Focus+Context Metro Map Layout and Annotation

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Abstract

Annotated metro maps, which are a graphic representation abstracting a city's transportation network and providing additional details about a city, can be difficult to draw because of the landmark density around many city centers. A focus+context illustrated map is therefore commonly used to provide detailed information around a focus region while preserving the context area, so that map readers can retain a mental image of a city. Nonetheless, conventional techniques do not sufficiently retain layout octilinearity of the navigation system, especially when large deformations are required, as when there are significant landmarks around central stations. This paper introduces focus+context annotated metro maps, a design emphasizing focus regions by embedding landmark icons around the stations together with aesthetically aligning metro lines and label leaders in an octilinear fashion. Our idea is to employ the conventional fisheye technique when considering appropriate edge lengths in a focus region and to generate sufficient space around the labeled stations by introducing a relative neighborhood graph for deformation purposes. This is accomplished by introducing appropriate design conditions into a linear program so that we can constrain the positions of stations and labels while preserving octilinearty within both the focus and context regions. The optimization problem is then solved in a least square sense. We also provide a user interface for customizing maps through intervention and present several design examples to demonstrate the effectiveness of the approach.

Keywords: Annotation labels; relative neighborhood graph; linear programming; conjugate gradient method;

Concepts: •**Human-centered computing** → **Geographic visualization;**

1 Introduction

Tourist maps are graphic representations that abstract the image of a city to support visitors in an unfamiliar city. Metro maps are typical tourist maps that depict station connectivity and show where to transfer for destinations within the metro systems. Annotated metro maps are metro maps embedded with significant information associated with the stations of the transportation system. To improve the usability of these maps, illustrators always consider readability and memorability of maps as their primary design factors. More than just providing information, these maps are designed to enhance readability so that users can understand and memorize significant information in a short period of time.

To improve the readability, schematic representations are often introduced to simplify complex layouts; the most commonly employed aesthetic criteria were developed by Beck in 1931 [Roberts 2003]. In his design, metro lines are aligned to horizontal, vertical, and 45-degree diagonal directions. In addition, as Lynch reported in 1960, people understand and form their mental map of a city consistent with elements such as paths, nodes, and landmarks in the city [Lynch 1960]. To support new visitors of a city, tourist maps are also intentionally designed by employing these representative elements, especially including metro lines and landmarks. However, due to the limitation of the screen space and the paper size, showing all network stations together with significant landmarks usually results in unexpected occlusions between objects or small annotations around the stations. To solve this, we introduce focus+context metro maps to provide detailed information around a focus region (urban area) while still preserving the secondary information of the context region (suburb area). Our focus+context annotated metro map is designed based on the aforementioned two factors and allows users to navigate the map by clicking on one of the points of interest (POIs).

The focus+context annotated metro map concept emphasizes focus regions by embedding landmark icons around stations together with aesthetic alignment of metro lines and label leaders in an octilinear fashion. This is accomplished by transforming appropriate design criteria to mathematical constraints in a linear program so that we can control the positions of stations and labels while preserving the octilinearty within both focus and context regions. The idea here is to expand metro edges effectively in the focus area by incorporating a relative neighborhood graph (RNG). Then we improve the conventional fisheye techniques to estimate appropriate edge length in the RNG and gradually expand the graph by preserving the relative position of stations on the maps. This problem is formulated as a linear system, and the optimization problem is solved in a least square sense.

The remainder of this paper is organized as follows: We first briefly summarize related work in Section 2 and then presents a system overview together with design rules for customizing our focus+context annotated metro maps in Section 3. Section 4 presents the algorithm, which consists of the graph construction and mathematical formulation of those design rules. In Section 5, several experimental results and a discussion are presented to demonstrate the feasibility of our system. We then conclude this paper and propose possible future extensions in Section 6.

2 Related Work

In this section, we review two research topics, including automatic metro map design and focus+context lens techniques.

