

Physical Visualization of Geospatial Data sets

Hessam Djavaheerpour, Ali Mahdavi-Amiri, Faramarz Samavati

University of Calgary

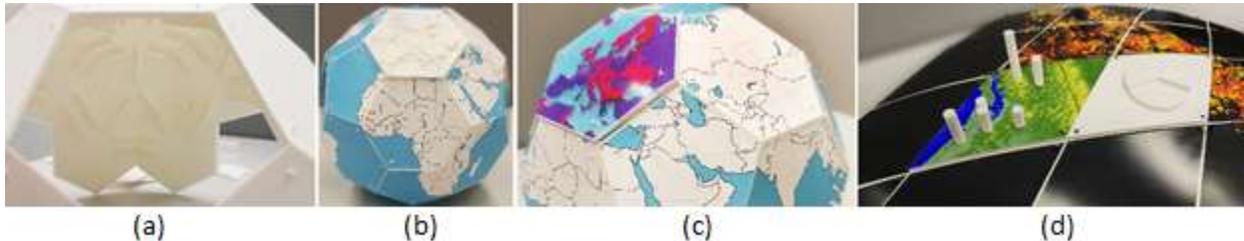


Figure 1. (a) Constructing a model of discrete globe on which data sets with different styles can be attached (b), (c). Our method can produce models at different scales as illustrated in (d).

Abstract

There exists a wide variety of geospatial data sets that are too complex to easily visualize and understand on a computer screen. A physical model of an architectural project usually helps one better understand and interact with the space. Similarly, a scale model of the Earth supporting a resolution independent data visualization can be a good visualization tool. 3D printing provides an opportunity to produce modular scale models for this purpose. In this paper, we use a Discrete Global Grid System (DGGS) to design such models, at different resolutions and scales, on which geospatial data sets can be attached. As examples, we have produced two models - one at the scale of the Earth and one at the scale of Western Canada - that support attachment of different data sets both in 2D and 3D format.

Keywords: Computer Graphics, Applications, Information Visualization, Digital Earth, DGGS, Digital Fabrication

1. Introduction:

Different types of traditional maps exist on which the locations of cities, roads, and other geographic features can be illustrated on a sheet of paper. Additional examples of physical models that visualize the Earth include spinning globes of the world. These physical models provide an opportunity to interact with a physical Earth, understand the relative distances between locations and explore the geographic properties of regions in a timely manner. Due to the emergence of new technologies for capturing geospatial data sets, our information about the Earth has expanded beyond simple name tags, major roads, and political boundaries. There exist various geospatial data sets that are hard to visualize.

Web maps (e.g. Google Maps) provide visualizations of geospatial data sets using computer generated 2D maps. These maps are presented at different resolutions and multiple layers of data (such as roads and

satellite images) can be visualized on these maps. However, due to the mapping distortion between spherical/ellipsoidal domains and (Euclidean) 2D domains, misinterpretations of areas and distances are common. As a result, Digital Earths and virtual globes (e.g. Google Earth) have been proposed to overcome these issues [1, 2]. Digital Earth is a 3D representation of the Earth on which various geospatial data sets are integrated and on which one can interact with the model to retrieve information related to a particular region. While similar, virtual globes primarily deal only with visualization whereas in Digital Earth, analysis and data integration, in addition to visualization, are important components. Although Digital Earth is useful in visualizing geospatial data sets, a computer generated model suffers from comprehension problems resulting from projecting 3D scenes to 2D screens for visualization [3].

On the other hand, a physical visualization can be greatly beneficial in developing an understanding of complicated data sets. A large physical 3D model can absorb more attention and help those interested to understand a concept in a timely manner through physical interaction and sensing [4, 5]. Thus, using physical models is an alternative solution to support better visualization of geospatial data sets. While a wide variety of techniques for producing paper craft models of the Earth exist, we propose using durable physical 3D models produced by digital fabrication. Such models are solid and stable enough to support attachment of different 2D and 3D data layers that physically display geospatial data sets.

To understand geospatial data sets of different regions and resolutions, such a physical model should be scalable. In order to achieve scalability, our models consist of pieces that can be attached to each other to cover larger regions. Not only is the final physical 3D model of the Earth useful as a tangible tool to learn and understand a geospatial concept, but the process of creating such a model is also beneficial to the learning process [4, 5]. Therefore, the process of creating the physical 3D model of the Earth should be affordable and repeatable.

Combining the technologies available in geospatial modeling and visualization with recent advances in fabrication and 3D printing provides a useful means of better conveying complicated geospatial concepts. In this paper, we explain how we can benefit from affordable 3D printing technologies to make scalable physical models that can visualize various geospatial data sets.

To keep the research repeatable, affordable, and useful, we have considered several goals. The physical model of the Earth (base) should be able to hold multiple geospatial data sets, and should be scalable (large or small). We should be able to fabricate data sets at different resolutions for the physical models. Finally, the 3D printer should be affordable (i.e. single color, and small).

To fulfill these goals, we require a discretization of the Earth into printable pieces, and the ability to retrieve geospatial data sets and connect them easily. This discretization should be defined in a hierarchical manner to enable the use of multiresolution data sets, if needed. For these purposes, we use a Discrete Global Grid System (DGGS) that discretizes the Earth into hierarchical cells on which geospatial data sets can be assigned. These cells are indexed using a hierarchical mechanism in which the index of a parent cell is the prefix of its children [6, 7]. We use the cells of the DGGS to define the printable pieces (which can be connected together using our provided connectors) and to determine which data sets may attach to them. In this way, data sets at appropriate resolutions may be retrieved from the DGGS cells and attached to the printed pieces (see Figure 1).

Our main contribution is in the combination of digital fabrication with a DGGs in order to provide a useful tool for visualizing multiresolution geospatial data sets. We also provide a mechanism to print and attach a set of printable segments to produce a scalable model of the Earth. Furthermore, we discuss some possible interactions and visualization techniques for this 3D physical model.

