SELF-LEARNING NAVIGATION MAPS BASED UPON DATA-DRIVEN MODELS USING RECORDED HETEROGENEOUS GPS TRACKS

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ABSTRACT

We present our innovative approach to keep navigation maps up to date by deducing map changes from recorded GPS tracks using adequate models and rules.

First, we describe, how models for receiver, mobility and terrain can be generated from adequately preprocessed recorded GPS tracks. These models are used by a server in order to predict plausible extensions of available navigation maps. In order to allow for multimodal track sources (pedestrians, automobilists, bicyclists, horseback riders, etc.), geometrical matches have to be further checked for plausibility. We give examples of such plausibility rules we have developed for this purpose.

The main benefits of our development are better maps and better guidance for various classes of possible users, from pedestrian, over cross-country skier, to bus driver, to name just a few.

Keywords: Global Positioning System – GPS, digital navigation maps, data-driven models, incremental map enhancement

1. MOTIVATION: SELF-LEARNING NAVIGATION MAPS

Although the navigation hardware market has changed rapidly during the last few years, the digital navigation maps market has remained rather inflexible: In some regions of the world, digital maps are still rudimental or even not available at all.

For instance, the off-road personal navigation for pedestrians as well as for outdoor and leisure activities (like mountain biking, hiking, horseback riding, or track skiing) is just in its infancy, and it is based on point-to-point navigation as opposed to full-fledged navigable vector maps of common vehicle navigation systems.

Thus, flexible, adaptive navigation using data that can be generated, updated, and personalized individually as well as for the public benefit still remains an interesting research topic with good chances for commercial value in the near future.

This contribution describes our approach to incremental navigation map generation based on data-driven models generated from recorded heterogeneous GPS tracks (Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J., 2001) gathered through tracing the paths of entities with heterogeneous mobility models (pedestrians, bicyclists, cars, etc.).

2. PREPROCESSING NOISY DATA

In order to enable adequate processing of the track data, i.e. filter-based preprocessing and verification, as well as the merging of the data with the existing map, we base our threshold values for algorithms on systematic data-driven models.

The data preprocessing covers filtering incorrect and insignificant track data. Since tracks based solely on the GPS data tend to be inaccurate in certain situations (e.g., reflections in built-up areas, changing satellite trajectories; cf. (Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J., 2001)), a track filter was implemented to filter out objectionable positioning errors: *Outliers* are removed using topological considerations and mobility constraints (velocity, acceleration) of the recording entity. *Accumulations* – which may for instance occur due to the recording entity staying at the same location for some time – are removed by appropriate clustering of GPS points and removing superfluous points.

We base our filter algorithms on configurable thresholds defined by the models as described in the following chapter. The composed data is processed by a proprietary graph matching algorithm combined with a set of models that take the varieties of input data into consideration. This approach provides the core functionality of incremental map learning.

For details on preprocessing and graph matching approach, we refer to (Vesely, M., Novak, C., Reh, A., and Mayr, H., 2008).

3. INDUCTIVELY GENERATED MODELS

From the preprocessed data, suitable models have to be derived describing the entity and its mobility as well as GPS signal quality depending on the terrain and the receiving device. These models can then be used for assessing the quality and topological soundness of future gathered data.

Depending on the type of entity used for recording the route (vehicle, pedestrian, bicyclist, etc.), a *mobility model* can be defined describing maximum velocity, probable and maximum curve radii depending on the velocity, among other parameters.

According to this model, and additionally taking the respective values from the GPS track data into account, the most probable path within the limits of the track data can be determined.

If the same geographic path is recorded several times by the same entity or different ones, the most probable course of the real path or road can be determined by a suitable weighted averaging method which uses additional models – like Kalman filters – as detailed in (Mayr, 2007).