The pioneer of the schematic metro map design can be traced back to 1933, when Harry Beck introduced several aesthetic design rules and created the first tube map of the London Underground [Roberts 2003]. To improve the readability of the maps from a perceptual point of view, Beck aligned metro line segments with one of the octilinear directions. Automatically generating such octilinear layouts is challenging because aligning line segments to octilinear directions has discrete properties which lead to high computational time, as described by Wolff [Wolff 2007] and Nöllenburg [Nöllenburg 2014]. These methods include energy-based algorithms and mixed-

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integer programming (MIP) techniques. The first model formulates the layout octilinearity property as a soft constraint, while the MIP model allows us to strictly align edges to octilinear directions by formulating this criterion as several hard constraints. More recently, Wang et al. revisited this problem and accelerated the energy-based optimization approach by separating octilinearity constraints into an additional optimization step [Wang and Chi 2011] [Wang and Peng 2016].

Moreover, to provide more information about a city, metro maps are also designed to incorporate additional guidance such hotels and restaurants as annotation labels [Takahashi 2015]. Böttger et al. proposed map wrapping [Böttger et al. 2008], where they added a distorted street map as annotation to the schematic metro maps. Claudio and Yoon then extended this technique on the schematic layout generated by the MIP model to compose a transit-centric map by adding points of interest (POIs) to metro networks [Claudio and Yoon 2014]. Both of these two techniques provided a semantic zoom function for exploring the detail of maps, but users unexpectedly lose the global context of transit information during navigation. Wu et al. also presented several techniques for creating annotated metro maps [Wu et al. 2012] [Wu et al. 2013] [Wu et al. 2015] based on the MIP model; however, fully optimizing this problem may not be applicable to navigation.

Lens techniques are also often introduced to explore data in detail [Tominski et al. 2014]. Geometric fisheye views, a magnification lens technique, is probably the most popular technique for generating focus+context views. The space around the focus is distorted to create a zoomed and detailed region that is also smoothly integrated with the surrounding context area. Gansner et al. presented topological fisheye views [Gansner et al. 2005] in which they successfully employed the concept of conventional geometric fisheye views and applied them on topological structures such as graphs. Afterward, Feng et al. demonstrated multifocus-context views for time-varying graphs by introducing triangle meshes for mental map preservation [Feng et al. 2012]. Interactive fisheye-based navigation of diagrams is also proposed to show the benefit of the magnification lens [Woo et al. 2009]. More recently, Cohé proposed *SchemeLens* [Cohé et al. 2016], whereby they magnify diagrams by referring to user navigation history.

Nonetheless, none of the previous lens techniques considers allocating additional space for thumbnail labels during the magnification process while still preserving schematic properties. In this paper, we improve the optimization framework provided by Wang et al. [Wang and Chi 2011] [Wang and Peng 2016] by incorporating the fisheye lens into the focus region on the metro maps. Thus, we can prepare sufficient space around the stations and assign appropriately sized landmark labels around the stations.

3 System Overview

We show the design framework of our focus+context annotated metro maps followed by an introduction of selected design principles in this section.

3.1 System Framework

In our approach, we aim to generate sufficient space around target stations to place labels that represent either landmarks or additional information. Figure 1 illustrates the flowchart of our system design. We first give network data with the geographical position of stations and their corresponding transfer information as input (Figure 1(a)). With this geographical map, the users are allowed to assign a point of interest and the magnification range and scale around the assigned POI. Users can also indicate their interest in landmarks near stations within the focus region (Figure 1). Once this setting is accomplished, the system will automatically compute a relative neighboring graph for controlling the geometry of the magnified metro lines, smoothing the layout for seeking possible space for the thumbnail labels, and therefore rearranging each edge orientation to its closest octilinear direction to compose a focus+context layout. To achieve this, a linear programming formulation is introduced to minimize the distortion of the map so that we can embed annotation labels in the focus region while still preserving the octilinearity of the layout.

3.2 Design Principles

In this section, we introduce important design principles for enlarging the focus area as well as placing labels within this area to compose our metro maps. After investigating several design examples in the published guidebooks [Takahashi 2015], the following are significant criteria we selected for composing a deformed focus+context annotated map:

(S1) Focus edge length: Edges at the center of a focus should be magnified; however, the ones close to the focus boundary should be as uniform as the ones in the context area.

(S2) Context edge length: Edges in the context area should preserve uniform length as conventional metro maps.

(S3) Maximal angles of incident edges: Maximize the angles between incident edges that are connected to the same stations.

(S4) Relative positioning: Preserve the vertex embeddings of a planar network.

(S5) Edge octilinearity: Align all line features (metro lines and label leaders) along octilinear directions.

(S6) Overlap-free layout: Avoid intersections and overlaps among line features and area features (annotation labels).