2. Related Work

Our physical 3D models, similar to Digital Earths, employ discretization of the Earth on which different data sets can be assigned. To discuss the related work of all the components of our work, we first describe the works related to Digital Earth and geospatial visualization, followed by digital fabrication techniques and the ways in which different data sets can be visualized using 3D printers.

2.1. Digital Earth and Geospatial Visualization

As data capturing technologies continue to advance (e.g., satellite imaging, crowd-based surveying and geo-tagging), we are constantly capturing ever larger amounts of geospatial data. This immense quantity of geospatial data has the potential to be used to address important challenges related to the Earth. However, this immense, multi-scale and diverse data needs to be processed and integrated into a common domain to harness this potential, with support from a system for visualizing and analyzing geospatial queries. One such a system is the Digital Earth. The most common approach to Digital Earth uses a discretization of the Earth into highly regular cells -a Discrete Global Grid System (DGGs)- to which data are assigned [8, 1]. In DGGs, a simple polyhedron is typically used to coarsely approximate the Earth. The faces of the polyhedron are refined and projected to the sphere in order to generate spherical cells discretizing the surface of the Earth. This discretization at different resolutions allows one to assign data to different locations and establishes a multiresolution representation of the Earth with mostly uniform cells. An indexing system is used to assign and retrieve geospatial data sets [6].

Digital Earth provides a framework to visualize, analyze and combine various types of data sets. Geospatial imagery data sets (i.e. aerial or satellite photographs) are often used to texture the cells of the Earth [1]. Elevation data, usually offered as Digital Elevation Models (DEM), are used to represent the height or elevation of a region [9]. Visualization approaches of these types for data sets are described in [2]. Vector data sets are another important type of data in a Digital Earth. They are defined by collections of points, polylines, and polygons that are used to outline political boundaries, rivers, roads, etc. Vector data sets and methods for their storage in a DGGs are discussed in [10]. To visualize, interact with, and compare these different types of data sets on a physical model, we provide some simple solutions using affordable 3D prints and 2D color prints.

2.2. Physical Visualization of Data

A physical visualization of data is a physical model that encodes data into its geometry and helps users understand and explore data [11]. Such visualizations have a long history dating back many years but recent advances in digital fabrication and tangible interfaces have opened up a wide variety of research

possibilities in this field. Several previous works have successfully employed physical visualization on geospatial data sets. Spinning globes, terrain physical models, prism maps, and modern interactive dynamic displays are all examples of physical visualizations of geospatial data sets [12]. Physical visualizations have a range of benefits in comparison with virtual models: they can be handled and controlled more easily, they can improve users' cognition, and they allow for more natural user interaction [13]. A user study in [14] also proves that a 3D physical visualization improves the efficiency of users' information retrieval.

There has been a substantial amount of research in the field of physical data visualization. In [15], it was noted that even non-experts in information visualization can explain their own visual representations of a specific data set through the tangible environment that a physical visualization provides for them. The physical visualization workflow from data filtering was integrated with physical fabrication in [16]. In this system, users can create their own physical visualization of their desired data. Physically dynamic bar charts were used in [13] for data visualization, and some interactions to support fundamental visualisation tasks (e.g. annotation and navigation) were employed.

In this paper, we propose a physical visualization of geospatial data sets that offers the possibility to choose and combine different data sets, and does not limit them to a specific predefined visualization or data type. Our method allows dynamic physical models to be produced via a facilitated assembly process that provides the user with interaction possibilities.

2.3. Digital Fabrication and 3D Printing

One of the oldest, most used, and most accessible forms of physical visualization for geospatial data sets is that of the spinning globe, which uses interrupted maps (resulting from cutting the surface of the earth using some chosen curves) folded to cover a sphere. The most common interrupted map used to make paper craft globes is a gore map using Apian's first projection [17]. This projection is a non equal-area projection, but its geometry can be built using a ruler and a pair of compasses. One can make a paper globe by printing this map on a piece of paper, cutting it using a hand cutter, and sticking its gores together as illustrated in [18]. There is also another approach to make a globe using folded papers. In this method, polyhedral globes are formed from an unrolled 2D pattern of the polyhedron. A variety of these polyhedral maps are provided in [19].

Although these paper craft models of the globe are more accessible and seem easier to fabricate, they cannot meet the requirements of an interactive physical visualization as they are not durable and strong enough to interact with. Furthermore, it is unclear how to produce a scalable paper craft capable of holding multiple data sets. However, well designed fabricated 3D objects can address these issues.

3D printing, as one of the digital fabrication methods, enables us to produce a physical model regardless of the complexity of this model [20]. 3D printing currently plays an important role in different aspects of life and science since it provides the opportunity to bring ideas to life that would otherwise be very difficult to produce.

3D printing for visualization also has positive impacts in education, both as a means of learning and as a method of designing and creating educational tools. In [21], the authors used open source 3D printing for

experimental educational scenarios by giving the students the chance to use 3D design software packages and to print their designs later on. In [22], a 3D printed physical hepatic segment model was used by medical students, resulting in significant improvements in learning.

In addition to the applications of 3D printing in physical visualization and its benefits towards learning and understanding difficult concepts, there have been efforts to overcome the shortcomings of affordable 3D prints, such as lack of color or material and limitations on the size of the printed objects. In [23], an efficient system was introduced to segment a model into printable pieces that could be connected together later on. In [24], a 3D model was segmented into printable pieces and later connected to a base made of an alternative material (such as wood) to reduce costs and material usage. To overcome color and material limitations, a 3D model was segmented into flat pieces in [25] and a guide was provided to attach any material with any color to the 3D print. In [26, 27, 28], an intermediate domain such as water or plastic - on which the desired texture can be printed - was used to paste the texture on the 3D print. As one of the stated goals of this research is accessibility by way of affordable 3D printers, we also need to come up with a design solution for the size and color limitations. Since any DGGs already provides a segmentation of the Earth into a set of cells, we use it to segment the Earth into printable pieces. To assign colorful data sets, we use additional layers that can be attached to the printed model of the Earth.

