

Real-Time Motion Trajectory-Based Indexing and Retrieval of Video Sequences

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Abstract—This paper presents a novel motion trajectory-based compact indexing and efficient retrieval mechanism for video sequences. Assuming trajectory information is already available, we represent trajectories as temporal ordering of subtrajectories. This approach solves the problem of trajectory representation when only partial trajectory information is available due to occlusion. It is achieved by a hypothesis testing-based method applied to curvature data computed from trajectories. The subtrajectories are then represented by their principal component analysis (PCA) coefficients for optimally compact representation. Different techniques are integrated to index and retrieve subtrajectories, including PCA, spectral clustering, and string matching. We assume a query by example mechanism where an example trajectory is presented to the system and the search system returns a ranked list of most similar items in the dataset. Experiments based on datasets obtained from University of California at Irvine's KDD archives and Columbia University's DVMM group demonstrate the superiority of our proposed PCA-based approaches in terms of indexing and retrieval times and precision recall ratios, when compared to other techniques in the literature.

Index Terms—Principal component analysis, spectral clustering, string Matching, trajectory retrieval.

I. INTRODUCTION

OBJECT motion-based analysis and recognition has gained significant interest in scientific circles lately. This is primarily due to unprecedented advances in hardware and software technologies that allow spatio-temporal data of objects to be easily derived from video and non-video sequences. These recent developments have led to a vast amount of spatio-temporal data resulting from spatial localization of objects of interest as a function of time. The object trajectory is typically modeled as a sequence of consecutive locations of the object on a coordinate system resulting in a vector in 2-D or 3-D Euclidean space. Examples of the object trajectory in this setting include tracking results from video trackers, sign language data measurements gathered from wired glove interfaces fitted with sensors, GPS coordinates of satellite phones and cars using CNS, animal mobility experiments, etc. One of the new areas of trajectory analysis and understanding is automated analysis of sports videos to assist the players, coaches and sports analysts with strategies used on the field based on

the motion patterns of players and their mutual interaction. Gesture- and sign language- recognition are other areas where the trajectory information plays more important role than other cues. Lastly, video surveillance which is based on techniques from object detection and tracking, human motion analysis and activity recognition, relies heavily on robust methods of trajectory indexing. We emphasize that object motion plays the key role in the domain of activity analysis in general and in video surveillance in particular. Psychological studies have shown that human beings can routinely discriminate and recognize the type of object motion using motion pattern, even in large viewing distances or poor visibility conditions where other familiarity cues such as clothes, appearance or hair style tend to disappear [17].

In all of these applications, a robust representation of the trajectories is needed to capture the spatio-temporal actions performed, particularly knowing the fact that dimensions of the feature spaces representing diverse motion trajectories are relatively large. Object trajectory indexing is thus the cornerstone of successful motion analysis systems. This paper focuses on the design of robust representations, efficient indexing mechanisms, and fast (real-time) retrieval techniques for motion trajectory-based indexing and retrieval of video sequences. The contributions of our work include the following.

- A fully translation-invariant method of indexing and retrieval of trajectories and subtrajectories.
- A statistically robust mechanism of motion representation based on trajectory segmentation.
- Principal-components-based representation of subtrajectories in a reduced-dimension space.
- Spectral clustering to automatically decide on the optimal number of clusters and to map subtrajectories into alphabets.
- An efficient retrieval mechanism to minimize the system response time to spatio-temporal queries.

The remaining sections of this paper are organized as follows: Section II surveys related work on motion trajectory-based indexing and retrieval systems. Section III presents our two subtrajectory-based approaches using PCA coefficients. Section IV provides a comparison and analysis of the motion trajectory-based indexing and retrieval methods developed in this paper. Experiments are performed on two datasets: the Australian Sign Language dataset obtained from University of California Irvine's Knowledge Discovery in Databases archive [13], and the sports video dataset provided by the Columbia University's Digital Video and Multimedia Group (DVMM) [6]. Details of these datasets and experiments conducted are provided in Section IV. Finally, in Section V, we present a brief

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summary and conclusion and outline future research in this area.