4 Layout and Annotation Optimization

This section describes the core of the present algorithm, which can be decomposed into three computation steps. It includes constructing a *relative neighborhood graph* (RNG) for controlling the layout geometry, smoothing the layout to retrieve possible good vertex positions, and rearranging the line features into octilinear directions. Note that in our formulation, the network is represented by a graph $\mathbf{G} = \{\mathbf{V}, \mathbf{E}\}$, where $\mathbf{V} = \{\mathbf{v}_0, \mathbf{v}_1, ..., \mathbf{v}_n, \mathbf{c}_0, \mathbf{c}_1, ..., \mathbf{c}_k\}$ represent the stations and the center of enabled labels, and $\mathbf{E}$ includes metro edges and label leaders. Each $\mathbf{v}_i = (\mathbf{v}_{i,x}, \mathbf{v}_{i,y})$ in $\mathbf{V}$ denotes the vertex position on the map, while labels can be considered as the same condition but with area. This needs to be carefully considered because the conventional deformation algorithm only consider stations as single vertices. In this paper, we introduce the optimization scheme proposed by Wang and Chi [Wang and Chi 2011] to achieve deformation while avoiding occlusions between stations and labels. Wang and Chi introduced three main mathematical constraints, including regular edge length, maximal angles of the incident edges, and minimal distances to the geographical positions, to the energy terms [Wang and Chi 2011]. The main purpose of their approach is to find the unknown position of stations V' and $\tilde{V}$ after smoothing and aligning steps, respectively. The energy terms are effectively solved in a least square sense. In our approach, we add a preprocessing step, constructing a relative neighborhood graph, to control the amount of deformation before aligning edges to octilinear directions.