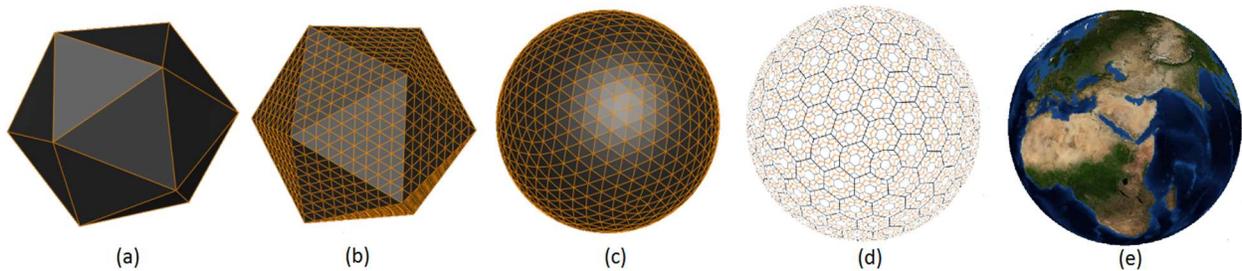


Figure 2. A triangular DGGs is made by refining a polyhedron and projecting the faces to a sphere. (a) The base polyhedron. (b) Refined faces of the polyhedron. (c) Projected faces to the sphere. (d) A hexagonal DGGs created by taking dual of cells in (c). (e) Data sets such as imagery can be assigned to these cells.

3. Methodology

Geospatial data sets are available through different sources and frameworks. The most well-known and accessible resources are Digital Earth, on which data sets are available at different resolutions. To support such a representation of the Earth, a Discrete Global Grid System (DGGs) is usually employed [8, 1]. We take advantage of DGGs in our application, as they exhibit several good characteristics that are compatible with our needs. In the following section, we briefly describe DGGs and then outline why such a representation is useful for our application in making a physical visualization of geospatial data sets.

In DGGs, the surface of the Earth is discretized into a set of cells resulting from projecting the faces of a refined polyhedron to the sphere. Beginning with a simple polyhedron that approximates the Earth, the

faces of the polyhedron are refined to a desired resolution and a hierarchy is established between the faces at consecutive resolutions. Different types of projections (usually area preserving) are then used to map the refined faces to spherical cells on the globe that represent the Earth in a multiresolution manner (see Figure 2). These cells in DGGs are used to organize data sets and are addressed by unique indices that indicate each's resolution and geospatial location. From these indices, one can also identify how the cells are connected to each other. Appropriate data sets can be retrieved from a geospatial database and attached to the cells using the indexing system [6].

DGGs offers important benefits for our application. First, since the surface of the Earth is discretized into a set of cells, the same discretization provides a natural and meaningful segmentation of the Earth model into units for fabrication in a modular manner. Using appropriate connectors, the printed units can be assembled and extended to create a scalable Earth model. Second, the multiresolution representation of the Earth provides an opportunity to build the physical model of the Earth at a desired scale with any associated data set. Third, since geospatial data sets are organized according to the cells, we can easily use these cells to retrieve the data associated with each cell (printable unit). Fourth, using the unique indices of each cell, one can determine how the printable units need to be connected to each other.

In this paper, we use an equal area icosahedral DGGs discretized into mainly hexagonal cells. The base model of such a DGGs is a truncated icosahedron with 12 hexagonal and 10 pentagonal cells, prized for approximating the Earth with low distortion. This representation is compatible with the framework of PYXIS world view [29], which we have used in this paper to provide a variety of geospatial data sets. The cells of the truncated icosahedron are refined by a 1-to-3 refinement to provide a multiresolution representation of the Earth. The number of pentagons is fixed throughout the resolutions while the number of hexagonal cells grows as the resolution is increased. To efficiently work with these hexagonal cells used to sample the Earth, they are converted to simple quadrilateral shapes (i.e. diamonds) by taking the dual of the hexagonal cells and merging the triangles resulting from the dual conversions [30]. A hierarchical indexing in base nine is used to index diamonds. A diamond receives the index of its parent and a digit of base nine is also appended to its index based on the orientation of the diamond and its parent [6, 7].

To efficiently access the data sets of this DGGs, the back end of our system is supported by a client-server framework that transmits the necessary data sets to clients [7]. The region of interest and its level of resolution are identified on the client side. On the server side, the cells composing the region of interest at the specified resolution, and their indices, are determined. Afterward, two types of cell-based geospatial information (i.e. geometry and data) are retrieved using the indices of the cells and transmitted to clients. The geometry provides the curved surface of the globe as a series of 3D meshes while the data is used to visualize location-based information, such as population or temperature within a cell. In this system, the geometry and data accurately correspond to each other, as the cells in both queries represent the same area.

The cells of the truncated icosahedron define the coarsest physical model of the Earth, and the diamonds are used as printable units of the high-resolution data sets. The DGGs employed in this paper is an efficient representation for analyzing and visualizing geospatial data sets as it employs an equal area projection. However, other types of DGGs can be also employed if one intends to emphasize other aspects of the data

set. For instance, if information related to navigation needs to be visualized, a DGGS with a conformal projection might be a better choice [1].

4. Physical Modeling

We fabricated two physical models at different scales. The first fabrication is a coarse print representing the entire Earth at a small scale, modeled as a truncated icosahedron (world globe), and the second is a curved print of Western Canada (curved model). The printer we use to fabricate the models is MAKERGEAR M2 single extruder. This is an affordable 3D printer capable of printing models with dimensions up to 200 mm × 250 mm × 200 mm. In the following, we discuss how we fabricated each of these models.

