Collaborative Map Generation – Survey and Architecture Proposal

Stefan Edelkamp*, Francisco C. Pereira+ Damian Sulewski*, Hugo Costa+

University of Dortmund
Germany
stefan.edelkamp@cs.uni-dortmund.de,
damian.sulewski@cs.uni-dortmund.de

+University of Coimbra
Portugal
camara@dei.uc.pt,
hecosta@student.dei.uc.pt

1. Introduction

The current widespread use and higher quality of GPS devices is leveraging drastically the need for up-to-date digital maps to feed better and more reliable intelligent traveling assistance services.

While, on the one side, we are observing big investments of the main industrial players in order to satisfy this demand, on the other side, a new trend is slowly emerging out of the Internet social networking trend (sometimes referred to as “Web 2.0”) which should not be neglected. As with many other cases, the commercial approaches start ahead in quality and in coverage, but the effect of collaboration in community brings unexpected power. See, for example, the case of Wikipedia (as opposed to encyclopedias such as Encarta or Britannica).

More specifically, we are speaking about Collaborative Map Generation, which consists of jointly building a geographical map of a region or a city out of shared geo-referenced traces (normally GPS). Thus far, a few efforts have been made, being the OpenStreetMap project[i] probably the most well known. There are, however, two big hurdles for the success of this approach: the aggregation of new traces has to be done manually and, even worse, rarely any individual trace is devoid of errors, in spite of the high quality that current devices have.

In this collaborative approach, the input data (GPS traces) is inherently rich in terms of information about individual and social mobility. Its aggregation can provide more than a roadmap, it represents real urban mobility. In this sense, since this framework needs necessarily a set of methodologies to automate common processes such as filtering and smoothing, mode detection or statistical analysis, a very useful outcome is the use of such information for transport and urban planners. For example, one could infer mobility trends and predict possible improvements in transport network. Thus far, this is done essentially manually, sometimes also using simulators calibrated with sampled data (sometimes even from lengthy personal interviews). A GPS sharing framework in the form that we describe here would allow for dramatic improvements in time efficiency.

It is thus clear that an automated Collaborative Map Generation platform also allows for a wealth of information regarding the individual and collective mobility patterns, provided that a contract of privacy, security and trust is provided to every contributor (as is the case in any Web2.0 platform). At the individual level, one can determine, for example, the “personal network” or suggest better routes and transport means. At the city level, we can detect, for example, congestion points, places where people stay for periods of time, transport means usage, to name a few indicators.

The first breakthrough in this context will happen when efficient trace aggregation is achieved. In this chapter, we intend to present the State-of-the-Art (Section 2) and discuss current and future prospects towards an automated methodology for map aggregation that takes into account the need for integration of mobility data and the social networking trend, which we believe will eventually become the main source of geographical maps. This will allow us to abstract a general architecture (Section 3) for a Collaborative Map Generation system and discuss in some detail the technical challenges for each module (and its current solutions). In doing so, we hope to show that as a very relevant and desirable “side effect”, a set of algorithms must be developed that will help in those Transport and Urban management tasks referred above. We address filtering, map matching, update and aggregation, steps for the construction of the maps, and some efficient algorithms and data structures that are used to compress, process and query the map once generated. The chapter is ended with conclusions (Section 4).

2. State-of-the-Art

2.1 Making Maps

Map making (or cartography) is a discipline that has had many technical revolutions during the ages. From angle measurement to the North star aided by sextants and telescopes, to more sophisticated settings, such as aerial photography and laser range finders, cartographers have gave their best to achieve maps of the highest quality. The still recent age of artificial satellites in the orbit of the Earth (which started in 1957 with Russia’s Sputnik) brought drastic improvements. This revolution brought two important new tools for map making: satellite imagery and the Global Positioning System (GPS). With the former, cartographers could start doing high precision global maps and, aided by the higher definition of airplane photography and localized measurements (e.g. altitude, pressure, temperature), quickly acquired large quantities of geographical data. With the advent of micro-computers, such high quantity and quality of databases eventually led to the emergence of Geographic Information Systems (GIS), which are nowadays fundamental for a range of applications.

Differently to satellite imagery, GPS technology reverts the referential to a single point (as opposed to entire maps given by pictures). This enables the individualized use of geo-reference and opens up a myriad of new applications: from navigation to location-based services, or LBS (e.g. “where is the nearest Restaurant?”, "What is the weather forecast for today?”). It is now common to find vehicles and mobile phones

or PDAs with GPS receivers, and we are observing a dramatic increase on the number of such applications, both commercial and freeware based.
Again, for the cartographer, GPS has also brought serious improvements. Particularly with Differential GPS (DGPS)[ii] and Real Time Kinematics (RTK)[iii], which allow for sub meter accuracy, these technicians can now guarantee a more than satisfactory accuracy in a large number of features (e.g. roads, buildings). Moreover, the popularity of GPS and handheld devices has contributed for the low prices and lightweight solutions that can now be found in the market, and which are getting big adherence on the side of cartography experts (Wadhwani, 2001).

At an industrial level (e.g. Tele Atlas[iv]), the mappings have to be made at a systematic and intense basis, so it is common to use special purpose vans with GPS (DGPS when available), odometer and cameras (Desmet, 2005). Such technique has been applied for several years (e.g. by Grejner-Brzezinska (1995)). The major problem with this solution is the need for constant updates. Whenever a change in the area is made (e.g. new roads, change in traffic direction, speed limit, etc.), an update has to be made to the map. Furthermore, these approaches tend to neglect pedestrian and alternative transport means (e.g. bike), which would imply even more unstable maps.

The common process for updating geographical maps uses GPS as well as satellite imagery. Some systems and algorithms exist (Yun et al, 2004; Gerke et al., 2004) that directly or indirectly help identify visible road geometry and associate it with geographic positions. However, such approaches still need close human attention and, above all, cannot identify several important route features (e.g. traffic direction and speed limits) or non-standard roads (e.g. off-road). Therefore, they still have to be complemented with careful high precision GPS data collection on ground. It is, therefore, still a very slow and resource consuming process.

