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Snake: A New Information Fusion Approach To Augment GPS Using Map-Derived Information[1]

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BIOGRAPHY

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ABSTRACT

A physically-based information fusion approach which greatly differs from the commonly used probabilistic approach is introduced. In this approach, a road is represented as a deformable model composed of an abstract elastic material. The combination of GPS measurements with map-derived information is accomplished by using a physically-based least action principle. The optimal information fusion can be achieved by solving energy-minimizing equations of the motion. Tests on simulated data show that this approach opened a new avenue for integrating map-derived information to augment GPS for vehicle navigation. The feasibility, effectiveness, and distinctive features of this new approach are demonstrated in this paper.

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INTRODUCTION

The combination of navigation technologies and computer technologies has advanced the development of Intelligent Vehicle Highway Systems (IVHS) in recent years. Positioning and locating are the two distinct requirements in land-based vehicle navigation. Positioning involves determining the positions of vehicles in a coordinate framework (e.g., geodetic or Cartesian system, etc.), while locating provides a vehicle's location relative to land features (e.g., roads or intersections, etc.) [8]. The primary objective of land-based vehicle navigation systems is to combine navigational information with route knowledge to provide drivers and/or navigators with real time positions and locations of the vehicles, and to assist dispatchers manage traffic flow and congestion. Map information plays an important role in these applications, and currently all techniques for vehicle locating and route planning make use of maps.

Currently, a total of 280 land navigation systems have been identified in an IVHS navigation system database [9]. Seventy percent of them have the capability of using GPS as a positioning source. Since stand-alone GPS is not adequate for continuous navigation, many technologies, such as DGPS, Hybrid-GPS, GPS/Dead-reckoning, GPS/Map, have been developed to augment GPS in terms of accuracy, reliability and coverage [7,10,12,13]. Among them, map-aiding has been recognized as an efficient and low-cost means for augmenting GPS navigation [2]. The distinct advantage of map aiding is that no additional hardware is necessary compared to DGPS or dead-reckoning. This feature greatly facilitates the implementation of a portable navigation system [1]. Moreover, digital map databases are already available in most land-based navigation systems. For these reasons, the use of map-derived information in navigation systems is increasing.

The major approaches to map aiding can be classified into three categories: (1) Displaying and monitoring: the map matching technique is applied to snap the computed vehicle coordinates (derived from navigation sensor data) onto the road network in order to show the driver or dispatcher the current road of travel; (2) Drift correction: the accurate map matching is required to extract the accurate positional information of roads (e.g., intersections) to correct drift errors arising from navigation sensors; and (3) Integration of road information: the further integration of road information with other sensor data is a trend to the utilization of map-derived information. The Kalman filtering based integration and map-aided optimal estimation approaches have been developed [1,10,13,14]. However, existing approaches appear to be incapable of utilizing the map-derived information efficiently with other information sources (such as GPS data). It is considered that a mathematical framework of integrating GPS measurements with map-derived information is still lacking. The exploitation of map information and, the optimal combination of different information sources has not been achieved yet. This leads us to explore a new theory on representing and integrating different information sources, so as to further improve map aided GPS navigation.

This paper presents a novel approach addressing the combination of GPS measurements with map-derived information. Following the introduction, the problem statement and a detailed analysis of previous approaches to the utilization of map-derived information are given. A new information fusion theory and its mathematical formulation are introduced. The implementation of a practical algorithm, *Snake*, for map aided GPS navigation is described. An experimental evaluation of the new approach is also presented.

PROBLEM STATEMENT AND ANALYSIS

The key to reliable vehicle navigation is the optimal fusion of information from a variety of sources. In land-based GPS navigation systems, three information sources are included: vehicle dynamics, GPS measurements, and map-derived information. In the previous approaches to the utilization of map-derived information, two processes are generally involved: (1) Road identification: determining the road on which the vehicle is traveling; and (2) Road information fusion: integrating the road information with GPS measurements.

Road Identification

The nearest point (NP) searching algorithm is intuitively used to perform road identification. It outputs a nearest point to the GPS computed point through searching the road network. If a wrong road is chosen, the performance of the information fusion may degrade dramatically. This is a reoccurring problem in current map aided GPS systems.

