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Exploring the Accessibility and Applications of Laser Cut Contour Topography Models

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Abstract

Existing elevation data may be represented via laser cut rapid prototyping in order to create physical models of terrain. Previous work has shown improved comprehension of elevation and contour data when a 3D model is provided, however such models are often difficult to manufacture and expensive. Rapid prototyping technologies, including 3D printing and CNC routing, have proven capable of producing cheaper, more accessible topographic models. Despite this, there is a distinct lack of academic exploration on how laser cut models may be utilized. This project aims to improve the accessibility of such models by developing a defined model creation process to aid in the creation of laser cut topology models, and further establishing where laser cutting offers benefits over alternative rapid prototyping processes.

1. Introduction

It is critical to have a solid understanding of elevation and terrain information for a vast range of applications, including engineering, land development, and conservation. It is for this reason that a significant amount of resources has been put into technologies such as LIDAR and GIS software, which allows for the gathering and interpretation of such information. Advancements in visualization software such as ArcGIS and Google Earth have vastly improved the virtual accessibility of such data, and technologies such as virtual reality (VR) have allowed for the investigation of virtual 3D models with far more interactivity than ever before. However, despite all of the advancements that have been made within the field of data visualization, there still exists a niche for physical models (Jansen et al. 2015). Benefits of a tactile model range include the ability for multiple individuals to observe from independant perspectives, superior transportability, improved memorization of spatial content (Giraud, Brock, Macé, Jouffrais, 2017), and better accessibility to individuals with limited sight (Koch 2011) (Schwarzbach 2011). In the case of topology, adding the third dimension allows for greater comprehension from individuals unfamiliar with contour lines as a means of showing elevation.

Past research has been done primarily on the production and utility of 3D topographic models, with most looking at custom manufactured maps, and more recently 3D printed models, with the conclusion that rapid prototyping technology is ideal for creating representations of elevation data (Rase 2012). The proliferation of publicly available datasets containing such data has resulted in a number of projects which allow for the generation of 3D-printable elevation models online, simply by indicating the selected area. For example, TouchTerrain is a web-tool which automatically makes 3D printable digital models from public elevation data (Hasiuk, Franciszek 2017), and projects such as TactileMaps and TouchMapper specialize in creating 3D printed maps for the vision impaired. Such models are excellent at portraying a single geographic dataset, such as elevation or land usage. While it is clear that there is a utility and demand for 3D maps, there is little to no literature on the utility and application of laser cutting for this purpose (Rase 2012).

In addition to 3D printing, computer numerical control machines offer another means of creating rapid prototypes at scale. CNC machines operate utilizing a tool bit that can move freely on multiple axes to carve out 3D shapes from inserted materials. Such machines have been utilized to create physical maps and excel in creating larger scale models with precision. Laser cutting technology has been around since 1965, however it is only over the last two decades that the technology has developed beyond commercial manufacturing into a rapid prototyping tool (Bromberg 1991). Utilizing a high powered laser, the machines are able to cut and engrave designs into the inserted substrate.

As rapid prototyping tools, 3D printers, CNC machines, and laser cutters each offer distinct advantages, and varied capabilities, and are the most commonly utilized rapid prototyping tools (Prinz 1997). Commercial laser cutters are distinct in several ways, including that 3D printers and CNC machines take 3D models as input, whereas a laser cutter takes 2D data, in the form of a vector and raster file. The vector file mathematically describes the paths which should be cut from the inputted material, and the raster file describes pixel data which is to be engraved on the surface of the inputted material. 3D printers lack the ability to engrave details into the surface of the object being printed outside of altering the 3D model, and extrusion models are unable to implement details smaller than the extrusion nozzle fitted to the printer. CNC machines are able to engrave details, however it again requires altering the 3D model of the object to be manufactured. Laser cutters are able to engrave (nearly) in 2D, and at much higher resolution than the alternatives along the X and Y axis, although are limited in the vertical Z axis by the thickness of the inserted material. Another difference between the machines is the time required to create a completed model. Generally, laser cutters are much faster than both CNC machines and 3D printers, especially when there is no engraving required, or the engraving doesn’t require extremely high resolution. This efficiency is a compromise with physical capability, as a laser cutter is only able to work on a single thin sheet of material at once which requires later construction if a 3D model is desired. In nearly all cases, the cost of material for a laser cutter is less expensive than that for 3D printing, especially considering the diversity of material that may be utilised, including paper, cardboard, plywood, acrylic, metal, and more. Furthermore, laser cutters are distinct in that they take 2D files as input rather than 3D models, which allows for individuals unfamiliar with 3D modeling software to still utilize laser cutters to manufacture unique creations. Given the accessibility of 3D printers and their utility for creating custom shaped three dimensional components, they have been the focus of most of the scholarly research into advancements in rapid prototyping, as evidenced by the quantity of papers and projects in which they are utilized.

