Drawing Georeferenced Graphs
Combining Graph Drawing and Geographic Data

Giordano Da Lozzo[1], Marco Di Bartolomeo[1], Maurizio Patrignani[1], Giuseppe Di Battista[1], Davide Cannone[2] and Sergio Tortora[2]
[1]*Engineering Department, Roma Tre University, Rome, Italy*
[2]*Product Innovation & Advanced EW Solutions, Elettronica S.p.a., Rome, Italy*

Keywords: Graph Visualization, Visual Interfaces, Networked and Geospatial Data.

Abstract: We consider the task of visually exploring relationships (such as established connections, similarity, reachability, etc) among a set of *georeferenced entities*, i.e., entities that have geographic data associated with them. A novel 2.5D paradigm is proposed that provides a robust and practical solution based on separating and then integrating back again the networked and geographical dimensions of the input dataset. This allows us to easily cope with partial or incomplete geographic annotations, to reduce cluttering of close entities, and to address focus-plus-context visualization issues. Typical application domains include, for example, coordinating search and rescue teams or medical evacuation squads, monitoring ad-hoc networks, exploring location-based social networks and, more in general, visualizing relational datasets including geographic annotations.

1 INTRODUCTION

We address the problem of exploring a georeferenced graph, i.e., a graph with some geographic information associated to it. Typical applications include for example, coordinating search and rescue teams, supervising medical evacuation squads, monitoring ad-hoc networks, visualizing Internet routing events, and, on a more familiar and playful side, exploring location-based social networks.

The requirements of the interface are the following: the area of interest consists of a terrain where a number of entities are located, and possibly move.

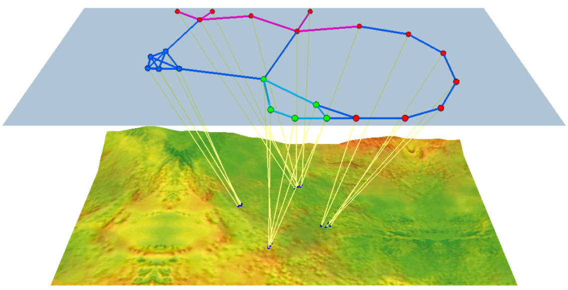


Figure 1: A snapshot of the proposed 2.5D interface. The *logical layer*, above, shows the networked data, while the *geographic layer*, below, displays actual locations of the entities contained in the logical layer, whenever available.

Their geographic position may be declared by the entities themselves, tracked by radar stations, inferred from their transmissions, or, in some cases, completely unknown. Entities have a number of relationships, such as established connections, similarity, reachability, etc. The purpose of the interface is to represent in the most intuitive and unambiguous way both the relationships among the entities and their positions, conveying at the same time the degree of uncertainty associated with the geographic information.

User's tasks involve the analysis of both the networked and the geographic dimensions of the information. Let's suppose, for example, that the data represented come from a social network. Typical queries may be: What is the shortest friendship chain leading from a friend of mine living in London to anyone located in Berlin? Is it possible to find a friendship chain from London to Berlin without involving any person living in Rome? How many friends of my friends are currently in the same location as I am now?

We propose an innovative 2.5D paradigm to visually explore data with both a relational and a geolocalized nature. Our proposal is based on first separating and then integrating back again the networked and the geographic information. Namely, the geographic information is shown within a map, called *geographic layer*, while a second *logical layer* is devoted to the relational information. The two equally-sized rect-

Da Lozzo G., Di Bartolomeo M., Patrignani M., Di Battista G., Cannone D. and Tortora S..
Drawing Georeferenced Graphs - Combining Graph Drawing and Geographic Data.
DOI: 10.5220/0005266601090116
In *Proceedings of the 6th International Conference on Information Visualization Theory and Applications* (IVAPP-2015), pages 109-116
ISBN: 978-989-758-088-8

angular layers are placed one above the other, and viewed from a side in a 2.5D fashion, so that there is no overlap among them, i.e., no ambiguity between the two types of information (see Figure 1).

Entities are placed on the logical layer in such a way to reduce cluttering and to make their relationships readable and clear, while leaders are used to relate each entity on the logical layer to its known location on the geographic layer, whenever available.

All the screenshots in this paper are taken from a JavaScript demonstrative prototype, implemented using the WebGL graphics library (The Khronos Group, 2013), that runs within any compatible web browser.