Recent considerations are focusing on searching a road segment rather than a road point (such as a NP). The method uses the results of a Kalman filter to determine a vehicle trajectory and to match this trajectory with a road segment in a road network [6]. To make use of this method, an accurate navigation result is required. The paradox is that the road information should be used at first so that an accurate navigation result could be produced. Solutions to this paradox are still being sought.

Road Information Fusion

Kalman filtering based information fusion methodology has been predominantly used in vehicle navigation. It has been proven that the Kalman filter has great capability of integrating multiple sensor measurements with the vehicle dynamics via a sequential solution. The understanding of the statistics of multiple information sources govern the performance of a Kalman filter. In [1], the map-derived information is treated as an observable and introduced directly into a Kalman filter with the other observables. The weighted point and slope-intercept constrained observation equations are incorporated into the Kalman filter for the navigation solution.

Another approach to augment GPS using map-derived information is given in [14]. The approach is based on the premise that the correct roads of travel have been identified. Due to the various noise sources affecting GPS measurements, the measured positions of the vehicle would not lie on the road. The approach takes into account the measurement noise statistics of GPS and optimally translates the raw position measurements onto the road network. A maximum a posterior (MAP) estimator is proposed to determine the translation using the spatial correlation of the measurement errors. This is an alternative approach of combining the GPS measurements and map-derived information. The advantage of the approach is that the NP searching is avoided. The performance of this approach depends heavily on the statistic model of GPS measurement errors. Temporally correlated GPS errors and biases introduced by Selective Availability (SA) may violate an implicit assumption of the MAP estimator [13].

The common characteristics of the above approaches can be summarized as: (1) Both the map-derived information and GPS measurements are investigated by means of the probabilistic approach and combined using statistical criteria. (2) Only discrete road points are used and their positional information is treated as constraints in the estimation model. (3) Road identification is critical. Incorrect road identification would greatly affect the results.

Problematic Domain Analysis

Absolute positioning systems, GPS, generally provide an accuracy of 30-100 m in a stand-along mode. Due to the various noise sources, the curve of vehicle positions determined by GPS alone is not smooth, and even vibrated when the vehicle is traveling in tree canopy or urban canyon areas. The spikes on the trajectory are caused by satellite signal blockage or the constellation changes. The multipath error is about 150 m commonly in urban canyon areas [1]. The above errors are not able to be modeled and corrected successfully in the GPS stand-alone mode. This fact implies that the GPS measurements are not a stable information source compared to maps.

Since the vehicle is always traveling on roads, map information seems to be reliable and stable to the vehicle navigation. The absolute accuracy in maps is smooth (usually less than 30m [8]), and the internal relative accuracy is very high. This is an important structure feature of maps. In the previous approaches, only the positional information of road points is used rather than the road segments or the road network. In fact, a road should not be decomposed into independent points. It should be treated as a whole body in order to consider its structure feature. In this sense, the optimized combination of GPS measurements with road information has not been achieved by using the previous approaches, in particular, the structure feature of maps has not been applied efficiently. This is a motivation for this research.

PHYSICALLY-BASED INFORMATION FUSION

The physically-based information fusion approaches greatly differ from the commonly used probabilistic approaches. The approach is fundamentally dynamic and governed by a least action principle (Hamilton's motion principle). The Lagrangian equations of motion form the basis of the mathematical framework of the approach [4,17]. Recently, the physically-based approach has been of increasing interest in image information processing [11,15,16]. The approach is applied to infer and reconstruct objects of interest from images. Due to the existence of large ambiguities of the object information in images, the physically-based approach shows great advantages on combining the geometric, physical and dynamic constraints. It is essentially a novel information fusion approach.