Despite the lack of academic interest, there has been a significant amount of work in both the creative and commercial industries in utilizing laser cutters for rapid prototyping. Individual posts on creating custom topographic models can be found online alongside retailers offering laser cut maps of popular tourist locations, and simple 2D maps. Without the accessibility of 3D printing, laser cut elevation models have been largely ignored, and left mostly to the artistic community. The workflow described here focuses on publicly available datasets and open-source software, with the intent of providing a means for greater accessibility for this methodology. The project further aims to explore how existing elevation data may be represented via laser cut rapid prototyping in order to create physical models of terrain, and how such a model compares to those made via current methods.

2. Implementation

The process of creating a laser cut topology model may be broken down into components: data collection, editing of the geographic information, preparing a cuttable file, and assembly. All of the steps have been thoroughly laid out in the Results, and each section below elaborates on the specifics of the process as well as the means by which the final results were established. The workflow as defined below utilizes QGIS, an open source and cross-platform geographic information system (GIS) application which enables viewing, editing, and analysis of the geospatial data, as well as Inkscape, an open source vector graphics editor.

Data

Within the United States, both federal and state governments maintain databases for accessing publically available geographic information online. This includes both vector data, such as elevation contours, road centerlines, and town boundaries, as well as raster data including aerial photography and digital elevation maps (DEMs). For the purposes of the topography models, both contour datasets and DEMs were considered. A DEM is a raster dataset consisting of pixel values which represent the elevation at a given point, which can be utilized via GIS software to create contours at any desired scale and distance. While potentially useful, in the course of researching available datasets, it was found that often converting DEMs to contours resulted in a significant number of artifact contours which would not be usable for a laser cut topography, due to being either too small to render accurately with the laser, or in shapes that would be extremely fragile if constructed out of physical materials. For this reason, the decision was made to focus on contour datasets, as they sport the benefit of generally having more useful geometry, and often offer a higher resolution. There exists numerous sources of documentation on how to generate contour paths from DEM datasets should the need arise, and is a reliable secondary option for locations and features for which a contour map cannot be found, such as underwater locations (bathymetry) or locations on other planets. Figure 1 demonstrates the difference between a DEM, a raster model from Open Street Maps, and an elevation contour model for the same location.

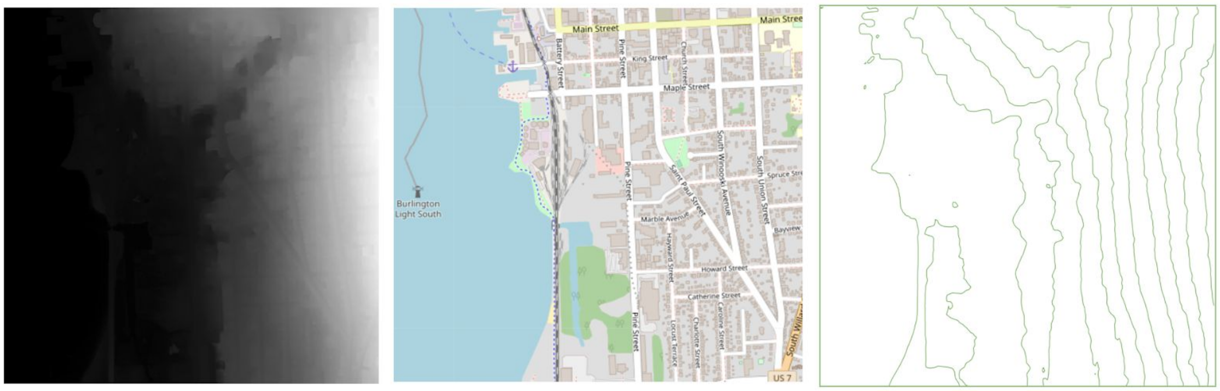


Figure 1: From left to right, a DEM, a raster model, and a vector elevation contour model of Burlington, VT.

