Sketch Based Spatial Queries for Retrieving Human Locomotion Patterns from Continuously Archived GPS Data

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***Abstract*— We propose a system for retrieving human locomotion patterns from tracking data captured within a large geographical area, over a long period of time. A GPS receiver continuously captures data regarding the location of the person carrying it. A constrained agglomerative hierarchical clustering algorithm segments these data according to the person's navigational behavior. Sketches made on a map displayed on a computer screen are used for specifying queries regarding locomotion patterns. Two basic sketch primitives, selected based on a user study, are combined to form five different types of queries. We implement algorithms to analyze a sketch made by a user, identify the query, and retrieve results from the collection of data. A graphical user interface combines the user interaction strategy and algorithms, and allows hierarchical querying and visualization of intermediate results.**

We evaluate the system using a collection of data captured during nine months. The constrained hierarchical clustering algorithm is able to segment GPS data at an overall accuracy of 94% despite the presence of location-dependent noise. A user study was conducted to evaluate the proposed user interaction strategy and the usability of the overall system. The results of this study demonstrate that the proposed user interaction strategy facilitates fast querying, and efficient and accurate retrieval, in an intuitive manner.

***Index Terms*— Sketch-based querying, locomotion patterns, spatial queries, GPS data, multimedia retrieval.**

I. INTRODUCTION

CONTINUOUSLY archived location data, obtained by tracking persons or objects, are useful in several application areas such as surveillance, navigational assistance, and behavioral studies. While different types of sensors are used for tracking indoors or in medium-sized outdoor areas, the Global Positioning System (GPS) provides a means of tracking over a very wide geographical area with reasonable accuracy. The data can be indexed by date, time and location, in order to speed up retrieval.

In some applications such as traffic parameter estimation, it is often necessary to search the archived data for a particular pattern of locomotion. Such queries can be categorized as *spatial queries* [11]. This is usually performed by reducing the search space using other criteria and viewing the tracking results manually to retrieve the desired locomotion pattern. Ability to query a collection of tracking data by a particular locomotion pattern will greatly enhance the efficiency of retrieval, and allow identification and analysis of long term behavioral patterns. Therefore, developing spatial queries to retrieve locomotion patterns in large collections of tracking data solves an important research problem.

However, facilitating spatial queries on a collection of tracking data from a large geographical area, captured over a long period of time, is a challenging task. There should be an intuitive and non-restrictive way to input queries on locomotion patterns into a computer. Such queries can entail very different levels of complexity, and the results can encompass various levels of granularity. For example, possible queries might include the following:

- "Which route did I take when I went from Tokyo to Yokohama last month?"
- "How many times have I travelled to places outside Tokyo since January 2008?"

Sketching is a common method used by people to specify or describe patterns of movement. People draw lines and arrows on printed maps to show directions to a particular location. Coaches and commentators of soccer and basketball games use sketches to describe player movement in the field. With several common factors such as area, distance and direction, sketching and locomotion has an intuitive mapping between them. Despite different sketching habits and techniques, people are able to interpret sketches made by others. Therefore, sketching is a highly prospective candidate for synthesizing queries on locomotion patterns.

In this research, we propose a system for spatial querying of locomotion patterns in a large collection of continuously archived GPS data. The queries are specified by making simple sketches with a pointing device, on a map displayed on a computer screen. We propose a novel clustering algorithm for segmenting GPS data accoring to the motion of the person bearing the GPS receiver, and a novel user interaction strategy that facilitates searching for different types of locomotion patterns with sketches that are simple, intuitive and unambiguous. We also design and implement serach algorithms for retrieving segments that match the patterns specified by the queries. The system consists of a graphical user interface that combines the user interaction strategy and the algorithms with interactive visualization for efficient retrieval.

The rest of this paper is organized as follows: Section II is a brief review of related work; Section III outlines the aquisition of GPS data; Section IV describes the algorithms for segmentation of GPS data; Section V explains the proposed user interaction strategy; Section VI describes the algorithms used for searching for locomotion patterns in GPS data; Section VII presents the user interface and describes how the systems is used for retrieval; Section VIII contains the details of a user study conducted for evaluating the proposed system, and the results; After a brief discussion in Section IX, Section X concludes the paper with suggestions for future directions.

TABLE I
FORMAT OF GPS LOCATION RECORDS

Date & Time	Altitude	Distance	Duration	Average speed	Direction	Lattitude	Longitude
2007/11/22 9:22:02	29 m	24 m	0:00:13	7 km/h	199 °	N35 ° 44.713’	E139 ° 44.755’
2007/11/22 9:22:15	29 m	39 m	0:00:21	7 km/h	200 °	N35 ° 44.700’	E139 ° 44.749’
2007/11/22 9:22:36	29 m	31 m	0:00:17	7 km/h	198 °	N35 ° 44.681’	E139 ° 44.741’

II. RELATED WORK

A number of researches use continuously archived GPS data to associate photos with locations and create visualizations on maps [8], [12]. Tancharoen et al. [17] use GPS data as a cue to summarize and index continuously archived video from a wearable camera. Adams et al. [1] propose algorithms for identifying socially significant places termed *social spheres* using GPS traces. Morris et al. [14] propose a framework for automatic modeling of recreation travel using GPS data collected at recreation sites. The *Cabspotting Project* [2] analyses a collection of GPS data from a large number of taxi cabs in an urban area, in order to discover the invisible dynamics contained within the data.

There has been some research towards a framework for spatial querying of locomotion patterns. Egenhofer [7] demonstrated how imprecise spatial queries can be dealt with in a comprehensible manner, using topological relations. A relational algebra is proposed there, for verifying the consistency of the resulting topological representations. Gottfried [10] uses a locomotion base and a set of relations to represent locomotion patterns, with emphasis on healthcare applications. However, an effective user interaction strategy for submitting spatial queries is essential for utilizing the above framework to retrieve locomotion patterns.

So far, there has been little research on user interfaces for spatial querying. Ivanov and Wren [11] use simple spatial queries for video retrieval from surveillance cameras. However, the functionality of this interface is limited to specifying the direction of movement along a corridor. In our recent research, we proposed a sketch-based user interaction strategy for retrieval of human locomotion patterns from a home-like smart environment [4]. The strategy proposed there, however, is not scalable to unbounded regions. Kimber et al. [6] propose a method of object based video playback, that can be used for querying for locomotion patterns.

In the following sections of this paper, we describe how we address the problem of spatial querying of locomotion patterns in continuously archived GPS data with the aid of a user interaction strategy that facilitates effective searching.

III. DATA ACQUISITION

This research is based on a collection of continuously archived GPS data from a handheld GPS receiver. One of the authors has been continuously carrying a *Garmin*® *GPSmap 60CSx* GPS receiver for data acquisition, since November 2007. Data are collected at all times other than when signals are not received. Data from different terrains and both rural and urban environments were collected. The author also carried a *SenseCam*® device [18] on certain days, for verification purposes. The data collection considered for this work can be summarized as follows:

- Duration: November 21, 2007 to August 20, 2008
- Area: Covers an approximate land area of 300,000km^2
- Total distance travelled: 26500 km (approx.)
- Signal reception: 8-24 hours per day (approx.)