4.1. Polyhedron Globe

For a simple physical visualization of geospatial data sets, we use the base polyhedron of the selected DGGS (truncated icosahedron in our approximation) as the world globe. Representing the Earth via simple polyhedrons or paper crafts is common and has some benefits [19], including the ability to cover them with low distortion maps. Such a representation can be used as a learning tool for understanding the underlying base polyhedron of DGGS. The fabrication process for the base globe and its associated data sets is easy and can be repeated for educational purposes.

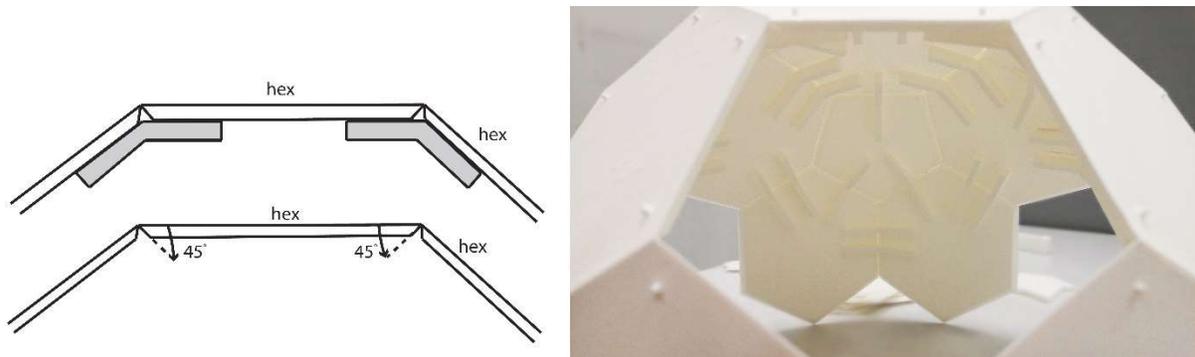


Figure 3. The designed connectors (on left) and the connected 3D printed faces (on right).

As the 3D printer used for this research is simple and affordable, we decompose the model into a set of separate printable pieces. In this case, the 32 faces of the truncated icosahedron (20 hexagons and 12 pentagons) are a natural choice to print. As a result of the printing size limits and the scale of the final model, we can print two hexagons or three pentagons in each printing session. Printing time took about 3.5 hours using a 20% infill and each printing session consumed about 80 gr of the filament.

Since these cells are printed separately, we need a mechanism to connect them together into a single stable model. Due to the thickness of each piece, they should be tapered as shown in Figure 3. We taper the pieces by 45 degrees so that the pieces fit nicely together. In addition, a set of connectors are needed to hold the pieces together. For this simple model, we designed connectors using the exact angles between neighboring cells in the truncated icosahedron (138 degrees, 11 minutes for hexagon-hexagon attachments and 142 degrees, 37 minutes for hexagon-pentagon attachments) (see Figure 3). To print all 32 faces and the required connectors, one kg of white PLA filament was used.

This polyhedron provides a rough estimation of the Earth and illustrates which portions of the Earth correspond to which DGGs cells at the coarsest resolution. In addition, this model can be viewed from different angles and does not need an additional support stand. Such a physical model can be used to hold data sets associated with the Earth at a coarse resolution. For instance, Figure 1 (b) and Figure 7 illustrate the world political boundaries attached on the polyhedron globe. In Section 5, we discuss how we can incorporate different data sets together for visualization on this polyhedron globe.

4.2. Curved Globe

In Section 4.1, we explained how we fabricate a simple base model that can be used to visualize data sets. This physical model offers ability to explore, understand, and attach data sets at a coarse level. However, it has two main limitations. It is piece-wise flat and is also too small to visualize higher resolution data sets (the maximum size of each piece is limited to the size of the printer). In the case of smaller areas of interest, it would be beneficial to have larger scale models of the Earth and higher resolution data sets. To address these issues, we design a larger scale model of the Earth with curved cells. Using DGGs makes the process of designing and building a higher resolution scale model possible, and allows us to print only a portion of a potentially very large Earth model. The printed portion of the globe can encompass any region or country required by the analyses one desires. As a proof of concept, we visualize the western part of Canada, including British Columbia, Alberta, Saskatchewan, and part of Manitoba (see Figure 4). We use resolution three of the PYXIS DGGs [29] to select printable cells for this area.

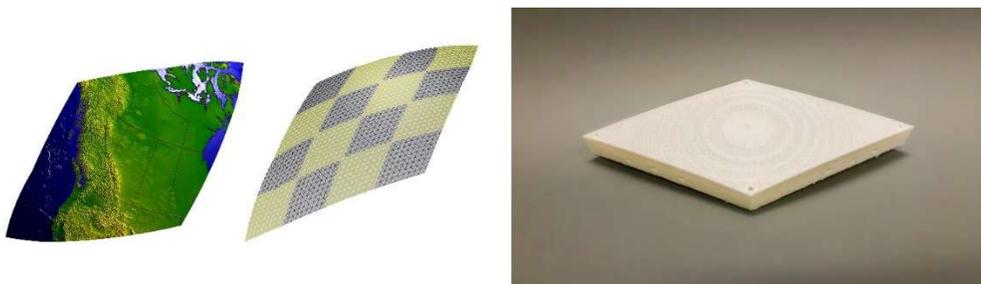


Figure 4. The area represented by our partial globe (on left). 16 diamonds needed to produce the model (middle). Fabricated diamonds (on right).

