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A New Approach to Map Matching for In-Vehicle Navigation Systems: The Rotational Variation Metric

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Abstract— **The purpose of the map-matching module of an in-vehicle navigation system is to locate the position of the vehicle relative to the map data that is referenced by the system. Map-matching allows the display module to accurately depict to the driver the position of the vehicle on the map and facilitates operations such as route calculation, rerouting, etc... The basic approach is to compare the historical vehicular path to possible candidate paths on the map, where candidate paths are the paths on the map which lie within the general vicinity of the vehicle at any instant in time. The candidate map path which best matches the vehicle path is the most likely path on which the vehicle is located. The map display module and other modules of the navigation system use this new position for further processing. Such a map-matching module is also used in vehicle safety applications such as Adaptive Cruise Control (ACC) where the velocity of the vehicle is adjusted based on point curvature of the road network. This paper presents a new metric, the Rotational Variation Metric, which provides a new method for comparing vehicular and map paths for the purpose of map-matching. The method described here is effective while being both intuitive and computationally non-intensive.**

I. Introduction and Overview

Many modern in-vehicle navigation and safety applications have been developed that provide warnings to the vehicle driver or that modify operation of the vehicle (or component thereof) based upon conditions around the vehicle or other factors. Examples of some of these new vehicle safety systems include automatic headlight aiming, adaptive cruise control, obstacle warning, curve warning, intersection warning, lane departure warning, collision warning, and adaptive transmission shift control. Some of these vehicle safety systems use sensor equipment (e.g., GPS receiver, gyroscope, speed sensors, etc) to detect the current absolute position of the vehicle, and digital map data as a component. Such applications require accurate, real-time positioning of a traveling vehicle with respect to a given set of digital map data. This process is known as map-matching. Thus, a good map-matching algorithm is required in these and other driver assistance and safety applications. There are two main aspects to the problem of map-matching:

1. Obtaining a fairly accurate absolute vehicle position (coordinate pairs consisting of longitude and latitude) using various sensors.
2. Development of robust and computationally non-intensive algorithms for determining to what position on the map the current position of the vehicle most likely corresponds.

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In this paper, a new approach to the problem of map-matching is presented. This paper is organized as follows. Section II contains background on map-matching for in-vehicle navigation systems and a brief discussion of conventional approaches to this problem. Section III provides the definition and development of the new Rotational Variation Metric. In Section IV, the application of the Rotational Variation Metric to map-matching is described. Section V contains an example which illustrates the application of the Rotational Variation Metric to map-matching. In Section VI, the paper is concluded with a summary of the results obtained herein.

II. Background

Map-matching is the problem of determining the location of a vehicle with respect to a map. This problem is important not just for navigation and map display in an in-vehicle navigation system, but also in ADAS applications such as Adaptive Cruise Control and Adaptive Lighting Control.

Some combination of dead reckoning and sensor fusion [3] is generally used by the navigation system in order to find the current probable vehicle position. This position is generally updated periodically, (every second or tenth of a second, for example). Because the sensors that are used for determining the vehicle position have errors and noise associated with them, the resulting position that they report has an associated probability; furthermore, the map data itself has errors. Therefore, map-matching is the problem of finding the position on a map at which a traveling vehicle is *most likely* to be located. Therefore, the function of the map-matching module is to use the sensor information (fused, or otherwise processed) provided by positioning sensors (GPS, inertial sensors) along with map data to determine this most likely position.

This principally involves comparing the historical vehicular path to paths on the map in the vicinity of the vehicle. Map-matching is thus a problem of comparing path geometries. Map-matching thus involves

1. determining which of these candidate paths is the true road segment on which the vehicle is currently located, and
2. on which position on the most likely path the vehicle is located.