II. RELATED WORK

This section provides a survey of the related work from recent literature in the areas of motion feature computation for trajectory representation, principal component analysis and applications of trajectory-based indexing and retrieval. Studies into human psychology have shown the extra-ordinary ability of human beings to recognize object motion even from minimal information system such as moving light displays (MLDs) [17]. Given its importance, MPEG-7 adopted the notion of motion activity and motion trajectory in a collection of motion descriptors that capture the different aspects of motion in videos with a broad range of precision. The standard defines concise descriptors including motion activity and motion trajectory that are easy to extract and match without providing the details of the indexing and retrieval process [10], [16], [29]. Object motion has been an important feature for object representation and activity modeling in video applications [1]. An object trajectory-based system for video indexing is proposed in [27], in which the normalized x - and y -projections of trajectory are separately processed by wavelet transform using Haar wavelets. Chen *et al.* [6] segment each trajectory into subtrajectories using fine-scale wavelet coefficients at high levels of decomposition. A feature vector is then extracted from each subtrajectory and Euclidean distances between each subtrajectory in the query trajectory and all the indexed subtrajectories are computed to generate a list of similar trajectories in the database. In [4], the longest common subsequence (LCSS) approach is used for grouping similar motion trajectories in an agglomerative clustering algorithm. The LCSS is defined recursively as increasing distance between two sequences based on their x - and y -projections. The similarity is then computed from the two sequences as the least distance under a set of translations. Shim [28] proposed a modification of the DTW algorithm using a k -warping distance algorithm by permitting up to k replications for an arbitrary motion of a query trajectory to measure the similarity between two trajectories. Their approach is tested on a content-based soccer video retrieval (CSVR) system in which the trajectory of the soccer ball is extracted by manually tracking the ball in a ground field using linear segments.

Object trajectory data can be viewed as a time series when x - and y -projections are combined for representation. There has been tremendous amount of activity in time series representation and retrieval in recent years. Lin *et al.* [20], [21], have presented a symbolic representation of a time-series approach (SAX) using piecewise aggregate approximation (PAA). Although quite close to our string matching-based system, there are two major problems with it for trajectory data. The PAA uses fixed box-bases to represent continuous noisy data which might not be very suitable for most time series. Also, the notion of fixed breakpoints used in their approach to map time series segments to symbols is questionable as it is perceptually not quite appealing for trajectory data. Fink *et al.* [12] represent time series by maxima, minima and major inclines. They identify all major inclines of all series in the dataset and index them using a range tree. Their piecewise linear approximation

is similar to polynomial approximation which was shown to perform worse than our PCA-based representation in [2]. Recently, significant research effort has gone into devising new space- and time- efficient index structures. Since space-efficient indexing of generic time series is not the main topic of this presentation, we refer the reader to [11], [19], [23].

An important application area of trajectory-based indexing is human activity modeling. Yacoob *et al.* [30] have presented a framework for modeling and recognition of human motions based on principal components. Each activity is represented by eight motion parameters recovered from five body parts of the human walking scenario. The high-dimensional trajectory using all the eight parameters of object motion is reduced using PCA. In [15], the issue of recognizing a set of plays from American football videos is considered. Using a set of classes each representing a particular game plan and computation of perceptual features from trajectories, the propagation of uncertainty paradigm is implemented using automatically generated Bayesian network. On similar lines, Nevatia *et al.* [14] have addressed the issue of activity recognition in single or multiple actor situations which exhibit some specific patterns of whole body motion.

III. EIGENSPACE DECOMPOSITION FOR TRAJECTORY REPRESENTATION

An object trajectory is represented by a 2-D N -tuple corresponding to the x - and y -axes projections of the object centroid location at each instant of time

$$r[k] = \{x[k], y[k]\}, \quad k = 1, \dots, N. \quad (1)$$

Our approach models the sequence of object trajectory points as a stochastic process with variability in both x - and y -directions. We compute the data-dependant orthogonal bases that transform the trajectory data into reduced dimension subspace keeping most of the original variation in the data intact. This step provides the necessary dimensionality reduction so the trajectory matching process can be performed in the lower-dimensional subspace spanned by the data-dependant orthogonal bases. In our previous work [2], we presented a PCA-based system that treats x - and y -projections separately and PCA is performed individually on each projection in a two-pass approach. This section presents our approach to segmented trajectory-based PCA systems for motion trajectory representation.

A. Segmented Trajectory PCA With Euclidean Distance Retrieval

The segmented trajectory-based system indexes trajectories by first segmenting them into subtrajectories using hypothesis testing-based approach. The set of subtrajectories are then processed for principal component analysis to represent the subtrajectories in the reduced dimension subspace spanned by the eigenvectors of the dataset covariance matrix. The retrieval process computes a PCA-based subspace distance between subtrajectories which is merged to form a distance between individual trajectories.

1) *Trajectory Segmentation*: As pointed out earlier, the perception of object motion is very sophisticated in humans even under poor visibility conditions as pointed out by Johansson's

MLD experiments [17]. Contemporary psychological studies have provided an instructive analysis of the atomic units of actions that are of substantial value to perception. These atomic units of actions are defined as motion events due to significant changes in motion trajectories [31]. Another advantage, apart from its perceptual appeal, is that using this approach, partial queries can also be evaluated when only a part of the object motion is available due to object being temporarily out of the field of view, or tracker losing track of the object for a while.