2 VISUALIZING NETWORKED AND GEOGRAPHIC DATA

In this section we describe a visualization system, based on a novel graphic metaphore, that overcomes the limitations of traditional solutions with respect to user tasks that are typical of the visualization of georeferenced networks.

2.1 Problem Statement

Our visualization problem has two different inputs: the first one is from the user, who controls a rectangular area on a map, which is the current *area of interest* to be monitored and that can be translated, rotated, and zoomed. The second one comes from the outside world and is, essentially, a set of relationships among the entities of the considered domain. Each entity comes equipped with its type, its position, and the degree of uncertainty of such geographic information, which is provided by specifying the size of a geometric shape (usually a circle) that approximates the area where the entity is assumed to be.

The available data defines a network, whose nodes are the entities and whose edges are the relationships among entities. The purpose of the system is to show both the networked and the geographic information, meeting the following high-level requirements.

Effectiveness. The visualization should show in a clear and readable way the number of entities located on the selected area, their current position, and their relationships.

Intuitiveness. The graphic metaphors and the interaction primitives should be natural and intuitive, with low cognitive load.

Robustness. The visualization should support incomplete information, handling, in particular, missing and uncertain geographic data.

Unambiguity. The representation should be accurate and unambiguous. For example, the degree of uncertainty of the geographic information should be clear.

2.2 User's Tasks

When exploring a georeferenced graph relevant user's tasks involve both the networked and the geographic dimensions of the information. Some of these tasks address simple quantitative queries, as estimating what is the amount of entities that share some target location, finding the location that hosts the more interconnected entities, determining whether a specific location hosts unconnected clusters of entities, etc.

We also identify more complex tasks that strongly rely on the analysis of the structure of the networked information. For example, finding the shortest chain of entities leading from a source placed in location A to any target located in B; finding a chain from location A to location B that does not involve any entity located in C; determining how many entities are reachable with two edges and are placed in a specific location; determining how strong are the connections among entities placed in location A and entities placed in location B, etc.

All these high level tasks primarily require the ability of the user to explore the structure of the relationships among the entities on the logical layer. Secondarily, the user needs to quickly grasp the area that hosts a given entity or, conversely, the set of entities that are located in a given area. These basic operations are complicated by the fact that some entities may not have a location associated and that a number of entities may share the same location.

2.3 Limitation of 2D Interfaces

The simple approach of placing icons on a 2D map based on the entities' geographic coordinates would not meet the requirements. In particular, since some entities share the same location, any 2D map would fail to unambiguously show both the location of the entities and their relationships. Also, entities on a geographic map are rarely equispaced. Instead, it is often the case that they gather in specific points (e.g., cities). Long and short distances among entities have to be simultaneously represented in the same view. When some entities have very close locations, their icons overlap unless the user zooms in on them. This zooming in and out has a dramatic effect on the usability of the interface due to focus-and-context issues: when some specific details are on focus the whole picture is no longer in sight and vice versa.

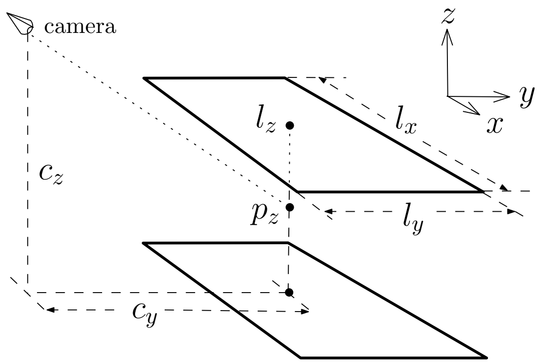
To complicate this scenario, some entities may have unknown geographic position. For example, users of a geolocated social network may disallow their applications to take advantage of GPS data; some devices of an ad-hoc network may not host a ground positioning circuit; routers of a computer network may not have an associated administrative site; end-points of a phone or radio conversation may be unknown; etc. Wherever such entities would be placed on a 2D map, it would result in an ambiguous representation since the user would assume that those positions are the actual positions of the entities.

Finally, a 2D map does not convey in a natural way the degree of uncertainty of the geographic information. Placing icons on the map at the center of the area where the entity is supposed to be may result in the user's false confidence about the actual position of the entity. Drawing on the map some shadowed shapes, rectangles or circles, proportional to the degree of uncertainty on the position of the corresponding entities yields a representation that is not self-evident and that is confusing when several entities, with different shapes and different degree of uncertainty, are close one to the other.