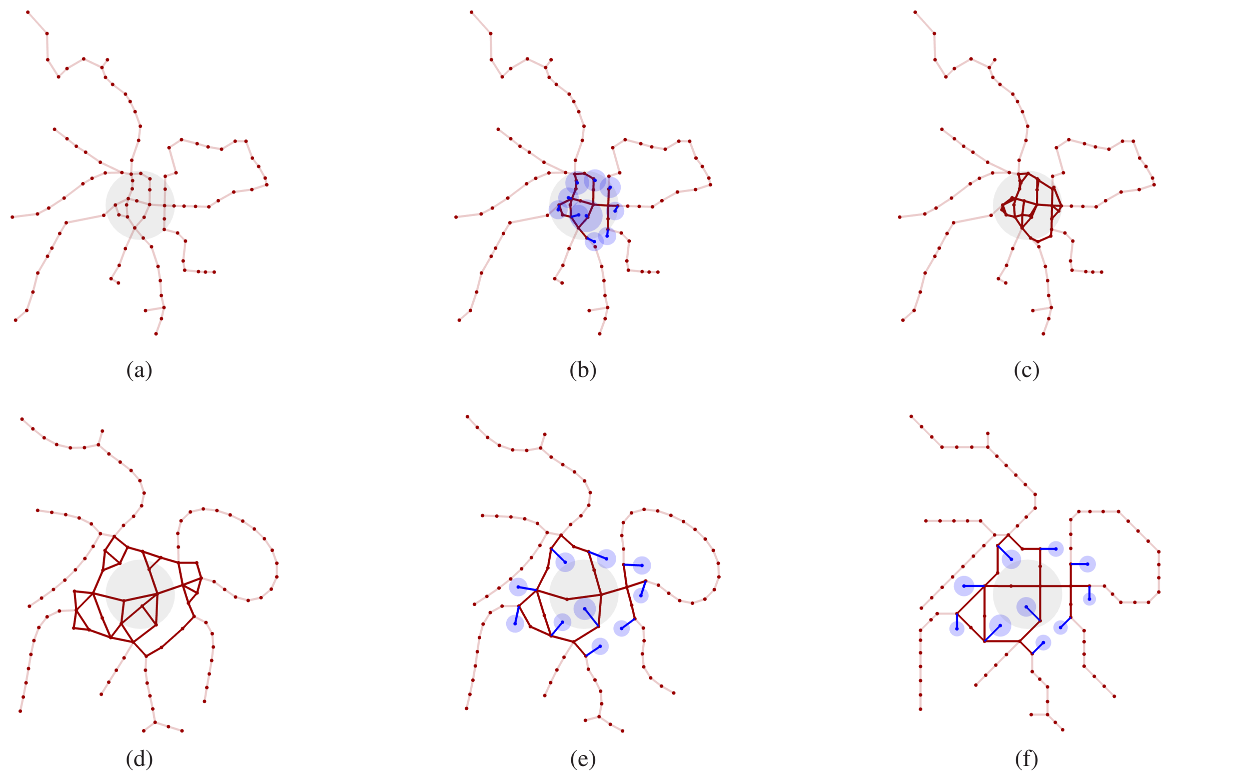

Figure 1: *A system scenario overview applying our approach to the Taipei metro system. This includes six steps. (a) A given input network with geographical position and connectivity of the stations. (b) User-enabled labels in a manually selected focus region. (c) The constructed Urquhart graph with magnified focal edges by referring to the focus center in (b). (d) The layout is then smoothed to enlarge the focus area for thumbnail pictures. (e) The labels are then placed according to the leader length after the smoothing process. (f) Finally, metro lines and label leaders are rearranged to octilinear directions; additional rendering styles are also incorporated at this step.*

4.1 Relative Neighborhood Graph (RNG) Construction

In order to preserve the sparseness and the geometry of the metro layouts, we introduce a relative neighborhood graph for controlling the metro layout in the focus region. Here, we choose the Urquhart graph as our RNG because we do not attempt to limit the degrees of freedom of the layout and increase the computational complexity. An Urquhart graph is type of relative neighborhood graph that can be simply computed by removing the longest edge from each triangle in the Delaunay triangulation [Urquhart 1980]. In other words, we first construct a Delaunay triangulation and remove any edge $e(i,j)$ in the Delaunay triangulation, if there exist edges $e(k,i)$ and $e(k,i)$ that satisfy the condition $|e(i,j)| > \max\{|e(k,i)|, |e(k,j)|\}$. Initially, we have an input graph and compute the corresponding Urquhart graph. Then we compare the input metro network graph and the generated Urquhart graph; if the edge appears in the Urquhart graph but not in the input network graph, we add the edge as long as one of its end points is located at the focus area. With this process, the resulting graph will be equal to the one obtained without the edge removing process if the target longest edge belongs to a metro line.

Once we have the RNG, we are ready to assign the ideal edge length in the focus area and the context area. For the vertex size, we extend the idea from SchemeLens [Cohé et al. 2016], where they limit the scale of magnification by referring to its intrinsic size to avoid disproportionally large vertices. For each vertex v_i in the focus region, we assign degree of interest (DOI) as

$$DOI_v(v_c, v_i) = doi_m - \frac{(doi_m - 1) \times |v_c - v_i|}{r}, \tag{1}$$

where r represents the radius of the circular focus region, and $|v_c - v_i|$ indicates the Euclidean distance to the focus center v_c. doi_m is a user-specified value for controlling the maximum doi scale in the focus region. Note that the vertex v_i outside the focus region is set to 1 to keep the uniformity of each edge length. As for each edge, we compute its DOI by averaging the DOI of its end vertices as

$$DOI_e(v_i, v_j) = \frac{DOI_v(v_c, v_i) + DOI_v(v_c, v_j)}{2}. \tag{2}$$

Once the DOI is computed, the scaling factor of the vertex v_i is then given by

$$F_v(v_i) = 1 + (DOI_v - 1) \times exp(-\frac{A(v_i)}{A_{\text{avg}}}), \tag{3}$$

where $A(v_i)$ indicates the surface area of v_i, and A_{avg} is the average of all vertex surface because we use larger circles for representing interchange stations in the layout.

As for the scaling factors of edges, in practice, we categorize edges into three types and assign an ideal length to each type as shown in Figure 2. In this figure, white vertices are stations and blue vertices represent centers of two labels. Thus, type a indicates edges that connect two stations, type b are edges connect one station and one label, and type c represents edges connect two labels, respectively. Note that we use the scale factor $F_v(v_i)$ for the corresponding leader edge l_k that is connected to v_i (type b in Figure 2(a)). Edges of type c in Figure 2(a) are a special case, where we sum the F_v of the corresponding endpoints to obtain the appropriate long edge length between two labels. With this, we can control the disproportionally long leader edges, especially the ones that are close to the interchange stations.