Conceptual Considerations

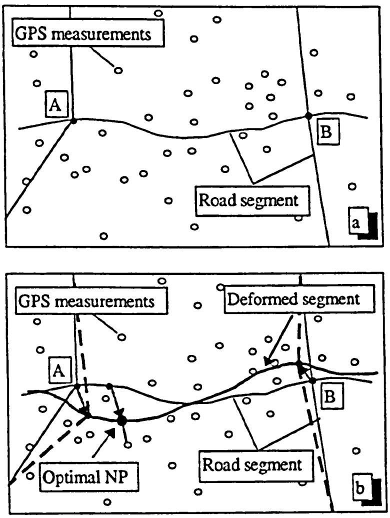

Figure 1. The physically-based combination of GPS measurements with map-derived information.

As can be seen in Figure 1a, from a geometry point of view, information fusion of GPS measurements and road information can be treated as a combination of the linear feature information and the point feature information. If using a probabilistic approach, both lines and points must be modeled as random objects associated with a probabilistic distribution. If we resort to a physically-based approach, we may treat this case as a force field in which the forces coming from different sources are acting upon each other. A curve composed of an abstract elastic material is placed in the force field. Each point of this force field acts a force onto the curve and deforms the curve (Figure 1a). The curve has its internal energy determined by the composed elastic material. This internal energy maintains the natural shape of the curve and resists the external deformation forces. According to Hamilton's least action principle [4], the motion of an elastic body, under the influence of shape constraints and deformation forces, follows a path from an initial state to a final state that minimizes the action energy. It shows that the deformation of the curve under the action of internal and external forces indicates an optimal energy combination. Figure 1b illustrates a deformed curve after an energy combination.

The combination of GPS measurements and road information can be accommodated by using this physically-based energy action theory. The road represents the curve while the GPS measurements represent the points. Since a road segment in maps has a high relative accuracy and a smooth absolute accuracy, it nicely fits to an elastic body associated with an internal energy. Thus a road segment becomes a whole body rather than the separated points. The advantage of this road modeling is that the structure feature of road information can be represented. The combination of GPS measurements with road information can be modeled as a deformation action, and such an action can be formulated by using the characteristics of different information sources. After an energy action process (information fusion), a deformed road model is obtained. This final road model reaches a state in which an optimal combination of the internal and external energies is accommodated. At this state, the nearest point to the GPS computed point can be considered as an optimal position of the vehicle, because this NP is determined by a dynamic synthesis of the road segment information and the surrounding GPS measurements. As illustrated in Figure 1b, the optimal NP of the GPS computed point *P*

Deformable Road Model (Snake)

A road network is composed of nodes and segments. Each segment is connected by two nodes. The physical meaning of a node is an intersection in maps. We treat each road segment as a deformable curve, termed a *snake*, composed of an abstract elastic material. In Figure 1, the road segment connected by nodes A and B are defined as a snake(A-B). The connecting relationship between the segments and the nodes are always maintained. Therefore, no matter how big the deformation of a road segment is, the topological relationship in the road network can never be destroyed (see Figure 1b). The parametric representation of a snake can be described as $v(u) = (x(u), y(u), z(u)), (u \in [0,1])$. Its total energy can be written as:

$$E=\int_0^1 [e_1 E_{int}(v(u)) + e_2 E_{ext}(v(u))]du \qquad (1)$$

where E_{int} is the internal energy of a road segment, and E_{ext} is the external energy. e_1 and e_2 are constants for weighting these two energies. During the minimization of the total energy *E*, the snake is deformed to reach an optimal compromise between the constraints introduced by the internal and external forces.

Internal Energy of the Snake

The internal energy represents the structure of roads. It maintains the local continuity and connectivity of the snake and controls the snake from deforming from its natural state. E_{int} can be described by a spline energy [17]:

$$E_{int}(v(u)) = \alpha(u)|v'(u)|^2+\beta(u)|v''(u)|^2 \qquad (2)$$

The first term is a measure of the distance discontinuities (stretching effectiveness), the second term is a measure of the orientation discontinuities (bending effectiveness). This spline energy imposes a smoothness force onto the snake. Adjusting the weights α and β controls the relative balance of stretching and bending forces. The structure features of the roads (e.g., absolute/relative map accuracy and road shape) are used to determine the weights α and β , and to partially control the magnitude of the deformation.

