Map Warping for the Annotation of Metro Maps

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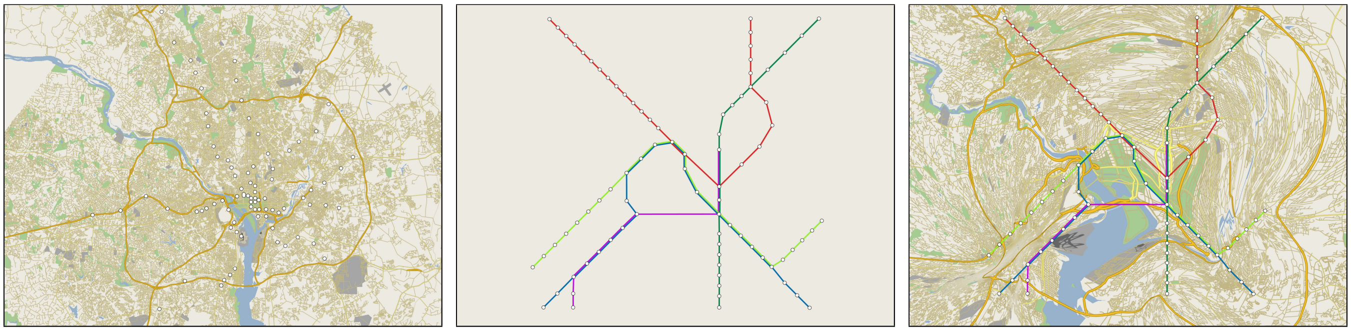

Figure 1: Geographic map of the Washington Metropolitan Area with positions of metro network stations superimposed (left). A metro map layout of the same area optimized for readability (middle). In our compound map (right), the metro map is annotated with the warped geographic map.

ABSTRACT

We augment schematic maps of transportation systems by superimposing them on street-level maps that are fitted using image warping techniques. While schematic maps are successful in conveying information about lines and connections in a public transportation network, they usually contain little or no detail describing the environment of stations or their embedding in the surrounding area. The annotation of a distorted city map therefore alleviates this deficiency and improves further the usability of schematic transportation maps by merging two different navigational spaces. Our technique for fitting the street map to the schematic map is based on moving least squares in combination with an overlap control technique. We thus obtain an easily readable transportation network map on which we can show all the typical city map features such as rivers, streets, and parks without compromising on the schematization. Furthermore, for the interactive exploration we couple zooming with warping and control over the level of detail in what we call *Warping Zoom*.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Graphical User Interfaces, Interaction Styles; I.3.6 [Computer Graphics]: Information Interfaces and Presentation—User Interfaces

1 INTRODUCTION

When people use a city's public transportation system, they are faced with a seemingly simple task: They start at one point somewhere in the city, want to get to a nearby station, look for the best connection to another station close to where they want to go, and finally want to reach that destination itself. Usually people use two maps to accomplish that task: On the one hand, an ordinary street-level city map, and on the other, a schematic map of the system of public transportation in the area.

The reason for that is, that both of these representations of our world have their advantages and disadvantages: The ordinary map is very well suited for gaining detailed information down to every single street, but for several reasons struggles to give a fast overview over the network of public transportation, even if that network is included in the map. A schematic map, on the other hand, is optimized for the readability of information concerning the connections and structure of the transportation network. However, it seldom shows the different stations in their surroundings and fails to deliver the needed contextual information for the task mentioned above.

In this paper, we describe a method to produce a compound map containing both, network and detailed street information, by warping the street map information to fit a schematized map of a public transportation network. For that warp, we use a mapping from the field of image distortion, which is especially well suited for geographical information. We also introduce a *Warping Zoom* which yields in a dynamic interactive map applicable for both, street-level navigation as well as navigation in the public transportation system.

The remainder of this paper is organized as follows: To put our work in context, in the next section we describe the properties of metro maps as well as of street-level maps. In Section 3 we introduce the basis of our method of augmenting the highly schematized metro maps with warped street-level maps. Our implementation of the method is described in Section 4. In Section 5 we present examples of the resulting technique. The paper ends with a conclusion and discussion of the results.

2 CONTEXT

We here concentrate on features of two different types of maps that serve as navigational aids in metropolitan areas. While maps of public transportation systems are designed to effectively and efficiently convey possible itineraries, street-level maps usually serve to convey relative positions and distances of a wealth of locations. These very different purposes have led to likewise differences in the design of such maps.

Maps are basically characterized by representing relations between locations. With this seemingly simple definition, we can eas-

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ily distinguish the main characteristics between the two types of maps considered here.

2.1 Street Level Maps

One goal of detailed street maps is to minimize distortion, which means showing the real world in a way which is geometrically similar to what we would see from a vantage point high above a city. Accordingly, street intersections have the same angles like in reality, and features like parks and rivers have the same distinct shapes they have in the real world. This makes it easy to mentally put ourselves on the map and to autonomously navigate through the city, since we can use the shapes to find out where we are.