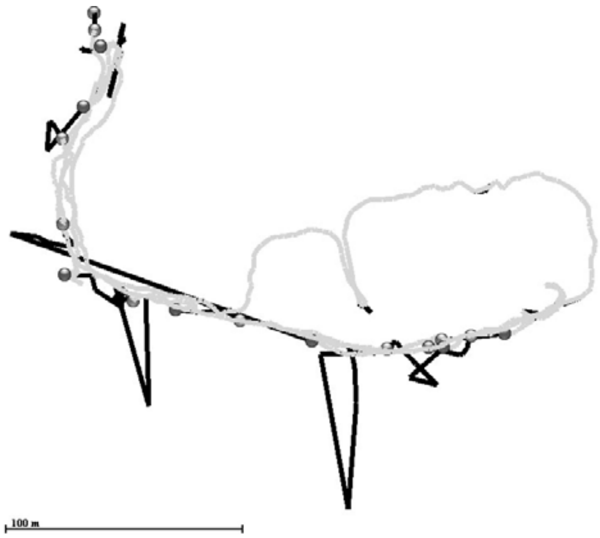

Figure 1: Filtered route (gray) on original (black)

Additionally to or instead of the Kalman filter used for preprocessing, a recorded route can be preprocessed by checking its attributes for plausibility (cf. Fig. 1). Therefore we define attributes, e.g. height and velocity of each recorded point as well as at the distance to the other points that confirm whether a recorded point is a plausible point that represents a real part of the recorded path. If the position data is incorrect because of errors due to inaccuracies in the position measurement or receiver-specific faults, it has to be filtered out.

For the preprocessing with plausibility checks three models are needed:

3.1. Receiver model

The quality of GPS, besides its standard error deviation due to atmospheric effects and clock synchronization, is heavily dependent on the satellite geometry. Every change in the satellite constellation can cause outliers (see (Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J., 2001) for details). Additionally, slow movement (< 4 km/h) causes GPS-positions to drift, thus deteriorating the quality of the recorded track. In some areas signal masking occurs and causes either signal loss or deficient positioning which makes the data inadequate for our self-learning system.

The quality of GPS data can be measured by *delusion of precision* (*DOP*) – the higher the DOP value the lower the quality. The receiver model defines thresholds for horizontal, vertical and positional DOPs (*HDOP*, *PDOP*, *VDOP*). Recorded positions that show DOPs above these thresholds don't suffice specified quality and are filtered out.

3.2. Mobility model

The mobility model entails attributes that describe the type of entity used for recording the route. These typical characteristics can be used for plausibility checks of the position data by comparing the recorded data with the model parameters.

Each entity has a maximum velocity that can be defined in the model. For pedestrians the absolute maximum velocity is assumed as 20 km/h, for cars as 260 km/h, etc., as points with a velocity above these defined thresholds are considered not plausible and thus cannot be used for the enhancement of maps.

The same applies to the difference in altitude per seconds as well as possible heading changes and curve radii depending on velocity. If the recorded curve radius is smaller than the minimum radius that would be possible at the recorded speed, the track data is not accurate at this part of the route. Table 1 (adapted from (FGSV, 1995)) gives an overview of minimum curve radii (r_{min}) depending on velocity (v) for the mobility model "car".

v [km/h]	r_{min} [m]
< 50	80
51 – 60	120
61 – 70	180
71 – 80	250
81 – 90	340
91 – 100	450
101 – 120	720
> 121	n.a.

Table 1: Minimum curve radii depending on velocity

3.3. Terrain model

After filtering a series of points it can be necessary to divide the preprocessed route into two or more new routes to enhance the learning process. Position values that are missing due to filtering or signal masking may lead to implicated connections between points that are not directly connected in reality. Therefore the system may learn incorrect data, because curves or intersections are not recorded.

Thus, to avoid negative influence on the enhancement of the map, the terrain model defines a distance threshold that specifies the maximum plausible distance between two points. Our empirical study shows that for instance for pedestrians the distance threshold should be set between 10-15 meters, if there are no mapped tunnels near the recorded route. Pedestrian routes can be very short which is why intersections and even whole parts of a route can be missed easily.

The threshold not only depends on the terrain of the route (e.g. existing tunnels) and on the type of entity, but also on the average point distance due to the velocity of the entity and the sample rate.

4. SYSTEM ARCHITECTURE

In order to enable the capability of extending and personalizing digital navigation data and, thus, continuously improve their quality and actuality, we have developed a software system that allows acquiring GPS tracks and environment-based attribute data automatically from the recorded GPS tracks, as well as integrating these into existing data (Fig. 2).