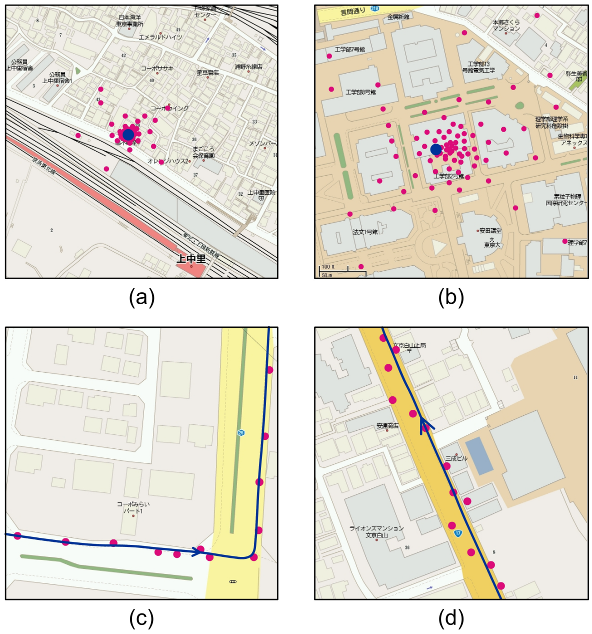


Fig. 1. Noise in GPS location records.

The sampling interval of the GPS receiver is 1 second. Samples corresponding to the same GPS coordinates are combined to form a *location record* in the format shown in Table I. The average speed is calculated by dividing the distance between current and previous samples by the difference between the starting timestamps of the two entries. The direction recorded is the angle of the vector from previous location to current, measured clockwise from north. The number of entries during a day varies between approximately 2000 and 20,000, according to the movement of the person and the availability of signals. The average number of location records per day is around 3000.

A few problems arise when extracting location and motion information using GPS data. First, due to poor or no reception of signals, the receiver might fail to record data at certain locations. Second, a GPS receiver takes some time to initialize recording data after being switched on (this problem, however, can be eliminated by using an external power supply while changing batteries). Hence, the collected data form a discrete time sequence that is ‘undefined’ for certain time intervals. Several factors contribute to the amount of noise present in GPS data [15], making it difficult to model and eliminate noise.

Figures 1a and 1b show the distribution of data recorded when the person was not moving. The locations recorded by the GPS receiver are shown as red dots. The blue dot indicates the actual location. The maps on both figures have been drawn to the same scale. While the recorded GPS coordinates show the same directional distribution, the distances are very different. The average accuracy for the location in Figure 1a is about 5m,

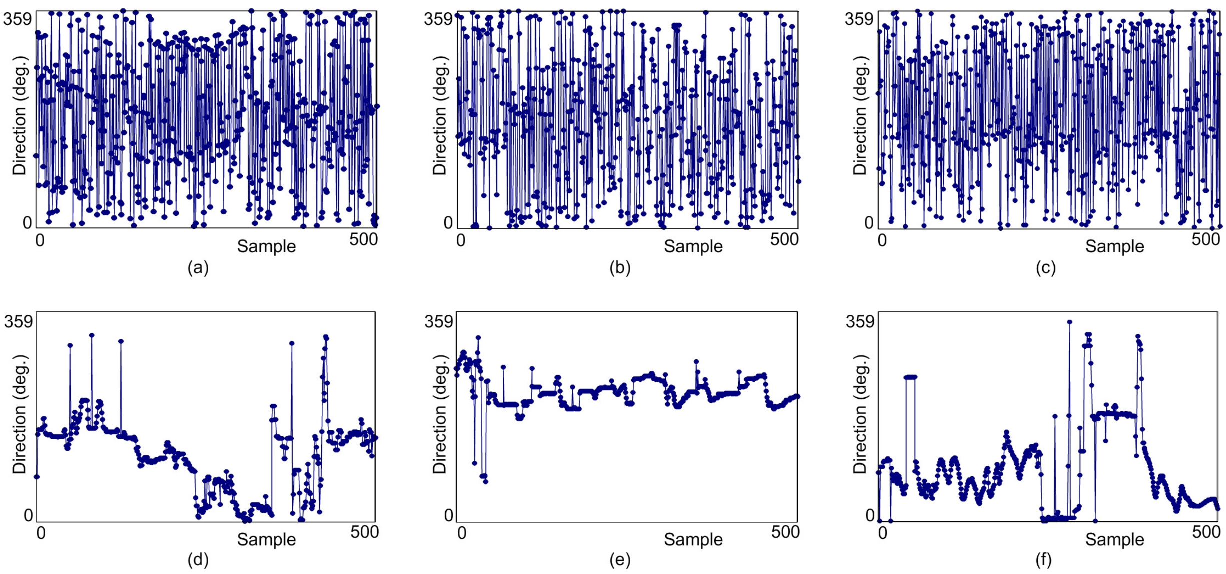


Fig. 2. Distribution of direction data in locomotion segments.

whereas that for Figure 1b is about 25m. Figures 1c and 1d show GPS data recorded while walking at different locations, on maps of the same scale. The blue lines indicate the actual path of movement. It is evident that data for the path in Figure 1d are less accurate than those for Figure 1c. Therefore, the proposed system has to be designed to perform well under these conditions.

IV. Segmentation of GPS Data

The result of data acquisition, as described in Section III, is a large number of location records ordered by time. Each record corresponds to a small time interval during which a person's location, average speed and direction have been estimated. We intend to combine these records to form a set of non-overlapping *locomotion segments*, representing the nature of the person's movement. The user queries can thereafter be made on the collection of the segments, instead of the entire data set, allowing faster and more efficient retrieval. We select the following two basic classes of locomotion, for segmentation of location records:

1) **Navigating**: instances of locomotion where the person makes a regular change of location with time. Examples are walking, driving or riding in a vehicle.
2) **Non-navigating**: instances of locomotion where a person stays within a small neighborhood. Examples are a room, a bus stop etc.

The same classes, in combination with a few others, have been used during the initial stages of activity classification based on GPS data by Liao et al. [13]. However, their approach is based on partitioning the GPS data into 10×10 meter blocks and applying supervised learning algorithms. Instead, we use unsupervised learning algorithms to discover the natural groupings in data and then classify the groups according to their statistical properties.

A. Ground Truth

We selected a data set corresponding to eight (non-consecutive) days from the captured GPS data, for extracting ground truth with respect to the above classes. The days were selected such that the following requirements were met:

TABLE II
Example Segments from Ground Truth

From	To	Class	Description
00:00	08:27	Non-navigating	At home
08:28	09:38	Navigating	Walking to the railway station (08:28-08:33), taking train to City A (08:34 to 09:38)
...	...	...	...
22:13	23:59	Non-navigating	At home

- GPS reception was available at least 20 hours each day
- The data were from both urban areas with a high density of buildings, and rural areas
- Data from the class *non-navigating* were available for both indoor and outdoor locations
- Data from the class *navigating* were available from different means of transport
- Data from both classes were available for any given time of day

We segmented the selected data according to the above two classes. Segmentation was performed manually by inspecting location records with the aid of *MapSource*® (a software provided with the GPS receiver for data visualization), and *SenseCam*® images. The resolution of labeling was one minute. Table II shows the results of the labeling for part of one of the selected dates. The descriptions are merely for ease of understanding the data, not for use by algorithms.

B. Feature Selection and Preprocessing

We analyzed the attributes listed in Table I and their combinations to find patterns that help to classify the data. A consistent pattern, evident in direction data, seemed prospective. Figure 2 shows the direction plots of 6 segments of GPS data. The segments were cropped to a length of 500 samples, to improve visualization. Figures 2a, 2b and 2c correspond to non-navigating segments from different locations. Figures 2d, 2e and 2f correspond to navigating segments corresponding to walking and different means of transportation.