One of the conventional approach to map-matching is to perform some type of comparison between the historical vehicular path (sometimes called the vehicle trajectory) to

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all possible paths in the map database that lie within the vicinity of the vehicle. This set of candidate map paths comprises the map path candidate pool. Many different pattern recognition techniques can be applied to this problem, the most obvious of which is a cross-correlation. See [4], [5], [6], [2], [1] for more details. Here we describe a new Rotational Variation Metric which can be used to perform this comparison. This metric is computationally less intensive than a true cross-correlation, and gives an effective and very intuitive measure of geometric similarity between path geometries.

III. Rotational Variation Metric

Translation and rotation are the only two shape and size preserving geometric transformations (besides reflection, which is not of interest for the types of applications being considered herein). If one shape is uniformly translated and/or rotated with respect to a second shape, the relative proportions are retained between the two shape representations. Thus, the problem of determining how closely two shapes compare is equivalent to determining whether one of the shapes is nearly a translated and/or rotated version of the other shape. As we show below, this can be determined by computing the Rotational Variation Metric between the two shapes.

In Figure 1, two shapes labeled shape A and shape B are shown. Without loss of generality, we designate shape A as the reference shape. As can be seen from the figure, shape B is translated and rotated with respect to shape A but is otherwise identical to shape A. Tangent vectors at corresponding points of shape A and shape B are determined at selected locations along the two shapes. Corresponding points along the two shapes are determined by moving an equal distance along each shape from the nominal starting point of each shape. The tangent vectors for shape A and shape B are shown.

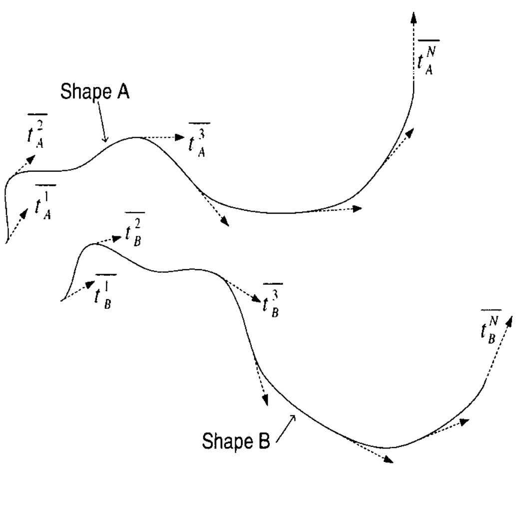

Fig. 1. Shape B identical to Shape A (reference shape) to within a translation and/or rotation

The angle θ between any pair of corresponding unit tangent vectors t_A^i and t_B^i is given by

$$\begin{aligned} \theta &= cos^{-1}\left(\frac{\bar{t}_A^i \cdot \bar{t}_B^i}{\|\bar{t}_A^i\|\|\bar{t}_A^i\|}\right) \\ &= cos^{-1}\left(\bar{t}_A^i \cdot \bar{t}_B^i\right) \end{aligned} \quad (1)$$

From Figure 1, it is clear that since shape B is a uniformly rotated version of shape A, if the angle between tangent vectors t_A^i and t_B^i is θ for some i, then the angle between all pairs of tangent vectors is $\theta\ \forall\ i$, i.e.,

$$cos^{-1}\left(\bar{t}_A^i \cdot \bar{t}_B^i\right) = \theta,\ \forall i \quad (2)$$

The distance between the two shapes clearly varies with length along the shapes. However, the angle between the tangent vectors at corresponding points along shape A and shape B is constant. Thus, if shape A and shape B are identical to within a rotation and translation, the angle between the tangent vectors at corresponding points along shape A and shape B is constant. We define the angle between each pair of tangent vectors as the angle through which the tangent to the shape B must be rotated so that it aligns with the corresponding tangent to the reference shape, shape A. Without loss of generality, let a clockwise rotation be defined as positive, and a counterclockwise rotation be defined as negative. The plot of the angle between the tangent vectors vs. length along the reference shape, shape A is constant, as shown in Figure 2.