2.4 Exploiting a 2.5D Visualization

Our strategy is to separate and simultaneously visualize the networked and the geographic information of the input dataset. Namely, the geographic information is represented on the *geographic layer*, which is in the bottom part of the interface, while the networked information is represented on the *logical layer*, which is parallel to the geographic layer and placed in the upper part of the interface. Leaders among the two layers relate nodes with their geographic locations, if any. The interface is shown in Fig. 1. In order to avoid overlaps between the two layers, which would give occlusion among the two types of information, we restrict their size to two equally-sized rectangles and suitably place the point of view on the longest side of the rectangles as shown in Fig. 2.

It has to be pointed out that the size and the orientation of the rectangles representing the logical and geographic layers are fixed with respect to the screen coordinates. Panning, zooming and rotating will have the effect of changing what is represented in the geographic and logical layers, but will not move the point of view with respect to the layers themselves. This design choice allows for a very simple and intuitive navigation of the scenario, that does not require the user to cope with fully 3D navigation primitives. Hence, in spite of its 3D flavor, our representation is a 2.5D one, both because the graph is actually drawn on the 2D surface offered by the logical plane and because the user interaction is limited to the 2D primitives of panning, zooming, and rotating. From a practical perspective, this is realized with four clipping planes that move together with the point of view and that cut out the world scene lying beyond the prescribed area.

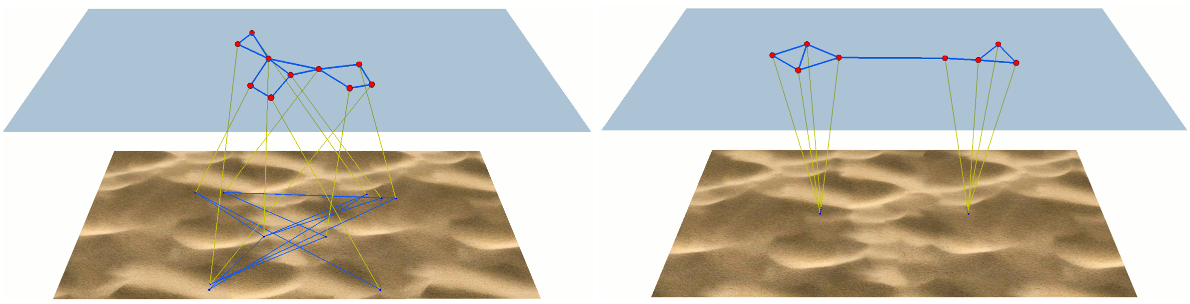


(a)

Figure 2: The position of the geographic and logical layers with respect to the point of view (we used $l_x = 1600$, $l_y = 900$, $l_z = 650$, $c_y = 2000$, $c_z = 1600$, $p_z = 260$).

Nodes are placed on the logical layer with the purpose of conveying as effectively as possible the structure of the graph, reducing cluttering and crossings among edges (see Fig. 3). To this purpose, we devised a specialized force-directed algorithm, described in Section 4. The computed layout tries to achieve both evenly-spaced distribution of nodes and few crossings among edges, while seeking to minimize the distance of each node from the corresponding position on the geographic layer. The goal of the geographic layer, instead, is that of displaying the current position of each node shown on the logical layer. Such a position is represented by means of a marker on the map with a straight-line leader connecting it to the corresponding node on the logical layer. When the position of the node is affected by uncertainty the marker on the map is a geometric shape, usually a circle, enclosing the area where the corresponding object is supposed to be, and the leader consists of a cone with its apex on the node. Nodes with no geographic information associated have no marker on the map (see Fig. 4).

Therefore, in our approach, we have two types of links: (i) the edges on the logical layer and (ii) the leaders connecting the two layers. We privilege the readability of the graph induced by the first type of links, by trying to reduce crossings on the logical layer, which severely jeopardize the comprehension of the graph structure (Purchase et al., 1997; Purchase, 2000). Crossings among leaders have lower impact on readability, since the structure of the graph induced by them is of limited interest to the user. In fact, each leader establishes a connection between an



(a) (b)

Figure 3: Two snapshots of the interface showing (a) crossings are reduced in the layout in the logical layer (the edges on the geographic layer are drawn for comparison) and (b) entities with common locations are clearly shown in the logical layer.

entity and a geographic location, and paths of leaders are never considered by the user. Also, when the mouse hovers a vertex on the logical layer, the interface highlights its incident leader to help the user identify the leader endpoint on the geographic layer.