Except for the leader edges, the scaling factor of edge $e(v_i, v_j)$ (type a in Figure 2(a)) is set as

$$F_e(v_i, v_j) = 1 + (DOI_e - 1) \times exp(-\frac{|v_c - v_i|}{r}). \tag{4}$$

Here, we expand shorter edges but retain the length of longer edges to prevent unexpected long edges in the relative neighborhood graph. Suppose the regular edge unit is set as 1, which we will discuss further in Section 4.4.

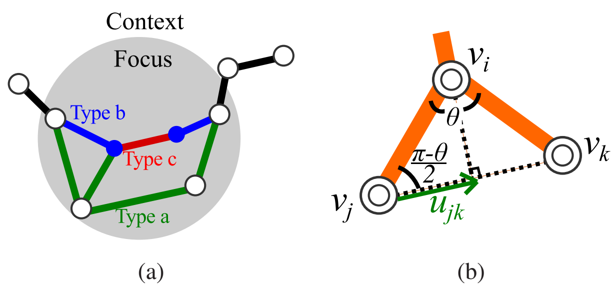

Figure 2: *Design of focus+context maps, including (a) types of ideal edge length and (b) ideal angles of incident edges sharing a vertex v_i.*

4.2 Smooth Deformation

Once we have determined the ideal length of each edge, we can then deform the layout with this information. Here, we improve the formulation by Wang et al. [Wang and Chi 2011] to create our focus+context annotated maps, but we follow their deformation scenario by smoothing the layout before aligning edges to octilinear directions. This is accomplished by formulating the aesthetic criteria to mathematical constraints and minimizing these constraint in a least square sense. The objective function is defined as

$$\Omega = w_{s1}\Omega_{s1} + w_{s2}\Omega_{s2} + w_{s3}\Omega_{s3} + w_{s4}\Omega_{s4}, \tag{5}$$

where $w_{s1}\Omega_{s1}$ and $w_{s2}\Omega_{s2}$ minimize the difference between real and ideal edge length in the focus and context area, respectively. $w_{s3}\Omega_{s3}$ maximizes the angles spanned by the incident edges and $w_{s4}\Omega_{s4}$ minimizes the distance to the geographical positions. More details will be described one by one as follow.

Focus edge length (S1): To achieve our focus+context layout, the ideal edge length is computed in Section 4.1 and we minimize

$$\Omega_{s1} = \sum_{e(v_i,v_j)\in E} |(v_i' - v_j') - d_{ij}R_{ij}(v_i - v_j)|^2, \tag{6}$$

where $v_i' \in V'$ represent station positions after this smoothing process, and $d_{ij} = F_e \times D_{\text{avg}}/|v_i - v_j|$. F_e is the scaling factor of the edges and D_{avg} represents the average of all ideal edge lengths. $R_{ij} = [\begin{smallmatrix} cos\theta_{ij} & -sin\theta_{ij} \\ sin\theta_{ij} & cos\theta_{ij} \end{smallmatrix}]$ is a rotation matrix that allows us to gradually adjust the edge orientation in the optimization process [Wang and Chi 2011]. In this matrix, θ_{ij} is the unknown rotation angle, which will be gradually updated at each iterative step of the optimization process.

Context edge length (S2): For the context edges, we set ideal edge length as $d'_{ij} = D_{\text{avg}}/|v_i - v_j|$ instead of d_{ij} in Eq. (6).

$$\Omega_{s2} = \sum_{e(v_i,v_j)\in E} |(v_i' - v_j') - d'_{ij}R_{ij}(v_i - v_j)|^2. \tag{7}$$

Maximal angles of incident edges (S3): To distinguish the metro lines effectively, the angles spanned by two incident edges of a vertex should be maximized. As shown in Figure 2(b), this idea can be accomplished by maximizing θ, whose maximal values is equal to $2\pi/degree(v_i)$, where $degree(v_i)$ is the number of edges sharing the same vertex v_i. We assume that edges connected to vertex v_i have identical lengths and thus the relative positions of v_i, v_j, and v_k can be preserved by minimizing the following energy term:

$$\Omega_{s3} = \sum_{v_i'\in V'} \sum_{\substack{e(v_i,v_j),\\ e(v_i,v_k)\in E_m}} |(v_i' - (v_j' + u'_{jk} + M_{jk}u'_{jk})|^2, \tag{8}$$

where $u'_{jk} = \frac{1}{2}(v_k' - v_j')$, and $M_{jk} = R(\frac{\pi}{2})tan(\frac{\pi-\theta}{2})$. E_m includes the embedding of edges sharing vertex v_i. Note that $R(\frac{\pi}{2})$ is a 90 degree counter-clockwise rotation matrix.