As previously discussed, one of the most significant advantages of laser cutting over other forms of rapid prototyping is the ability to take 2D files as input, both to define the vectors that are to be cut as well as the image to be rastered. The combination allows for most of the geographic data designed for traditional maps to be rendered on a laser cut model, opening up a far greater selection of datasets to be utilized. In addition to federal and state resources, one promising database that was extensively considered was OpenStreetMaps (OSM), a digital map of the world generated through crowdsourced data gathering in combination with existing geographic data. OSM offers a particularly unique database as the data is constantly being updated and fact checked by users around the world, ensuring that data is as accurate as possible. Features that are often unable to be found from other resources, such as footpaths, hiking trails, structures and transportation networks. In addition to providing a highly in-depth map of most inhabited areas, OSM is additionally used for humanitarian mapping, providing accurate maps of places in need of humanitarian aid.

A common difficulty in working with geographic information, especially from varying sources is differences in map projection, the way in which the 3D world is transformed to fit a 2D representation. This issue can be resolved through aligning and converting the projections of each dataset, a task made significantly easier through the use of a designated geographic information system software tool.

GIS

For many projects that work with geospatial data, utilizing geographic information system software is a requirement. Factors such as map projections, large file sizes, and XYZ all make working with geographic data difficult, yet can all be resolved by a functional GIS program. The initial proposal for this project suggested that the data manipulation could be done separately, however further research into how the tasks of geodata management and manipulation could be done revealed that the software would essentially need to recreate a functioning GIS application to perform the desired functions. For this reason, the decision was made to utilize the open source GIS program QGIS. Specifically, QGIS is utilized to format, edit, and preprocess the data before convening the various datasets into a singular scalable vector graphic (SVG) file. The software additionally provides additional benefits such as the ability to add accurate measurement scales, legends, and comes with extensive documentation. Although designed to work with large datasets, it is worth noting that large geographic datasets will take significantly longer to load and process, especially on older machines. The issue is compounded when the large files are exported as SVG files, where they have to be further processed by the designated vector graphics editor.

Vector Graphics

Most modern laser cutters utilize a vector based file format for their input, which is then translated into precision movements of the two axis motors that drive the laser. Although the GIS software utilized is capable of outputting files into a vector format, the resulting files are not separated into the appropriate layers for cutting a topographic model, and still need to be formatted such that the symbology is able to be appropriately interpreted by the laser cutting machine. The open source vector graphics editing program Inkscape fulfilled these requirements, as outlined in the results. Generally, the process of preparing files for a laser cutter requires appropriate sizing, symbology, and for multi-layered projects, separation of the elements for each layer, such that they may be independently cut and later assembled. Depending on the desired number of contours to be shown contour maps may require any number of layers to be differentiated and cut. While for this purpose the full raster image could be engraved for every layer, the rastering process takes significantly more time than vector cutting, a problem which is compounded when the raster requires a high resolution. Although the resolution of the raster may be lowered the best solution is to only engrave on each layer what will be visible in the final assembly. In order to do so, there are a number of possible methods, such as setting up transparency masks or creating additional border elements. For the purposes of this project, it was deemed acceptable to simply select the desired raster elements by hand, as the process of setting up the other methods requires considerable technical prowess with the vector graphics software, and a primary goal is to simplify the process to promote accessibility. Beyond allowing for preparation of the exported vector graphics the software additionally enables the addition of custom elements, such as titles, labels, vector art, images, etc. Once converted to a format that can be inputted into the laser cutter, the files may be reused later with minimal effort to display new maps of the same area, potentially with features added or removed using the vector graphics editor.