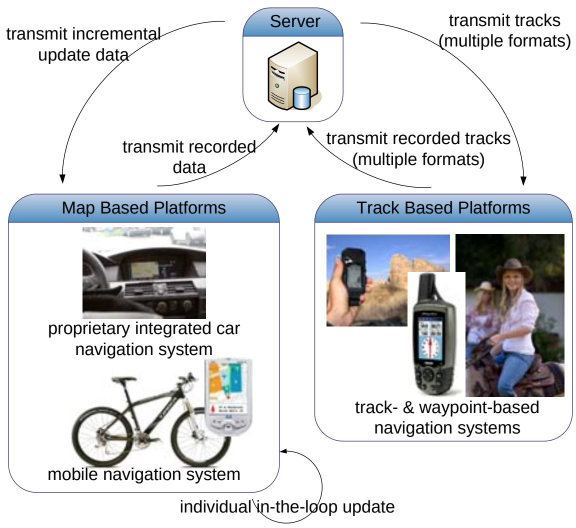

Figure 2: System Architecture Overview

Our system is comprised of four essential components, 1. navigation entities, 2. central server, 3. data exchange interfaces, and 4. a data management component, which are described in more detail below.

4.1. Navigation Entities

Basically, all kinds of GPS-enabled mobile devices can be used for recording GPS tracks to be uploaded to the server, if their output data format is among the supported ones.

In order to prove the feasibility of our approach as a whole on concrete implementations, we utilize two map-based navigation systems for mobile devices: an adapted car navigation system and a PDA-based mobile navigation and recording system developed from scratch. For more details on the navigation entities, we refer to (Vesely, M., Novak, C., Reh, A., and Mayr, H., 2008).

4.2. Central Server

The server comprises the ability to receive the data from the recording entities, process them, as well as generate and administer incremental map updates to be offered via a public service. This results in the following module design (cf. Fig. 3):

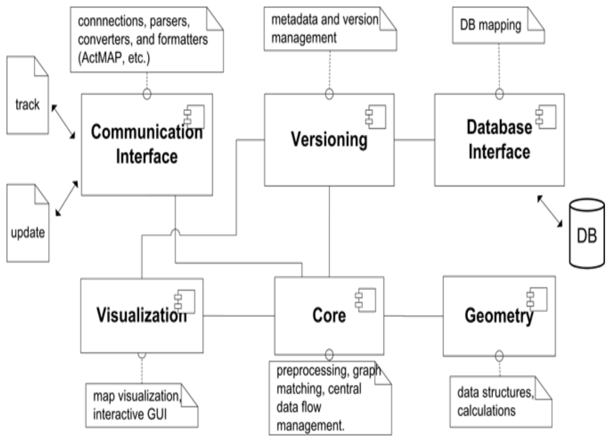

Figure 3: Server Modules Overview

The *communication interface module* administers multiple connection interfaces for receiving the data. The parsers and converters for the most common track data formats are consolidated in a separate *formatters sub module*.

After extracting the raw track data to internal data structures pooled in the *geometry module*, data processing is done in the *core module*.

In order to enable manual inspection of our approaches and algorithms, we developed a *visualization module* that enables visual evaluation, editing, and further management of the digital map data stored in the relational database.

For the proper management of a vast quantity of incremental map updates, we have developed a metadata-based *versioning module*.

All of the above modules rely on the central *database interface module* which provides an object-oriented abstraction layer above an exchangeable relational database, allowing manageable parceling and adaptation of the map data.

For details on our system architecture as well as on our algorithmic solutions regarding the incremental map generation and graph matching technique, we refer to (Vesely and Mayr, 2007; Vesely, M., Novak, C., Reh, A., and Mayr, H., 2008).

4.3. Data Exchange Interfaces

In order to enable the exchange of attributes and other metadata related to the tracks, we utilize the XML-based GPX format (GPS Exchange Format, 2008) as the main data exchange format. Thereby the users can either upload their data directly from their navigation system (if supported, like in our PDA-system), or upload the raw output data via a web portal and specify the metadata and attributes using an interactive web interface.