Relative positioning (S4): Since the relative position of vertices have been defined in the current formulation, geographical positions help to determine where the stations should be placed on the map. This can be achieved by slightly minimizing the distance between the current position and the geographical position of a station. The corresponding energy is then given by

$$\Omega_{s4} = \sum_{v_i'\in V'} |v_i' - v_i|^2. \tag{9}$$

To achieve the first smoothing step of the approach, in our experiment, we set the weight of each energy term as $w_{s1} = 5.0$, $w_{s2} = 2.5$, $w_{s3} = 1.0$, and $w_{s4} = 0.025$.For more details, please refer to [Wang and Chi 2011].

4.3 Edge Octilinearity (S5)

In this second step, the edge orientation is discretized to be aligned horizontally, vertically, and diagonally at 45-degree direction. We have already obtained the implicit edge length in the first step. The objective function is then rearranged as

$$\Omega = w_{s4}\Omega_{s4} + w_{s5}\Omega_{s5}, \tag{10}$$

where

$$\Omega_{s5} = \sum_{e(v_i,v_j)\in E} |(\tilde{v_i} - \tilde{v_j}) - O(v_i' - v_j')|^2. \tag{11}$$

Note that $\tilde{v_i} \in \tilde{V}$ and O is a function that rotates the edge to its closest octilinear direction and is precomputed before the optimization process. Here, in our experiment, we set the weight of each energy term as $w_{s4} = 0.025$ and $w_{s5} = 10.0$.

4.4 Implementation

In our optimization scheme, we consider each label center as a single vertex with various height and width in the graph. Thus, we can apply the optimization technique introduced by Wang et al. [Wang and Chi 2011] in order to align metro lines and label leaders in an octilinear fashion. In this optimization scheme, the system tries to find the deformed station position V' in the smoothing step, and $\tilde{V}$ in the alignment step can be achieved in a similar way. The aforementioned constraints are transformed into a linear system $\mathbf{AV}' = \mathbf{b}(\mathbf{V}')$. Since we have more constraints than variables, the matrix is overdetermined and is then solved using $\mathbf{V}' = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}'$. In practice, we apply the conjugate gradient method [Hestenes and Stiefel 1952] for minimizing the objective function.

Because the conjugate gradient method allows us to iteratively solve this problem, we avoid the overlaps of labels by testing the overlaps and introducing additional terms at each iterative step (S6). The term is defined as follows:

$$\Omega_{s6} = \sum_{v_i, e(v_j, v_k) \in C} |(v_i' - p_{jk}') - \delta(v_i - p_{jk})|^2, \qquad (12)$$

where $\delta = \epsilon / v_i - p_{jk}$. ϵ indicates the minimum distance between vertex v_i and edge $e(v_j, v_k)$, so we assign the value as the length of the corresponding label leader. p_{jk} is the closet point to vertex v_i on edge $e(v_j, v_k)$ and can be roughly estimated at each iterative step. The weight w_{s6} is then set as 20.0.

5 Results and Discussion

In order to demonstrate the usability and feasibility of our approach, we have developed an interactive visualization system that allows users to operate the system with the given network data. Our system has been implemented on a desktop PC with Quad-Core Intel Xeon CPUs (3.7GHz, 10MB cache) and 12GB RAM. The source code was written in C++ using OpenGL for rendering the network layouts, OpenCV for handling images, CGAL library for constrained Delaunay triangulation, and Eigen library for matrix computation.

Figure 3 presents focus+context Taipei metro maps in octilinear layouts as the cursor explores from the left to right side of the map. As shown in the figure, several significant landmarks of Taipei city pop up dynamically when the users click the center focus region using a mouse. These landmarks are placed close to the station while still preserving their relative positions with metro stations. Figure 4 demonstrates another example generated using our approach. This is the focus+context metro map of Vienna. The effective map deformation allows the users to interactively explore the center of the city while creating effective mental maps of the city. We also give a comparison with different doi_m in Figure 5, where small doi_m generates small map distortion, and large doi_m provides a larger view of the focus area. As a limitation of the approach, we do not claim that the approach fully aligns the edges octilinearlly, but it provides a visually plausible alignment.