Given above considerations, we segment the trajectories at perceptually significant points of change. The change points in trajectory data are detected as the points of change in velocity (first-order derivative) and acceleration (second-order derivative of the data). For this purpose, we use the spatial curvature of a 2-D curve given by

$$k[k] = \frac{x'[k]y''[k] - y'[k]x''[k]}{[x'[k]^2 + y'[k]^2]^{3/2}}. \quad (2)$$

This feature measures the sharpness of a bend in the spatial 2-D curve.¹ Our hypothesis testing based approach locates these points of change. From the curvature data, two non-overlapping windows of equal dimension n are extracted. Let X and Y be two such windows where X contains the first n samples of curvature and Y contains the next n samples. Let Z be the $2 \times n$ dimension window formed by concatenating X and Y . We perform the likelihood ratio test to determine if the two windows X and Y have data drawn from the same distribution. Specifically, we have two hypotheses:

$$\begin{aligned} H_0 : f_x(X; \theta_x) &= f_y(Y; \theta_y) = f_z(Z; \theta_z) \\ H_1 : f_x(X; \theta_x) &\neq f_y(Y; \theta_y). \end{aligned} \quad (3)$$

Under the assumption of Gaussian i.i.d. random variables, we first compute the maximum likelihood estimators of the mean and variance in each window with their likelihoods being $L(X; \theta_1)$, $L(Y; \theta_2)$, and $L(Z; \theta_3)$, where θ_i is the corresponding parameter vector of the underlying distribution of data. Then, the formulation in the equation computes distance d between the distributions of X and Y

$$\begin{aligned} L_0 &= \frac{1}{\sqrt{2\pi}\sigma_3} \exp\left(-\frac{(x - \mu_3)^2}{2\sigma_3^2}\right) \\ L_1 &= \frac{1}{\sqrt{2\pi}\sigma_1\sigma_2} \exp\left(-\frac{1}{2} \left[\sum_{i=1}^2 \frac{(x - \mu_i)^2}{\sigma_i^2} \right]\right) \\ \lambda_L &= \frac{L_0}{L_1} \\ d(X, Y) &= -\log(\lambda_L) \\ &= -\log \sqrt{2\pi} \frac{\sigma_1\sigma_2}{\sigma_3} \\ &\quad + \frac{1}{2} \left[\frac{(x - \mu_3)^2}{\sigma_3^2} - \frac{(x - \mu_1)^2}{\sigma_1^2} \right. \\ &\quad \left. - \frac{(x - \mu_2)^2}{\sigma_2^2} \right]. \end{aligned} \quad (4)$$

¹We have also experimented with the so-called ‘‘spatio-temporal curvature’’ [25]. Based on better segmentation, we stick to this definition of curvature which is more popular in image processing community.

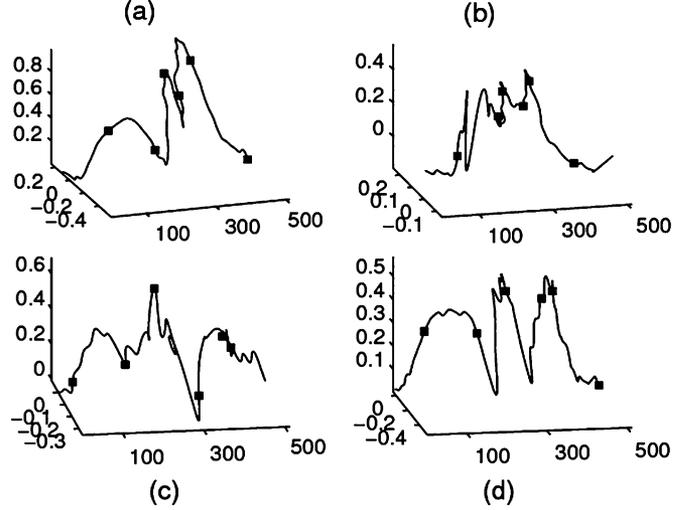


Fig. 1. Trajectory Segmentation. (a), (b) Segmentation of trajectories for ‘‘Norway’’ signed by two different signers. (c), (d) ‘‘Alive’’ signed by the same two signers.

Distance d is large when X and Y have different distributions. The windows are then slid by $m < n$ samples and the process is repeated for this configuration. This process is repeated for all the curvature data samples. A 1-D vector of distance function is then formed, and distinct local maxima separated by valleys in this distance vector are located. Fig. 1 displays the segmentation results on four trajectories, two each from two different classes. Additional details can be found in [3].