We base our incremental map data update strategy on the specification of the EU-supported project “ActMAP”, which specifies the strategies and the exchange format for online incremental updating of digital map databases. The exchange format specification is based on the ISO standard *Geographic Data Files* (GDF). For further details on ActMAP, we refer to (Otto, H., Beuk, L., Aleksic, M., Meier, J., Löwenau, J., Flament, M., Guarise, A., Bracht, A., Capra, L., Bruns, K., and Sabel, H., 2004).

4.4. Data Management

The navigation map is based on a graph of vertices and edges, where the vertices represent the junctions of more than two edges. In order to provide a serviceable map, further edge attribute data must be contained in the map, e.g. the shape points which approximate the true course of the edges, categorization data, direction of trafficability, average time of travel on an edge, etc. The data are stored in a relational database.

In order to enforce performance and minimize memory load of algorithms working with huge amounts of graph data, the earth surface is logically divided into tiles, so-called *parcels*. They are of the same geographical size and their indexing is based on geo-coordinates. The indexes of neighboring parcels can be identified by simple calculations, thereby allowing for fast and systematic retrieval of relevant data.

For the appropriate management of all generated map changes in the relational database, all elements in the database are version-controlled in order to allow for backward compatibility, version-switching and update definition generation for a specific map revision at any time.

Since our PDA-based navigation solution has to provide the same data update functionality independent from the server (“in-the-loop”), we utilize the server’s data management concept in our mobile solution as well.

5. USING OUR MODEL BASE FOR PREDICTION OF PLAUSIBLE EXTENSIONS OF AVAILABLE NAVIGATION MAPS

Since our graph matching algorithm (Vesely, M., Novak, C., Reh, A., and Mayr, H., 2008) relies on the simple map matching approach, its results reflect only the pure geometrical match of the given GPS track to the available map data. In order to improve the decision of the graph matcher, we use a model-driven approach to check the plausibility of the geometrical match.

A typical example for these induced plausibility checks is a combination of a pedestrian-recorded track misleadingly matched by the graph matcher to an edge classified as highway. Based on the according mobility model of the recorded track the graph matcher decides whether a new edge should be generated, or the affected section of the track is matched to the corresponding edge in the available map. Fig. 2 shows that, using the rule base, our algorithm correctly implies that no intersection between the pedestrian route and the highway exists (black – no match, dark gray – match, light gray – highway).

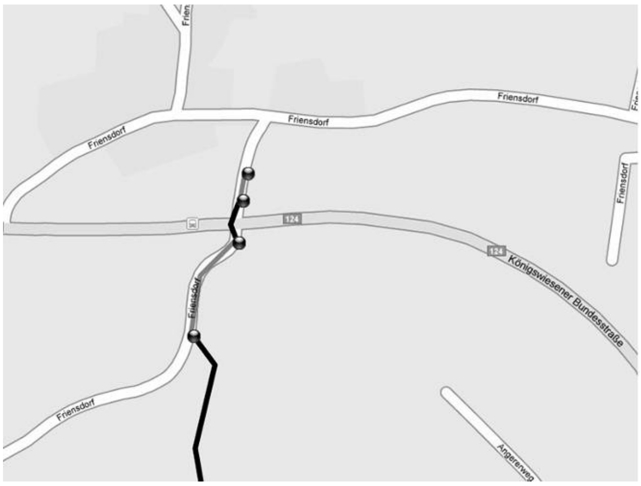

Figure 4: Pedestrian track crossing a highway

Another example may be a new highway bridge built over an existing road. Geometrically, such a bridge may be misleadingly classified as a crossroads, since in current map data of navigation systems altitude information is not stored for navigation graph elements. However, the correct inclusion of the bridge into the existing map data may be deduced from the driving behavior of automobilists passing the bridge. If several recorded tracks show that cars pass the “crossroads” without reducing the speed, our rule base correctly implies that no intersection between the two roads do exist and the map data is correctly adapted.

Some routes restrict which type of road users are allowed to access. If the user who recorded the track is not allowed to use the mapped route, it is not plausible that this route is the way the user walked or drove on. A car route for example can never be matched to a pedestrian way, a route recorded by a mountain biker never to a freeway, etc.

The same applies to a driving restriction for certain road users or at certain times. For example a truck may be transporting fuel during recording a track. If this track goes past a road leading through a water protection area, the graph matcher would match the route to this road. According to our rule base there exists a cargo restriction rule whereas the mapped road is not considered a plausible representation of the driven track.