2.2. Autonomous Systems

Given the need and costs of constant map updating, the search for autonomous systems became a logical next step. The two main map provider companies (TeleAtlas and NavteQ) and four major car manufacturers (BMW, FIAT, Daimler and Volvo), have been involved in two projects under the coordination of the ERTICO European consortium on Intelligent Transport Systems (ITS) (ERTICO, 2007): ActMAP and FeedMAP. ActMAP (Flament, 2005) lasted for 3 years (2002-2005) and its aim was to investigate and develop “mechanisms for online incremental updates of digital map databases into the vehicle. Up-to-date map components containing dynamic or static location-based content should be integrated and/or attached to the in-vehicle digital map”. The final results include a reference architecture for the on-line update of digital maps. In the design specification developed, the authors propose methodologies, procedures and data formats to enable an efficient process of updating maps, from map providers to users.

The FeedMAP project expects to complete the loop by transmitting data from the client to the provider, integrating it semi-automatically into the map. This project started in 2006 and is expected to finish by the end of 2008. In FeedMAP, the main aim is to “assess the technical and economic feasibility of map data correction by providing a map data feedback loop applied to a map data updating framework using the ActMAP standardized exchange formats and mechanisms”. As we can see from Figure 1, the authors propose a complete cooperative process that takes as actors the map providers, the clients and public authorities.

Commercially, we can already see results of these and related projects. The most salient example is TomTom Map Share technology[v], in which the user can record traces and send them to the map server. The whole process is still essentially manual (the symbolic information, the error correction, the aggregation), so it strongly resembles OpenStreetMap philosophy, mentioned in the next section.

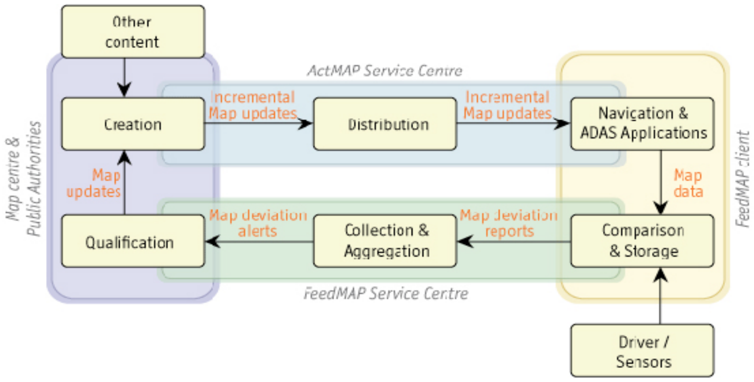


Figure 1 – Architecture of FeedMAP

On the academic side, Schroedl et al. (2004) fully specify a system for generating geographical maps out of DGPS traces. Their approach consists of successive processing steps: individual vehicle trajectories are divided into road segments and intersections; a road centerline is derived for each segment; lane positions are determined by clustering the perpendicular offsets from it; and the transitions of traces between segments are utilized in the generation of intersection models (Schroedl et al., 2004). Although as far as we know the most extensive as yet within academia, no further results have been published, possibly due to any industrial strategy (an associated patent was registered – US Patent nr. 6385539).

Partly a follow-up, the work of Brüntrup et al. (2005), "Map Generation", is possibly the first that explicitly considers the collaborative side. In this project, the authors developed a system that incrementally generates a map of the world, starting from an "empty" map and gradually adding new data collected from GPS traces. The system applies Artificial Intelligence search techniques to perform what is commonly known as Map Matching, the task of identifying to which parts of an already existing map should a given set of coordinates correspond to. When no map segment is found, then that set of coordinates should correspond to a new road (and thus aggregate it as a new segment of the map). "Map Generation" performs reasonably well when the first traces for each segment have high quality, however it finds difficulties in improving an initial map that has GPS errors (which is rather common in a realistic setting). In other words, it lacks a more precise feedback correction mechanism, perhaps with a “forgetting factor”.

The observable investment in ActMAP and FeedMAP allows us to predict an improvement on the quality of maps in car navigation commercial systems during the next years. However, the essence of these approaches (particularly the FeedMAP side) relies on having users participate and contributing. Such approach is mostly common in Web 2.0 applications (e.g. Wikipedia, del.icio.us, MySpace, Blogspot, WikiMapia), and is rarely successful when based on a commercial relationship.
On the other side, although with less resources, the academic approaches are improving in quality and its constituents (namely the Map Matching modules) are nowadays extremely efficient. It becomes difficult to compare technically the two sides, because of lack of information. From what is publicly known, industrial players are focused on improving maps for car navigation and integrating the system with other ADAS (Advanced Driver Assistance Systems), while academia is focused on general-purpose solutions (e.g. bike or pedestrian navigation).

2.3. Mapmaking and Web2.0

There already exist collaborative projects for manually creating maps out of GPS traces. We name here the most popular and complete one: OpenStreetMap (OpenStreetMap, 2007). OpenStreetMap is a project “aimed squarely at creating and providing free geographic data such as street maps to anyone who wants them.” In this project, each user can upload his/her GPS trace logs and use an editor (jOSM) to complete/correct the data (e.g. define directions, connections to other segments, add names, etc.). Then, the resulting joint “map of the world” can be seen and the data can be treated for other uses (such as car navigation). In general, the major drawback of such a system is the manual effort demanded to the normal user.

2.4. Map Making and Mobility Analysis

The space is still rather unfilled in terms of the relationship between these systems and urban mobility analysis. Other than average speed, hot spots, points-of-interest and typical map features (e.g. gas station, parking lot, hospital, etc.), there is not much more information in the process added to the inferred routemaps. OpenStreetMap representation is still open for added features and some related projects are actually adding external statistics (e.g. Stockholm GIS info[vi], with dangerous and goods roads, nature reserves, built up areas, etc.), but plenty has to be done to achieve valuable content.

3. An architecture for Collaborative Map Generation

From a detailed analysis of previous work, we abstracted an architecture for Collaborative Map Generation (Fig. 2) that covers those works and that will lead our own next steps of research, described in this section. We assume that the system is fully automatic, and that a base map may be initially absent (an initial empty map of the world).