2) *Translation-Invariant Subtrajectory Representation*: The subtrajectories are normalized before PCA-based representation, to achieve temporal- and spatial- translation invariance. The starting point of each subtrajectory is shifted to the origin which will ensure that matching process at retrieval stage does not depend on what point of time the subtrajectory in a given trajectory starts. Spatial invariance is achieved by normalization

$$\begin{aligned} X'_k &= \frac{X_k - X_{\min}}{X_{\max} - X_{\min}} \\ Y'_k &= \frac{Y_k - Y_{\min}}{Y_{\max} - Y_{\min}}. \end{aligned} \quad (5)$$

The median segment size of set of subtrajectories is computed from the segmentation results. The X - and Y -data of each subtrajectory are concatenated into one vector which is then resampled to twice the median segment size determined before. Finally, we form a data matrix from subtrajectory data and perform the PCA on this matrix. We compute the optimal dimensionality m by observing that principal components are successively chosen to have the largest possible variance, and the variance of the k th PC α_k is its eigenvalue λ_k . We compute a cumulative sum threshold as

$$t_m = 100 \times \frac{\sum_{j=1}^m \lambda_j}{\sum_{j=1}^r \lambda_j} \quad (6)$$

where $r \gg m$ is the rank of the data matrix. Choosing a cut-off of say $k = 95\%$, and retaining m PCs, where m is the smallest

integer for which $t_m > k$, provides a rule which can be used, in practice, to preserve, in the first m PCs, most of the information about the trajectories in the dataset. Based on this computation, the first m principal components resulting from PCA are stored as the PC transformation matrix Φ_m which is used to compute the PCA coefficients of trajectories

$$B = \Phi_m^T [A - \text{Avg}] \quad (7)$$

where A is the matrix of original subtrajectories, B is the matrix of corresponding PCA coefficients, and Avg is the average subtrajectory. The subtrajectories are then represented by their low-dimensional PCA coefficients.

3) *Retrieval Using Euclidean Distance*: The retrieval process is tailored to produce results quickly with the aid of pre-computed indexing structures. The query trajectory is segmented and transformed to its PCA coefficients using the PCA transformation matrix computed in the indexing phase

$$D = \Phi_m^T [C - \text{Avg}] \quad (8)$$

where C is the set of p -dimensional query trajectories, and D represents the corresponding m -dimensional PCA coefficients where $m \ll p$. The subtrajectory distances are finally merged using the following metric:

$$E_k = \sqrt{\sum_{t=1}^M \sum_{i=1}^{N_k} \min_2(E_{k_i t}, \mu)} \quad (9)$$

where M is the total number of subtrajectories in query trajectory, N_k is the total number of subtrajectories in k th indexed trajectory, μ is an arbitrary penalizing constant for nonmatching subtrajectories in a full trajectory and represents Euclidean distance between the PCA coefficients of the l th query subtrajectory and the i th subtrajectory of the k th full trajectory in the database.

We have tested the subtrajectory PCA-based algorithm on the Australian Sign Language (ASL) dataset. The details of this dataset are provided in Section IV. The first experiment presents full trajectories from a known class in the dataset and computes the precision-recall metrics. The second experiment simulates the effect of partial trajectories where one portion of the trajectory is unavailable due to occlusion, loss of tracking, etc. Also, the system is tested for its spatio-temporal sensitivity in trajectory representation. For each of the 35 full-length queries, we add five random x - and y -translations to it and pose the resulting 175 trajectories as queries. The corresponding precision-recall metrics for full-length query and for its shifted version are exactly the same demonstrating that the normalized subtrajectory-based representation is translation invariant. The results are displayed in Fig. 2.

We shall now present a major improvement to the indexing and retrieval system which uses string matching methods on clusters of segmented subtrajectories.

B. Subtrajectory PCA Using String Matching for Retrieval

This variation of the PCA-based trajectory retrieval process is motivated by the fact that if the segmentation process is stable, it results in quite similar sets of subtrajectories for the trajectories

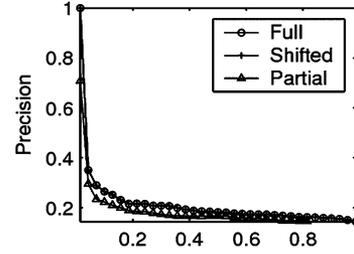


Fig. 2. Precision-recall metrics for PCA-based system using Euclidean distance retrieval. Average precision-recall for 35 full-, 35 partial-, and 175 shifted-trajectory queries are shown.

belonging to one class. Our indexing system proceeds the same way as in the previous approach until the PCA computation of subtrajectories. Once the PCA coefficients of all the subtrajectories have been computed, we use spectral clustering to group the subtrajectory data. Once this grouping is found, each cluster is treated as an alphabet and each trajectory is represented as a string in the dataset. The query trajectory is transformed into a string using the same process and Edit Distance is used to measure the distance between the query trajectory and all trajectories in the dataset. The indexing and retrieval process based on this approach is sketched in Fig. 3. The next two subsections describe the components of this system in more detail.