Although annotations are usually disproportionate (e.g., real streets are often narrower than they are shown on a map), distances and angles between geographic features are not. The spatial relations represented in a street-level map are thus on an interval scale.

The street-level maps contain a lot more information than only the network of streets, such as landmarks, public facilities and many other aspects of the surrounding environment. By representing geographical information in addition with this very high level of detail the street-level maps show a large variety of relations between locations. This abundance of detail is necessary, since a city map is used for many different tasks, most of which require navigational decisions on a much smaller scale than the decisions that have to be made while traveling in a public transportation network.

2.2 Metro Maps

Schematic transportation maps are designed to clearly show the navigational information of the transportation system on a preferably small map. The pioneer of schematic public transportation maps, Harry Beck, conceived his well-known Tube Map of London – which is considered a design landmark and forms the basis for schematic public transportation maps today – in 1931 [1]. To achieve an expedient representation of the underground map he found it was necessary to make the central area appear larger, since the stations were closely crowded there. Drawing a map of the whole area in a limited space mapped the stations in the center too close to each other to leave space to make their connections distinguishable. Beck imagined he was using a convex lens to ensure readability in the center and in the periphery at the same time. He formulated the general design principle for metro maps to place all the stations at equal distances, although their geographical distances are very different. This also reflects the fact that the travelling time of a metro is approximately independent from the distance of the stations in the real world, since it takes a train a relatively long time to drop off and pick up passengers, and to accelerate and decelerate.

Another typical schematization requirement for metro maps is straightening the route lines by placing the stations of a line on straight lines, if possible. The overall shape is further simplified by restricting the positions of the stations to be only at a few discrete angles relative to each other, which, for example, leads to route lines only being mapped to verticals, horizontals or diagonals. This makes it easy to mentally connect stations belonging to the same line.

The resulting metro maps avoid intersections with small angles, and are generally easily and intuitively readable. The automatic layout of metro maps has recently grown into an active field of research [2, 4, 7]. However, most of the metro maps in use are still manually fabricated by designers, who tweak the maps until they look just right, and do not always strictly adhere to the aforementioned design principles. We use manually fabricated layouts as input for our method. One argument for the use of existing manually fabricated layouts is, that the inhabitants of a city are already familiar with them. We assume, that over time people have adapted their mental map of the whole city to these layouts. Subsequently adapting to a different layout imposes mental strain on them. Nevertheless, our method works with automatically generated metro maps as well.

For finding a way from one station to another station within a public transportation system the user only requires an overview of the relations between the stations concerning connectivity. Therefore, the type of relations represented in a schematic map of a transportation system is very different from that of a street-level map, because the easy perception of the existence of services and connections takes precedence over geographic accuracy. Spatial relations are preserved on an ordinal scale, if at all.

To analyze these changes, Jenny [3] used MapAnalyst, a tool originally developed for the visualization of geographical errors in historical maps. He annotates the schematic map with visual hints to aid the understanding of the implied distortion. Applying this to the London tube map, Jenny observes the typical features of schematic transportation map layouts. For example, in his scale isoline visualization, the fisheye character of that map is clearly noticeable.

Today, many schematized metro maps contain no detailed information other than the stations and their connections, but rather restrict themselves to describing the navigational space of using the transportation system as well as possible. Evidently, such maps are strongly specialized, since there is no reliable possibility of reading out any geographical accurate information about the transportation system or its surroundings.

2.3 Combination

Many city guides contain street-level maps that are annotated with the stations and lines of the local transportation system. These annotated geographic maps are suitable for many purposes, but since all advantages of schematization are lost, metropolitan areas around the world rely on schematized maps of their transportation systems.

One approach for combining schematic transportation maps with street level information are Spider Maps[1,2], which are transfer guides for metropolitan areas. A Spider Map is a schematic transportation map that centers on one station and displays the local area surrounding the station as a geographic street map, aiding the user while changing bus and metro lines. However, this makes it necessary to adjust the schematic layout for providing display space for the station of interest and its surrounding streets. Additionally, starting at an arbitrary point in the city and having to chose one of the nearby stations to walk to, a street network map centering this specific starting point is more useful than a street map centering on one station.

To alleviate the above mentioned disadvantages, we propose to annotate schematic maps with all the information usually incorporated into city maps without modifying their design, which is the opposite approach to the annotated geographic maps.

Designers sometimes include real world items such as coast lines of the sea or large rivers, but apart from that, most of the features of the real world are not shown, partly because their placement in the schematic map is not trivial. Due to the lack of distance relations in the schematic map the expedient positioning of street-level details requires an extrapolation of the deformations caused by the schematization.

The essential feature both types of maps have in common is that they contain position indicators for station locations. Since schematic maps are designed to preserve relative positions of stations, it seems natural to use them for aligning the street-level map with the schematic map.