External Energy of the Snake

Another factor affecting the snake deformation is the external energy defined by the GPS measurements and the correlation to the roads. The GPS measurements are the estimates obtained by Kalman filtering, DOP fix, least squares or other methods [1]. In order to quantify this energy, a gravity-type force field is introduced. The reason is that the closer the distance between the GPS measurement point and the road, the greater the force. Shown in Figure 2, a gravity-type spring is imposed between the measurements and the road. To avoid the singularity when the distance is approaching zero, we employ the following function in defining the external energy:

$$E_{ext} = f(D_P / r), \qquad f(x) = \begin{cases} x^2, x < 1 \\ x^{-1}, x \geq 1 \end{cases} \qquad (3)$$

where D_p represents the distance between the measurement P and the curve points. The coefficient r controls a singularity of the action. The corresponding external force can be derived :

$$F_{ext} = \nabla E_{ext} = f'(D_P / r) / r \qquad (4)$$

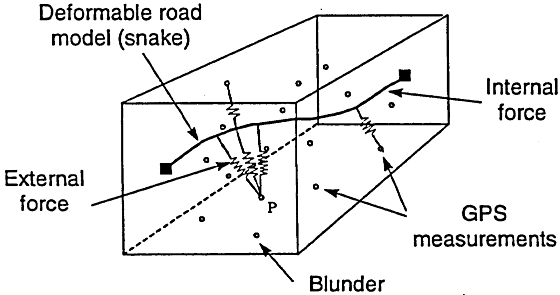

Figure 2. Combination of the internal and external forces

It should be noted that the accurate error model of GPS measurements and its spatial correlation model with the roads can also be used to define the external energy. The reason of the use of a gravity-type energy definition is that the above-mentioned models are not available or not accurate to be applied. On the other hand, the current model has a strong robustness. The effects of blunders and points distant from the snake are minimized.

ALGORITHMIC IMPLEMENTATION

B-Spline Based Snake Modeling

The solution of an energy-minimizing function E in Equ. (1) involves a large number of unknowns. In order to implement an efficient algorithm for navigation, 3D cubic B-splines are applied to represent the snake. Thus, the model of the snake (*B-Snake*) becomes :

$$\begin{aligned} Q(u_j) &= (\, x(u_j\,),\, y(u_j),\, z(u_j\,)\,) \\ &= (\, \sum_{i=0}^{m-1} V_i B_i(u_j)\,\,),\ j=0,1,\ldots,n-1 \end{aligned} \qquad (5)$$

where B_i are the basis functions of B-splines, $V_i=(X_i,Y_i,Z_i)$ are a set of control vertices to this B-spline curve, n and m are the numbers of sampling points on the curve and control vertices, respectively.

Snake Model Based Vehicle Navigation

The GPS measurements are updated when the vehicle is traveling on a road segment which has been modeled as a snake. Substituting Equ. (5)

and (2) into Equ. (1), the discrete version of the motion equation is obtained,

$$E = \sum_{j=0}^{n-1}\{e_1[\alpha(u_j)(\sum_{i=0}^{m-1}V_iB_i'(u_j))^2 + \beta(u_j)(\sum_{i=0}^{m-1}V_iB_i''(u_j))^2]$$
$$+e_2F_{ext}\,[Q(u_j)]\} \qquad (6)$$

To obtain the minimum of E, the solution of a variation extreme is involved. The final form of the solution ends up with the following matrixes [15]:

$$X = (A+\gamma I)^{-1}(\gamma X\text{-}F)$$
$$Y = (A+\gamma I)^{-1}(\gamma Y\text{-}F)$$
$$Z = (A+\gamma I)^{-1}(\gamma Z\text{-}F) \qquad (7)$$

where γ is an Euler step size, and A is a banded matrix (m×m). It should be noted that the dimension of the inversion is m instead of n. The computation of the inversion by LU decomposition only needs a linear time O(m).

After solving the motion equations, the deformed snake is determined. And then, an optimal vehicle position at the current time epoch is obtained which is defined by a nearest point on the snake to the latest GPS estimate (see Figure 1b). If a new GPS measurement is added, the balanced force field would be damaged and the new position of the snake is to be determined via solving the updated motion equations.