Physical Manufacturing

Anyone operating a laser cutter should be trained on proper use and maintenance of the equipment before using, as failure to do so can result in serious injury. Considerations to take when using a laser cutting machine for the purposes ascribed in this paper include the power and speed of the cut, the power, speed, and resolution of the raster, as well as the size of the bed. Altering the power and speed of the vector cut will cause the laser to either cut deeper or shallower, and is set based on the type and thickness of the material that is being cut, and altering the raster will change the strength of the laser while engraving, resulting in a darker or lighter raster. The resolution of the raster refers to the dots per square inch (DPI), which will alter the clarity and definition of the final raster. Laser cutters come with a reference guide for common materials that indicate specific settings, however it is recommended to test settings before committing to cutting any actual project files.

As most laser cutters have a cutting bed of a specific size, dimensionality must be a consideration when creating a topological model. Each layer cannot be larger than the size of the bed, however larger maps may be created by tiling multiple smaller maps, which in theory allows for models of unlimited size. Laser cutters are traditionally able to work with much larger surfaces than 3D printers, and increased size is a benefit that laser cut maps have over 3D printed counterparts. Assuming the files have been correctly prepared, using the laser cutter should be a relatively straightforward process, resulting in each layer being individually created. An issue that may occur in cases where there is a limited raster is confusion over where layers are meant to be positioned when assembling the completed project. A simple solution to this problem is to raster the outline of the following contour onto each layer, such that alignment only requires lining up each layer with the identical raster on the layer below. Once cut, layers may be painted, sides sanded, stained, or otherwise colored before assembly, although for best results any sort of sealing agent should be applied after adhesion. To assemble the finished model, starting from the bottom two layers: Line the layers up, apply appropriate adhesive, and clamp. Wait for the adhesive to set before applying the next layer.

Figure 2: Completed laser cut bathymetric model of Maui that has been stained and decorated.

3. Results

Data

For demonstrational purposes, the following model was constructed of the UVM campus and nearby downtown area of Burlington, VT.

Elevation contour data may be downloaded from the Vermont Open Geodata Portal, through the Vermont Open Geodata Portal. The site hosts a significant number of datasets, and so the datasets may be filtered to only select contour data. This search yields six potential datasets, all of which could potentially be used. At this point, it depends on the scale of the project for which dataset should be utilized. Given that the area over which this map will cover has a somewhat significant elevation difference over a small area, the 20’ contours are selected. The size of the contours refers to the distance in elevation between contour lines, and the resolution refers to the accuracy of the lines as a whole.

Year	Product	Source	Resolution	Quality Level	Description	Download	Metadata
	Contours	Lidar	0.7m	QL2	1' Contours derived from 2013 - 2017 QL2 lidar data - Statewide	Download	Metadata
	Contours	Lidar	3.2m	QL4	10' Contours derived from lidar data - Chittenden	Download	Metadata
	Contours	USGS	30m	N/A	VT 100' Contours generated from USGS 30 meter NED DEM	Download	Metadata
	Contours	USGS	10m	N/A	VT 20' Contours generated from USGS 10 meter NED DEM	Download	Metadata
	Contours	USGS	30m	N/A	VT 50' Contours generated from USGS 30 meter NED DEM	Download	Metadata
	Contours	Lidar	Varies	Multiple	2' Contours derived from lidar data - 35 percent of VT	Download	Metadata

Figure 3: Various options available for contour datasets within VT

Selecting to download the contours leads to a tile selection page, where the specific data can be selected. Datasets with a high resolution will often be broken down into tiles, which allows for smaller portions of the data to be downloaded at a single time. Downloading this file results in a compressed folder which contains several files,including the vector data as well as metadata about the contours. If the area being modeled is significantly larger than the tiles, a lower resolution dataset may be more manageable.

