrix D. Figure 7.a shows an example of a user's current trajectory.



(a) (b)

Figure 7. (a) A user's current trajectory and (b) superimposed trajectories.

Matching the Current Trajectory to the Restored Trajectories

This research uses the Equation 5, listed as follows, to measure the similarity between two matrices C and S:

$$r_{i,j} = c_{i,j} \Delta s_{i,j} = \begin{cases} \frac{|C \cap S|}{|C|}, & if\ (c_{i,j} = 0\ and\ s_{i,j} \neq 0) \\ & \quad or\ (i = i_e\ and\ j = j_e) \\ 0, & otherwise \end{cases} \quad (5)$$

An example of a result matrix R_k after matching is given in Equation 6.

$$R_k = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&1/4&1/4&1/4&1/4&0&0&0&0 \\ 0&0&0&0&0&1/4&0&0&0&0 \\ 0&0&0&0&0&1/4&1/4&1/4&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix} \quad (6)$$

Superimposing the Result Matrices

This step superimposes the result matrices from the previous step:

$$R = R_1 + R_2 + \cdots + R_h \quad (7)$$

where h is the number of the restored trajectories and $r_{(i,j)} = r_{1(i,j)} + r_{2(i,j)} + \cdots + r_{h(i,j)}$. An example of a superimposed matrix, encoding a tree rooted at the entry $(3,5)$, is given as follows:

$$R = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&2&0&2&0&0&0 \\ 0&0&4&4&4&3&2&1&0&0 \\ 0&0&0&0&0&3&0&0&0&0 \\ 0&0&0&0&0&2&1&3/4&0&0 \\ 0&0&0&0&0&0&0&3/4&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix} \quad (8)$$

The superimposed matrix contains a weighted tree, whose root node is the current/end location of the current trajectory and branches are the possible extended trajectories. An example of superimposed trajectories is shown in Figure 7.b.

Finding the Core of the Tree, the Predicted Trajectory, in the Superimposed Matrix

The core of the tree in the superimposed matrix is treated as the predicted trajectory. Figure 8 shows an example of a predicted trajectory and Figure 9 shows an example of a tree core and its corresponding matrix and trajectory. The core of the tree in Equation 7 is given in Figure 9.a. The predicted trajectory is therefore the entries with a value 1 in the final matrix. It starts from the root tile at the entry $(3,5)$ and ends at the leaf tile at the entry $(8,8)$. Figures 9.b and 9.c are the corresponding 10×10 trajectory matrix and trajectory. The predicted trajectory is not shown on a map because our sample matrix is small and the result trajectory on a map could not show the advantages of our method.

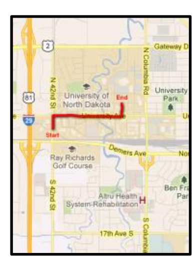
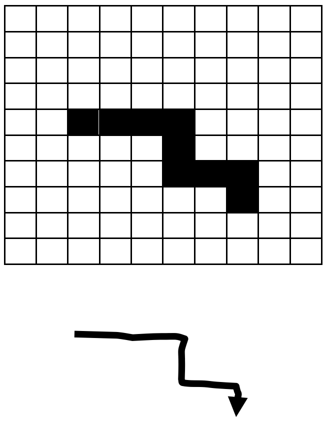


Figure 8. A predicted trajectory.

$$R = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&1&1&1&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&1&1&1&0&0 \\ 0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$ (a)



(b)

(c)

Figure 9. An example of a tree core and the predicted trajectory: (a) a tree core, (b) the corresponding 10×10 trajectory matrix, and (c) the corresponding trajectory.

5. CONCLUSION

Location-based services are very popular these days because of the ubiquitous smartphones. One of the LBS is spatial trajectory predication, which could be used for many areas such as travel recommendations and traffic planning and control. Spatial trajectory prediction requires a complicated processing of trajectories (lists of locations) such as trajectory collection, storage, indexing, transmission, and matching. This research tries to predict a spatial trajectory based on the current and previous trajectories. The proposed method works as follows. The mobile user sends his/her current location along with several dummy locations to the server. Based on each location it receives, the server sends the user a 3D trajectory matrix, which encodes a set of trajectories passing through the location before. The user then restores the trajectories from the 3D matrix and matches the current trajectory to the restored trajectories. The predicted trajectory is found as the core of the tree, which is built by superimposing the matching results. The proposed method makes trajectory prediction simple and effective by using an innovative matrix representation for trajectories. At the same time, user privacy is fully protected because the matrix representation allows the trajectories to be predicted at the mobile clients instead of the server. By using our method, trajectory processing becomes matrix processing, which is well documented and includes a variety of tools and methods. Experimental results show the proposed methods are effective and secure. This research represents spatial trajectories by using matrices, which are spare most of the time. Future research directions include using another data structure such as dictionaries of keys and coordinate lists to represent spatial trajectories and expect the processing speed could be increased and storage size could be reduced.

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