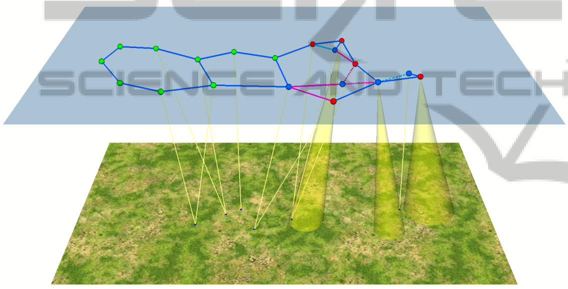


Figure 4: A georeferenced graph where the position of some entities is unknown and the position of other entities is known with some approximation.

The graph represented in the logical layer is composed by all the entities inside the area of interest of the user (*in-sight entities*) and all the entities that have links with such entities (*linked entities*). When the user zooms, rotates, or translates the area of interest (for example by pressing keyboard combinations or by dragging the mouse) the system updates the graph. Appearing nodes are placed on the border of the logical layer, in the point which is nearer to their actual geographic position or in the point which is nearer to the position of one of the nodes they are linked to (in case of linked entities with no geographic position).

3 RELATED WORK

Visual Links in 2.5D Visualizations. The use of visual links (i.e., edges) to highlight relationships between multiple views has been pioneered in the two-dimensional setting in (Weaver, 2005; Aris and Shneiderman, 2007; Shneiderman and Aris, 2006) and further explored in (Steinberger et al., 2011; Hadlak et al., 2011). The third dimension has been often used to add extra information to a traditional 2D layout. In particular, the use of inter-plane edges accounting for the relationships between nodes of separate 2D visualizations of the same graph has been proposed by the authors of VisLink (Collins and Carpendale, 2007). The VisLink system allows the user to change the position of the planes hosting the drawings of the graph, stacking them horizontally, placing them side-by-side vertically, viewing them from the top, etc. In (Streit et al., 2008; Lex et al., 2010) a similar approach has been used for the exploration of interconnected pathways. In this case, the planes are usually more than two, and the system does not rely on the user ability for arranging the planes and for efficiently using the available screen space. Instead, the planes are placed on five sides of a cube and the user looks at them from the remaining side.

Spatial and Non-Spatial Data in Cartography. Our target visualization problem can be viewed as a particular case of integrated spatial and non-spatial data visualization, where the non-spatial data can be modeled as a graph composed of entities and relationships among pairs of entities. Providing an integrated visualization of spatial and non-spatial data is a traditional topic in cartography where thematic maps are used to visualize the distribution of statistical variables. The values associated with the points on the maps can be represented, for example, by colors (choropleth maps), by the sizes of suitable symbols (proportional symbols maps), by the density of dots (dotted maps), etc. Although thematic maps may go so far as to represent a small chart for each location (Wood et al., 2011), usually the non-spatial data represented has a very simple structure.

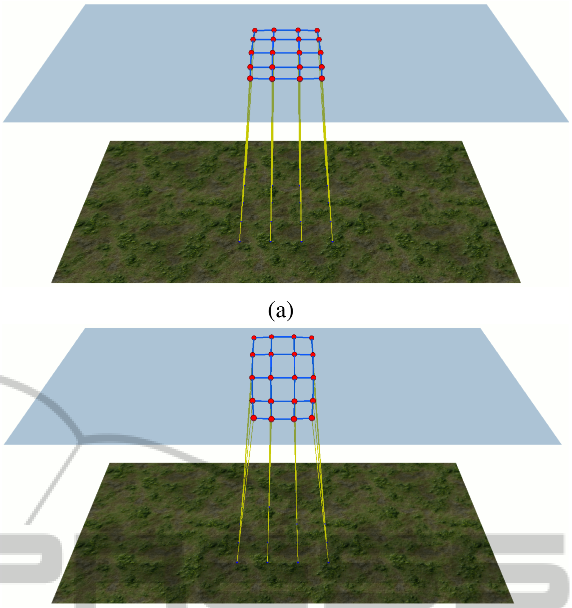
Reducing the Visual Clutter in Spatial Data. The problem of reducing the visual clutter of symbols on interactive maps has been approached with different techniques. Google Earth (Google Inc., 2013) automatically collapses into a single symbol spatially coincident placemarks, which are exploded again in a cluster when clicked. Spatial dithering and changes in symbology (e.g., colour, opacity, line thickness and size) can be used to reflect the existence of unseen or coincident data (Wood et al., 2007).