[1] `sfcityscape.com/maps/spider.html`
[2] `tfl.gov.uk/tfl/gettingaround/maps/buses`

3 Method

The basic idea of our method is to use the positions of the stations in both of these maps to merge them in one compound depiction by warping the street-level map to fit the schematic map. Towards this end, we use the corresponding pairs of positions as control points in a warping technique from the field of image warping. The positions in the detailed map serve as starting positions, and the positions in the schematic map as end positions for this warp. This yields a mapping function which, when applied to the geographically correct map, shifts the stations to their positions in the metro map, and distributes all the other features of the real world smoothly between them. We then use this warped map to augment the schematic metro map, in order to support navigation and orientation in the parts of the real world between the metro stations.

3.1 Warping

In order to merge the two maps, we use mappings from the field of image warping. Ruprecht and Müller [5] describe different methods used for the distortion of two-dimensional information. All these methods solve the basic problem of warping: Given two-dimensional information and a set of control points in this information, the goal is a mapping function moving these control points from their starting positions to arbitrary end positions. The mapping function should have several properties for a satisfactory warping: It is supposed to be interpolating, which means that the starting positions of the control points are precisely mapped to their end positions. Furthermore, the mapping should be smooth, that is, it should not introduce discontinuities between the control points. Ideally, the mapping should also be free of overlap. This additional constraint is the main difference between our mappings and the mappings used for the above mentioned distortion analysis by MapAnalyst [3].

Triangulation-based methods suffer from foldover and other discontinuities, which are not easily solved. We therefore chose to use a warping method using scattered data interpolation and producing smooth and interpolating mapping functions. In addition, we want to keep angles in the distorted map as similar to the angles in the real world as possible, since this keeps the shapes of real world features recognizable.

Schaefer et al. [6] describe a moving least squares algorithm that interpolates a similarity transformation between the control points. This way, angles are less distorted compared with only interpolating with general affine transformations. As the authors point out, the mappings still suffer from overlap. Contrarily to the analysis and visualization of distortion, for warping geographic information, it is very important to avoid overlap, since otherwise parts of the information completely disappear. Thus, we combined the above mapping method with the overlap control described by Tiddeman et al. [8] to achieve our mapping functions.

For sake of completeness, we show all the details necessary for an implementation of our method in this section.

3.1.1 MLS

Given a set of control points p, their position after the warping q, and an arbitrary single point v, Schaefer et al. solve for the optimal affine transformation l_v that minimizes

$$\sum_i w_i |l_v(p_i) - q_i|^2. \tag{1}$$

The method is called a Moving Least Squares minimization, because the weights w_i depend on the point v:

$$w_i = \frac{1}{|p_i - v|^{2\alpha}} \tag{2}$$

The parameter α controls the decay-profile for the distance, and should be larger than 1. For our examples, we experimentally chose it to yield satisfying results, and a typical value was 1.5.

This leads to a different transformation $l_v(x)$ for each single point v. Restricting the allowed transformations to similarity transformations, Schaefer et al. find the following optimal mapping functions for the single points v:

$$l_v(x) = (x - p_*) \frac{1}{\mu_s} \sum_i w_i \begin{pmatrix} \hat{p}_i \\ -\hat{p}_i^{\perp} \end{pmatrix} \left(\hat{q}_i^T - \hat{q}_i^{\perp T} \right) + q_* \tag{3}$$

Here, p_* and q_* denote the weighted centroids:

$$p_* = \frac{\sum_i w_i p_i}{\sum_i w_i} \tag{4}$$

$$q_* = \frac{\sum_i w_i q_i}{\sum_i w_i} \tag{5}$$

Furthermore, $\hat{p}_i = p_i - p_*$, $\hat{q}_i = q_i - q_*$, $\mu_s = \sum_i w_i \hat{p}_i \hat{p}_i^T$, and $\perp$ is an operator which maps a vector (x,y) to $(-y,x)$.

We apply these mapping functions for single points individually to the points in our geographical datasets. A simple example clarifying the resulting overall mapping functions by applying them to a regular grid can be seen in Figure 2(a). In Figure 2(b), the overlapping parts of the resulting 2D mapping function are clearly visible.

3.1.2 Overlap Control

Tiddeman et al. describe a general method to avoid overlap problems. One key observation of the method is, that for any given mapping function, another mapping function can be derived by scaling the mapping, i.e. interpolating it with the identical transformation. Such a scaling operation with a scaling factor s yields, for our case, the following mapping function:

$$l_s(v,s) = (1-s)v + s l_v(v) \tag{6}$$

The other key observation of the method is, that overlap occurs at any point in a given mapping function if the determinant of its Jacobian changes signs. It is therefore necessary to restrict this determinant J to be at least positive. Since values of J close to 0 mean, that the mapping at that point compresses the warped information very strongly, Tiddeman et al. restrict J further by requiring it to be larger than a minimal value J_{min}.