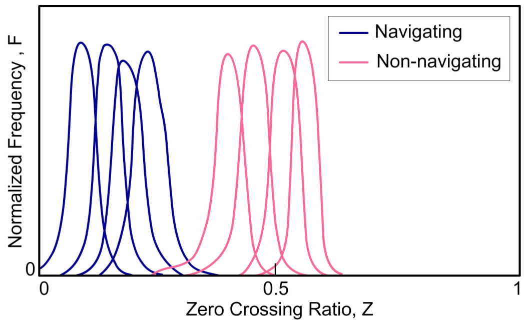


Fig. 3. Distribution of zero crossing ratios.

A consistent pattern that distinguishes non-navigating segments from navigating segments is evident. We examined data from two other types of GPS receivers (namely IO-DATA® *USBGPS 2* and IO-DATA® *CFGPS*), and verified that the same distribution is present. The pattern in non-navigating data is caused by the noise in GPS data dominating the calculation of direction, due to the absence of actual movement. While the magnitude of noise in GPS coordinates varies from place to place depending on the signal-to-noise ratio of reception, it is evident that the direction provides a bounded measure that has a similar pattern irrespective of the signal strength at the location. Another important thing to note is that the time between adjacent location records can vary according to the speed and the reception of GPS signals. Since we are considering the sequence number of location records as the domain, this does not create a problem. Given these observations, we select direction as the main feature used for this classification.

We preprocess the direction data as follows. We define the vector of direction data elements as $D(n)$ where n is the sequence number of the samples. To highlight the change of direction, we offset the direction vector by 180° and define the adjusted direction vector $A(n)$ as

$$A(n) = D(n) - 180$$

For a given window of size W around $A(n)$, we define the zero crossing ratio $Z_W(n)$ as:

$$Z_W(n) = \frac{No.\ of\ times\ A(n)\ crosses\ 0\ within\ the\ window}{W}$$

The value of $Z_W(n)$ is a measure of relative frequency of direction changes in GPS data, and therefore a single feature vector that highlights the pattern shown in Figures 2a, 2b and 2c. We calculate $Z_W(n)$ for $W =$ 16, 32, 64, and 128. The selection of the optimal value for W will be discussed later in Section IV(E).

Figure 3 illustrates the normalized histograms of $Z_W(n)$ for several different segments extracted from ground truth. It is evident that $Z_W(n)$ of non-navigating segments is higher than that of navigating segments. The deviation of class means of segments within each class is fairly high, whereas the standard deviation of within class segments have a very small difference. Table III summarizes the overall probability distributions of the two classes, created by combining segments from ground truth. The parameters of these distributions, with notations indicated in Table III, will be used in the classification algorithm described in the following section.

TABLE III
PROBABILISTIC MODELS FOR THE TWO CLASSES

Parameter	*Navigating*	*Non-navigating*
Mean	$E_{nav} = 0.15$	$E_{non} = 0.50$
Std. deviation(σ)	$\sigma_{nav} = 0.07$	$\sigma_{non} = 0.06$
Minimum value	$min_{nav} = 0.00$	$min_{non} = 0.24$
Maximum value	$max_{nav} = 0.40$	$max_{non} = 0.65$
Max. σ in a segment	$\sigma_{nav}^{max} = 0.08$	$\sigma_{non}^{max} = 0.07$

C. Constrained Hierarchical Clustering

Since the data are naturally grouped into the two classes with little overlap and varying class means, we use unsupervised learning during the initial stages of classification. Since the segments are sets of contiguous samples, a hierarchical clustering algorithm seems more appropriate. Hence we propose the following Agglomerative Hierarchical Clustering (AHC) algorithm as the first stage of classification:

1) Start with a single sample per cluster
2) Group the neighboring clusters into contiguous pairs
3) Calculate distance between the means, D_M of the two clusters in each pair
4) Calculate mean, E and standard deviation, σ for a cluster created by combining the pair
5) Combine clusters if

$$D_M < 3 \times \sigma_{max} \tag{1}$$

$$\sigma < \sigma_{max} \tag{2}$$

$$E \notin L \tag{3}$$

where, σ_{max} = max(σ_{nav}, σ_{non}) and $L = (\frac{min_{non}+max_{nav}}{2} - \sigma_{max}, \frac{min_{non}+max_{nav}}{2} + \sigma_{max})$

6) Repeat steps 2 to 5, N_1 times where, $N_1 = 1 + \log_2(n)$, and $n =$ the no. of samples in the current data set

The basic idea in this algorithm is to form larger clusters by combining contiguous location records. The clustering process is controlled using the parameters of the probabilistic model created from ground truth. The number of steps, N_1 is sufficient for convergence of the algorithm in the worst case scenario of all samples belonging to the same cluster.

The main difference between the above algorithm and conventional AHC algorithms is constraint (3) in step 5. This constraint creates a *no-man's land* where clusters cannot be formed. The constraint was added to prevent the formation of clusters at and across class boundaries where the difference between cross ratios is less due to noise. Such clusters, if formed, can lead to the misclassification of small segments.

In the second stage of classfication, constraint (3) is removed and the same algorithm is applied to the results from the previous stage. The steps are now repeated N_2 times where $N_2 = \log_2(n)$, or until there is no further change in clusters. The algorithm usually converges within 5 to 10 iterations for data from one day. The clustering process is now dominated by larger clusters that have already been formed, thereby reducing the chances of misclassification. Figure 4 demonstrates this with an example. Figure 4a shows the result of clustering without imposing constraint (3) at the start. It is evident that the navigating segment, shown in ground truth, was not classified properly. Figure 4b and 4c shows the results of the first and second stages of clustering respectively,

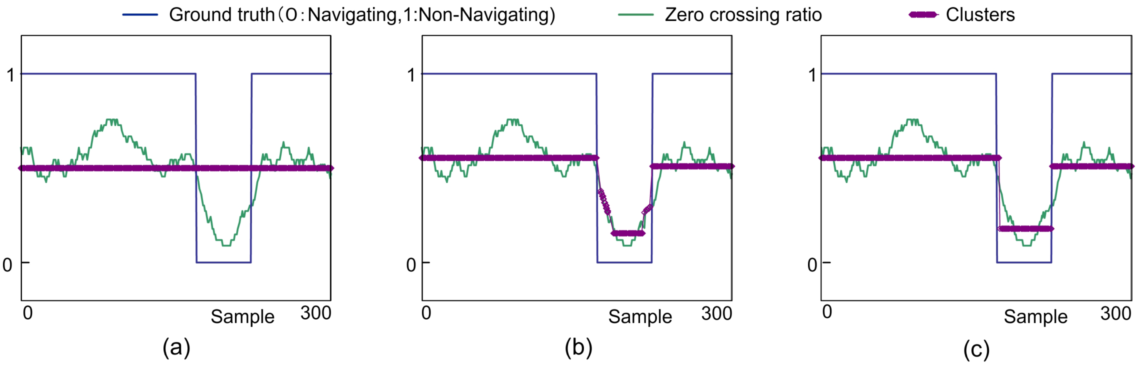


Fig. 4. Effect of constraining the clustering algorithm.