These examples show that some rules are considered expedient only for certain mobility models. Another example is the check if the gross vehicle weight exceeds the permissible maximum weight of the matched road segment. In this case the entity cannot be driven there (legally). This rule, as well as the same rule applied to height or width doesn’t make sense for pedestrians or bicyclists.

For checking gathered geometric constellations are compared to our defined models by our rule base which concludes whether a match is plausible in order that the map data can be adapted correctly. If a map or a recorded path contains new or additional information, our rule base as well as our models can be easily extended.

6. A STEP-BY-STEP APPROACH TO PLAUSIBILITY CHECKS

To check the plausibility of the geometrical match we define a rule base that classifies whether a match defined by the graph matcher is a plausible one, using three models. Therefore the preprocessing models are extended to combine information about the map data as well as additional rule specific information:

- *Terrain model for map data:* Digital maps do not only contain information about the position of streets and their form but also additional characteristics that can be used for our rule base. The Navteq Core Map for instance includes 14 different attribute categories that comprise 204 map attributes which are used for the map representation as well as for route planning (Navteq, 2008).
  Our terrain model for map data combines street information like intersections, street type or direction as well as restrictions concerning users, velocity, direction, turns , etc.

- *Terrain model for route data:* GPS receivers do not only record the position but also information about the date, quality, velocity, etc., which are combined in a terrain model for route data to be used in our rule base.

- *Mobility model:* Additionally to the parameters needed for the preprocessing steps, we define the height, width and gross weight of the entity as well as cargo for checking restrictions and regulations.

According to our models we implement a rule base that checks step-by-step whether a recorded track or parts of it are represented in a plausible way by the results of the graph matcher. The match is considered plausible if no rule applies that rates the match as not plausible. If there is more than one match rated plausible, the one with the total best result in the graph matching and the plausibility check is considered the best match for the recorded track.

The rules defined in our rule base are applied to the terrain model and the motion model of the currently observed track point as well as to the terrain model of the point on the edge that is considered a geometrically plausible match by the graph matcher. If the data is comprised by different entities and therefore more than one mobility model is used, some rules have to be checked several times.

In the following, examples of our rules are described, abbreviating the terrain model for map data as *TM*, the terrain model for route data as *TR*, the mobility model as *M*, “plausible” as *p* and “not plausible” as *u*:

- $\neg EQ((TM), type(M)) \rightarrow u$

  On some streets there are only certain groups of users allowed. If the type of the entity, defined in the mobility model, is not declared as an admissible type of the map edge (*EQ*), the map edge candidate is not considered to represent the recorded route. If there is no information in the terrain model of the map about which users are allowed, the comparison is made using the type of the map street. Therefore the rule base needs the explicit knowledge that in pedestrian zones only pedestrians are allowed, on freeways only cars, etc. This information may differ from country to country, wherefore in certain cases also the country is needed.

- $v(TR) + \varepsilon > v_{max}(TM) \rightarrow u$

  If the driven velocity exceeds the velocity that is allowed on the matched edge by more than the threshold ε, the match is not plausible.

- $v_{max}(B) < v_{min}(TM) \rightarrow u$

  If the maximum possible velocity of the entity, defined in the mobility model, is lower than the minimum allowed velocity on the matched map path, then the edge candidate can neither possibly represent the recorded path nor cross it.

- $H(TR) \pm \varepsilon \neq H(TM) \rightarrow u$

  If the sea level is defined in the map and exceeds the sea level recorded at the current point by a predefined threshold ε either there is no representation of the recorded path in the map or another candidate, that was considered geometrically plausible by the graph matcher, has to be checked for logical plausibility.

- $one\text{-}way(TM)\ \&\ (dir(TM) \neq dir(TR)) \rightarrow u$

  If the matched street is a one way street and the direction (*dir*) of the street does not match the direction of the recorded route, the match is not considered plausible.

- $restriction(TM, type(M), cargo(M), date(TR)) \rightarrow u$

  If there is a driving restriction on the matched street at the date and time when the path was recorded for the type of mobility model and/or regulations concerning the transport of certain goods, the street is no candidate for representing or crossing the recorded path.