J can be calculated using estimates of the partial derivatives by mapping two points close to a point v as follows:

$$\left(\frac{\partial f}{\partial x}, \frac{\partial g}{\partial x} \right) \approx \frac{l_v(v) - l_v(v + (\delta, 0))}{\delta} \tag{7}$$

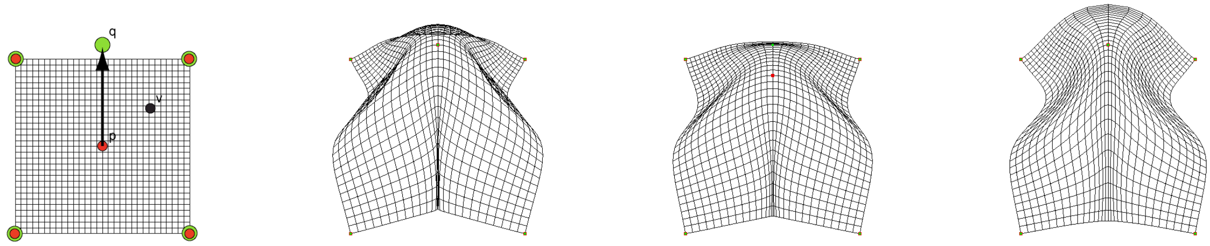
$$\left(\frac{\partial f}{\partial y}, \frac{\partial g}{\partial y} \right) \approx \frac{l_v(v) - l_v(v + (0, \delta))}{\delta} \tag{8}$$

$$J = \frac{\partial f}{\partial x}\frac{\partial g}{\partial y} - \frac{\partial f}{\partial y}\frac{\partial g}{\partial x} \tag{9}$$

Here, δ is some small value. For several scaling factors s, with $0 < s < 1$, it is guaranteed that the resulting mapping function is free of overlap. To find an optimal scaling factor, it is necessary to solve the quadratic equation

$$J = \left(\left(s\frac{\partial f}{\partial x} + 1 \right) \left(s\frac{\partial g}{\partial y} \right) + 1 \right) - s^2 \frac{\partial f}{\partial y}\frac{\partial g}{\partial x} = J_{min} \tag{10}$$

for the Jacobian determinant to be J_{min}. Solving a quadratic equation yields between two and zero roots. Since the Jacobian determinant is always equal to 1 at $s = 0$ and only gets smaller than



(a) (b) (c) (d)

Figure 2: Undistorted grid (a) with fixed control points at the corners and one control point moving the middle of the grid p to a position outside of the grid q. The MLS method results in overlap in the 2D mapping function (b). Scaling the mapping yields a mapping function (c) which moves the control point closer to its destination position. Iterating this process and concatenating the partial mappings results in a mapping function (d) fulfilling the constraints without overlap. Note how the angles at the corner are still right angles after the mapping.

the minimal value J_{min} at the roots of the equation, the mapping is locally free of overlap or strong compression for all scaling factors larger than 0, but smaller or equal to the smallest root in the interval between 0 and 1. To ensure quick convergence, the method uses this root as scaling factor. Since the control points should not overshoot their destination, 1 is used if there is no such root.

It would be necessary to solve the equation for all points in the mapping function in order to find an overall optimal scaling factor. Since this is not possible, the equation is usually solved at discrete positions on a regular grid. We solve it for every single point we map individually. Then, the overall best scaling factor is the minimum of all the locally optimal factors.

Scaling the whole mapping with the derived scaling factor yields a new mapping, which does not fulfill the constraints of the warp, but already brings the control points some portion of the way closer to their destinations, as can be seen in Figure 2(c). Iteration of the process and concatenation of the partial mappings brings the control points arbitrarily close to their destinations. A drawback of this method is, that the convergence is not guaranteed for all cases. Also, choosing J_{min} too small leads to unnecessarily strong compression, while choosing it too big prevents quick convergence. A typical value we used was 0.5. We found that with this value the overlap control worked very well for several different examples, which converged within 5-15 iterations. The result of the iterative process for our simple example can be seen in Figure 2(d).

4 Prototype Implementation

As proof of concept, we implemented a prototypical system that generates combined schematic and geographic maps.

Schematic maps are the eminent representations of public transportation services and therefore available for most larger cities.

For the geographic information, we use U.S. Census TIGER map data[3], which contain vector data of detailed street information and landmarks such as water surfaces, parks, airports and public institutions. An advantage of these vector data is the possibility to provide good quality of rendered maps over a wide range of resolutions. They also allow to transform the topography independent from, e.g., textual and symbolic labels to ensure readability. Moreover, these particular data are in the public domain and sufficiently detailed to demonstrate the potential of our approach for actual city plans. We manually annotated the data with the geographic positions of metro stations, compiling this information from other publicly available sources like GoogleMaps[4]. Figure 1 on the first page shows a geographic map of the Washington Metropolitan Area annotated with the geographically correct positions of the metro stations, the corresponding schematic metro map, and the metro map annotated with the warped geographic map.