TABLE IV
ATTRIBUTES OF *Navigating* SEGMENTS

Starting Time	Ending Time	Starting Location	Ending Location
2007/11/27 10:32:41	2007/11/27 13:21:20	N35° 37.866', E139° 16.032'	N35° 37.820', E139° 16.039'
2007/11/27 13:27:40	2007/11/27 16:29:11	N35° 37.864', E139° 16.024'	N35° 39.894', E139° 45.695'

TABLE V
ATTRIBUTES OF *Non-nagivating* SEGMENTS

From	To	Mean Location	Maximum deviation
2007/11/27 10:16:23	2007/11/27 10:32:41	N35° 37.938' ,E139° 16.188'	0.001161
2007/11/27 13:21:20	2007/11/27 13:27:40	N35° 37.844' ,E139° 16.036'	0.000276

TABLE VI
PERFORMANCE OF CLUSTERING

	Ground Truth	
	Non-navigating	Navigating
Classified as Non-Navigating	10985	923
Classified as Navigating	305	9887

for the proposed algorithm. Due to controlled clustering in the first stage of the algorithm, the segment can now be retrieved.

In the third and final stage of classification, the clusters are labeled using a nearest-neighbor classification algorithm. The following steps are performed on each cluster C resulting from clustering in stage 2:

1) Calculate the mean of the Zero crossing ratios, E_c for the current cluster
2) Calculate mean distances D_1 and D_2 as

$$D_1 = |E_c - E_{nav}|$$

$$D_2 = |E_c - E_{non}|$$

3) if $D_1 < D_2$, label C as *Navigating*. Otherwise, label C as *non-navigating*

The location records are indexed by the results of classification, for efficient querying. Tables IV and V show example entries of indices for navigating and non-navigating segments respectively. The standard deviations of the lattitudes and longitudes of locations in non-navigating segments are calculated and compared, and the larger value is recorded as *maximum deviation* in Table V. This is intended to be used in visualization of results.

D. Refinement of Segments

The segments created by the above algorithms might have some discrepancies due to loss of signal reception, in some situations. Consider a scenario when the person carrying the GPS receiver waits at location A, takes an underground passage (no reception of GPS signals) from location A to location B, and then using above-ground transport (GPS signals available) from location B to location C. The result will be a pair of contiguous segments that have different geographical locations as the boundary. Such situations are refined by modifying the navigating segment according to the time and location information in the non-navigating segment. While it is impossible to predict the exact locomotion patterns that occured during the time GPS data were not captured, this refinement attempts to maintain data integrity at the segment level.

E. Quantitative Evaluation

We evaluated the accuracy of the constrained AHC algorithm using the ground truth from 8 days of GPS data. A different set of dates from those used for modeling the probability distributions were used. From the 22100 location records in the data set, 10810 belonged to 34 navigating segments and the remaining 11290 belonged to 30 non-navigating segments.

We segmented this collection of data using the proposed clustering algorithm, and compared the results with the ground truth. Table VI shows the confusion matrix for the data set. The overall accuracy of classification of location records is 94.4%. The clustering algorithm was able to identify 29 of the navigating segments, and 23 of the non-navigating segments. The average accuracy of the timestamps at segment boundaries was 2 minutes and 45 seconds.

The main reason for missing a segment was the small number of location records within that segment, due to poor reception of GPS signals. Slow walking at crowded locations resulted in segments being misclassified as non-navigating segments, in some occasions.

The optimal value for the window size W for calculating the zero crossing ratio $Z_W(n)$ was found to be 64. Using smaller window sizes resulted in the detection of *false non-navigating segments* with short durations. However, such window sizes allowed the detection of brief stops with duration less than a minute (which were not counted when estimating ground truth). Therefore, it might be desirable to allow the user to control the window size and decide the level of detail interactively, through the user interface.

V. User Interaction Strategy

Our objective here is to design a user interaction strategy that allows the user to query for locomotion patterns by making a sketch pattern on a map. This should allow the user to submit different types of queries in a simple and intuitive manner. There should be no ambiguity between different types of queries. The relative complexity of queries is also important. Less specific queries, resulting in a large amount of results, should take less effort to sketch. On the other hand, it is fine for specific and more detailed queries to require more time and effort to sketch them. The algorithms should be sufficiently robust to interpret the sketches correctly, despite different sketching habits and speeds. We take a user-centered approach based on that of a previous system we developed for querying locomotion patterns in an indoor environment [4], for designing a strategy that fulfills the above objectives.

In real-life descriptions of locomotion patterns, a person is usually referred to as being within a *region*, or moving along a given *path* within or between such regions. Therefore we identify the entities "region" and "path" as the *query primitives* for locomotion patterns. The size and boundaries of regions are sometimes approximate or even ambiguous, while they can be precisely specified at other times. When describing a path, sometimes only the starting and ending locations are important. On other occasions, the path traversed is important. This diversity of detail is inherent to sketching, making it a strong candidate for specifying locomotion patterns.

We select *sketch primitives* for the query primitives mentioned above, based on the results of a user study on sketching locomotion patterns [5]. During one section of this study, we asked the subjects to sketch multiple locomotion patterns and studied the common notations among sketches. We observed that a region was specified with a closed or near-closed curve in approximately 85% of the sketches. In 75% of the sketches, paths were specified with arrows with arrowheads drawn in different styles. It was also observed that some of the subjects implied the direction of a path by the direction the line was drawn, instead of drawing an arrowhead. Based on these observations, we select the following two sketch primitives for a region and a path. The user draws a closed curve on the map to specify the enclosing region. A path is specified by sketching a line, to which an arrowhead is automatically added. These two sketch primitives form the basis of the following detailed spatial queries:

- **Type 1: staying within a region**: The user specifies the region by sketching a closed curve around it. Figure 5a corresponds to the query "in Ireland."
- **Type 2: entering a region**: The user specifies the region, and draws a path into the region from outside of it. Figure 5b corresponds to the query "entering Stanford University premises"
- **Type 3: leaving a region**: The user specifies the region, and draws a path from inside of the region to the outside. Figure 5c corresponds to the query "leaving Stanford University premises."
- **Type 4: moving from one region to another, irrespective of the actual path taken**: The user specifies the two regions (in any order), and then draws a path from the originating region to the destination. Figure 5d corresponds to the query "From Dayton to Columbus."
- **Type 5: specific path**: The user draws the path that he/she wishes to retrieve, on the map. Figure 5e corresponds to a query for a specific path within the University of Tokyo.

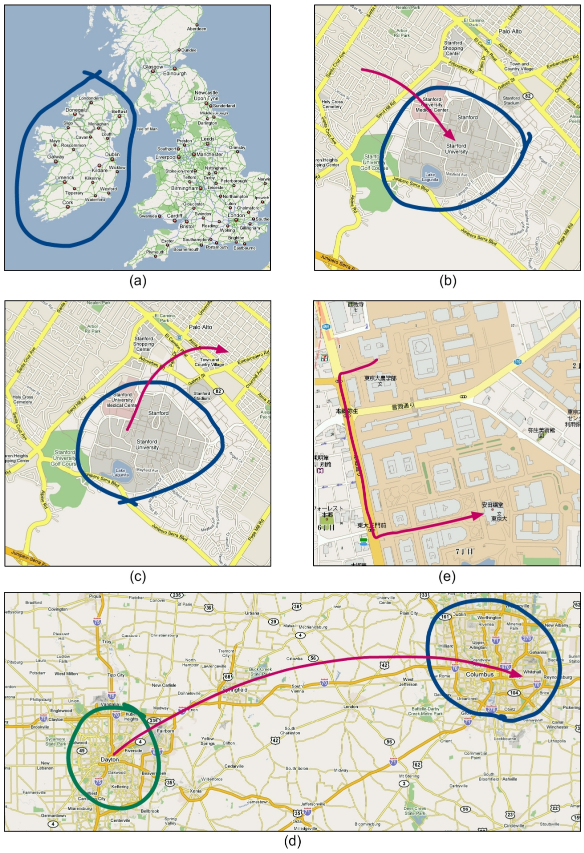


Fig. 5. Different types of spatial queries.