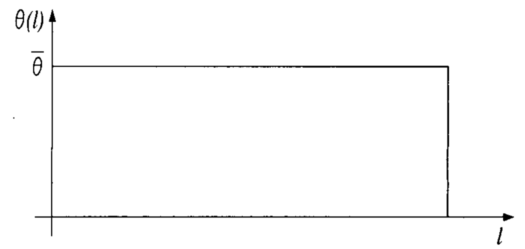

Fig. 2. Rotational Variation Metric Between Shapes A and B

The variance of the plot around the mean value is a quantitative measure of the similarity in shape. We call this variance the **Rotational Variation Coefficient**, or RVC. Furthermore, we call the totality of this coefficient and the plot from which it is derived the **Rotational Variation Metric** or RVM. The RVC is thus a quantitative measure of geometric distortion between a pair of geometric shapes. An RVC of zero indicates that the objects may be mutually translated and or rotated, but are otherwise identical. A large RVC indicates that the angle of rotation is not constant, which means that the objects have very dissimilar shapes. Note that this method of shape comparison is invariant to relative rotation between the two shapes.

Now consider the case where shape B no longer has the same perimeter as shape A as shown in Figure 3 below. This poses no difficulty at all, because we can simply scale shape B so that its total length equals that of shape A, or alternatively, we can scale both shapes to a nominal length of unity. Then the plot of the Rotational Variation Metric is identical to the one shown in Figure 2.

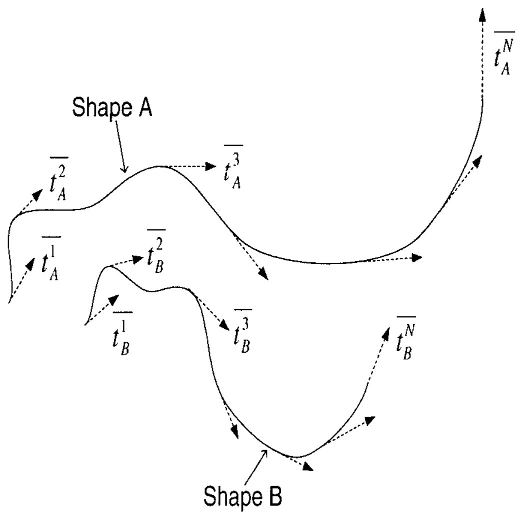

Fig. 3. Shape B smaller than Shape A

Finally, consider an example where the objects are not identical in shape, as shown in Figure 4. In order to compare shape B to shape A, shape B is scaled so that its length equals that of shape A. Alternatively, both shapes can be scaled to a nominal length of unity. In this case the plot of the angle between corresponding pairs of tangent vectors is no longer a constant. It will instead have the appearance shown in Figure 5. The variance of the plot around the mean value is a measure of the geometric distortion between the shape A and shape B.

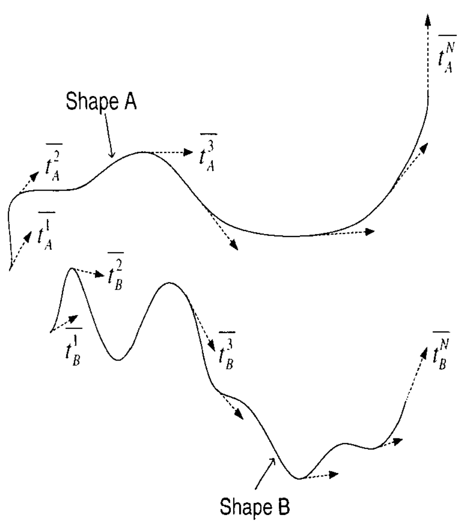

Fig. 4. Shape B and Shape A dissimilar

To summarize, the Rotational Variation Metric makes use of the fact if a pair of geometric shapes are identical, then