To warp the geographic map, long lines in the original data are first sampled sufficiently fine to avoid artifacts when rendering them, and the polygons between them. This is necessary because, although the mapping functions described earlier are smooth, straight lines are mapped to curves. Note that mapping only the start and end of a line, and connecting these in the warped image again by a straight line, does not yield the desired result of smoothly deformed curves in general. After subdivision, we evaluate the mapping function for every point of the geographic vector data as described in Section 3. We neither use a grid with fixed cell size nor rasterize our data beforehand, like it is usually done in the process of applying image warping functions. The calculation of the mappings itself is time-intensive; our examples took around 1 hour to process on an ordinary desktop computer. However, the mapping has only to be calculated and saved once for every set of control points. To preserve quality, we render the distorted street-level data consisting of lines and polygons after the warp using OpenGL and GLUT, reaching interactive frame rates. In the end, the metro stations, which were manually drawn into the street-level map, have the same positions as the stations in the schematic metro map. We thus obtain a compound map showing topological and topographic information – the schematic metro map annotated with the distorted geographic map.

4.1 Gradual Distortion

A particularly nice feature of our warping approach is that it allows to interpolate the mapping between exact geography and schematization. Placing stations in a convex combination of their geographic positions and their positions in the schematized map yields a compromise between geography and schematization. This compromise can be extended to the entire compound map by linearly interpolating between the geographic map and its distortion based on the schematic map.

We will sketch an important application of this feature in the next section.

5 Examples and Use Cases

The main purpose of our work is to ease the transition between schematic maps, which are useful for navigating in a transportation system, and geographic maps, which are better suited for autonomous navigation and locating sites.

We can envision three different use cases for our method: Firstly, on large, static depictions, like wall maps at metro stations, it would

[3] `tiger.census.gov`

[4] `maps.google.com`

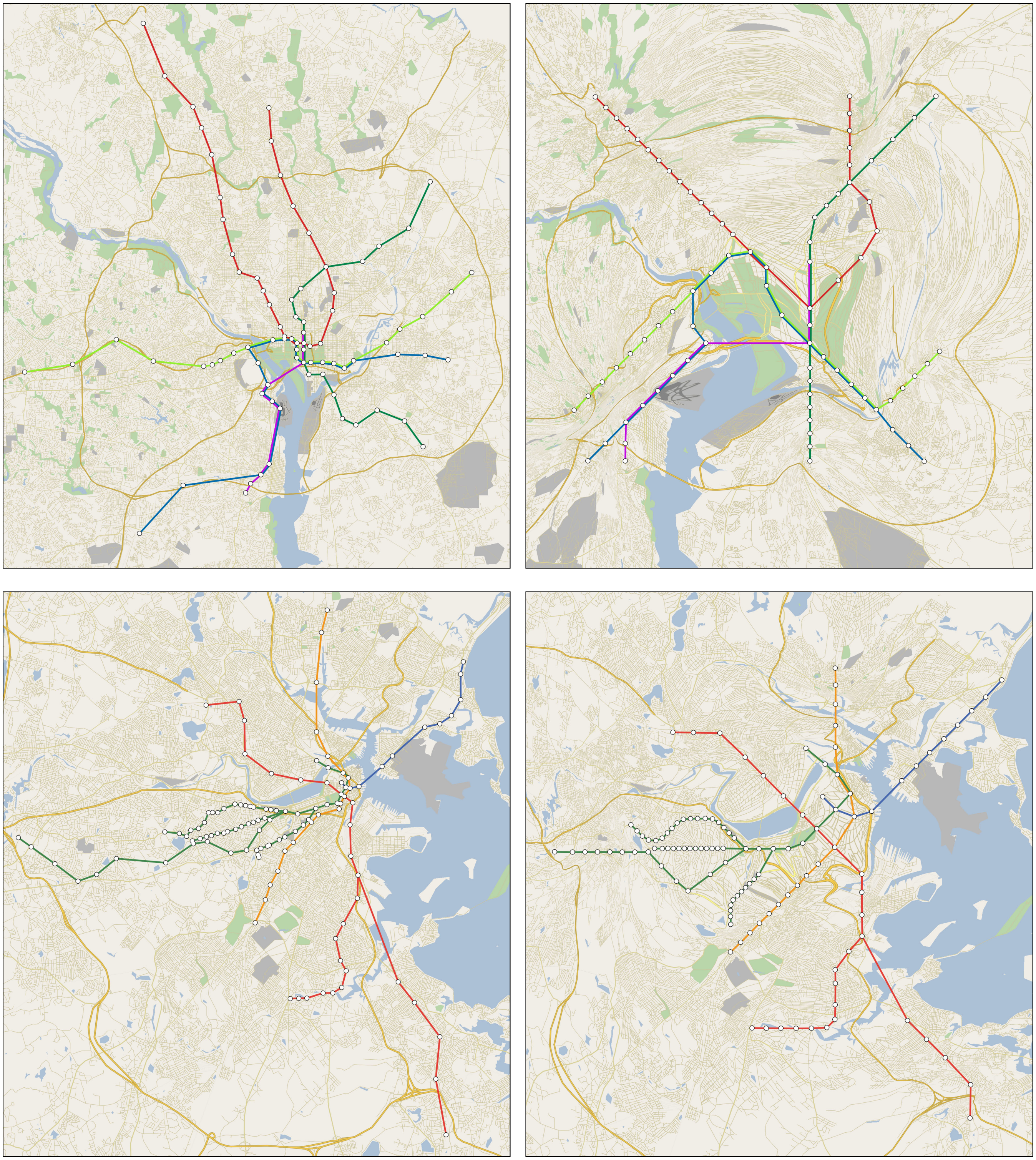


Figure 3: Geographic maps of Washington (top left) and Boston (bottom left). On the right, the maps are fitted to the respective schematic metro maps. Note that it is now possible to discern details in the cities' centers, which are not visible on the left, due to the fisheye-like character of the implied mapping functions.

be possible to show more detail where it is needed compared with an ordinary map.