The queries are sketched on images created by extracting map segments from the *Google Maps* Database [9]. A query results in one or more ordered set of points in the form of $P = \{p_1, p_2, ...p_N\}$ where $p_i = (X_i, Y_i)$ are specified in image coordinates. After preprocessing and coordinate conversion (from screen coordinates to latitudes and longitudes), the system analyzes the sketch and determines the type of query. Search algorithms are selected accordingly to extract and display the results. The following section describes these stages in detail.

TABLE VII
IDENTIFYING THE TYPE OF QUERY

No. of Primitives	No. of Regions	Relationship between the path and region/s	Query Type
1	1	N/A	1
1	0	N/A	5
2	1	Path starts inside the region	3
2	1	Path finishes inside the region	2
3	2	Path starts inside one region and finishes inside the other	4

VI. SEARCHING FOR LOCOMOTION PATTERNS

A. Preprocessing

First, the sets of points are processed to identify the type of sketch primitive they belong to. If a set of points forms a closed curve, it is identified as a region primitive and trimmed to remove the parts that do not enclose the region. If a set of points does not form a closed curve, it is identified as a path primitive.

The type of the query is determined after preprocessing using a hierarchical decision making process, following the columns in Table VII from left to right. This method prevents ambiguities in interpretation of query types. The possibilities that are not listed in the table are not recognized as valid queries. However, the decision making process can be expanded to cover such possibilities, where necessary. For example, a query with multiple regions and no path can be used to query for segments within only those regions.

In the next stage, the points are converted from image coordinates to geographical coordinates (latitudes and longitudes). Since Google Maps use Mercator's projection with an adjustment, we calculate these points using the inverse Mercator projection [16]. After conversion, a path is represented as an ordered set of points $P = \{p_1, p_2, ..., p_N\}$ on the path. A region is represented by a set of points $R = \{r_1, r_2, ..., r_K\}$ along its perimeter.

B. Algorithms

The detected region(s) and path are submitted as input to the search algorithm for the appropriate query type. The following is a description of the search algorithms we propose:

- **Query type 1**: We retrieve the navigating segments that are contained within the region specified by the sketch, and the non-navigating segments having their centers within the region specified by the sketch. The results are ordered by the starting time of the segments.
- **Query type 2**: We retrieve all navigating segments with their end points contained in the sketched region. The results are ordered by the starting time of the segments.
- **Query type 3**: We retrieve all the navigating segments with their starting points contained in the sketched region. The results are ordered by the starting time of the segments.
- **Query type 4**: Let R_1 be the region where the path starts from, and R_2 be the region where the path ends. First, we extract navigating segments that have starting points in R_1. From this set of segments, the set of segments with end points in R_2 are extracted. The results are ordered by the starting time of the segments.
- **Query type 5**: We define a *search area* by expanding the dimensions of the bounding box of the sketched path by 10% in each direction. We extract a set of *candidate paths* by selecting all navigating segments contained within this search area. For each candidate path $C = \{c_1, c_2, ..., c_M\}$ selected, we apply the following directional matching algorithm.

1) Set overall mean distance $D = 0$
2) for the first point c_1 in the selected candidate path C, find the closest point p_a in P
3) Add the geographical distance between c_1 and p_a to D
4) Repeat steps 2 and 3 for the next point in C and $P' = \{p_a, p_{a+1}, ..., p_N\}$ until all points in C are used in the calulation
5) Divide D by M and record the overall mean distance

This algorithm looks for navigating segments that are similar to the sketched path, while preserving direction. The results are presented to the user in ascending order of the overall mean distance. The common approach is to set a threshold value and remove the results that have higher distances than the threshold value. However, given that sketches can be imprecise, we believe that it is desirable to order the results according to similarity and show them to the user.

VII. USER INTERFACE DESIGN

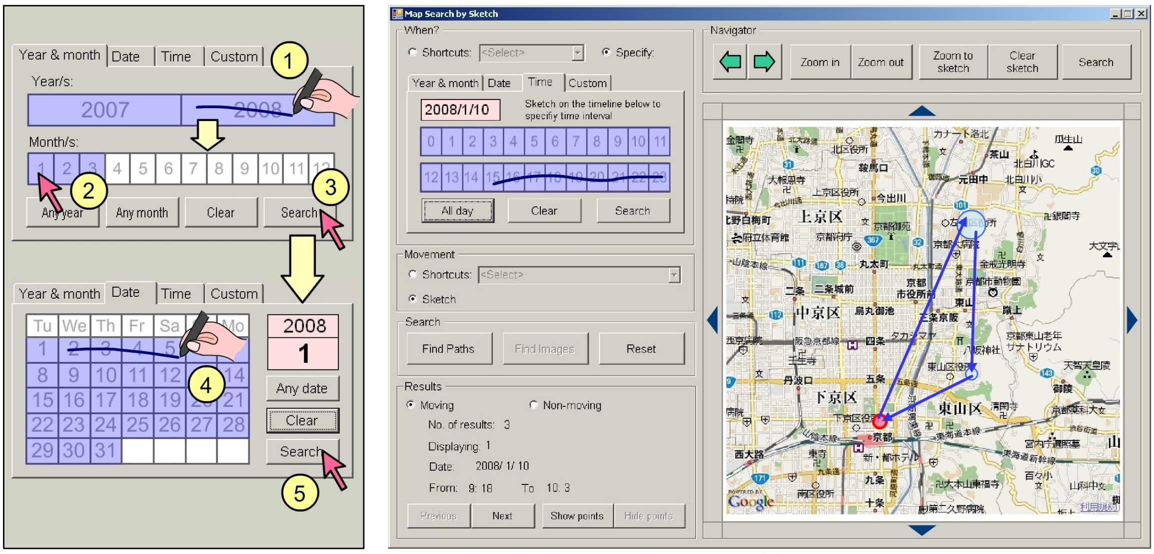
We design a graphical user interface based on the above strategy for retrieval of locomotion patterns. The interface is designed in such a way that only a pointing device is necessary to use it. The interface facilitates hierarchical segmentation of the data collection interactively using spatial queries, temporal queries or a combination of them to retrieve the desired results. The following sections describe how the user interface allows these types of queries.

A. Temporal Querying

The temporal queries also can be specified using sketches, making the interaction consistent with the query-by-sketch user interaction strategy for spatial queries. The users can sketch on a calendar-like interface to select a duration to retrieve data from. Figure 6a shows how a user queries for the duration "from the 2^{nd} to the 5^{th} of January, 2008". Where only one item is selected, clicking can be used in place of sketching, facilitating faster interaction.

Figure 6b shows the results retrieved from a temporal query. Once a selection is made, the map is scaled and scrolled to show only the regions where data have been captured. The non-navigating segments are shown as circles with the mean location as the center and scaled standard deviation as the radius. The radius of the circle visualizes the confidence of the location estimation. This helps the user to identify the exact location with his memory and knowledge, where the accuracy of the data is less. The navigating segments are visualized with arrows. The detailed results for the segments are shown to the left of the map, and can be selected one at a time. The starting segment is shown in red on the map. This summary is much easier to interpret than the actual GPS data for the queried duration (Figure 7).