EXPERIMENTAL EVALUATION

Tests on simulated data have been conducted to evaluate the feasibility and viability of the new approach. A road network database is established in which the roads are spaced at about 100-200 m (Figure 3a). Most urban areas have similar road spacing. The bold line in Figure 3a represents a simulated vehicle trajectory. A number of random points along the vehicle trajectory are generated for simulating GPS measurements. These random points serve as zero-mean uncorrelated Gaussian distributions. The standard deviations of these point sets are randomly varied from 0 to 100 m, the actual accuracy of the stand-alone GPS mode.

In this test, 12 nodes (intersections) are involved. A total of 37 snakes are generated on this travel, e.g., snake(1-2), snake(2-3), snake(1-13), etc.. The average length of involved road segments is 158 m. The relative accuracy of the road network is assumed to be 15 m (the claimed accuracy of Etak maps). The spacing of the control vertices in the snake model is set up as 15 m. Thus the number of unknowns of the motion equations ranges from 7 to 15. Without using the B-spline representation, the number of unknowns would be 35-75 (assuming the spacing of the sampling points along the road is 3 m). In this test, since the accuracy of positions derived from the road database is better than that of GPS, the constants $e_1=0.6$ and $e_2=0.4$ are chosen for balancing the action of the internal and external energies. The weights $\alpha=0.7$ and $\beta=0.5$ are used according to the experiences. The singularity coefficient $r=15$ m is determined in this case.

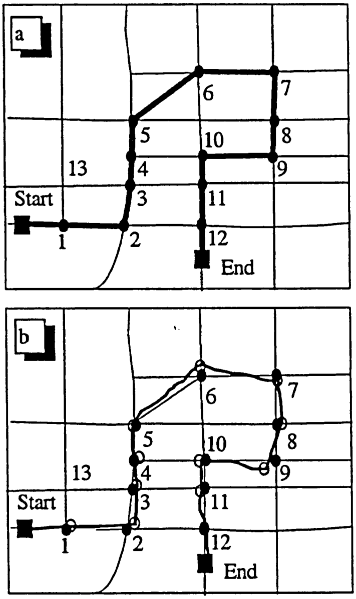

Figure 3 (a) A simulated vehicle trajectory (bold line) and a road network; (b) The final results of the positions (bold line) combining both GPS measurements and road information.

The final result is illustrated in Figure 3b. The marks "o" represent the positions of the deformed intersections. The effectiveness of this physically-based approach is demonstrated. The obtained trajectory is very smooth. The common problem of "Jumping from road to road" is alleviated, because the snake model is always attached to a current road segment. The wrong road identification could be avoided even though the neighboring road is very close to the current road (e.g., the road B is far close to the road A in Figure 3b). In order to evaluate the performance of the intersection identification, we placed five branches at the node 5. As can be seen the correct road was identified using the designed candidate election algorithm. At node 9, the neighboring nodes are very close and it is usually very easy to snap a wrong road. Since the end point of the snake was deformed together with the whole body, the wrong road will not be snapped when the vehicle makes a turn. In fact, the common problem coming from the use of a NP searching to identify the road is completely avoided in this approach.

CONCLUDING REMARKS AND FUTURE WORK

The physically-based approach for information fusion demonstrates its advantages and distinctive features to augment GPS using map-derived information. The following characteristics of the new approach can be summarized:

(1) The synthesis of multiple constraints can be implemented by a physically-based least action principle. The geometric, physical and dynamic constraints can be unified into the motion equations. The information fusion becomes a physical problem of solving the motion equations.
(2) A road segment is modeled as a deformable model (snake). It allows us to efficiently use the significant structure features of maps rather than the positional information of the independent road points.
(3) The deformation mechanism is endowed with the snake so that the constraints coming from the GPS measurements and map-derived information can be combined through an optimal and robust solution of energy minimization.
(4) The common problems of the wrong road and wrong intersection identification are resolved.
(5) The numeric advantage of using B-splines based snake technique is significant.