Secondly, with limited space, a static overview over the compound map yields annotation of the schematic map with a focus on large streets and landmarks, but can still aid rough orientation in the city. These two cases already make it obvious that level of detail needs to be addressed.

The most interesting use case is the interactive application of our method for small displays, like PDAs. Here, our method can really demonstrate the advantages of linking the two navigational spaces, as we will describe in Section 5.2.

As mentioned earlier, we require as input a street-level map of an arbitrary city annotated with the stations of its transportation system and a schematic transportation map of the respective city. We applied our method to maps of the Washington and the Boston area. We chose these two cities because they contain typical features like airports, lakes, rivers, coastlines, islands, harbors, parks as well as a fairly complex transportation system with nontrivial graph structure. Exemplarily we present geographic and compound maps of the transportation systems of the cities in Figure 3. In the Boston case, the center of the area is greatly magnified compared to the surrounding area, similar to a fisheye lens. This effect is even more clearly visible in the compound map of the Washington map. The mapping functions manage to keep the areas close to the stations relatively undistorted, while areas between the stations are more strongly stretched.

5.1 Level of Detail

Addressing level of detail turned out to be an important issue for our technique. Since showing all the small details on a limited space can lead to indistinguishable visual clutter, it was necessary to consider the local magnification and compression for the depiction of the different features of the geographic map. During the iterative mapping, we calculated for each point an estimation of the partial derivatives at that point for overlap control. We can use these estimations for level-of-detail control as well, since the determinant of the Jacobian yields the local area magnification, and its condition number is proportional to the local compression.

We found it helpful to modify the thickness of linear features like streets directly proportional to the local magnification, and indirectly proportional to the compression. This way, the density of features is evenly distributed over the whole depiction.

5.2 Interactive Warping Zoom

For the task of street-level navigation, the typically small map size of schematic metro maps is inapplicable. In order to read the navigational information of the street level, the annotated metro map needs to be enlarged to the size of a regular street-level map or the compound map needs to be enhanced by an interactive zooming technique.

The enlargement of the compound map contradicts the main advantage of schematic maps, which is to give a quick overview over the transportation system on a preferably small map. So we chose to implement a zooming technique, which couples scaling of the viewport with a transition between our schematic compound map and the geographically correct compound map, which equals the undistorted street-level map annotated with a geographical transportation map. To achieve the transition between the two maps we take advantage of the gradual distortion technique introduced in Section 4.1. While zooming, we interpolate between the distorted and the undistorted map and simultaneously translate the map in a way that keeps the center of the map at a constant position on the screen. This technique we call *Warping Zoom*.

The effect of our *Warping Zoom* technique is shown in Figure 4. The resulting dynamic compound map is especially well applicable on mobile devices: because their display size is usually very small, dynamic maps with zooming functionalities are generally favored. While zoomed out of an interactive general city map, the user wants to get a quick overview of the city. When zooming in, the user wants to get detailed information about a specific region or point or even wants to read navigational information of the street level.

Contrarily, in case of navigation within the city with use of public transportation, the destination is reached approximately by public transportation. This navigation step is aided adequately by a schematic transportation map. So, when zooming out, the user gets a quick overview of the transportation system – which is naturally a schematic layout of the transportation system. In our implementation this schematic transportation map is annotated by warped street-level information in an adequate level of detail. The stations of the transportation system are the interfaces between two navigational spaces – the transportation system and the street-level space. Leaving the transportation system at a specific station, the user has to navigate on the street level to reach the destination exactly. Therefore, the user requires geographical accurate information about the surroundings rather than a quick overview of the transportation system he just left. Additionally, since just a few stations are displayed on the zoomed section, the advantages of schematization are invalidated. Thus, when zoomed in, the compound map has to be displayed in an undistorted/unschematized layout.

We found that, in order to make the interpolation between the distorted and the undistorted map feel intuitive, we had to define start and end scaling factors for the transition considering the configuration of the different maps and display sizes. We display the undistorted compound map when only a few stations are visible. The other extreme is defined once the whole schematized metro map just fits into the viewport.

The level-of-detail-control makes all steps of the transition readable: On the coarsest level, the schematic map is mainly annotated with the most prominent features of the city, like parks, rivers and large roads. The smaller streets appear more clearly when the user zooms in and wants to navigate in the street network.