Querying data by time is facilitated using two additional methods, to allow easier input. The user can choose some frequently-used common time intervals directly from a combo box (Figure 8a). While the above methods are easy to use, controls for querying the data for more precise time intervals are also provided in a separate tab (Figure 8b).



(a) (b)

Fig. 6. Submitting temporal queries by sketching: (a) input sequence to retrieve the summary of locomotion between the 2^{nd} and the 5^{th} of January 2008; (b) summary of locomotion on the 10^{th} of January 2008 - the red circle indicates the starting segment.

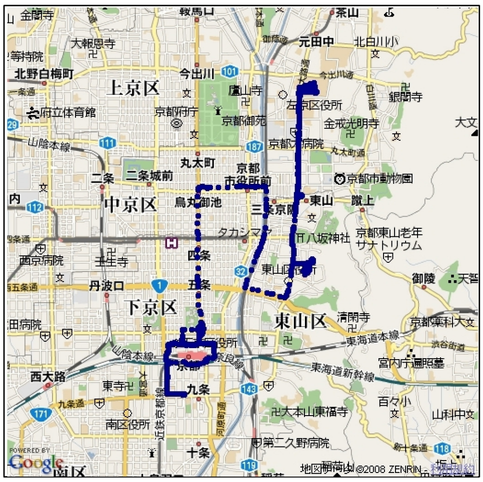


Fig. 7. GPS data recorded on the 10^{th} of January 2008.

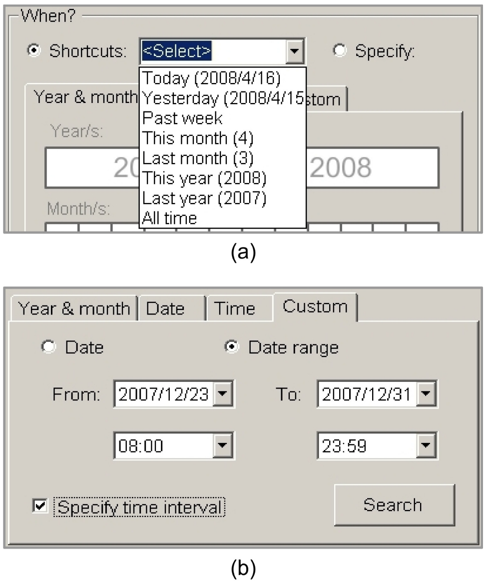


Fig. 8. Additional methods for submitting temporal queries.

B. Spatial Querying

The user can start a spatial query by navigating the map to the region that he/she wishes to query. In addition to zooming, unzooming and scrolling, which are common methods for navigating to a location on an electronic map, we include the facility to *zoom to sketch*. The user can draw a curve (open or closed) and zoom directly in to the region containing that curve, as illustrated by Figure 9a. This is much faster and more efficient than the conventional method of zooming and scrolling, as both the location and the amount of zoom required can now be specified using a single interaction.

We implemented the user interaction strategy described in Section V, to facilitate spatial querying. After the user reaches the desired area of the map, he can sketch spatial queries and retrieve the results. The results for non-navigating segments are shown in the same format as that of temporal querying. For navigating segments, the actual GPS data points are plotted on the map, joined by lines. The color of the data points and the line segments change from blue to red with time, to indicate direction.

Figures 9b to 9f show spatial queries of different types, together with the retrieved results. Location names are rewritten in English, and timestamps related to results are inserted as text boxes where relevant (in the actual interface, the dates and timestamps for individual segments are shown separately as shown in Figure 6b). Figure 9b shows a type 1 query for answering the request “show me a summary of my travel in Matsudai area”. Figure 9c shows a type 2 query that can answer the question “When did I go to Tokyo Disney Resort?”. The question “which places outside Tokyo have I been to?” can be answered with the type 3 query shown in Figure 9d. A type 4 query that retrieves movement between the towns “Ushiku” and “Oji” is shown in Figure 9e. Figure 9f shows a type 5 query retrieving locomotion patterns for a specific path between two buildings.

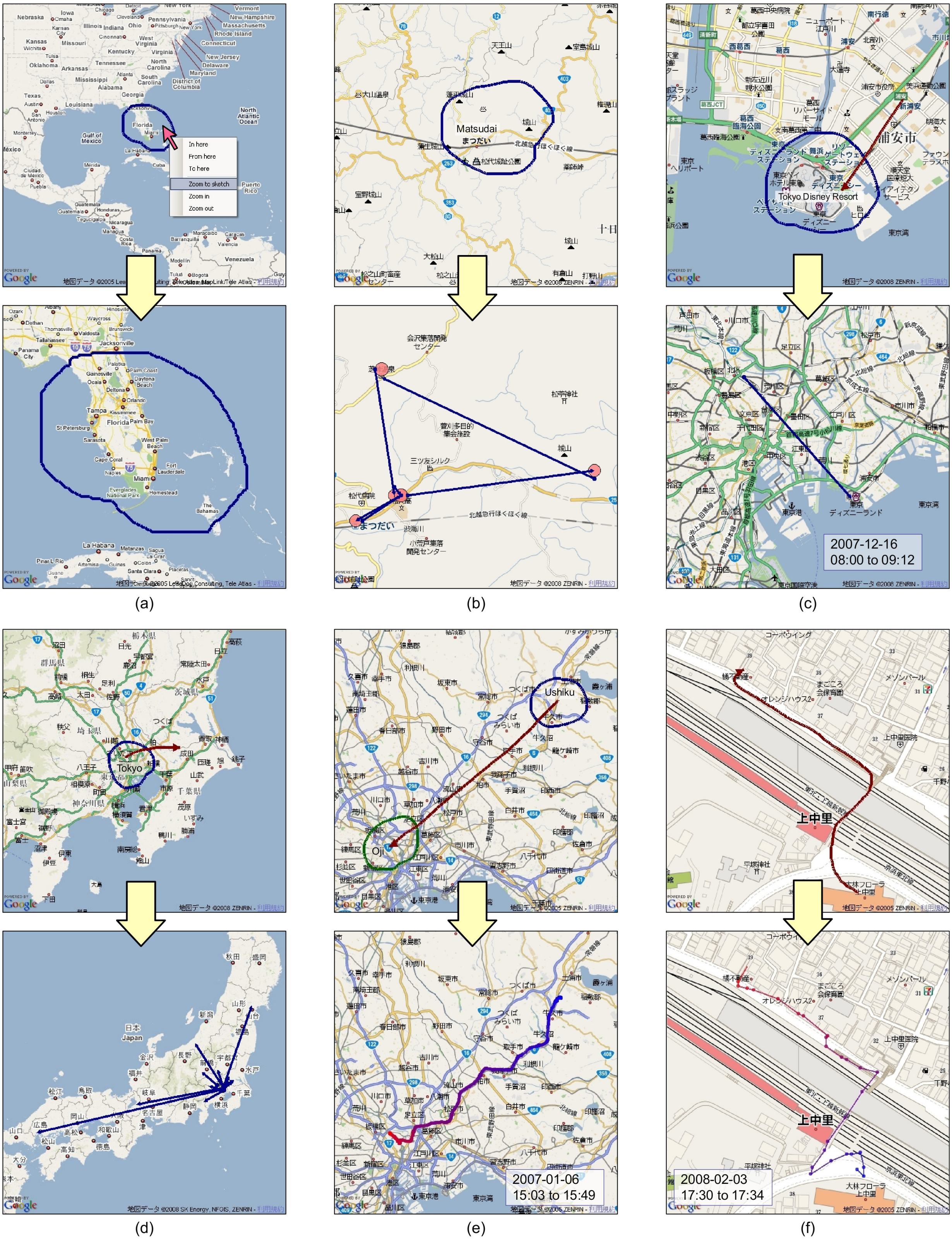


Fig. 9. Example spatial queries and results: (a) zoom-to-sketch, (b) type 1, (c) type 2, (d) type 3, (e) type 4 and (f) type 5 queries.