In the underlying structure of PYXIS world view, cells can be packed and transformed into diamond like meshes. These diamonds are curved meshes (Figure 4(Middle)) obtained using the dual conversion between hexagons and triangles [30]. Our region of interest (Western Canada) at resolution three encompassed in 16 diamond, each covering roughly ten million square meters. To make a physical model

associated with this region, an appropriate size and connecting technique for diamonds need to be determined. A globe diameter of 2 meters provides an appropriate scale for the region of interest and its corresponding data sets, hence the printable diamonds are sized to achieve this scale (Figure 4 (Right)). Although, the resulting diamonds have different geometry provided by the DGGs, their apparent shapes are very similar. Therefore, we require a reference system in order to be able to attach them once they are printed. To this end, we employ the indices of the chosen DGGs as a reference to connect the diamonds together by engraving the index of each diamond on its back (Figure 5 (a)). The indexing used in our DGGs is a hierarchy based indexing system with numbers in base 9 [6].

One important factor for the modularity and scalability of this partial globe is the ability to add new regions to the old ones. Consequently, each piece should be attachable and detachable. To do so, we have designed a supporting wall (with 1 CM thickness) at the edges of each diamond into which three female connectors are carved on each wall (see Figure 5 (b)). To connect these diamonds, we have also designed separate male connectors (2 CM length) that can fit tightly in the female connectors (see Figure 5 (c)).

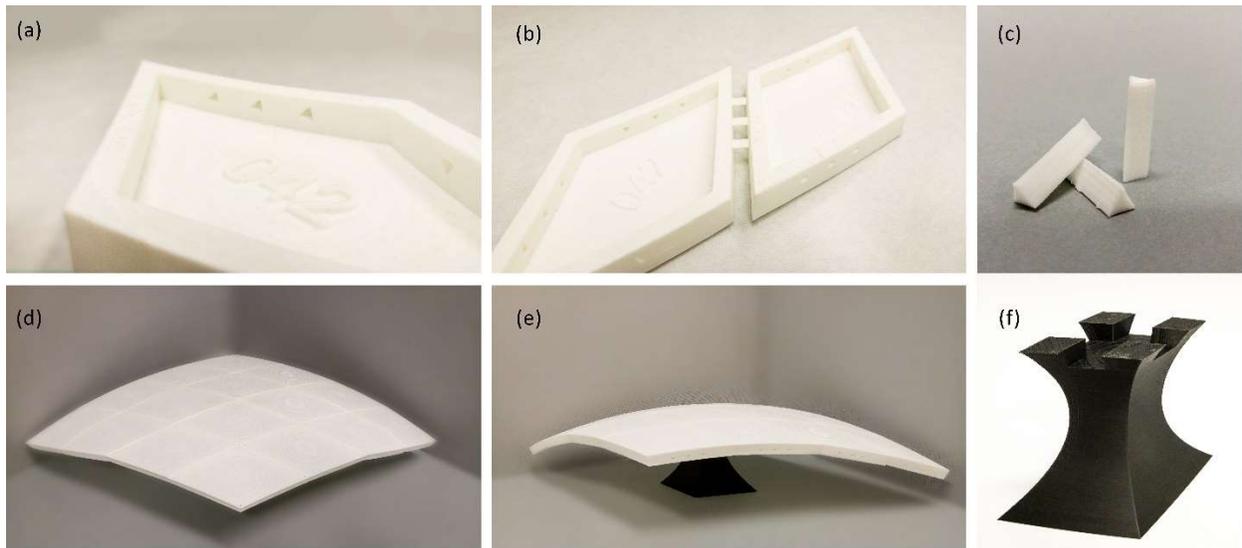


Figure 5. (a) The index of each diamond is engraved at its back. (b) Female connectors are made on the edge of diamonds. (c) Male connectors used to attach diamonds. (d) A curved model of the globe with no attached data from top view. (e) The curved model from side view. (f) Base of the curved model to hold the whole structure.

To ensure a proper fit and an appropriate thickness, we modeled three different connectors via offsetting from the female connectors by multiples of 0.1 mm (0.1 mm, 0.2 mm, and 0.3 mm offset). After testing the printed male connectors, the best grip was obtained using a 0.1 mm offset from the female connectors. The infill amount also plays an important role here; the results showed that the fabricated connectors using a 20% infill were more likely to break during the assembly process. As a result, using infill amounts of 50% or more is suggested.

Our curved model representing western Canada consists of 16 diamonds connected to each other (Figure 5 (d)). We fabricated each diamond using 20% infill structure in approximately 4 hours and 45 minutes. Each printing session consumes about 120 gr of the filament. Counting all 16 diamonds and connectors, we required two kg of white PLA filament.

Since the model is curved, we need a stand to hold the structure (Figure 5 (e)). This stand has been designed to hold the edges of the four diamonds that meet at the middle of the curved model (Figure 5 (f)). To achieve this goal, we have designed the top of the stand with a cross-shaped depression into which the intersection of the four diamonds can be placed. Once these parts have been fabricated, it takes about 30 minutes to assemble the physical model.

We use the physical model of the partial Earth as a base for attaching geospatial data sets. This model can also provide a physical visualization of geospatial data sets. In the following section, we describe different methods of data visualization that our physical model can support and we describe how they can be connected to the base model.

5. Data Visualization

As discussed in Section 4, our goal is to make a model which allows us to visualize different types of data sets. In this section, we explain the process of fabricating geospatial data sets and attaching them to the base model. Our main approach to handling several data sets is to use a pin-hole design that supports attachable and detachable physical layers for these data sets. To attach data sets to the base model, each piece of the model should be able to hold the corresponding piece of the data set. To accomplish this, we have designed some connecting pins on the surface of each printed cell to hold physical data layers (see Figure 6).

Such a pin-hole mechanism allows us to support different types of data, as multiple layers can be attached on the physical globe (see Figure 6 (Right)). These layers can be printed on paper (opaque or transparent) or as a 3D print. Based on the characteristics of the base globe, the nature of the data set, and the method of visualization, we can use various layering methods.