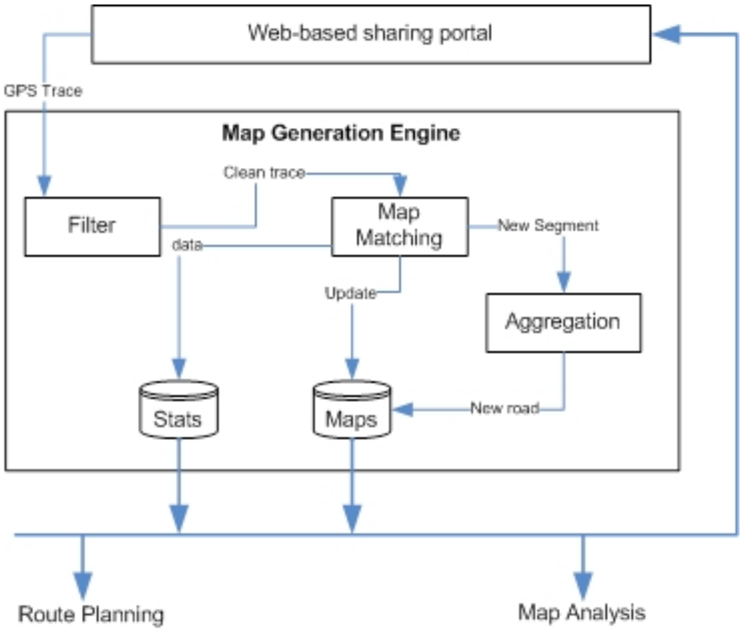


Figure 2 – General Architecture

As with many other Web2.0 applications, we include a *front-end interface* accessible via a Web browser. This will be responsible for feeding the Map Generation engine with GPS traces. Notice that we expect each trace to be analysed separately (as opposed to what happens in the above mentioned work of Schroedl et al. (2004), where traces are processed in batches). Each incoming GPS trace will then be *filtered* for consistency (as in the Map Generation project by Brüntrup et al. (2005).
The filtered trace will then be matched to the existing map in the *Map Matching* module. The parts of each trace that achieve a correct match to the map (i.e. points that fall within the already existing roads of the map) will serve to *update* the *Map*. The procedure to be used in this correction mechanism consists of averaging the centerline according to the number of previous estimates and the confidence – according to DOP[vii] – of the current one). The traces that reflect a “new road” shall be *aggregated* taking into account the intersection treatment suggested by Schroedl et al. (2004). Regardless of being updated or aggregated, the Map Matching module will allow inference of mobility data that will feed the statistics (*Stats*) database (e.g. average speed, time spent in locations, most probable transport means used).

External services can be connected to this platform, for example for route planning or for map analysis (e.g. visualizing cycling routes, transport usage, places where people stay for long times).

3.1. Filters

GPS traces always bring a considerable amount of errors. There are many reasons for this: receiver clock errors; satellite clock errors; satellite orbit error; atmospheric effects (particularly Ionosphere and Troposphere); and multipath effect (e.g. when a signal is reflected in a building). Such error essentially affects the positioning estimation in each new calculation. This means, for example, that from one second to the other the difference on estimation may vary on the order of meters. A study from Refan and Mohammadi (2001) focused on averaging positioning estimates to a fixed point gives approximately 7 meters of standard deviation (with an amplitude of approximately 30 meters) for each axis, with a 5 minute sample of GPS points. These error values grow considerably when the receiver starts moving.

Many improvements to GPS accuracy are being under research and some are already in production. In the case of DGPS and RTK, specific hardware conditions are necessary to effectively get accuracy improvement that are not available for low cost devices. A different technique, called Dead Reckoning, consists of using other information (e.g. accelerometers, inertial sensors, assumption of correct route) to infer precise location. These are particularly useful in "urban canyons" or even when no access to satellites is possible (e.g. indoors, tunnels). Although no special GPS hardware is necessary, Dead Reckoning normally uses other sensors or assumes uncertain facts, thus making the solution complex. In our case, we intend to use common off-the-shelf and low cost GPS receivers, thus neither of these solutions is applicable. The accuracy improvement has to be made exclusively with software post-processing of the traces. In other words, using filters.

Kalman filters, Recursive Least Squares and Linear Regression are being currently studied, with attention to car, bike and pedestrian traces. For example, in Figure 3, we show the result of the application of Cumulative Displacement Filter (inspired in Kalman filter). Particularly in slow movements (e.g. curves) we can see that the error may strongly affect the road geometry. In terms of pedestrian traces, results thus far show that Kalman related filters give extremely bad results, while linear regression demonstrates fewer weaknesses. It is, however, noticeable that using a rule based approach (e.g. people cannot move faster than 2m/s) allows for a reasonable first pass (without smoothing). In Figure 4, we show an original pedestrian trace and a filtered one (indicating sub-traces, their beginning and ending, and places where the person stayed).

Notice that the problem we face goes beyond the common approaches: processing is made off-line (we have the entire time series, not only the "past") and no auxiliary hardware resources are available.

Figure 3 – Filter application to a GPS trace. The arrows indicate trace points, while the thick line corresponds to the filtered path proposed.