1) *Spectral Clustering Using K-means On PCA Coefficients*: Spectral clustering is a relatively new technique which employs eigenspace decomposition of the symmetric similarity matrix between items to be clustered. Ding *et al.* [8] prove that when optimizing the K -means objective function for a specific value of k , the continuous solutions for the discrete cluster indicator vectors are given by the first $k - 1$ principal components of the similarity matrix. In [9], they discuss an eigenspace method for grouping and re-ordering the objects for cluster assignment once the continuous cluster indicator vectors are estimated. Other interesting applications can also be found in [22], [24]. Given the set of n subtrajectories in R^p represented in a matrix form S , we look for the number of clusters k and put the n subtrajectories into k clusters. We then compute the cluster validity score proposed in [24]

$$\alpha_k = \sum_{c=1}^k \frac{1}{N_c} \sum_{i,j \in Z_c} W_{ij} \quad (10)$$

where Z_c denotes the cluster c , N_c the number of items in cluster c , and W is the matrix formed out of Y , the normalized eigenvector matrix defined below.

We use the following algorithm to find the number of clusters k and to perform the clustering.

- 1) Form the subtrajectory affinity matrix $A \in R^{n \times n}$ defined by $A_{ij} = \exp(-\|s_i - s_j\|^2 / 2\sigma^2)$ if $i \neq j$, and $A_{ii} = 0$. Here s_i refers to the PCA coefficients of the i th subtrajectory.
- 2) Define D to be the diagonal matrix whose (i, i) -element is the sum of A 's i th row, and construct the Laplacian matrix $L = D^{-1/2} A D^{1/2}$.
- 3) Find the n principal components x_1, x_2, \dots, x_n of L .

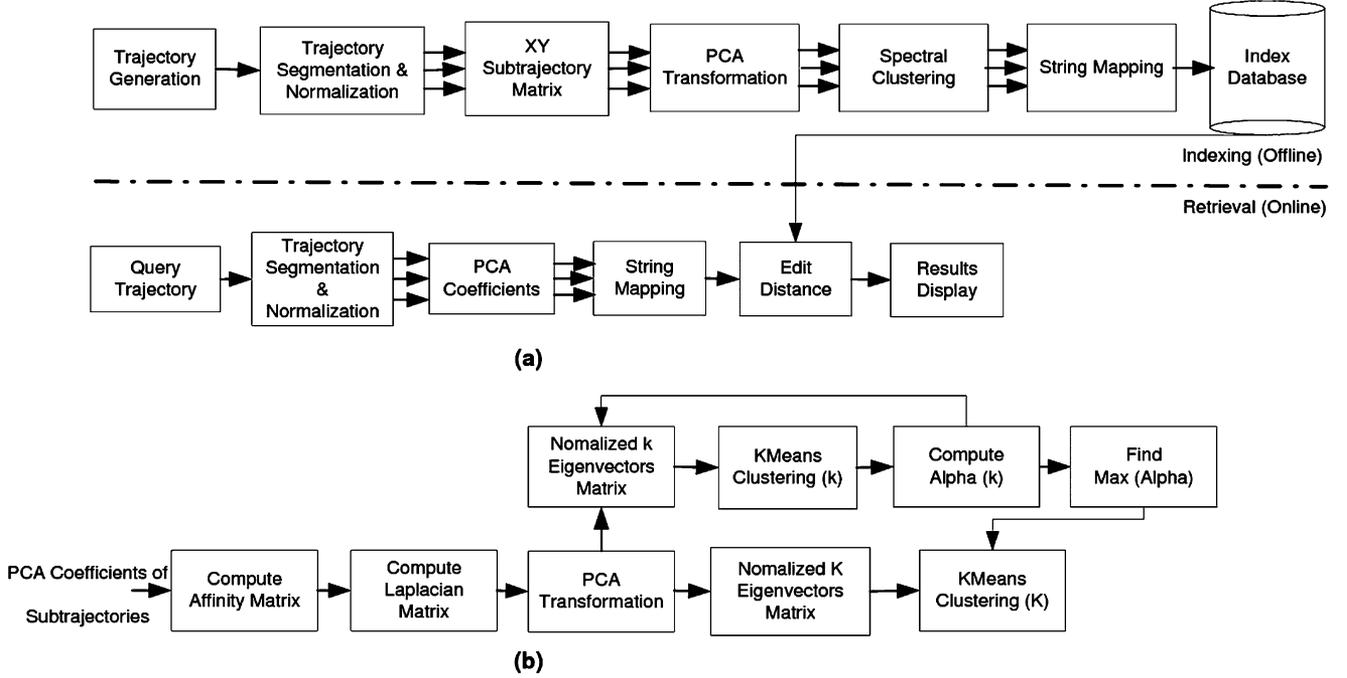


Fig. 3. (a) Block diagram of segmented trajectory-based system using string matching. (b) Spectral clustering using K -means on PCA coefficients.