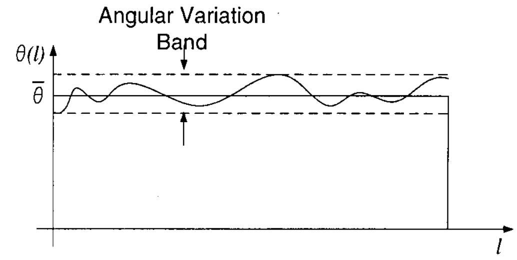

Fig. 5. Rotational Variation Metric between Shapes A and B

1. one shape can be considered to be a translated and/or rotated version of the other shape
2. in this case the angle between corresponding pairs of tangent vectors to the two objects is constant; i.e., each point of one shape is rotated by a constant angle to obtain the second shape
3. the larger the variation in the angle of rotation, the greater the dissimilarity between the two shapes

The Rotational Variation Metric thus measures the degree of similarity between a pair of shapes by measuring the variation in the angle between corresponding pairs of tangent vectors. No variation in the angle (i.e., the angle is constant) implies that the shapes are identical (to within a rotation and translation) and a large variation implies that the shapes vary greatly.

IV. Application of the Rotational Variation Metric to Map-Matching

The Rotational Variation Metric presented in Section III can be directly applied to map-matching to measure the similarity in shape between the vehicle trajectory (historical vehicular path) and all possible map paths in the candidate pool. The new method can be used to enhance or replace map-matching algorithms which are currently in use.

To implement the algorithm, at fixed intervals (e.g., once every second or ten seconds) the respective Rotational Variation Coefficient values between the vehicle trajectory and all of the possible paths in the map database are computed. The path corresponding to the smallest RVC value is the one on which the vehicle is most likely to be located.

Figure 6 below shows a vehicular path (obtained from positioning sensors) and several possible road network paths which are determined from data stored in a map database. By computing the RVC value between the vehicle path and all possible candidate road paths, we can select the path for which the RVC value is minimum as the most likely path on the map (in this case, the path labeled Path B), because the vehicular path is a more or less uniformly rotated version of Path B.

V. Example

This section contains an example of the application of the Rotational Variation Metric to map-matching. Figure 7 shows a portion of a road network. Figure 8 shows an example of a sample vehicular path over some finite time period. The goal of the map-matching operation is to lo-

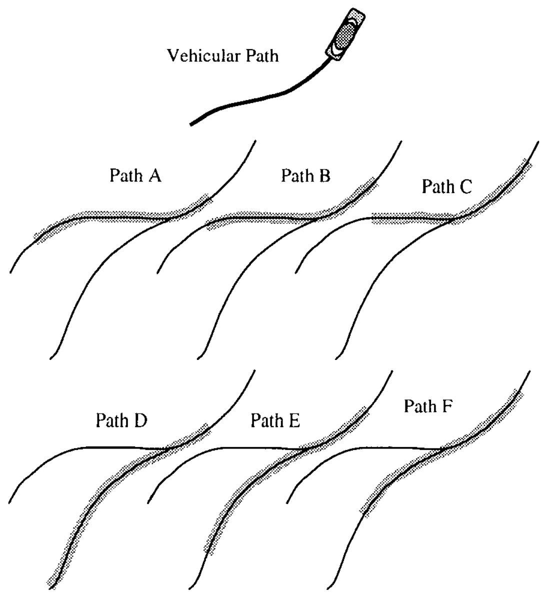

Fig. 6. Application of Rotational Variation Metric to Map-Matching

cate the portion of the road network that corresponds to the sample vehicular path. Figures 9 through 14 show six possible map paths (drawn in bold) on the road network; next to each map path is a plot of the Rotational Variation Metric between the sample vehicular path shown in Figure 7 and each of the possible map paths. Each RVM plot also indicates the value of the Rotational Variation Coefficient. We can see from these plots that the Rotational Variation Coefficient is minimum for the map path shown in Figure 13. This is also apparent from a visual comparison of the sample vehicular path to the map paths. The vehicle is therefore most likely located on the map path shown in Figure 13, specifcally at the leading end of this path.