4 THE `Retina` LAYOUT ALGORITHM

In this section we describe the algorithm that computes the network layout on the logical layer. Spring embedders are natural candidates for our application, since they grant, besides good quality results, the flexibility needed by our interactive system.

Although spring embedders are standard force-directed graph layout algorithms, our visualization problem is somehow special, as the logical layer is viewed from a side by the user, who, therefore, sees a picture distorted by the perspective. This has the effect of increasing the cluttering of the objects in the background with respect to those in the foreground. Hence, we conceived a variant of the spring embedder algorithm that computes the layout directly on the view plane, which is essentially the user's retina. This is why we dubbed it `Retina` layout algorithm.

A spring embedder boils down to be a very simple iterative process that, given the configuration at iteration i, computes the configuration at iteration $i+1$ by summing up, for each node, the forces acting on it, and then translating the node in the direction of the resulting force and proportionally to its magnitude. Such process then stops as soon as the sum of the forces acting on the nodes drops below a certain minimum threshold. Like (traditional) spring embedders, Algorithm `Retina` searches for an equilibrium configuration of a physical model obtained by replacing nodes with equally charged particles and edges with springs. On the one hand, since particles have the same charge, the *Coulomb force*, decreasing with the square of their distance, pushes them apart. On the other hand, as edges are replaced by springs, the *Hooke force* tends to keep adjacent particles close together (our springs have natural length zero and never exert a repulsive force). Further, in order "to keep the node close" to its geographic position, we introduced a *geographic force* that attracts each node to the point on the logical layer corresponding to the node geographic position. Algorithm `Retina` introduces a major, although conceptually simple, difference with respect to standard spring embedders. The forces and their sums are computed on the projections of the nodes' positions on the view plane, so to avoid the perspective distortion perceived by the user. Once the sum of the forces is computed for each node projection, the translation vectors are unprojected again from screen to world coordinates, yielding the new positions for the nodes. Boundary constraints are not implemented as forces, but rather as restrictions on the nodes' translations.



(a)

(b)

Figure 5: The effect of the `Retina` algorithm is apparent when grid graphs are represented. (a) A grid graph drawn by a traditional spring embedder. The perspective distortion is apparent. (b) A grid graph with the `Retina` algorithm.

Figure 5 shows a drawing of a 5×4 grid graph with and without the `Retina` algorithm. The perspective distortion of the traditional spring embedder that computes the layout on the logical plane is apparent in Fig. 5(a). Such distortion is reduced in Fig. 5(b).

5 EXPERIMENTAL EVALUATION

We evaluated the effectiveness of the proposed 2.5D visualization and of Algorithm `Retina` by contrasting them with "traditional 2D visualization" where entities are place in their geographic position and the screen is fully devoted to a 2D representation of the area of interest. With respect to the problem requirements, we claim the following statements.

1. The interface allows us to unambiguously represent networked data enriched with geographic information which may be missing or uncertain for some entity (Req. *Unambiguity*, *Robustness*).
2. The interface allows us to clearly represent entities that have coincident or very close locations

(Req. *Unambiguity*).

3. The logical and the geographic layers allow us to represent the networked information in a readable way (Req. *Effectiveness*, *Unambiguity*).
4. Algorithm `Retina` improves the readability of the drawing with respect to a traditional spring embedder run on the logical layer (Req. *Effectiveness*, *Unambiguity*).

The first claim, in our opinion, is self-evident, as we are not aware of alternative visualization techniques to represent in an unambiguous way geolocated networks where part of the entities have missing or uncertain geographic information. Therefore, we will give evidence of the other three claims by assuming that all the entities have a known position. To this end, we set up the experimental setting described in the following subsections. In all the experiments we allowed the on-line layout algorithm to reach an equilibrium configuration.

5.1 Quality Measures

To assess the effectiveness of the interface we adopted the following readability measures.

Crossings Percent Reduction ($\mathfrak{cpr}$). There is strong evidence in the literature that reducing the number of edge crossings is by far the most important aesthetic to improve the readability of a drawing (Purchase et al., 1997; Purchase, 2000). This metric estimates the ability of the interface to reduce the number of edge crossings in the representation of the networked data. In particular, we measured the average percent reduction of the number of crossings on the logical layer with respect to the number of crossings that would occur if the nodes were placed at their actual location, as in a traditional 2D visualization.