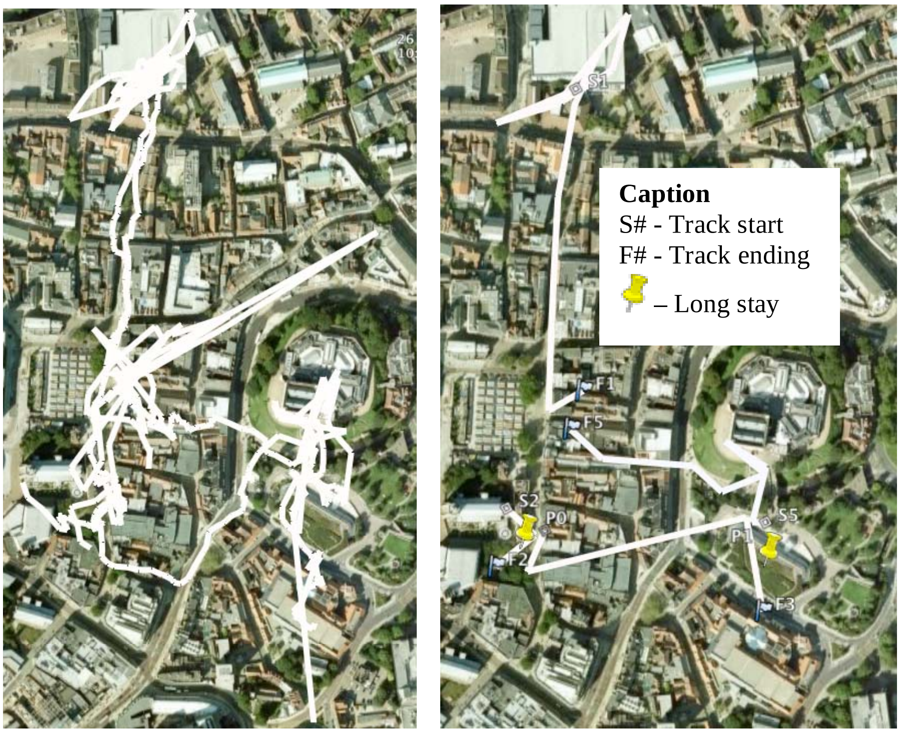


Figure 4 – Pedestrian trace (from Norwich, Spatial Metro project). On the left side, the original trace data; on the right side, the filtered results.

3.2. Map Matching

For the task of map matching, we need a method that takes advantage of the topology of both the new trace and of the map constructed so far. Furthermore, the offline nature of the system allows for preference on precision over performance (of course, within reasonable limits). A genetic algorithm is being designed that evolves each potential match according to minimization of distance, penalization of gaps and incorrect topology. For the reader unaware of genetic algorithms (GA’s), we summarize the concept: in a GA, several solutions to a problem are generated randomly in the beginning (the initial population); according to a fitness evaluation, a portion of them can be selected to generate the following generation; these solutions can be crossed with each other, providing their “genetic material” to new individuals, and be subject to “genetic mutation”; this process is thus repeated iteratively, generation after generation; after a number of generations or a satisfactory solution is found, the algorithm stops with the best solution (“individual”) so far[viii]. In our case, a solution, or “individual”, is composed of a sequence of “point-to-curve” matches (the “genes”). Thus, in theory, each individual could have as many genes as points in the trace. To limit this complexity involved, we are using segmentation of the trace according to the idea of Sudarshan Chawathe (2007), in which a trace is divided into shorter parts bounded by points with high confidence matches. Our fitness function consists of the weighted sum of average, maximum and minimum distance, sum of gap size (subsequences of unmatched points), sum of jump size (when two consecutive points in a trace match to different roads). In Figure 5, we show an example with the initial map obtained from previous traces (5a), the trace being evaluated (5b) and the GA result (5c).

Figure 5a – Initial map (white line)

Figure 5b – Recorded trace

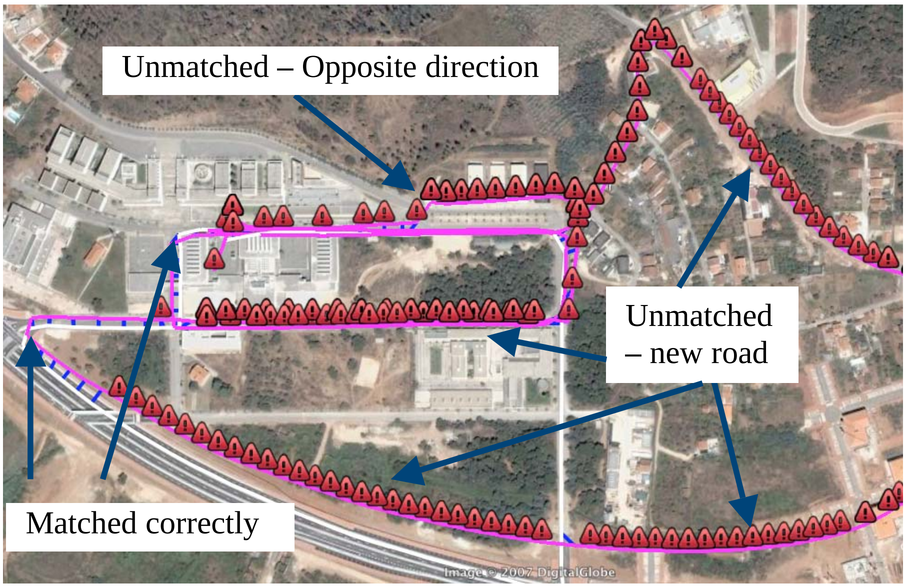


Figure 5c – Matching obtained with the GA (Triangles mean unmatched)

This algorithm will soon be compared to others: Depth First Search (Brüntrup et al., 2005), Frechet curves (Brakatsoulas et al., 2005), Least Squares Estimation (Blewitt and Taylor, 2002), Multiple Hypothesis (Marchal et al., 2005). Again, the experiments will be directed towards bike, car and pedestrian traces.

3.3. Aggregation

Whenever a trace is found that doesn't match the existing map, we have to consider a possible new road in the map. There are essentially two approaches to aggregation: incremental and batch-based. In the incremental approach, we determine the points of intersection of the new set of segments with the existing map. In the batch-based approach, we recalculate the entire sub-network that fits the area of traversal of the new trace (by recovering all the original traces).

3.3.1 Incremental Aggregation

An incremental approach for map generation has the advantage of time-efficiency, when compared to the batch-based approaches. For this reason, it can also be used online. However, due to the error in normal GPS receivers, particular care has to be taken not to propagate this error.

The algorithm we currently have, from the Map Generation project (Brüntrup et al., 2005) subdivides the world into tiles and, for each new trace, the *trace processor* interpolates new trace nodes. In the main processing loop, three modules *walk* along the trace. The *scan module* is the first module and scans the environment of the trace for nodes that are candidates for merging. After each scan the *AI module* decides which of the nodes should actually be used. Finally the *apply module* uses these results to merge the nodes with the trace (which would actually correspond to an *update*, not to an *aggregation*) or create new nodes on the map. In Figure 6, we can see an example of the original traces provided (Fig. 6a) and the resulting portion of the map (Fig. 6b). An improvement for the inference results for off-roads, roundabouts applies genetic algorithms to tune parameters (Scholz 2006). The dynamically generated map can serve a series of applications, namely for navigation and for providing up-to-date statistical information about the roads (e.g. average speed/congestion). In Figure 7, we can see a sequence of map “snapshots” in time: the map grows as new traces come.