4) Using the matrix formed by stacking k largest PCs $X = [x_1, x_2, \dots, x_k] \in R^{n \times k}$, form the normalized eigenvector matrix Y by renormalizing each of X 's rows to have unit length, $Y_{ij} = X_{ij} / \left(\sum_j X_{ij}^2 \right)^{1/2}$. Also, compute $n \times n$ matrix $W = Y \cdot Y^T$.

5) Use K -means clustering on the PCA representation of subtrajectories S to form k clusters.

6) Calculate α_k .

7) Iterate the steps 4–6 for $k = 1, 2, \dots, K$, and find the maxima.

Once the clustering is done, each cluster is assigned a distinct alphabet mapping each trajectory to a string. At this time during indexing when the clusters are ready, we also compute their centroidal PCA coefficients representation. These centroidal PCA coefficients will be used in retrieval stage to map the query trajectory into its string representation.

2) *String Matching-Based Retrieval*: The indexing process represents the trajectories as strings with a sequence of alphabets. At query time, the query trajectory is segmented and transformed to its PCA coefficients. Each query subtrajectory is then mapped to an alphabet by computing minimal PCA-based distance between the query subtrajectory and the set of cluster centroids

$$\psi(Y_q) = \{I : d(Y_q, Y_i) < d(Y_q, Y_j), \forall i \neq j, l \leq |C|\} \quad (11)$$

where $|C|$ represents the total number of all clusters, Y_q the PCA coefficients representation of the query trajectory, Y_j represents the PCA coefficients of the j th cluster centroid, and $d(\cdot, \cdot)$ represents the Euclidean distance operation. The trajectory matching

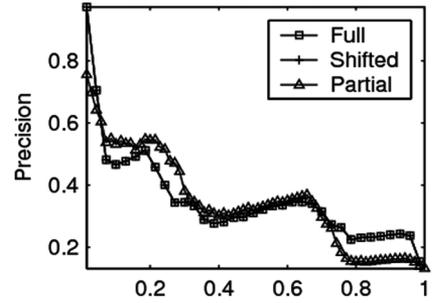


Fig. 4. Precision-recall metrics for PCA-based system using string matching for retrieval. Average precision-recall metrics for 35 full-, 35 partial-, and 175-shifted trajectory queries are shown.

process then boils down to that of string matching. Our string matching approach is based on the edit distance (ED), implemented using dynamic programming, which is widely used in bio-informatics and speech recognition to measure the similarity between two strings, as given by the *Needleman-Wunsch Edit Distance Theorem* [7]. The ED between two sequences is defined as the number of insert, delete or replace operations needed to change one sequence into another. The query trajectory distance with all the trajectories in the database is thus computed and the distance list is then sorted to obtain the ranked list of matching trajectories in the database.

We report the results on the same dataset using the same set of full-, partial-, and shifted- query trajectories as in previous section. Fig. 4 shows the precision-recall metrics for these experiments.

IV. COMPARISON AND ANALYSIS

This section compares the performance of the two approaches proposed in the previous section with a global approach from

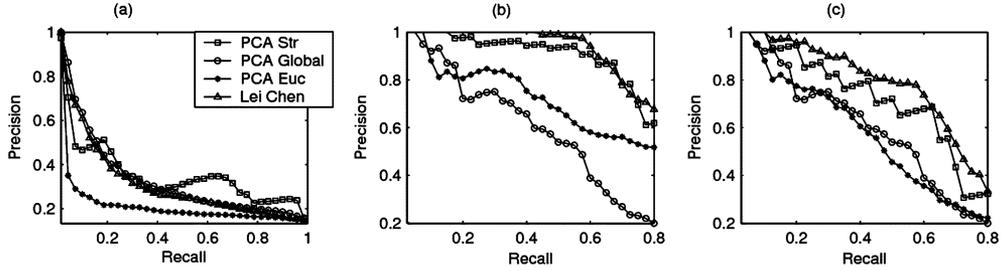


Fig. 5. Precision-Recall metrics for proposed systems based on the three datasets. (a) ASL (552). (b) HJSL (108). (c) HJSL (408).