Figure 7 demonstrates the use of three data layers on the world globe (i.e. the truncated icosahedron). In this example, the first layer is an opaque layer printed on photo paper visualizing world political boundaries. To illustrate the possibility of visualization in 3D, we have attached on one of the cells a sample 3D printed layer which visualizes the populations of different countries in Europe. In this visualization, the population of each country is proportionally mapped to the height of the country. To fabricate this physical layer, the boundary of each country is triangulated and the resulting 2D mesh is extruded based on the height of each country with a closed smooth B-Spline curve. In addition, we have attached a transparent layer to illustrate the possibility of visualizing another analytical data set (e.g. energy use of each country) atop the cell (see Figure 7).

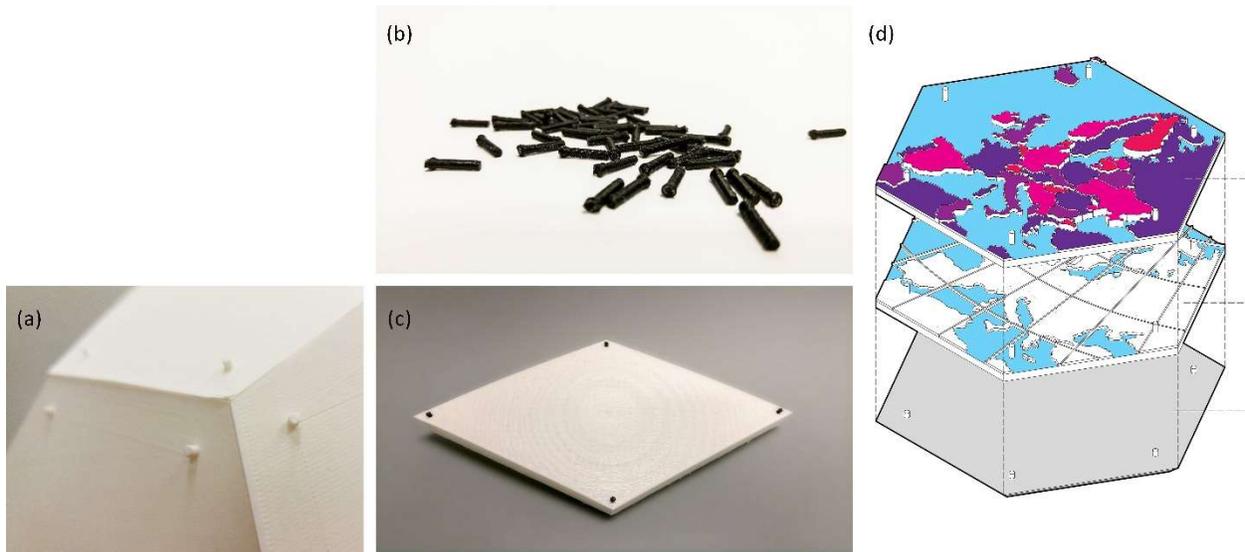


Figure 6. On left, (a) pin-hole structure for the polyhedron globe. Middle: pin-hole structure for the curved globe. The pins (b) are inserted in holes carved into each diamond (c). On right, data layers to attach on cells. (d) The bottom layer is the main surface of the polyhedron globe. The middle layer is world political boundary data. The top layer is population data on a transparent paper.

To create cell-based data layers, we can use the same DGGs used for the base model. We initially import any desired data sets into a DGGs (e.g. PYXIS world view). Afterwards, we can retrieve the data associated with one or more printable units at specific resolutions. Using DGGs, we export the geometry (mesh) of the desired cells and their data associated layers. Since the geometry of each cell is not necessarily flat, we map the data associated to a 2D domain such that, after (2D) printing, this 2D domain can be mapped to these cells. In our case, the only curved cells are diamonds, for which we use an orthogonal projection after finding the plane that best fits the four corners of the diamond. More complex projections or parametrizations such as ABF [31] can be used when the curvature of the cells is high. However, as these diamonds are small pieces of a sphere with relatively low curvature, such a mapping produces fairly good results (see Figure 8).

Now, given the possibility to map data sets on printable and attachable 2D pieces, we can produce various visualizations for our physical model. For example, we attached an elevation data set with a Canadian National Fire data set as opaque layer samples (see Figure 8 (b) and Figure 9. In the next section, we provide some results of our physical visualization model.

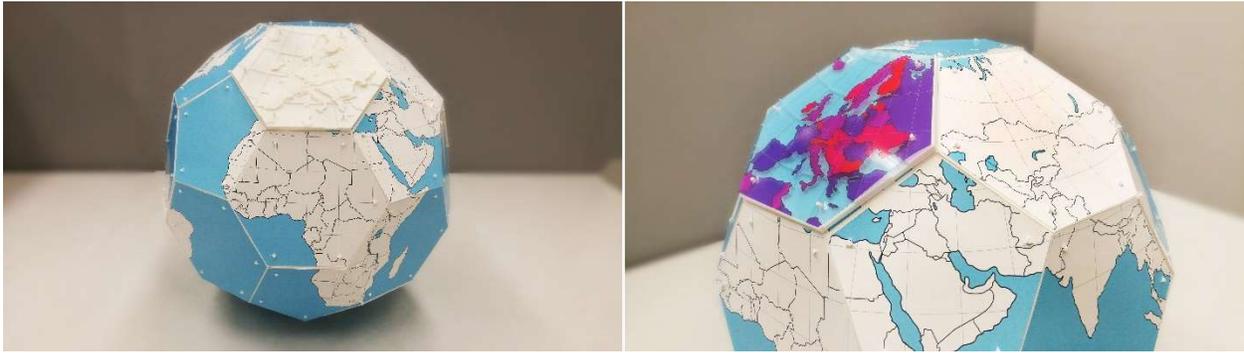


Figure 7. On left, an opaque layer showing political boundaries. On right, a sample 3D printed layer together with a transparent analytical data layer can be attached to the polyhedral globe model.