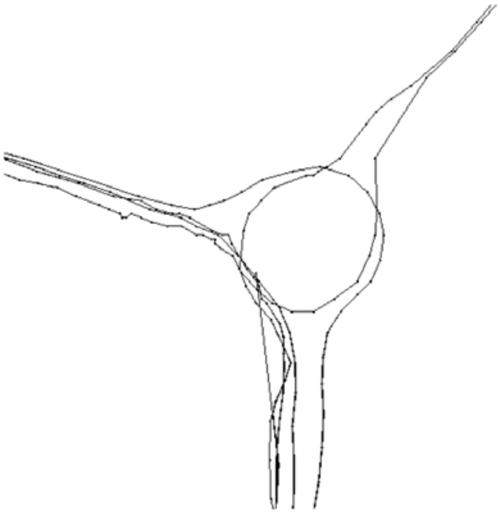


Figure 6a – Set of traces around a roundabout

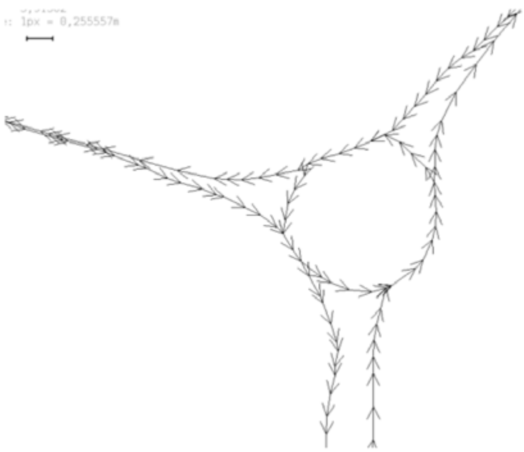


Figure 6b – Aggregated map, obtained from the traces

Figure 7 – Incremental Map Construction.

The map matching algorithm can already provide us with a *triage* that separates two different tasks: updating the tiles with corrections to existing maps (Update phase); adding entirely new segments to the map, that represent new roads (Aggregation phase).

The quality of the map will be sensitive to the successive updates and aggregations of traces. Although each new pass will provide correction, a bias towards the most recent ones will be inevitable. Such problem can be attenuated if we apply batch-based construction periodically, by using all received traces so far (kept in the database) and applying them at once. This is described in the next section.

3.3.2. Batch-based Aggregation

In a batch-based map construction algorithm, we take all the traces at once and organize them in clusters (and sub-clusters) in order to make a *travel graph*, which is the embedded overlaid set of GPS traces together with the according intersections. To compute the superimposed graph, the sweep-line segment intersection algorithm (Bentley and Ottmann, 1979) has been adapted (see Figure 8). In difference to the original algorithm, the generated graph is weighted and directed. At the intersections, the newly generated edges inherit direction, distance and time from the original data points. In typical travel networks, the number of edges is proportional to the number of nodes, because the node degree is bounded by a small constant. If one can assert that the graph is *planar* - as often the case - the number of edges is linear in the number of nodes. Once the travel graph is built, many nodes of degree 2 remain. For computing the shortest paths these nodes can be merged, adding distance of adjacent edges and travel times. Actually, only start, end and segment intersections remain, reducing the space complexity of the graph.

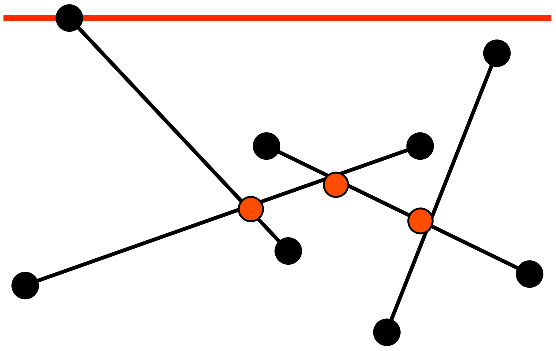
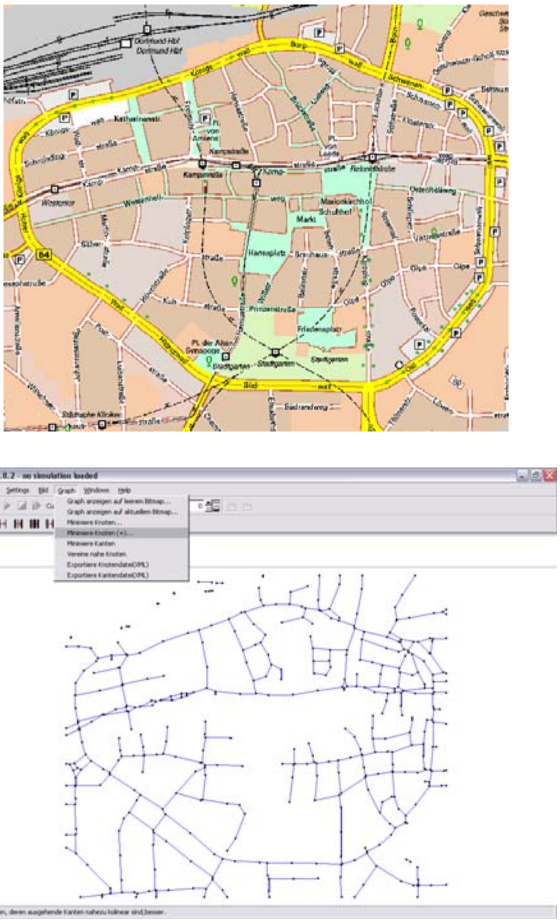


Figure 8 – Segment Intersection of Batched-based Map Construction.

Batch-based map construction thus proposes to build the map “all at once” from a batch of traces. This is only possible in an off-line basis. As said above, we propose the use of this method periodically (applied to a tile at a time) in order to “re-scan” the graph with all traces obtained for a period of time. Other methods can be applied, such constructing a Base Map from (satellite or raster map) images.