6 Conclusion and Future Work

This paper has presented an approach to generating focus+context annotated metro maps. The present approach allows us to effectively deform the focus area to allocate sufficient space for annotation labels. A fisheye magnification lens is introduced to expand the focus region while still visually preserving the octilinearity of the layout. Our future work will include extending the single focus lens to a multi-focus lens and employing schematic road maps around the metro layout. Moreover, we also consider proposing a more sophisticated user interface for editing the maps, as well as introducing a formal user study to demonstrate the effectiveness of the approach.

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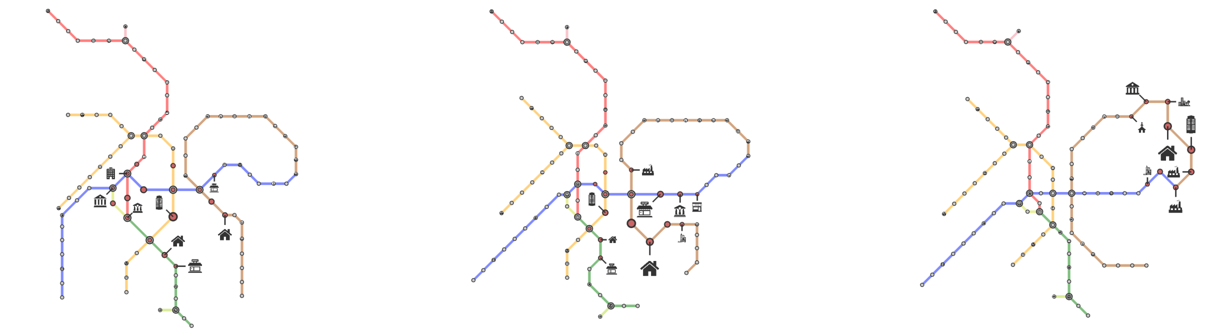
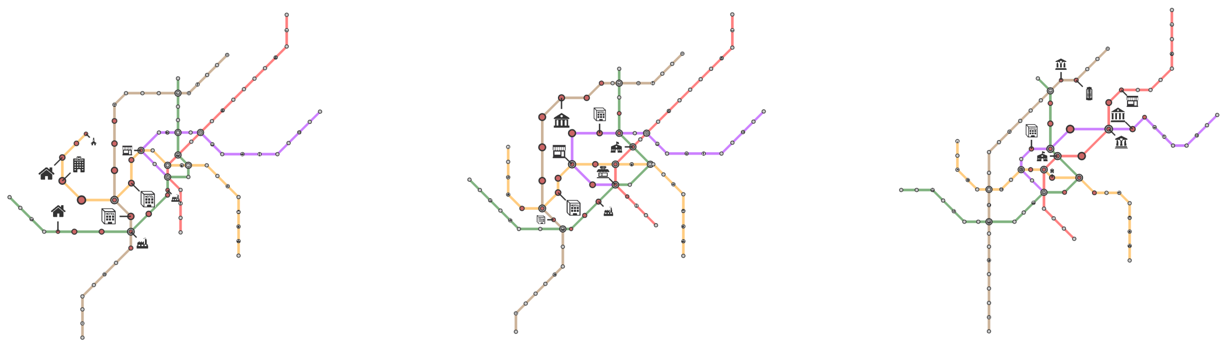


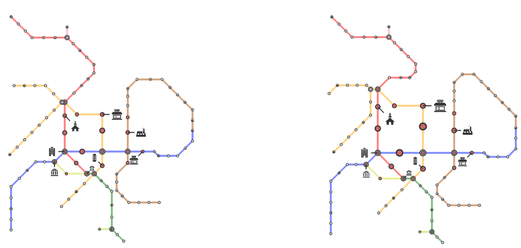
(a) (b) (c)

Figure 3: *Taipei annotated metro maps. Exploring the annotated map from (a) left, (b) middle, and (c) right.*



(a) (b) (c)

Figure 4: *Vienna annotated metro maps. Exploring the annotated map from (a) left, (b) middle, and (c) right.*



(a) (b)

Figure 5: *Taipei annotated metro maps with different maximum scales, where (a) $doi_m = 2$, and (b) $doi_m = 6$.*

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