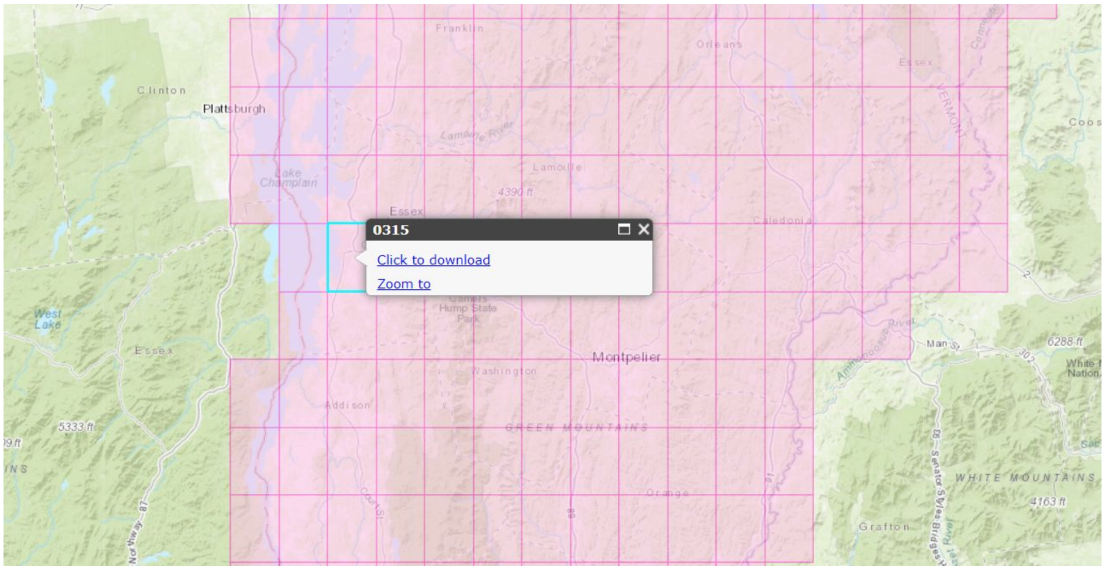


Figure 4: The data is split into tiles that cover the mapped region, which may be selected by clicking on them.

In order to find data to utilize for the surface engraving of the finished project, it depends on the intent of the model. A model intended to simply display the elevation of a wilderness area may not need any additional information, whereas a map of a city may require street data, building data, and more. For this project, two more datasets are downloaded from the Vermont Open Geodata Portal: Road Centerlines, which contain vector data describing the centerline of roads in the desired area, and E911 building data, which includes the vector geometry of building footprints throughout Vermont. Another source of reliable data, especially for data that is high resolution and specific, is OpenStreetMaps. Getting data from OSM is simple, by navigating to a frame which contains the area you want data for, and selecting “Export” from the top right. To find datasets for a project, state geodata portals are often a reliable and recently updated source. Utilizing a search engine to look for particular datasets can also be useful. Often geodata portals will include multiple options for downloads: For the purpose of this project the shapefile is required, as opposed to a metadata spreadsheet or KML file.

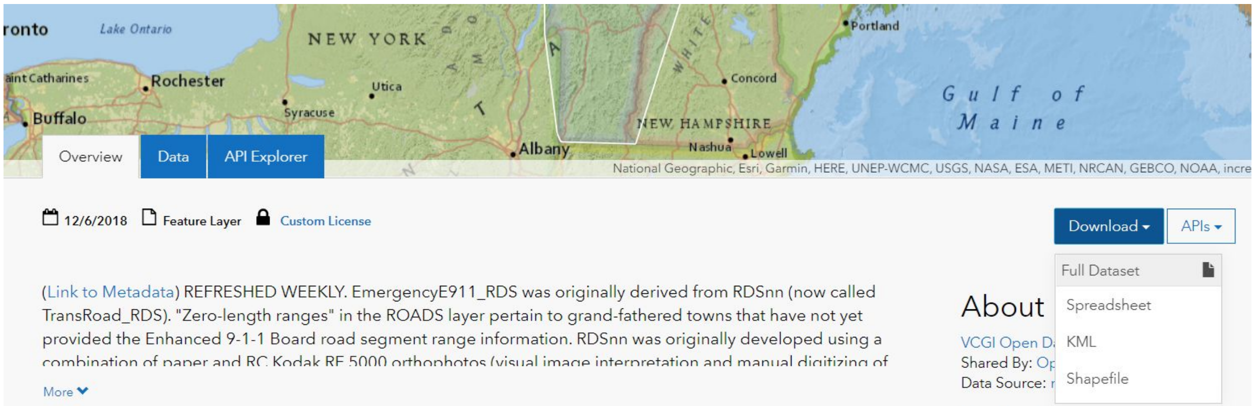


Figure 5: Individual pages for datasets in the Vermont Open Geodata Portal provide a preview of the data being mapped out, as well as a tab to look at the metadata, additional information about the dataset, and download options.