Homogeneous Edge Length ($\mathfrak{hel}$). This measure is based on the average percent deviation of edge lengths using a mean central tendency (Fowler and Kobourov, 2013). We compute this metric on the projections of the edges on the view plane:

$$\mathfrak{hel} = 1 - \frac{1}{m}\sum_{j=1}^{m}\left|\frac{|e_j| - |e|_{avg}}{\max\{|e|_{avg}, |e|_{max} - |e|_{avg}\}}\right|$$

where m is the size of the edge-set of the graph, $|e_j|$ is the length of the jth edge, $|e|_{avg}$ is the average edge length, and $|e|_{max}$ is the maximum edge length. Observe that $0 \leq \mathfrak{hel} \leq 1$. A value of $\mathfrak{hel} = 0$ could indicate that half of the edges have length zero while the other half have length $2|e|_{avg}$. A value of $\mathfrak{hel} = 1$ indicates all the edges have the same length.

Node Separation ($\mathfrak{ns}$). Our purpose is to measure how well the interface is able to separate close nodes. Metric $\mathfrak{ns}$ is the minimum distance between the projections of the nodes on the view plane divided by the length of the diagonal of the viewport

We remark that our 2.5D visualization is unfavored by measures $\mathfrak{hel}$ and $\mathfrak{ns}$ as it uses only a portion of the viewport to distribute nodes, whereas in a 2D visualization the whole viewport is used by the map. We also observe that our readability measures do not take into account the crossings among the edges that link the entities on the logical layer to their geographic positions. Such crossings are due to the 3D perspective and remain in the background when the user explores the network on the logical layer. Hence, they may have a reduced effect on the comprehension of the structure of such a network.

5.2 Testsuite

For our experiments we adopted a mix of real-life and synthetic data. In particular, we obtained real-life data about geolocalized entities from the maritime data collected by the Automatic Identification System (AIS), which is an onboard navigation safety device that broadcasts time-labeled messages with the location and characteristics of vessels in real time. We used a historic dataset of AIS data collected by the U.S. Bureau of Ocean Energy Management and by the U.S. National Oceanic and Atmospheric Administration (NOAA Coastal Services Center,). Precisely, we used the dataset relative to the *Zone 14* of the Gulf of Mexico area, collected during January 2009. Starting from this dataset, we produced 300 test instances of increasing size and density.

First, we chose an arbitrary rectangular region whose aspect ratio is 16:9. We selected ten time instants uniformly distributed in the available time window. For each time instant, we selected in the area of interest the last s vessels broadcasting their position and considered their last update, with s ranging from 10 to 100 with a step of 10. This produced 100 sets of geolocated entities with distinct geographic positions.

AIS data are not provided with information about relationships between the vessels. Therefore, we created graph instances with different edge densities as follows. We randomly added edges to each set of n vertices, among all the possible $\frac{n*(n-1)}{2}$ edges, until we reached the density of 5%, 10%, and 15%. This produced 300 geolocated graphs, which compose the testsuite for our experiments.