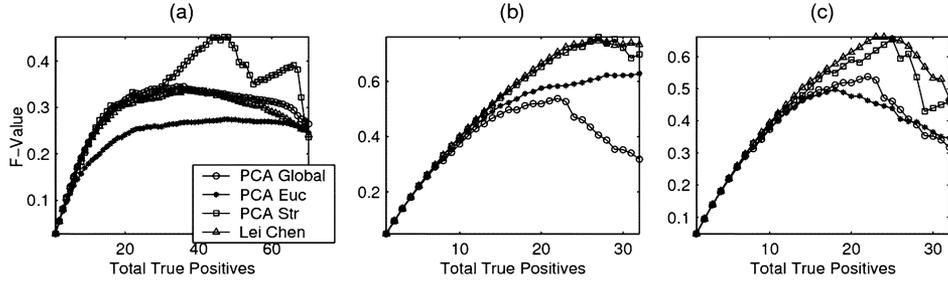


Fig. 6. F -values for proposed systems based on the three datasets. (a) ASL (552). (b) HJSL (108). (c) HJSL (408).

recent literature [5]. This method has been selected for comparison since it has superb retrieval performance and it is a global method for trajectory retrieval. Their approach transforms the x - and y -projections of the trajectory into quantized movement direction and movement distance ratio pairs and mapped to an alphabet character. This results in a string representation of the trajectory. At the time of query, the normalized edit distance (NED) is computed between the query string and all strings in the database. We also compare our results with a global PCA-based approach which represents trajectories using PCA coefficients without segmentation [2].

A. Data Sets

We use two datasets in our simulations: The Australian Sign Language (ASL) dataset is obtained from the University of California at Irvine’s KDD archives² [13]. We extract the x - and y -locations corresponding to eight words signed by five signers resulting in 552 trajectories. The second dataset in our experiments has been provided to us by Columbia University and contains object trajectories tracked from video clips of sports activities, like high jump, slalom skiing, etc. This dataset, HJSL (108), contains around 40 trajectories of high jump, and 68 trajectories of slalom skiing objects. A superset of this dataset, HJSL(408), is formed by extracting some 300 trajectories from random object motions to be treated as noise.

B. Simulation Results and Discussion

This section summarizes the results of our computer simulation experiments. We measure two performance metrics for all the trajectory indexing and retrieval systems: the accuracy of the content-based information retrieval system is measured in terms of precision and recall metrics, while the efficiency is measured

in terms of indexing and retrieval times as well as asymptotic complexity of retrieval process. The precision-recall metrics are computed for multiple trajectories being posed to the system under various degradation conditions such as random translations and partial queries.

The first experiment poses a set of 35 full-length queries to the underlying systems and retrieves the ranked list of responses. Precision-recall metrics are computed for each of these 35 queries and average value of precision is computed for each value of recall. The results are shown in Fig. 5. We also report the F -value curves³ for this experiment for all datasets and retrieval methods in Fig. 6. The F -values are plotted against the total number of true positives in the ranked list of responses for a query. The F -value curves are used since it is sometimes difficult to interpret the results based on the pairs of precision and recall and it is easier to assess the performance based on their harmonic mean which is provided by their F -value. To avoid repetition, other experiments are reported in terms of precision-recall only. Based on these results, we see that our segmented PCA-based system using the string matching approach presents the best trade-off between accuracy and efficiency. It performs at least as well or better as compared to the exact matching-based approach by Lei-Chen [5]. The next two experiments are designed to test the sensitivity of our systems to spatio-temporal shift and partial trajectory information. The 35 full-length query trajectories from the previous experiment are randomly shifted in both the x - and y -directions to produce shifted query trajectories. For each query trajectory, five randomly shifted versions are generated which results in 175 query trajectories. These queries are then posed to the underlying system and average precision-recall results are computed. The third experiment highlights the robustness of the indexing and retrieval systems to object occlusion. Here, 35

²KDD archive: <http://kdd.ics.uci.edu/databases/auslan/auslan.html> Original donor: <http://www.cse.unsw.edu.au/~waleed/tml/data/>.

³The F -value is given by $F\text{-value} = 2 / (\text{precision} + 1/\text{recall})$

TABLE I
INDEXING AND RETRIEVAL TIMES OF ALL SYSTEMS FOR THREE DIFFERENT DATASETS. HJSL(108) IS A SUBSET OF HJSL (408)

*- TOTAL TIME FOR 35 QUERIES = 9.3311 HOURS.