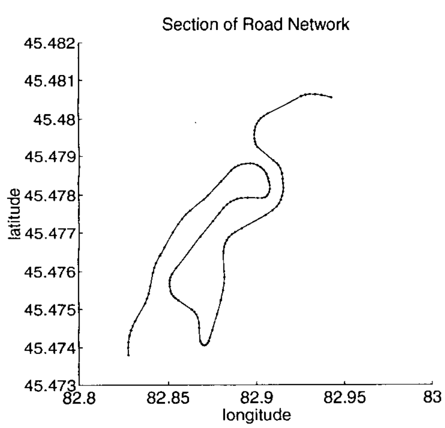

Fig. 7. Portion of Road Network

This example illustrates that the new Rotational Variation Metric is an effective and computationally efficient tool for map-matching, and provides an alternative to conventional map-matching techniques such as cross-correlation.

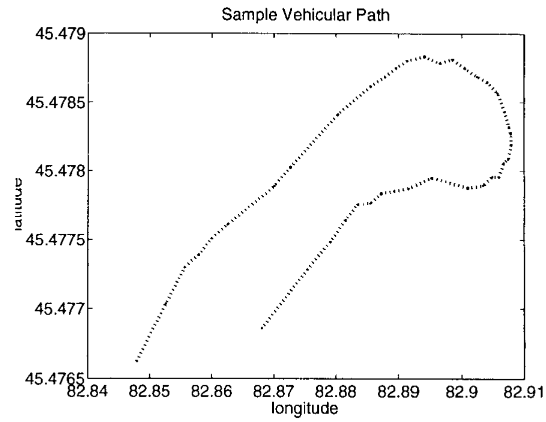

Fig. 8. Sample Vehicular Path

VI. Summary and Conclusions

A new, intuitive method for map-matching was described. The new method is based on the Rotational Variation Metric which quantifies the degree of similarity between two shapes in terms of the variation in the angle between corresponding pairs of tangent vectors to the two shapes. The new method is simple and effective yet computationally less intensive than traditional pattern matching techniques such as cross-correlation. The technique is useful for map matching in in-vehicle navigation systems as well as for other applications that require accurate positioning of the vehicle with respect to the underlying map data referenced by the system. Examples of such applications are safety applications such as Adaptive Cruise Control, as well as Adaptive Lighting Control. The Rotational Variation Metric described herein and the methodology for applying this metric to the problem of map-matching can be used to improve the performance of map matching and ADAS applications that require accurate positioning of a vehicle with respect to a map.

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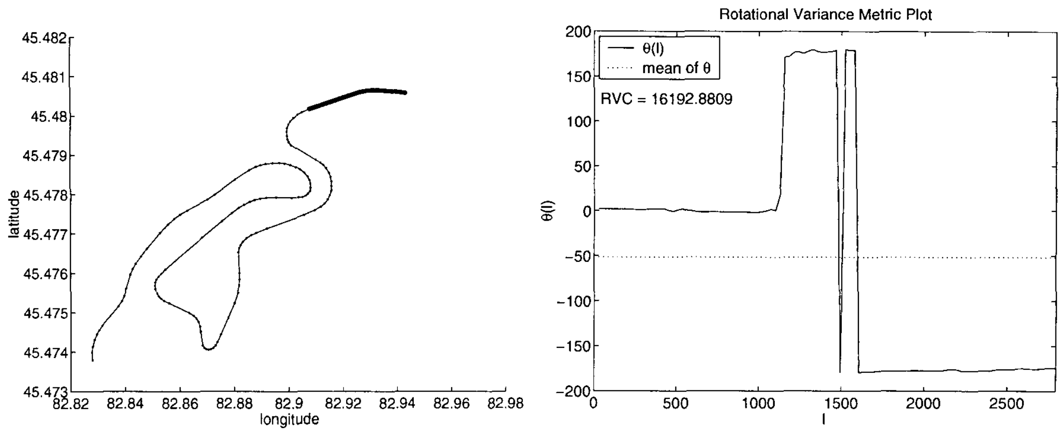

Fig. 9.