5.3 Distance Information

To aid in the understanding of the geographical distance relations in the schematic view, we found it helpful to annotate the metro map with isolines at certain distances from the closest stations. During the iterative mapping, we distort the points of a regular grid in addition to the street-level data. Towards this end, we apply the mapping function to the single grid points, which results in a distorted grid as can be seen in Figure 5.

We can then visualize the real world distances from points in the map to the next station by firstly calculating the distance of every regular grid point to the closest station. Then, applying a marching squares algorithm to the distorted grid yields isolines denoting equal distances to the closest station in the real world.

While for the undistorted grid, these isolines consist of circular shapes centered around each station, the shapes are more complex after the distortion, as can be seen in Figure 6. For example, two stations, which are close to each other, are connected by an hourglass-like structure. Moreover, a gap between these structures indicates large distances between the corresponding stations.

This way, for example, the appropriate selection of the nearest station to a specific destination can be supported.

6 Conclusion and Future Work

We presented a method to annotate schematic transportation maps with street-level information of the respective city. With the introduced *Warping Zoom* we attain a dynamic map that is as applicable for street-level navigation as for navigation in a public transportation system. When the user switches navigational spaces by leaving the station of a public transportation system, switching map layouts

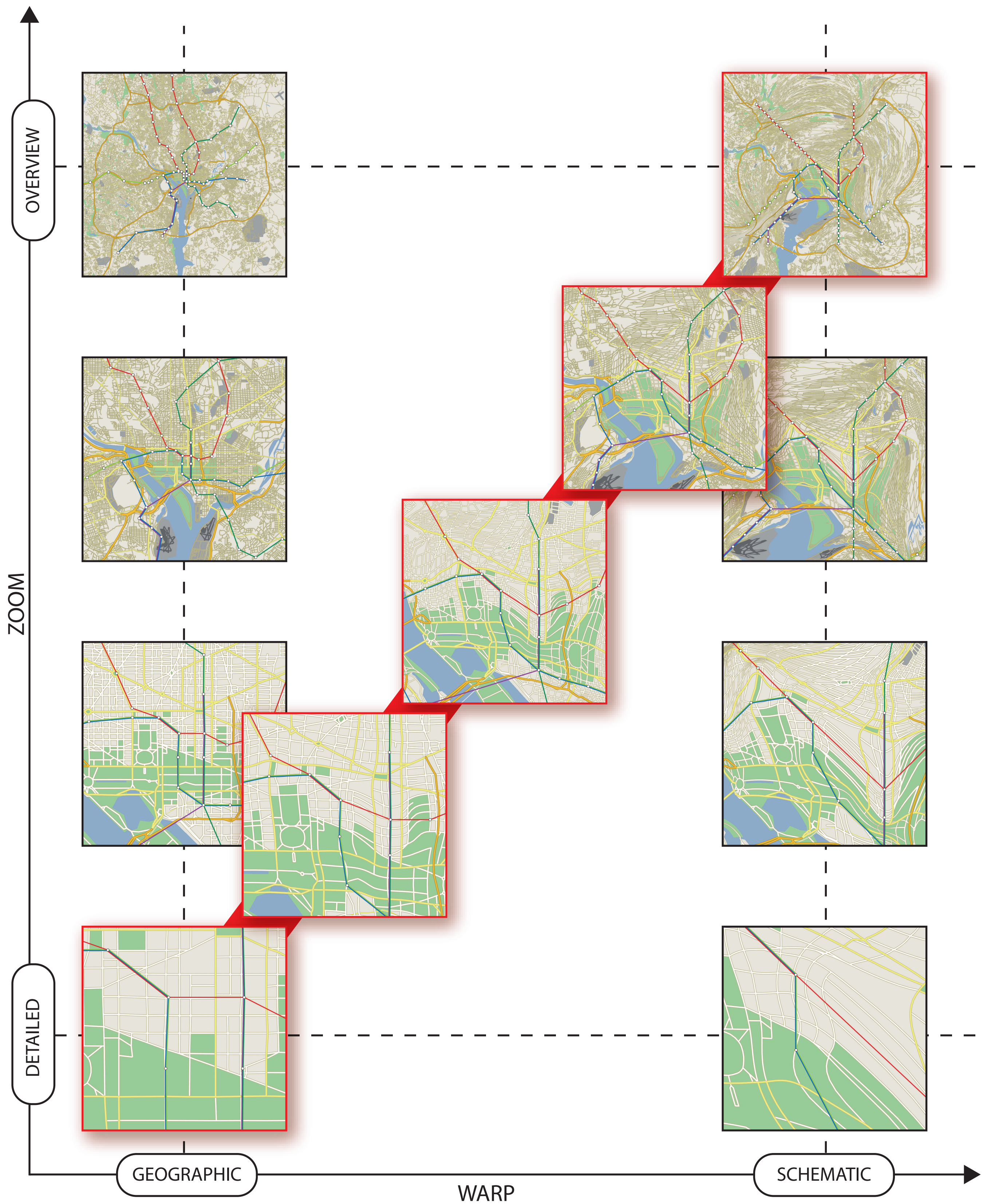


Figure 4: The Warping Zoom (here shown on the diagonal in red) is a combination of zooming and at the same time warping between the schematized and the geographically correct map: This makes it possible to employ the schematized layout for an overview, and to employ a detailed geographical layout for localization and street-level navigation. Note that it is not possible to discern the connections in the center of Washington in the geographic overview (top left) in this resolution.