GIS

Once the desired datasets are downloaded, the compressed files may be extracted and moved into a directory. At this point, the data needs to be prepared before converting it into a format which the laser cutter can take as input. To do so, the open source geographic information editing program QGIS Desktop may be utilized, although the steps involved should be possible with any GIS program, such as ArcGIS. Full documentation and download links are available from the QGIS website. The vector data can be imported into QGIS by selecting *Layer → Add Layer → Add Vector Layer…*, which opens a file selection window, where the shape files are selected.

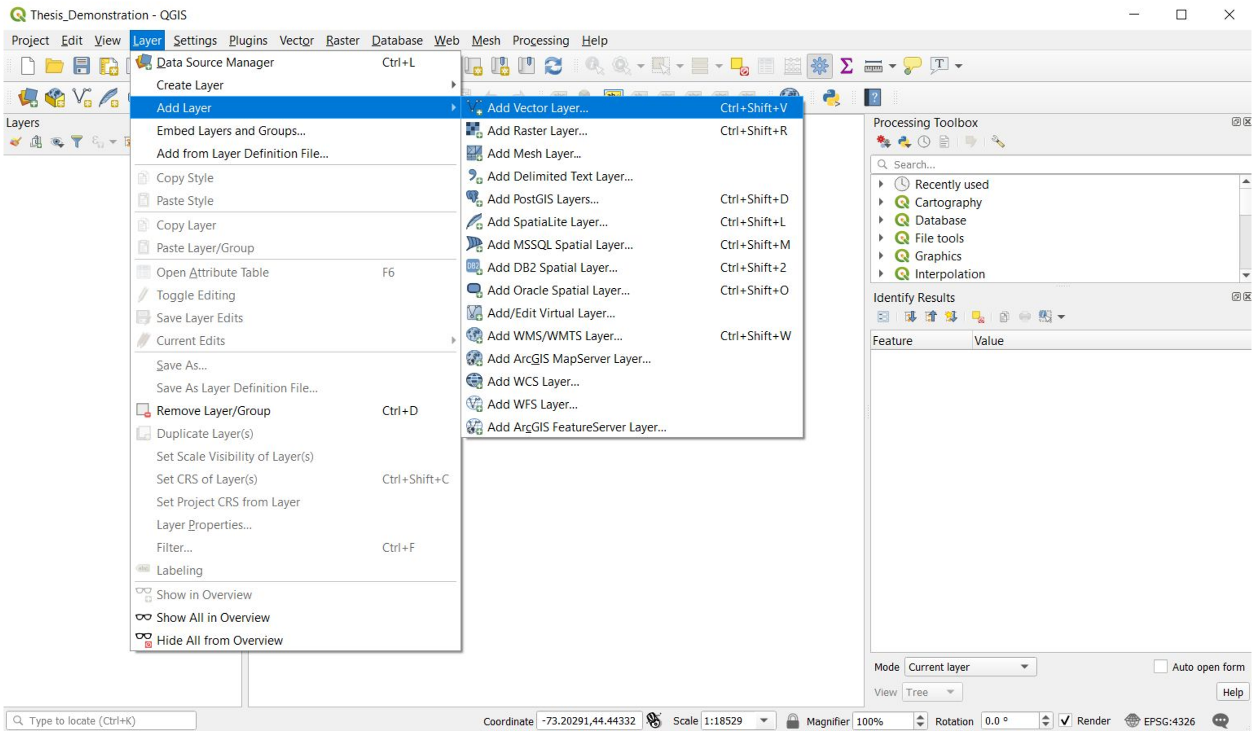


Figure 6: The *Layer → Add Layer* tool can be used to import vector and raster layers

After the vector layers are imported, the vectors appear in the program. If they do not, the issue may be that they have been hidden, which can be disabled by ensuring that the check boxes next to the dataset names in the Layers tab are all checked off. Zooming to the area of interest, there may be a lot of visual activity on the screen, which the next steps seek to organize.