6. Results

In the previous section, we demonstrated the results of polyhedron globe and visualization techniques for different data sets. In this section, we provide more results for the curved globe model. For this model, our first example, Figure 8 (a) shows paper layers attached to Western Canada. These paper layers include an elevation data set, a Canadian National Fire data set, and a combination of the two.

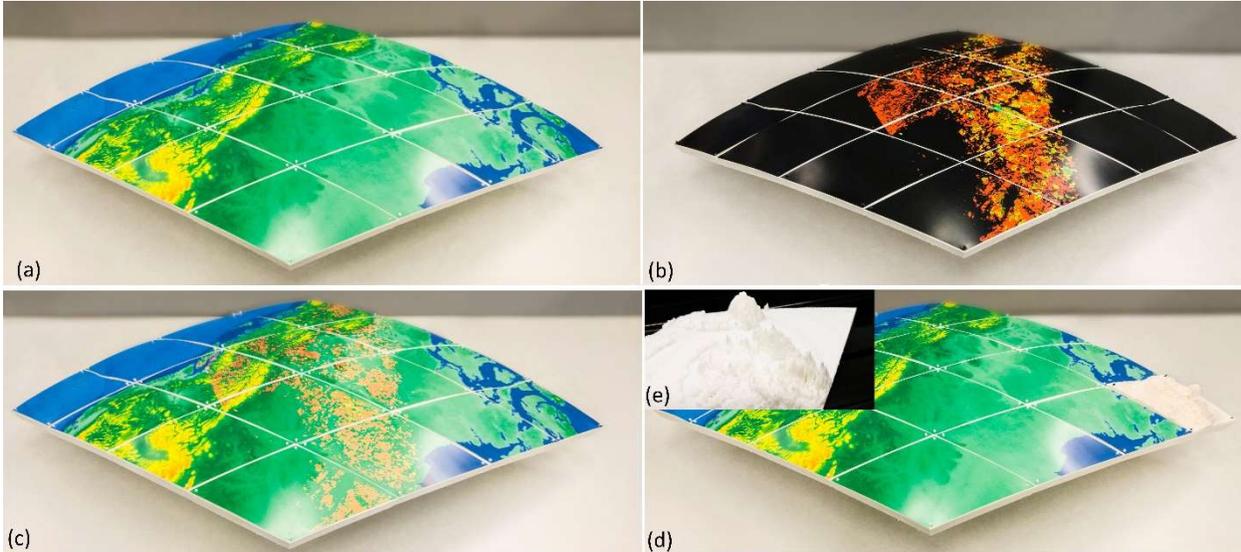


Figure 8. (a) Elevation data set of the western Canada attached to the 3D printed partial globe model. (b) Canadian National Fire data set. (c) The combination of the two data sets (Bottom). (d) A sample diamond containing 3D printed elevation data set.

Using fabricated 3D layers provides us with a unique opportunity for creative visualization of geospatial data sets. For instance, since the elevation data can be better visualized in 3D, we can use a physical layer for this data set. We have used PYXIS world view to retrieve the elevation data associated with one of the diamond cells (see Figure 8 (d), Figure 8(e)).

To compare data sets of different regions, we can visualize different statistical data sets related to our region of interest. Figure 9 shows a 3D printed pie chart which illustrates the number of different tree types found in its corresponding diamond. The bar chart in Figure 9 also illustrates the populations of different regions. These 3D printed charts can be combined with different paper layers, for instance by making cuts on the paper layer and placing it on top of the 3D printed charts (Figure 9). To do so, the 3D chart models are projected to a flat 2D diamond under the same orthogonal projection used to make paper layers (see Section 5). The resulting flat 2D diamond provides the exact locations of the cuts to be made. This can be done using either a desktop silhouette cutting machine or a laser cutter. By subtracting these pieces, the printed paper easily fits over the 3D printed chart and can be attached to the globe using pins.

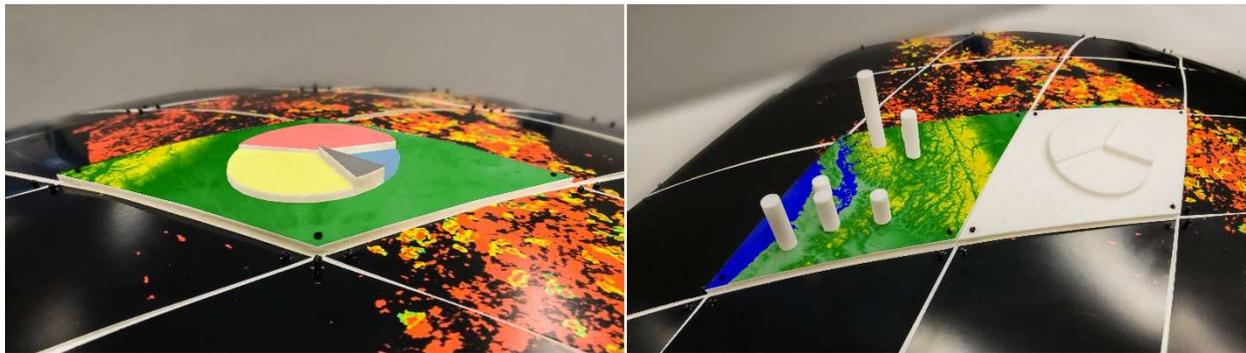


Figure 9. Pie chart and bar charts printed and assigned on the partial curved globe model.

In order to interact with the model, we can use a transparent layer attached to the diamonds on which sketches may be made, supporting decision-making and design processes at the provincial or national scale. Adding pins to different parts of the partial globe is another interactive use of this model. By adding pins to the region of interest we can observe the relative distances between multiple regions or compare their associated data sets. Figure 10 illustrates such interactive possibilities.