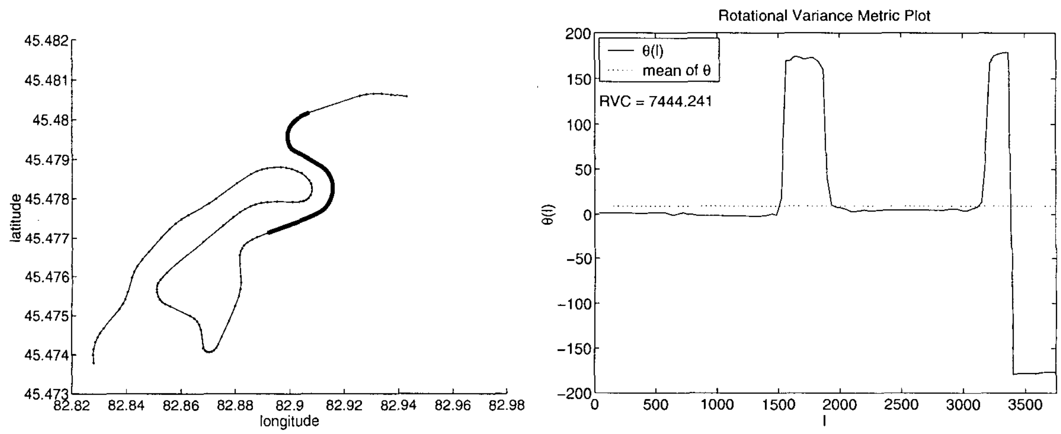

Fig. 10.

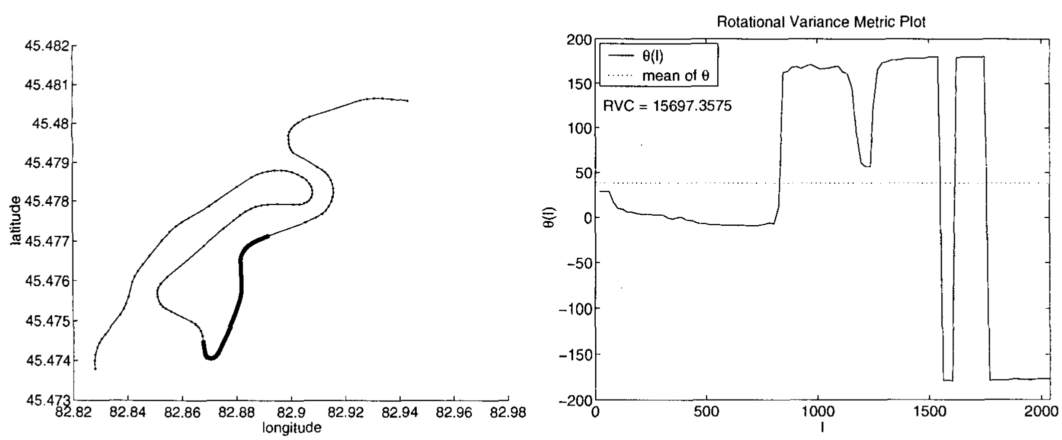

Fig. 11.