	Indexing Time (sec.)			Average Retrieval Time (sec.)		
	ASL(552)	HJSL(108)	HJSL(408)	ASL(552)	HJSL(108)	HJSL(408)
PCA-GI	22.36	31.124	32.5	0.262	0.226	0.216
PCA-Euc	185.391	43.3330	194.4	0.877	0.549	0.737
PCA-Str	2875.0	76.8800	1199.1	0.426	0.425	0.613
L-C [5]	10.109	3.455	26.2	959.8*	399.4	1356.9

partial queries synthetically generated from the 35 full-length queries in the previous experiments are used. The partial query trajectories are formed by cutting away the last 1/4 of the full-length trajectories. The results of these two experiments are shown in Figs. 2 and 4. These experiments demonstrate the invariance of our approach to such transformations. Our extensive experiments on the two standard datasets thus reveal that our subtrajectory-based PCA systems provide a superior representation of the trajectory information, yield high precision and perform within real-time requirements. Further investigation of the scalability of trajectory indexing and retrieval methods to extremely large datasets using high-dimensional indexing data structures is required.

We have implemented the above methods using Matlab 6.5 and running times are noted on an Intel Pentium IV 3-GHz machine with 1-GB RAM. The indexing and retrieval times are presented in Table I. In this table, PCA-GI refers to the global PCA-based system used as baseline [2], PCA-Euc refers to the segmented PCA-based system using the Euclidean measure in Section III-A, PCA-Str refers to the segmented PCA-based system using string matching on segment clusters in Section III-B, and L-C [5] refers to the string matching-based system proposed by Lei Chen *et al.* [5]. It is evident from the results in Table I that while the exact match philosophy-based approach [5] takes impractical amount of time, our PCA-based systems can easily perform in the real-time requirement settings. Table II compares the retrieval complexity analysis of the four trajectory-based indexing and retrieval systems considered in this work. Here, only the retrieval times are considered. Table II shows an increasing complexity of retrieval processes among the three PCA-based systems while attaining better precision-recall metrics and tolerance for partial trajectory information. The retrieval complexity of PCA-based systems is far less than that of [5].

V. SUMMARY AND CONCLUSIONS

In this paper, we have laid out a detailed discussion on the topic of motion trajectory-based indexing and retrieval of data captured from any form of hardware/software setting capable of object tracking. We alleviate the drawbacks of global processing approaches—inability to handle partial trajectory information—by segmenting the object trajectories and then representing the original segments by their PCA coefficients. The results are further improved by clustering the subtrajectories by using a spectral clustering approach to estimate the

TABLE II
ASYMPTOTIC COMPLEXITY ANALYSIS OF THE RETRIEVAL TIMES OF PROPOSED AND COMPARED ALGORITHMS

N: SIZE OF EACH TRAJECTORY (FIXED AFTER NORMALIZATION).

M: TOTAL NUMBER OF TRAJECTORIES IN THE DATABASE.

P: DIMENSIONALITY OF THE PCA SUBSPACE.

K: AVERAGE NUMBER OF SUBTRAJECTORIES IN QUERY AS WELL AS DATABASE TRAJECTORIES.

L: TOTAL NUMBER OF CLUSTERS. SAME AS THE SIZE OF ALPHABETS.

PCA-GI	$T_{retrieval} = T_{projection} + T_{dis\ tan\ ce} = p.O(N) + M.O(p)$
PCA-Euc	$T_{retrieval} = T_{segmentation} + T_{projection} + T_{dis\ tan\ ce}$ $= O(N) + k.p.O(N/k) + k.M.O(p)$
PCA-Str	$T_{retrieval} = T_{segmentation} + T_{projection} + T_{mapping} + T_{dis\ tan\ ce}$ $= O(N) + k.p.O(N/k) + k.l.O(p) + k.M.O(k^2)$
L-C [5]	$T_{retrieval} = M.O(N^2)$

optimal number of clusters in an unsupervised way. We have based our experiments on two parameters to be measured: accuracy and efficiency. The accuracy is measured in terms of retrieval effectiveness using precision-recall metrics. The efficiency is measured in terms of the time taken by indexing and retrieval processes, as well as their asymptotic complexity. Based on this analysis, our segmented PCA-based systems have shown a marked improvement in precision at wide range of recall values. As compared to a similar string matching-based approach which operates without trajectory segmentation, our systems show an exceptional amount of improvement in online retrieval time.

Future research must focus on motion trajectory-based indexing and retrieval of video sequences that are robust to camera orientation and movement. An important extension of our approach would be required to perform multiple motion trajectory-based indexing for “semantic” retrieval from video sequences. It is also possible that the basis of our approach could be used for video sequence mining by detection and identification of motion trajectories in the video query.

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