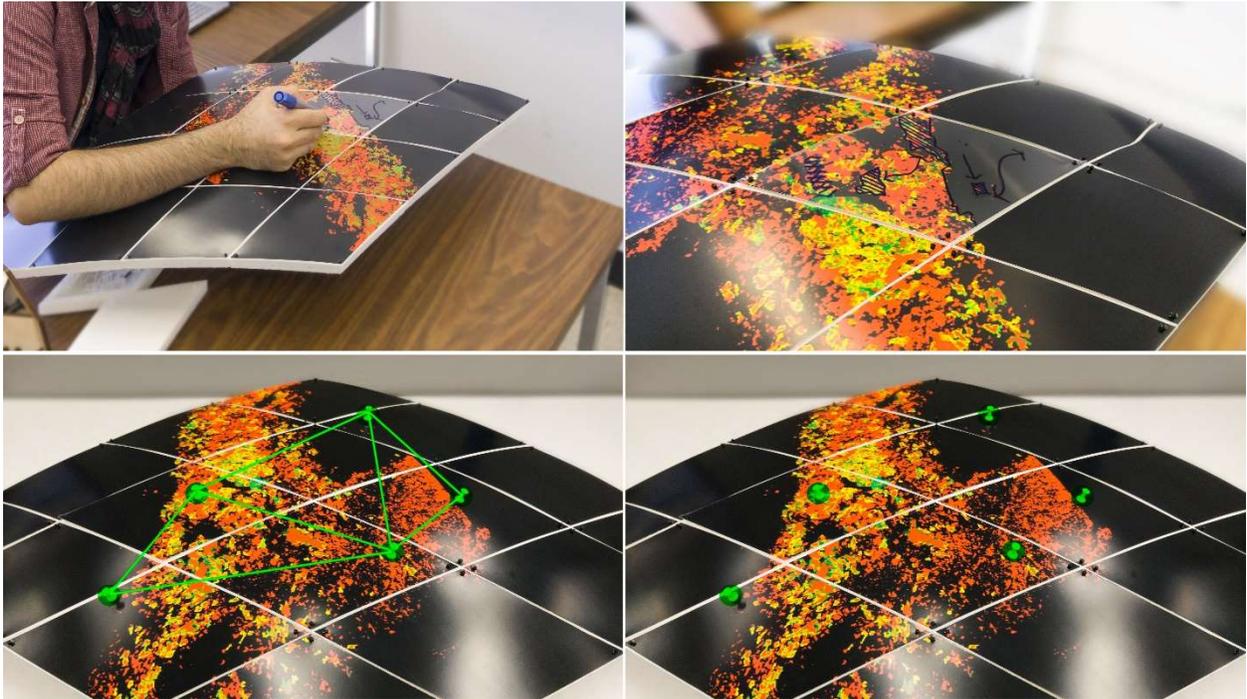


Figure 10. Using the surface of the globe to make sketches (top left and right), adding pins to the globe (bottom right), and using the attached pins to show vector data sets (bottom left).

7. Limitations and Future Work

There are several directions to improve or extend this work. Making visualization methods more creative is something we can achieve by designing more functionality for the globe scale model. A good example could be the use of LED lights on the surface model to visualize different types of dynamic data sets.

We intend to use these visualization techniques in practical applications, such as education, and evaluate our techniques in conveying geospatial concepts. For this we may choose higher resolutions which can illustrate the details needed for urban projects. Urban planners, urban designers, and even architects will be able to use this as a basis for making design decisions and for presenting their results to clients. We need to do a set of formal user studies to evaluate our proposed method and its potential applications to education, urban planning, urban design, and architecture.

The final goal of this project has been to make a dynamic system for representing and visualizing various geospatial data sets within context. The result should provide users with a range of good interaction possibilities and enable them to visualize anything they have in mind without being dependent on a specific resolution. 3D printing will still play an important role in the future of this project since it is the key factor to facilitating the building of virtual models without being forced to use complicated manufacturing techniques.

8. Conclusion

Despite the advances in rendering and visualization technologies, some data sets (particularly geospatial data sets) need to be physically visualized in order to provide users with better interaction and understanding of these data sets. As digital fabrication techniques become more and more popular, designing a system which enables users to use 3D printers for visualization plays an important role. This physical fabrication needs to be based on a system which guarantees a reliable model of the globe suitable for representing data sets.

We explored the possibilities of creating scale models of the Earth at both a coarse and high resolution such that any geospatial data set may be physically visualized. Using these scales allows us to visualize different types of data in different ways via attachment on a physical globe at the desired resolution. Such a system even provides interaction tools for highlighting data using sketches and designs.

This physical Earth will work hand in hand with any type of geospatial data set, giving users the chance to work with any that are needed. Different techniques for data visualization also give the ability to attach various data sets on the globe as layers so that necessary analyses and studies may be performed.

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Hessam Djavaheerpour (Hessam.djavaheerpour@ucalgary.ca)

Hessam Djavaheerpour is a PhD student in Computational Media Design (CMD) at the University of Calgary. He has a master's degree in Architecture from the Iran University of Science and Technology. His main research interests are Responsive Architecture, Dynamic Structures, Digital Fabrication, 3D Printing, Physical Visualization, and Data-centric Approach to Design.

Dr. Ali Mahdavi-Amiri (a.mahdavi.amiri@gmail.com)

Ali Mahdavi-Amiri has received his PhD from the University of Calgary. He is currently an NSERC postdoctoral fellow at Simon Fraser University. His main research interests are Computer Graphics, Geometric Modelling, and 3D Fabrication.

Dr. Faramarz Famil Samavati (samavati@ucalgary.ca)

Faramarz F. Samavati is a Full Professor in the Department of Computer Science at the University of Calgary. His research interests include: Computer Graphics, Visualization, 3D Imaging, and Geometric Modeling. Dr. Samavati has published more than hundred and twenty papers and one book. In the past four years, he has received four best paper awards, the 2013 Digital Alberta Award for Best in Cross-Platform Content, a Great Supervisor Award, and the 2014 University of Calgary Peak Scholar Award, which honors his contribution to the development of new technologies and innovations.