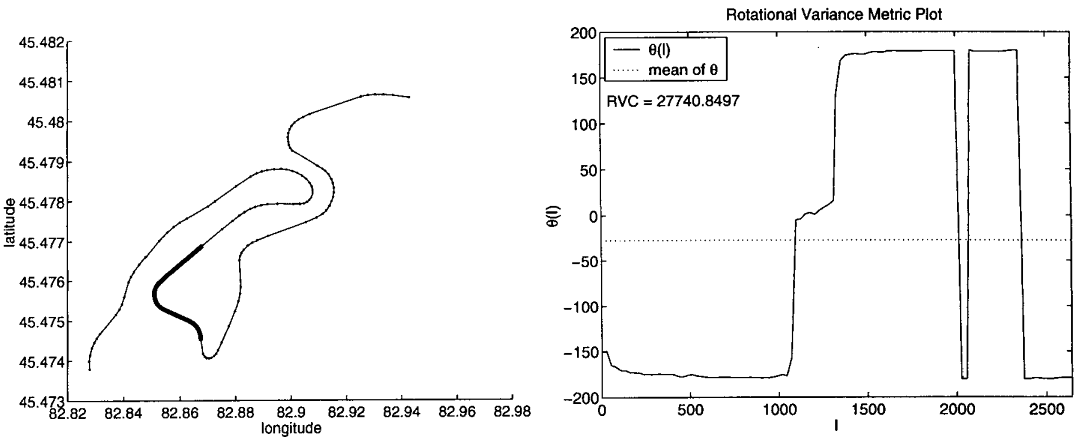

Fig. 12.

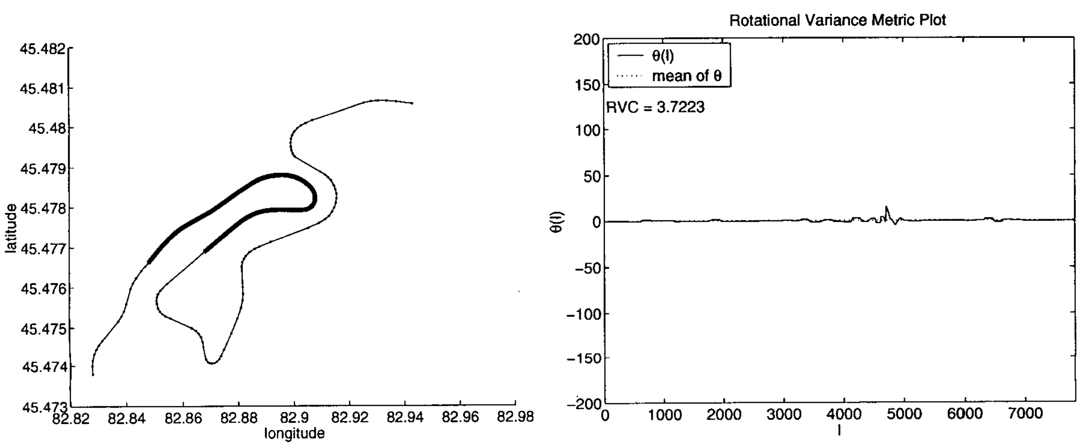

Fig. 13.

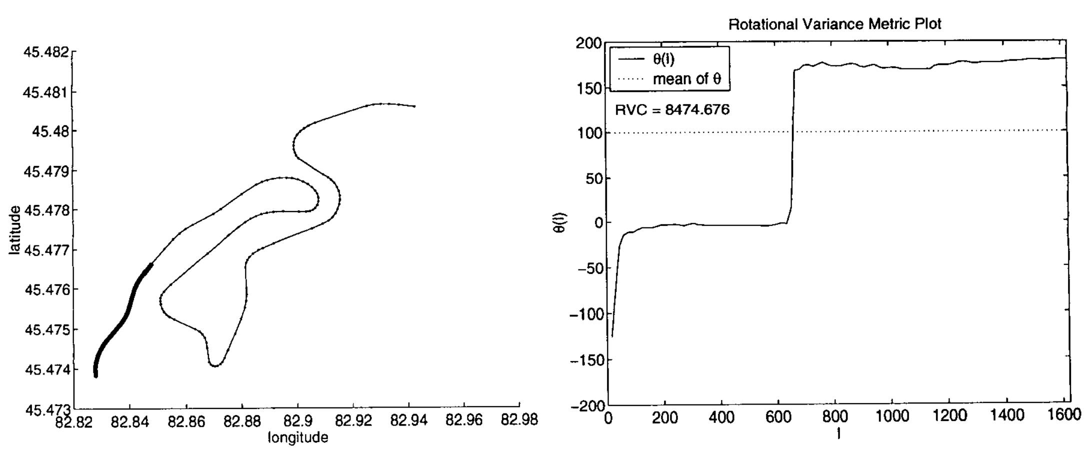

Fig. 14.