3.3.3. Base Map Construction

Aside from satellite images, as referred to in section 2.1, we may also use a method to extract calibrated road topology from raster maps to provide a *base map* for the collaborative map generation process. In many areas of interest, detailed vector maps are scarcely available and in some regions of the world, vector maps are not available at all. On the other hand, low-cost raster maps are frequently accessible. The images are often calibrated with respect to some form of global coordinate system to be translated to GPS. One approach takes a bitmap and uses different graphics filters to infer the road geometry. We propose an aggregation algorithm that extracts road fragments and constructs a graph of the road network. To evaluate the proposed algorithms the approach was integrated into SUMO (Figure 9), a state-of-the-art traffic simulation tool for urban mobility (Drodzynski et al. 2007).



Entfernt Knoten, deren ausgehende Kanten nahezu kollinear sind,besser.

Figure 9 – Base Map Generation and Inclusion in a Traffic Simulation Tool.

3.4. Efficient Map Representations

A map is beneficial to a user only if it can answer location queries fast. Before a query on the map based on given start and goal locations can be processed, their nearest corresponding entry nodes have to be found, i.e., we have to do efficient map matching in real time. For a set of queries, this is best accomplished by an assisting point localization structure that supports nearest neighbor information.

3.4.1 Tile Regions

If the map is organized in form of tiles, then we first have to find, in which set of tiles a trace is located, e.g. by looking at its bounding box of coordinates and retrieve this set for further processing. This has the advantage that the integration of data can be distributed as far as the affected tiles do not overlap. The drawback is that a uniform distribution of fine-grained tiles is memory inefficient. One of the most interesting dynamic data structures for storing and retrieving tile information quickly are *Quadtrees* (Finkel and Bentley, 1974), a balanced tree with children NW, NE, SW, and SE at each node (see Figure 10).

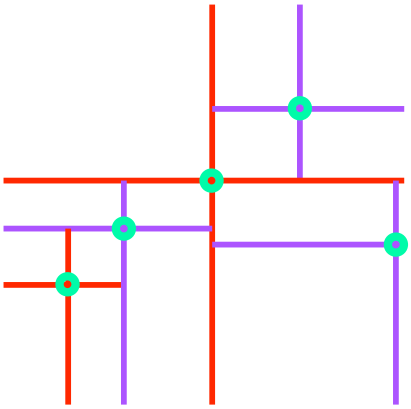


Figure 10 – Point Localization Structures Quadtree (left).

3.4.2 Voronoi Regions

Another apparently suited data structure for nearest neighbor localization is the *Voronoi diagram* (Voronoi 1907). The structure consists of Voronoi regions *V*(*p*) such that all points in the interior of *V*(*p*) are nearer to *p* than to any other point in the point set (see Figure 11). A search structure can be associated on top of the diagram or by its geometric dual, the Delaunay triangulation. A randomized construction for the triangulation and the associated search structure is presented by Berg et al. (1997).

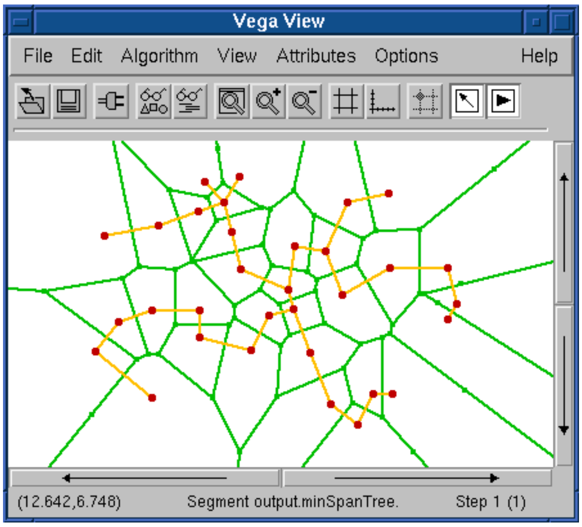


Figure 11 – Point Localization via Voronoi Diagram.

3.4.3 Routing

Even though routing first seems to be unrelated to the map construction process, many search enhancements can be preprocessed and included to the map. Searching for the shortest route in the inferred graph can sufficiently be accomplished with a single run of the single-source shortest paths *algorithm of Dijkstra*.

Many modern navigation systems either provide their services through Internet portals, so that portable devices access large databases through communication with a server, or rely on portable devices with limited capacities. In the following, we address efficient algorithms and data structures to reply frequent queries. Most of the algorithms exhibit the fact that the graph is embedded in the plane, so that refined geometric information on the set of all possible shortest paths can be associated to nodes or edges.

A* Search

Heuristic search is a well-known technique to reduce the number of expansions for a shortest path. This technique of *goal direction* includes an additional node evaluation function h into the search. The estimate that is applied to accelerate route planning measures the straight-line distance to the set of goal nodes. For this case, A* mimics Dijkstra's algorithm by changing the edge weights from $w(u,v)$ to $w(u,v)+h(v)-h(u)$ together with offset $h(s)$ given at the start node s (see Figure 12). If one is interested in the shortest path not only in terms of mere distance, the heuristic has to be adapted.

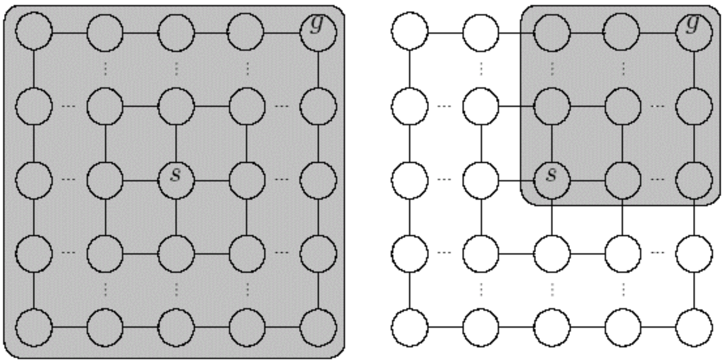


Figure 12 – Effect of Straight-line Distance Heuristics on the Search Space.

Geometric Containers

Another possibility to make the search space smaller is to ignore some neighbor points. The neighbors (or more precisely the incident edges to these neighbors) that can be ignored safely are those that are not on a shortest path to the target. In a preprocessing step, for each edge, we store the set of nodes that can be reached on a shortest path that starts with this particular edge. Then while running Dijkstra's algorithm or A*, we do not insert edges into the search queue that are not part of a shortest path to the target. The problem is the quadratic amount of space to store this information, which is not available even for contracted graphs. Hence, we do not remember the set of nodes that can be reached on a shortest path for an edge, but approximations of it, so-called *containers*. Incorporating such geometric pruning preserves the completeness and optimality of a route planning algorithm, since at least one shortest path from the start to the goal is preserved.