The user can perform more detailed searches, by combining temporal and spatial searches. A temporal query reduces the search space on the map by scrolling and zooming in to the area where GPS data were recorded for the specified interval. Instead of browsing the retrieved segments manually as described in Section VII(A), the user can submit a sketch and retrieve results from only the specified time interval.

VIII. User Study

We conducted a user study on the sketch-based user interaction strategy and the overall system, with the following objectives:

- Evaluate the proposed user interaction strategy
- Evaluate the proposed system for retrieving locomotion patterns
- Obtain feedback related to the above, to identify possible improvements
- Identify future directions and possible applications

Since it was not possible to find an existing method of evaluation that fulfills all of the above, we designed and conducted our own user study. This study consisted of five sections. The first two sections consisted of two different tasks related to sketching locomotion patterns on a map. The third and fourth sections contain a usability study of the proposed system. The fifth section asked questions regarding the system and the user interaction strategy, and allowed the users to write their comments freely. The following subsections of this section describe the user study and results in detail.

A. Content of the user study

- **Section 1:** interpreting a locomotion pattern by observing a sketch

  The objective of this section is to examine the users' ability to learn the proposed sketching notation for specifying locomotion patterns, and identify ambiguities and difficulties from a user's perspective. The proposed notation was explained to the subject with the aid of examples. The subject was allowed to try at least one example query from each type by himself, to familiarize with the notation.

  The section consisted of 10 tasks. During each task, the subject was shown a screen capture of a spatial query, and asked to interpret the query and its type. While interpreting the query type is a task for the system, not the user, this section helps us to understand whether there are situations where the user is not sure how to interpret a sketch, due to either ambiguity or the lack of intuitiveness. Ten screen captures, consisting of two queries from each type, were shown to the subject in random order.

  After the tasks were completed, the following questions were asked:

  1) Were there any movement patterns that were difficult to interpret? Describe briefly
  2) Out of the sketch types used in this notation, which type do you think is the most useful when specifying movement patterns in a wide area?

- **Section 2:** sketching a locomotion pattern based on a textual description

  The objective of this section is to evaluate the proposed notation for sketching locomotion patterns and identify any difficulties or ambiguities that the users encounter. The section consisted of seven sketching tasks. In each task, the subject read a textual description of an instance of locomotion (example: "Going from Nagoya to Tokyo") and sketched it on a map. The descriptions were selected in such a way that they describe different locomotion patterns. Some descriptions with a certain degree of ambiguity were deliberately included.

  All the sketches were made on answer sheets with pre-printed maps of the corresponding regions. After the tasks were completed, the subjects were asked whether there were any particular movement patterns that were difficult to sketch. They were allowed to describe freely (in writing), if there were such difficulties or comments.

- **Section 3:** using the proposed system for retrieving locomotion patterns

  The objective of this section is to evaluate the overall system that we designed for retrieval of locomotion patterns. At the start of the section, the subject was given a brief introduction the system. The subject was allowed to use the system and submit a few queries to familiarize with it. The section consisted of ten tasks. In each task, the subject used the system to answer a question about the locomotion of the author who colleted GPS data (referred to in first person, in the questions). The questions included spatial, temporal and spatio-temporal queries. The following are the questions that correspond to the ten tasks:

  1) "Retrieve a summary of my travel during this year"
  2) "Have I been outside Tokyo in December 2007?
  3) "In which city was I staying on the 10^{th} of January, 2008?"
  4) "Have I ever been to Hokkaido since I started collecting GPS data?"
  5) "How many times have I been to Kyoto this year?"
  6) "When did I travel from Tokyo to Sendai?"
  7) "On which date in this spring did I go to Kyushu?"
  8) "Find the date that I left Kyushu, after going there in this spring"
  9) "How many days did I stay in Niigata prefecture during this winter?"
  10) "How many days in last year have I traveled from Hongo Post Office to the lab, entering the university through the main entrance and then passing the auditorium?"

  After retrieving the relevant results using the system, the subjects wrote their answer to each question, on the answer sheet provided.

  In addition to answering the above queries, the subjects performed three "navigating" tasks. In each task, the subject was shown a printed copy of a map of a given region. First, the subjects started the system with a complete map of the world being displayed, and used the "zoom-to-sketch" function to make the map similar to the printed copy (similar to the task shown in Figure 8a). Then, they opened a web page with the complete map of the world, displayed using the Google maps API, and used the mouse buttons and the wheel to display a similar map. The times consumed for navigating using each method was recorded. Maps of different zoom levels and regions were selected for the three tasks.

  After completing all tasks, the subjects were requested to answer the follwing questions:

- Were there any queries that were difficult to make?
- Was it difficult to understand any of the results that you obtained? Describe briefly

- **Section 4:** usability evaluation of the proposed system
After using the system further if they thought it necessary, the subjects rated its usability by answering a questionnaire, based on the guidelines by Chin et al.[3]. A seven point response scale was used with 1 being the worst rating (very poor performance) and 7 the best (very good performance).
- **Section 5:** feedback and comments
In this section of the experiment, the subjects answered the following general questions:
  - Do you think it is easier to specify a pattern of movement by sketching on a map than a verbal description?
  - What are the other applications you would suggest for a sketch-based interface that can accept movement patterns as input?

  After answering the questions, the subjects were given the opportunity to make additional comments and suggestions in free format.

B. Experimental Procedure

Eight voluntary subjects participated in the user study. The subjects were regular computer users with no other common background. They were in the age range of 18 to 40. None of the subjects were involved in work related to designing or using spatial queries. Each subject was briefed about the task at the beginning of each section, and also provided with written instructions. One of the authors was available throughout the experiment to provide additional clarifications if needed. Breaks were allowed between sections.

The subjects answered all the sections on answer sheets provided to them. In addition to the responses on paper, the time taken for performing the tasks and the stroke order of sketches were recorded. The subjects took 32 to 53 minutes to complete the experiments. The average time consumed was 43.4 minutes. This time included short breaks between sections.

C. Results

The responses gathered during the user study consisted of sketches, numerical ratings, and textual descriptions. In addition to these direct responses, information regarding the stroke order was also recorded. The following subsections summarize the results of each section of the experiments, and our inferences based on the same.