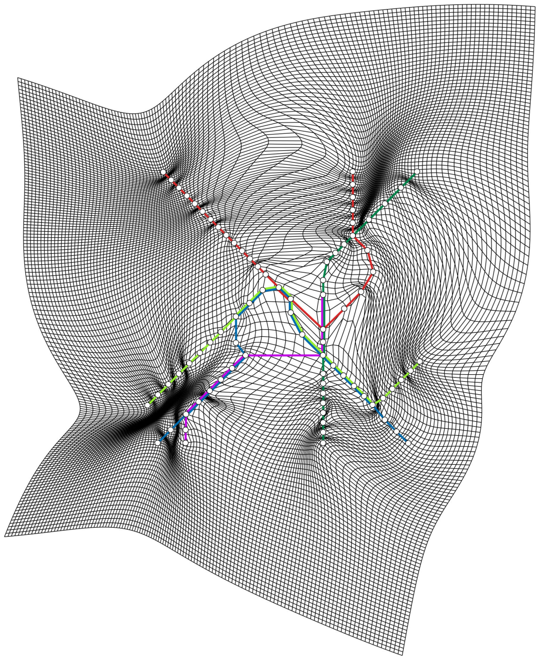


Figure 5: A regular grid distorted with the same mapping as the one used for warping the Washington data in Figure 3. The grid is used to render isolines around the stations in order to aid in the understanding of the geographical distance relations.

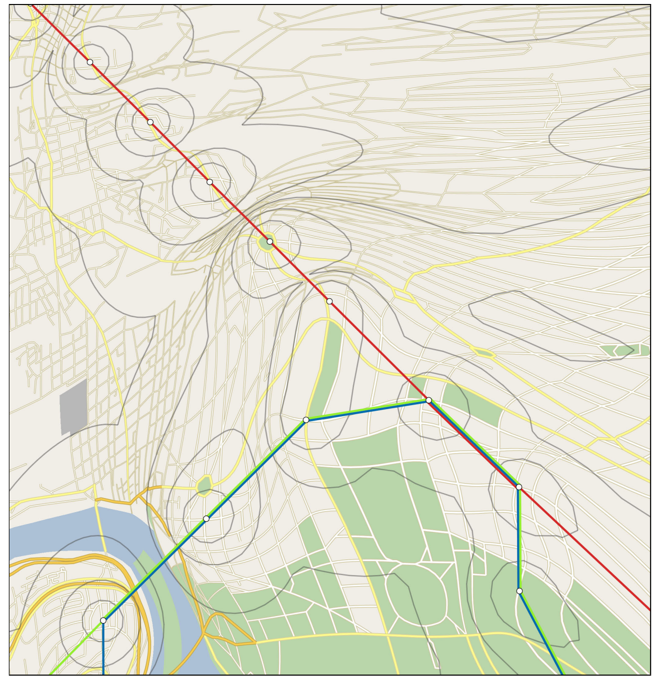


Figure 6: Isolines around stations. The lines are at constant geographic distance to the closest station, so that nearby stations are connected by blob-like shapes, while gaps between these shapes indicate large distances.

is advisable as well. The reason is, that the user needs to read out disparate relations by switching navigational spaces: connected stations versus geographical relations of streets and city details. Our zooming technique implements this switching of layouts by continuous warping between the distorted schematic compound map and the geographical compound map. Only applying an ad-hoc map switch apart from zooming would require the user to find the old position on the new map. In addition the user might lose orientation. The in-between layouts, which are partially distorted/schematized, can support more complex navigation scenarios, for example, in a situation where a trade-off between the readability of walking distances and connectivity between metro stations has to be made.

Our method has still some shortcomings: First of all, it is not clear whether the used mapping functions are optimally suited for our perception of geographical information. They stress the importance of keeping angles locally intact, maybe at the expense of readability for extreme distortions.

Although we think existing handmade metro map layouts are still clearly superior to automatically generated ones, merging our method with a method for the automatic generation of metro map layouts seems promising. This way, it might be possible to find an even better compromise between detail and schematization, avoiding extreme distortions in the street-level map and hard to read configurations in the superimposed schematic representation.

We are aware of the fact that our renderings do not posses all the features of commercial city maps. We have not addressed, nor implemented more advanced algorithms for the rendering of labels, symbols and additional data sources. However, their application is independent from our technique. The purpose of this paper is to demonstrate the utility of our method for combining schematic and geographic maps, not a fully-featured map generator.

We also believe that there are other opportunities for the application of our technique in the area of graph visualization, annotation of route sketches and similar fields.

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