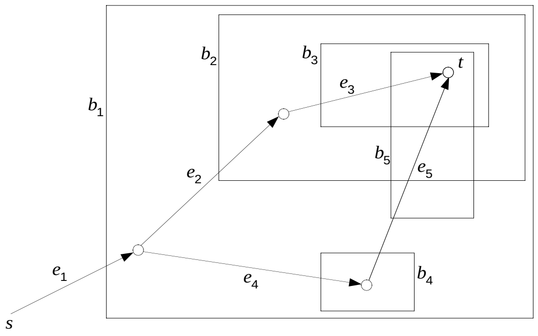


Figure 13 – Enhancing the Search with Geometric Containers.

Graph Rewriting

It can be advantageous to modify the routing graph simply to accelerate shortest path queries. One option is to apply abstraction to the graph structure by contracting nodes, to obtain a hierarchy of graph layers. More refined techniques have been established that reach out up to recent developments. A very influencing approach is to insert *transit nodes* into the map to separate the base graph from the *highway graph* (Bast et al., 2007). Speed-ups of factors 100 and more have been obtained.

4. Conclusions

In this chapter, we have seen a smooth introduction to the rising requests for collaborative and automated map construction on a set of GPS traces recorded by a host of individual devices. Besides the emergent roadmap, such methodology allows for elicitation of important information regarding individual and collective mobility. Examples include the inference of individual and crowd pedestrian networks or urban space use, correlated with time. By themselves, the statistics obtained from such a voluntarily built database can be enormous, for example for better calibration for simulations and to obtain detailed Origin-Destination matrices.

In terms of the motivation for the individual, collective map making is an answer to many important challenges for generating highly accurate, multi-modal and up-to-date maps. Automatically preprocessed and adapted positioning data can be used to accelerate the usability cycle on top of low cost devices. The map that is in current use e.g. for navigation on the device is extended and refined on-the-fly by recording and integrating new traces.
In our working prototype (see Figure 14) we illustrate the advantage of the collaborative approach by comparing the aggregated map (top left) on top of Google Earth (top right), Google Street Map (lower left – notice the big error) and OpenStreetMap (lower right).

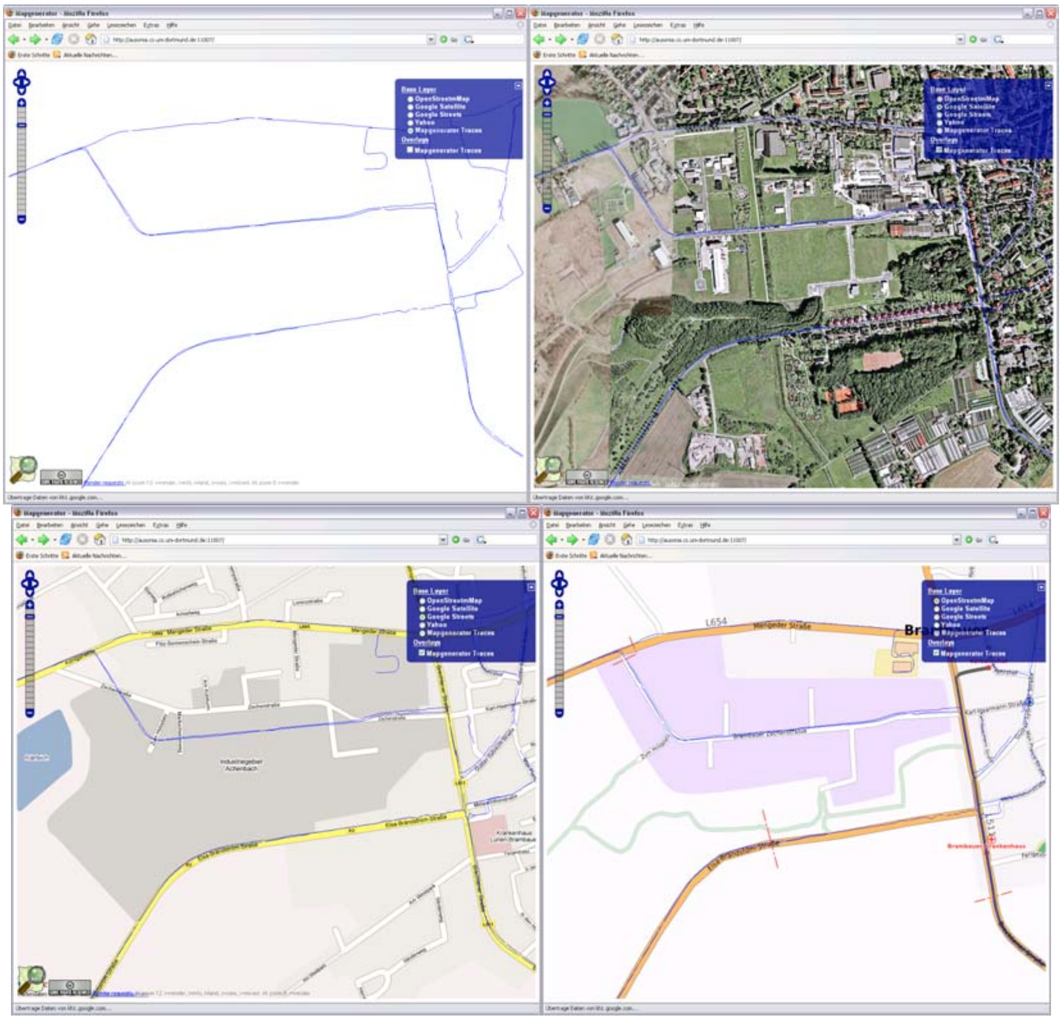


Figure 14 – Collaborative Map as an Overlay on top of Google and OpenStreetMap.

Besides surveying projects and existing solutions, this chapter reflected many algorithmic details as a portfolio to build a working architecture. We start with filtering of data, turn to incremental map aggregation via segment intersection, then to batch-based map construction, and the construction of a quick base map from raster map images. Moreover, for enhanced use of the map in a route planning system we show how to organize it for location queries and annotate it for accelerated shortest path search.