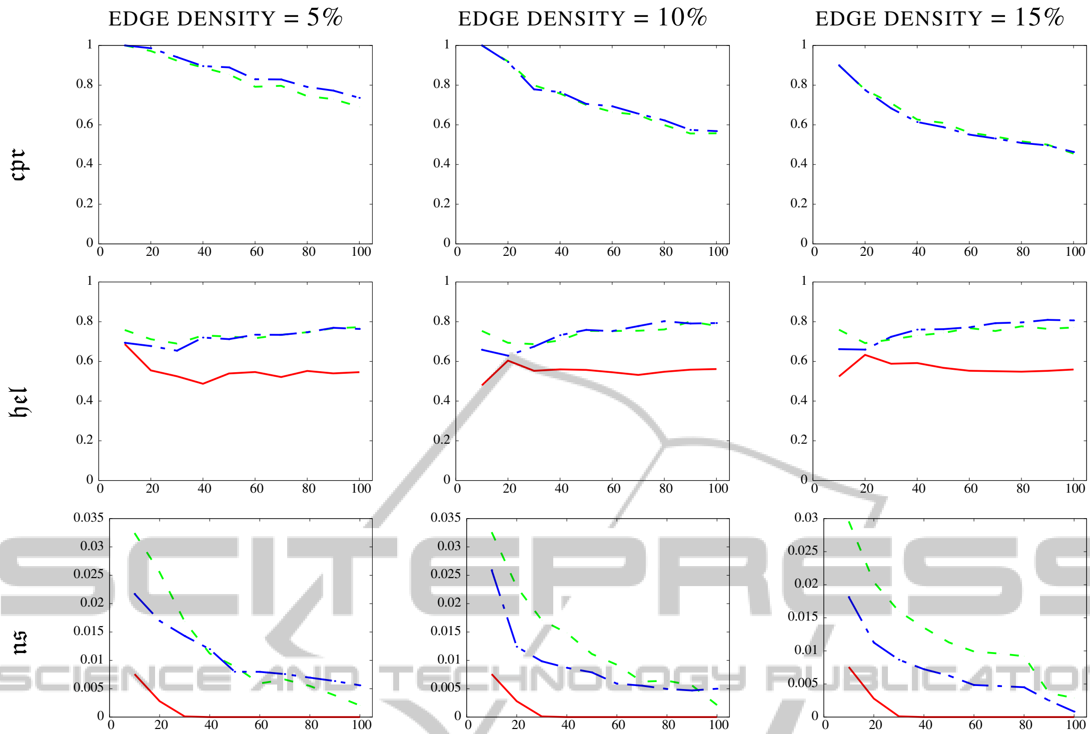


Figure 6: Results of the experiments. Charts in the first row report $\mathfrak{cpr}$ measure; the second row is devoted to $\mathfrak{hel}$; and the third row to $\mathfrak{ns}$. The density of the graphs varies over the columns. The x-axis shows the size of the graphs, while the y-axis reports the measure of interest. The solid red line is the measure for the 2D visualization. The dashed green line is the measure for Algorithm `Retina`. The dash-dotted blue line is the measure for the traditional spring embedder with no `Retina` distortion.

5.3 Results and Discussion

Figure 6 shows the results of the experiments. Each dot corresponds to the average over ten values. Regarding measure $\mathfrak{cpr}$ (Figs. 6, first row), crossings are completely removed for sparser and smaller graphs and are greatly reduced both by the traditional spring embedder and by Algorithm `Retina`, with the latter performing negligibly worse for sparse graphs (see Fig. 6, first row, first column). Even for bigger and denser instances of our dataset crossings are reduced of more than 40%. We remark that the number of crossings on the geographic map for the denser graphs is huge (for example, the last point of Fig. 6, first row, last column, corresponds to more than 6,000 crossings). The second row of Fig. 6 is devoted to metric $\mathfrak{hel}$. For all the tested densities and sizes the readability of the layout is steadily improved both by the traditional spring embedder and by Algorithm `Retina`, which appears to behave better for small graphs. The advantage of using a 2.5D interface is confirmed by these charts. It should be also noted that georefenced graphs coming from many real-life applications have the property that adjacencies are more likely among nodes that are geographically close. However, in order to prove the effectiveness of Algorithm `Retina` with respect to metric $\mathfrak{hel}$, we decided to perform our tests against unfavorable instances that do not exhibit this property. Algorithm `Retina` performs better than the traditional spring embedder with respect to metric $\mathfrak{ns}$ (see Fig. 6, last row), while the 2D visualization has very unsatisfactory results. Denser graphs are more effectively handled by Algorithm `Retina`. Overall, our experiments confirm that the 2.5D interface meets the system requirements. In particular, it allows us to represent the networked information in way that is considerably more readable than a traditional 2D interface. The adoption of Algorithm `Retina` is justified by its improvement on measures $\mathfrak{hel}$ and $\mathfrak{ns}$ at the expenses of a negligible worsening of the $\mathfrak{cpr}$ measure. When the user focuses on smaller instances, the superiority of Algorithm `Retina` is apparent.

6 CONCLUSIONS AND FUTURE WORK

We described a 2.5D visualization technique for ex-

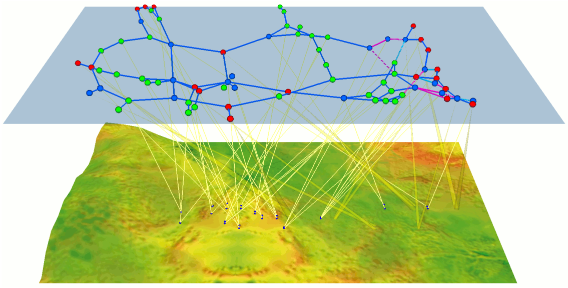


Figure 7: A georeferenced graph with 76 entities and 96 edges. The size of the graph makes cluttering hard to avoid.

ploring networked data enriched with geographic information, where the latter may have uncertain or missing values. Adapting, to our knowledge, for the first time a force-directed algorithm to a 2.5D setting, we conceived a variant of a spring embedder algorithm that directly computes the layout on the view plane (i.e., on the user's screen).