- **Section 1:** interpreting a locomotion pattern by observing a sketch
All the subjects were able to identify the type of the query and accurately describe the corresponding locomotion pattern. Asked if there were any sketches that were difficult to interpret, the subjects responded that none of them was difficult. The response demonstrates that the proposed notation is easy to learn.
Asked which type of queries are most useful, four of the eight subjects stated that all types of queries are equally useful. Three subjects voted for query type 4 as the most useful to them, while one subject found type 5 queries the most useful. The responses show the diversity of locomotion patterns of people, and the need to support several types of queries.
- **Section 2:** sketching a locomotion pattern based on a textual description
All subjects were able to make accurate sketches according to the proposed notation, for all of the given descriptions. Asked if there were any sketches that were difficult to make, six of the eight subjects responded that none of them were difficult to make. The other two subjects mentioned that they preferred to make simpler sketches instead of type 5 sketches. The results demonstrate that the selected notation is easy to use, and that people like to use simple sketch primitives instead of detailed sketches.
- **Section 3:** using the proposed system for retrieving locomotion patterns
The users were able to provide accurate answers to the questions by using the system. The number of errors within the set of 80 subject-queries (8 subjects $\times$ 10 queries) was only 3. Out of the three errors, one was due to a programming error in the system. Another was due to an erroneous sketch. The third error was due to incorrect interpretation of results by the subject. The low error rate shows the fact that the subjects were able to learn to use the system and find answers to questions of different levels of complexity.
The *search time* for answering each question was calculated as the difference between the time that the subject started using the system to find the answer, and the time he/she proceeded to write the answer. The search time for each question varied depending on the complexity of the corresponding query, and the mapping between the displayed results and the answer. For example, answer to question 1 can be found by selecting a shortcut and looking at the resulting map, whereas the answer to question 9 can be found only by browsing through all the results. The minimum time taken to answer a question was 3.13 seconds and the maximum 56.12 seconds. Table VIII shows the minimum, maximum, mean and standard deviation of the search time for different questions. The relatively low means and standard deviations show that most of the users were able to find answers quickly.
The results of the navigating task demonstrated that the “zoom-to-sketch” method was faster than the normal zoom and scroll methods used in online maps. The average time for zooming using the zoom-to-sketch method was 6.16 seconds, compared to 8.05 seconds with online maps. One of the authors, who has been using the system for a few months

TABLE VIII
SEARCH TIMES FOR DIFFERENT QUESTIONS

	Search time (seconds)			
	Minimum	Maximum	Average	Standard Deviation
1	3.13	4.54	3.83	0.44
2	5.02	9.26	6.53	1.27
3	7.60	11.68	9.71	1.52
4	3.61	6.66	4.73	1.13
5	13.11	25.61	20.49	3.84
6	15.98	23.92	20.57	2.91
7	12.56	28.18	20.98	4.46
8	13.00	25.12	19.94	3.94
9	24.54	56.12	39.34	8.63
10	18.15	33.38	26.88	4.79

while developing it, was able to record an average time of 4.45 seconds with the system compared to 7.76 seconds with online maps.

Asked if any of the queries were difficult to make, three of the subjects said that question 10 was difficult due to having to make a more detailed sketch. One subject said that Question 9 was difficult due to having to browse the results manually to find the answer. Another subject said that it would need more practice to learn to make more effective queries for answering a given question. Asked whether it was difficult to understand any of the results, none of the subjects reported any difficulty. However, two subjects said that the visualization of results could be improved.

- **Section 4:** usability evaluation of the proposed system

  Below we list the criterion descriptor, response mean, mode (in parentheses), and the range of responses for each criterion evaluated during the usability study.
  - Ability to understand the prompts for input: 5.9 (6) 4-7
  - Ease of submitting inputs: 6.3 (5,6) 5-7
  - Ability to correct mistakes: 6.0 (6) 5-7
  - Speed: 7.0 (7) 7
  - Reliability: 6.3 (7) 5-7
  - Organization of results: 6.0 (6) 5-7
  - Learning to use the system: 6.8 (6) 6-7
  - Ease of using the system: 6.5 (6,7) 6-7
  - Flexibility: 6.0 (6) 5-7
  - Usefulness as a means of input: 6.9 (7) 6-7

  The results show that the system is quite easy to learn and useful. We believe that the reason for this is the intuitive nature of querying for a locomotion pattern using a sketch.
- **Section 5:** feedback and comments

  Answers to the first question of this section, “Do you think it is easier to specify a pattern of movement inside a house by using a sketch than a verbal description?” are listed below (the number of subjects responding in this way is indicated in parentheses):
  - Sketching is definitely easier (7)
  - Sketching is easier in most cases (1)

  While most of the subjects agreed that sketching is easier than describing verbally, the subject who disagreed stated that for some simple queries (such as entering or leaving a building with a single entrance), a textual description is easier than making a sketch.

  The following are the answers to the second question “What are the other applications you would suggest for a sketch-based interface that can accept movement patterns as input?” organized in the same format as above:
  - Travel diary (3)
  - Travel information guide (2)
  - Surveillance (2)
  - Social behavioral analysis (1)
  - Education and entertainment (1)

  More than half of the subjects provided additional comments at the end of section 5. The following are the comments most related to the main focus of this work:
  - It is desirable to be able to sketch paths for queries such as “from *City A* to *City B* and then to *City C*”
  - Different means of transport such as “bus, train” should be added to queries
  - Instead of sketching an entire path, it should be possible to sketch using a set of points
  - I would like to use this system on a touch screen
  - If there is a method to specify the area by clicking or touching (on a touch-screen), it is a better method than drawing a closed curve for specifying a region

  Most of the subjects desired to see more functionality and control. Some others looked for more flexibility in entering queries, and easier interaction.

IX. Discussion

While there exist other research that classify GPS data into activities at higher semantic levels, we decided to segment the data into only two basic classes of locomotion. The main reason for this decision is the logical mapping of simple sketches to such classes. The sketch primitive “path” maps naturally to *navigating* segments. Both *navigating* and *non-navigating* segments can be referred to as contained within a “region”.

The search algorithm for type 5 queries is somewhat simple. While the experimental results show that the users were able to accurately retrieve results using queries of this type, a more robust algorithm will be useful in situations where only a few data points with a high amount of noise are present.

Speed is one of the important aspects in locomotion patterns. While regions and paths map naturally from sketches to locomotion patterns, specifying the speed seems not so straightforward. The system will be much more versatile if speed can be incorporated to the queries.

There were several programming issues in implementing the proposed user interaction strategy on publicly available application programming interfaces for mapping. For example, Google Maps API does not allow sketching in the same way as a typical drawing application (that is, by holding the mouse button down and moving the pointer to make the sketch). We use several programming workarounds to enable free hand sketching on the map. Dragging the map is not possible since it uses the same gesture as sketching, with respect to the pointing device. Instead, scrolling is facilitated using the rectangles around the map (see Figure 6b).

The subjects who took part in the user study were querying locomotion data of one of the authors. The study could have been more interesting if they were browsing their own data instead. Such a user study allows evaluation of the usability of the system as a memory assistant.

X. Conclusion

We have proposed a system for retrieving human locomotion patterns from continuously archived GPS data. The proposed constrained agglomerative hierarchical clustering algorithm is capable of segmenting the data with an accuracy of approximately 94% despite the presence of noise. The sketch-based interaction strategy provides an intuitive way of querying the large collection of segments. Five types of queries have been designed by combining two simple sketch primitives, making effective and unambiguous querying possible. The clustering algorithm and the user interaction strategy are integrated using an interface that supports both spatial and temporal querying, to allow fast retreival of results.

A user study was conducted to identify how people sketch human locomotion patterns and evaluate the proposed system.

The results indicate that the user interaction strategy is easy to learn and use, and the system facilitates fast and accurate retrieval of locomotion patterns. The overall accuracy of retrieval was 96.25%. The proposed ”zoom-to-sketch” interaction results in a speed-up of approximately 42%.

The clustering algorithm and the user interaction strategy can be applied to other applications based on GPS data, such as vehicle fleet monitoring and interfaces for navigational support systems. The user interaction strategy can be enhanced both by designing new types of queries using the current primitives, and adding new primitives. We are working on creating a formal model for the queries including time and speed, to increase the versatility of spatial queries.

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