Acknowledgements

The authors would like to thank DFG for support in the project ED74/3. Moreover, the work has participated from running the map generation software by Björn Scholz and the filters and aggregator by Nuno Pereira.

References

Bast, H., Funke, S., Sanders, P., & Schultes, D.. 2007 Fast routing in road networks with transit nodes Science Magazine, April., 2007

Bentley, J. L. & Ottmann, T. A., 1979. Algorithms for reporting and counting geometric intersections, *Transactions on Computing*, vol. 28, pp. 643–647, 1979.

Berg, M., van Kreveld, M., Overmars, M.& Schwarzkopf, O. 1997. Computational Geometry. Algorithms and Applications, Springer Verlag. 1997.

Blewitt, G. & Taylor, G., 2002. Geoffrey Blewitt and George Taylor. Mapping Dilution of Precision (MDOP) and map-matched GPS. In International Journal of Geographical Information Science 16(1): 55-67. 2002.

Brakatsoulas, S., Pfoser, D., Salas, R. & Wenk, C., 2005. On map-matching vehicle tracking data. In Proceedings of the 31st international conference on Very large data bases (VLDB), Norway, 2005.

Brüntrup, R, Edelkamp, S., Jabbar, S., & Scholz, B., 2005. Incremental map generation with GPS traces. In Procs. of Intelligent Transportation Systems, IEEE Publications. 2005.

Chawathe, S., 2007 Segment-Based Map Matching. In Intelligent Vehicles Symposium, 2007 IEEE, 1190-1197. 2007

Drodzyinski, M., Edelkamp, S., Gaubatz, A., Jabbar, S., & Liebe, M., 2007. On Constructing a Base Map for Collaborative Map Generation and its Application in Urban Mobility Planning. In IEEE Conference on Intelligent Transportation Systems, pp. 678-683, IEEE Press, 2007.

Edelkamp. S., Jabbar, S. & Willhalm, T., 2005. Geometric travel planning. In *IEEE Transactions on Intelligent Transportation Systems*, 6(1):5–16, 2005.

ERTICO, 2007. ERTICO ITS Europe. http://www.ertico.com

Finkel, R. & Bentley, J.L., 1974. R.Finkel and J.L. Bentley, "Quad trees: a data structure for retrieval on composite keys". *Acta Informatica* **4** (1): 1-9. 1974

Flament, M., 2005 ACTMap Final Report, ERTICO. http://www.ertico.com/en/subprojects/actmap/public_documents/ 2005

Gerke, M., Heipke, Ch. & Busch, A., 2004. Automated image-based verification of road databases. In Proceedings of 7th AGILE Conference on Geographic Information Science 29 April-1May 2004, Heraklion, Greece

Goldberg, D., 1989. Genetic Algorithms in Search, Optimization and Machine Learning, Kluwer Academic Publishers, Boston, MA. 1989

Grejner-Brzezinska, D., 1995. Positioning Accuracy of the GPSvan. In Proceedings of the 52nd Annual National Technical Meeting of the Institute of Navigation, pp. 657-665, Palm Springs, Calif., 1995.

Jabbar, S.,2003. GPS-based navigation in static and dynamic environments. Master's thesis, Universität Freiburg, 2003.

(Krajewicz, D., Hartinger, D., Hertkorn, G., Mieth, P., , Rössel, C., Zimmer, J., & Wagner, P., 2003. Using the road traffic simulation (SUMO) for educational purposes. In *Traffic and Granular Flow (TGF)*, 2003.

Marchal, F., Hackney, J. & Axhausen, K. W., 2005. Efficient map-matching of large GPS data sets - Tests on a speed monitoring experiment in Zurich. In TRB annual meeting, Washington D.C., Jan. 2005.

OpenStreetMap, 2007. OpenStreetMap website. http://www.openstreetmap.org/ as of April 2007.

Otto, H., Beuk, L., Aleksic, M., Meier, J., Loewenau, J., Flament, M., Guarise, A., Bracht, A., Capra, L., Bruns, K. & Sabel, H. 2004 ACTMap Specification. ERTICO. http://www.ertico.com/en/subprojects/actmap/public_documents/ 2004

Refan, M.H. & Mohammadi, K., 2001. Point averaging of the position components, before and after S/A is turned off. Asian GPS Conference. India, 2001.

Scholz, B., 2006. Automatic inference of streetmaps based on GPS traces. Master's thesis (in German), Universität Dortmund, Germany, 2006 .

Schroedl, S., Wagstaff, K., Rogers, S., Langley, P. & Wilson, C., 2004. Mining GPS Traces for Map Refinement. In Knowledge Discovery and Data Mining, 9, 59-87. 2004

Voronoi, G., 1907. Nouvelles applications des paramètres continus à la théorie des formes quadratiques. Journal für die Reine und Angewandte Mathematik, 133:97-178, 1907

Wadhwani, A., 2001. Recent advances in mobile GPS/GIS mapping technology. In MAP India 2001. GIS Development Newsletter. gisdevelopment.net. 2001.

Yun, L., Uchimura, K. & Wakisaka, S., 2004. Automatic Extraction of main road from Ikonos satellite imagery based on fuzzy reasoning. In Proc. the 8th International Conference on Applications of Advanced Technologies in Transportation, no. 325, (CD-ROM), Beijing, the P. R. of China, pp. 641-646, May 26-28(2004.5)

Endnotes

---

[i] See http://www.openstreetmap.org/

[ii] In Differential GPS (DGPS), each earth-fixed station, which extremely accurately knows its position, detects the error of the incoming GPS signal and propagates a correction to the surrounding receivers through radio communication

[iii] In Real Time Kinematics (RTK), the philosophy is similar to DGPS, but corrections are made to the *carrier phase* measurements (as opposed to the messages contained in it).

[iv] www.teleatlas.com

[v] http://www.tomtom.com/page.php?Page=Mapshare

[vi] http://www.gisdata.se/

[vii] Dilution Of Precision – An estimate of GPS quality based on satellite alignment with respect to the receiver

[viii] To know further on this subject we suggest for example (Goldberg, 1989)