Practical tests for this new approach are obviously necessary. This defines our ongoing work. The accommodation of the model of GPS measurement errors and its correlation to roads into the snake energy model needs further research. In fact, the statistics of information sources can be incorporated implicitly into this physically-based approach. However, the further combination of the physically-based approach with the probability approach appears to be important. Thus, a mathematically more rigorous approach can be obtained.

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REFERENCES

[1] Bullock, J.B., 1995. "A Prototype Portable Vehicle Navigation System Utilizing Map Aided GPS." Proceedings of ION GPS-95, pp. 319-329.

[2] Buxton, J.L., S.K. Honey, W.E. Suchowerskyi, and A. Tempelhof, 1991. "The Travelpilot: A second-generation automotive navigation system." IEEE Transaction on Vehicular Technology, Vol. 40, No. 1, pp. 41-44.

[3] Collier, W.C, 1990. "In-vehicle route guidance systems using map matched dead reckoning," Proceedings of IEEE Position, Location and Navigation Symposium (PLAN'90), pp. 359-363.

[4] Courant, R. and D. Hilbert, 1953. Methods of Mathematical Physics, Vol. I, London: Interscience.

[5] French, R.L., 1989. "Map Matching Origins, Approaches and Applications." Proceedings of Land Vehicle Navigation. July 4-7, Koln, Germany, pp. 91-116.

[6] Harris, C.B., 1989. "Prototype For A Land Based Automatic Vehicle Location And Navigation System." M.Sc. thesis, Dept. of Geomatics Engineering, The University of Calgary, Canada.

[7] Krakiwsky, E.J. and J.F. McLellan, 1995. "Making GPS Even Better With Auxiliary Devices." GPS World, November 1994, Vol. 6, No. 3, pp. 46-53.

[8] Krakiwsky, E.J. and J.B. Bullock, 1994. "Digital Road Data: Putting GPS On The Map." GPS World, May, Vol. 5, No. 5, pp. 43-46.

[9] Krakiwsky, E.J., M.A. Abousalem, D.J. Szabo, and J.B. Bullock, 1995. IVHS Navigation System Database, Version 4.5, Dept. of Geomatics Engineering, The University of Calgary, Canada.

[10] Krakiwsky, E.J., C.B. Harris, and R.V.C. Wong, 1988. "A Kalman Filter For Integration of Dead Reckoning, Map Matching, and GPS Positioning." Proceedings of IEEE Position, Location and Navigation Symposium (PLAN'88), pp. 39-46.

[11] Pentland, A. and S. Scaroff, 1991. "Closed-form Solution for Physically-based Shape Modeling and Recognition." IEEE Transaction on Pattern Recognition and Machine Intelligence, Vol. 13, No. 7, pp. 715-729.

[12] Schwarz, K.P., M.E. Cannon, and R.V.C. Wong, 1989. "A Comparison of GPS Kinematic Models for the Determination of Position and Velocity Along a Trajectory." Manuscripta Geodetica, Vol. 14, No. 5, pp. 345-353.

[13] Scott, C.A., 1994. "Improved GPS Positioning for Motor Vehicles Through Map Matching." Proceedings of ION GPS-94, pp. 1391-1400.

[14] Scott, C.A. and C.R. Drane, 1994. "Increased accuracy of motor vehicle position estimation by utilizing map data, vehicle dynamics, and other information sources." Vehicle Navigation Information Systems Conferences (VNIS'94), August, 1994.

[15] Tao, C. 1996, "Road Centerline Reconstruction from Sequential Images Based on Shape From Sequences." SPIE Proceedings on Visual Communication and Image Processing (VCIP'96).

[16] Terzopoulos, D.A. and A. Witkin, 1988. "Physically Based Models with Rigid and Deformbale Components." The Visual Computer, Vol. 4, No.6, pp. 306-331.

[17] Tezopoulous, D. A. Witkin, and M. Kass, 1988. "Constraints on deformable models: Recovering 3D shape and nonrigid motion", Artificial Intelligence, Vol. 36, pp. 91-123.

[18] Yamaguchi, F., 1988. "Curves and Surfaces in Computer Aided Geometric Design." Springer-Verlag, New York.