We measured the effectiveness of the proposed visualization and layout algorithm by contrasting them with a traditional 2D visualization with respect to three relevant readability measures. Both the experimentation and our experiences with the interface support our confidence about the effectiveness of the proposed techniques for small instances of geolocalized graphs. In fact, when the entities are more than a few dozens the readability measures show very poor performances and the drawing on the logical layer becomes too cluttered to be clearly readable (see Fig. 7).

Although the results are promising, our experiments only evaluate the static setting and do not account for the dynamic scenario, where changes occur both in the area of interest selected by the user and in the environment. An evaluation of the effectiveness of the dynamic scenario would be much more complex and could not leave aside a thorough user study. An interesting evolution of the `Retina` algorithm could consider additional forces to take into account crossings among leaders. One line of further investigation is given by the possibility of representing on the logical layer further information. A simple idea is to show a network that is wider than the area of interest (we call it *neighborhood visualization*), so to enhance the situational awareness of the user. Our preliminary experiments in this direction are encouraging.

ACKNOWLEDGEMENTS

We wish to thank Francesco Elefante, Marco Passariello, and Maurizio Pizzonia for their friendship and help with this project. This work is partially supported by the MIUR project AMANDA "Algorithmics for MAssive and Networked DAta", prot. 2012C4E3KT_001, and by EU FP7 STREP "Leone: From Global Measurements to Local Management", no. 317647.

REFERENCES

Aris, A. and Shneiderman, B. (2007). Designing semantic substrates for visual network exploration. *Information Visualization*, 6(4):281–300.

Collins, C. and Carpendale, S. (2007). VisLink: Revealing relationships amongst visualizations. *IEEE Trans. on Visual. and Comp. Graph.*, 13(6):1192–1199.

Fowler, J. J. and Kobourov, S. (2013). Planar preprocessing for spring embedders. In *Graph Drawing GD '12*, volume 7704 of *LNCS*, pages 388–399. Springer.

Google Inc. (2013). Google Earth. http://earth.google.com.

Hadlak, S., Schulz, H., and Schumann, H. (2011). In situ exploration of large dynamic networks. *IEEE Trans. on Visual. and Comp. Graph.*, 17(12):2334–2343.

Lex, A., Streit, M., Kruijff, E., and Schmalstieg, D. (2010). Caleydo: Design and evaluation of a visual analysis framework for gene expression data in its biological context. In *PacificVis 2010*.

NOAA Coastal Services Center. http://www.marinecadastre.gov (acc. 2014).

Purchase, H. C. (2000). Effective information visualisation: a study of graph drawing aesthetics and algorithms. *Interacting with Computers*, 13(2):147–162.

Purchase, H. C., Cohen, R. F., and James, M. I. (1997). An experimental study of the basis for graph drawing algorithms. *J. Exp. Algorithmics*, 2.

Shneiderman, B. and Aris, A. (2006). Network visualization by semantic substrates. *IEEE Trans. on Visual. and Comp. Graph.*, 12(5):733–740.

Steinberger, M., Waldner, M., Streit, M., Lex, A., and Schmalstieg, D. (2011). Context-preserving visual links. *IEEE Trans. on Visual. and Comp. Graph.*, 17(12):2249–2258.

Streit, M., Kalkusch, M., Kashofer, K., and Schmalstieg, D. (2008). Navigation and exploration of interconnected pathways. *Comput. Graph. Forum*, 27(3):951–958.

The Khronos Group (2013). WebGL, Web Graphic Library – OpenGL ES 2.0 for the Web. http://www.khronos.org/webgl/ (acc. 2014).

Weaver, C. (2005). Visualizing coordination in situ. In *INFOVIS 2005*.

Wood, J., Dykes, J., Slingsby, A., and Clarke, K. (2007). Interactive visual exploration of a large spatio-temporal dataset: Reflections on a geovisualization mashup. *IEEE Trans. Vis. and C. Graph.*, 13(6):1176–1183.

Wood, J., Slingsby, A., and Dykes, J. (2011). Visualizing the dynamics of London's bicycle hire scheme. *Cartographica*, 46(4):239–251.