- $EQ(location(TM), DOP(TR)) \rightarrow p$

At some locations, like for instance in forests or street canyons, the quality of positioning with GPS is often low. The plausibility of a match increases if the rule applies that the location of the matched route fits the recorded DOP (*EQ*).

- $\neg EQ(intersection(TM), v_{max}(TM), type(M)) \rightarrow u$

  If the recorded route intersects a street on the map, our rule base checks whether an intersection is valid (*EQ*).

The more detailed the models are, the more rules can be concluded to reason about the plausibility of the graph matching result and therefore enhance the quality of the deduction process. For further details on our rule base we refer to (Franz, 2008).

7. BENEFITS FROM OUR APPROACH

Our model-based approach allows the integration of various types of recorded data into one basic set and enables the computation of the most probable map graph representing real world paths and roads used by the recording entities. This results in the following major improvements:

- *Better Maps*: By individual additions of missing map segments as well as broadcasting them via a server (after verification), the continuous incremental update of navigation maps ("improving and extending the map with each usage") based on data integration from different sources (pedestrians, bicyclists, automobilists, etc.) results in harmonized, accurate, and up-to-date maps, particularly for highly frequented areas.

- *Better Guidance*: Our approach enables the creation of personalized maps adjusted to the personal preferences and needs of the user, e.g. training courses for sport and leisure activities (e.g., scenic and smooth routes, etc.), footpath-maps for pedestrians, specialized maps suited to navigation of people with disabilities like wheel-chair users, visually-challenged or elderly people, etc.

Moreover, due to the modular architecture of our system, it can be tailored to the target group's needs, thus enabling future navigation systems to utilize our modules selectively, according to requirements.

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REFERENCES

Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J., 2001. *GPS: Theory and Practice*. Wien New York : Springer-Verlag.

Vesely, M., and Mayr, H., 2007. Using Self-adapting Navigation Data for Intelligent, Personalized Vehicle Guidance. *In: Proc. R. Moreno-Díaz et al. (Eds.): EUROCAST 2007, LNCS 4739*, pp. 1097–1104. Feb. 12-16, Las Palmas de G.C., Spain.

Vesely, M., Novak, C., Reh, A., and Mayr, H., 2008. Incremental Navigation Map Enhancement with GPS Tracks from Heterogeneous Sources. *In Proc. 2008 International Conference on Machine Learning Models, Technologies and Application*, pp. 787-793. July 14-17, Las Vegas, Nevada, USA.

Mayr, H., 2006. Model-Based Navigation Using GPS: One Step Closer to Intelligent, Incremental Maps. *In Proc. International Mediterranean Modeling Multiconference*, pp. 641-646, Oct. 4-6, Barcelona, Spain.

Mayr, H., 2007. I-Navigate: Intelligent, Self-adapting Navigation Maps. *In Proc. 14th IEEE Intl. Conference and Workshop on the Engineering of Computer Based Systems,* pp. 397–402, March 26-29, Tucson, Arizona, USA.

FGSV, 1995. *Richtlinien für die Anlage von Straßen, Teil: Linienführung RAS-L (Guidelines for the Creation of Roads, Part: Trajectory Recommendations RAS-L; in German)*. Forschungsgesellschaft für Straßen- und Verkehrswesen, Arbeitsgruppe Straßenentwurf, Düsseldorf (Germany).

Franz, B., 2008. *Plausibilitätsprüfung von Karten für Navigationssysteme auf Basis aufgezeichneter Strecken (Plausibility Checking of Navigation Maps Based Upon Recorded Tracks; in German)*. Master's thesis, School of Informatics, Communication and Media, Upper Austria University of Applied Sciences, Hagenberg, Austria.

NAVTEQ, 2008. *NAVTEQ Core Map*, Available from: http://developer.nav teq.com.

GPS Exchange Format, 2008. *GPX: The GPS Exchange Format*, Available from: http://www.topgrafix.com/gpx.asp.

Otto, H., Beuk, L., Aleksic, M., Meier, J., Löwenau, J., Flament, M., Guarise, A., Bracht, A., Capra, L., Bruns, K., and Sabel, H., 2004. *ActMAP ISO Input.* Technical Report D 3.3, ERTICO.