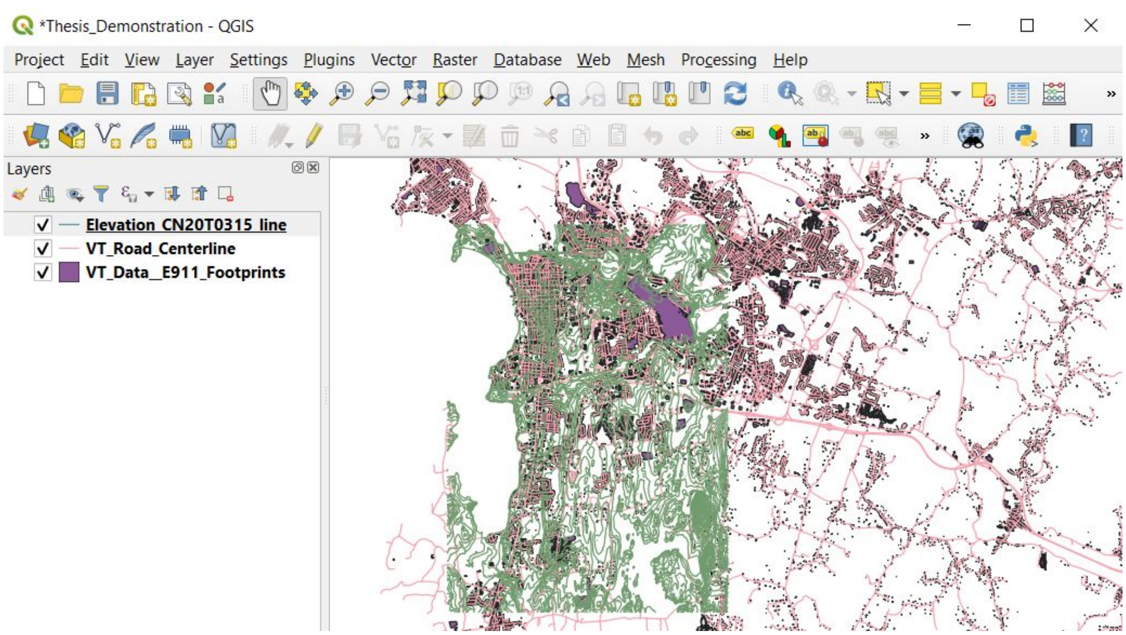
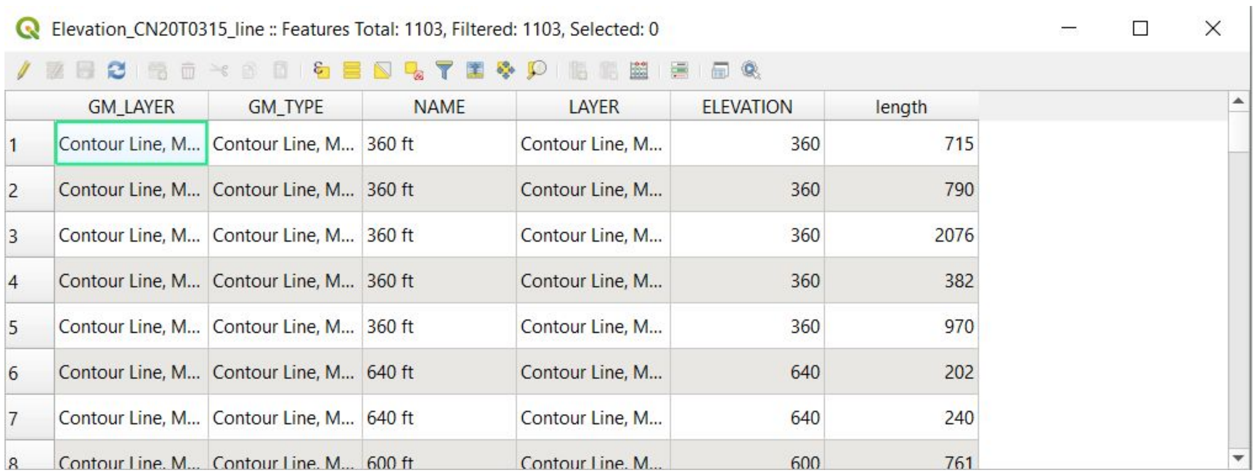


Figure 7: View of imported data without any organization.

The layers can be shown or hidden by toggling the checkboxes in the Layers menu, and for the first step all of the layers except the elevation data are hidden. In this case, it seems that for the desired area there are quite a few contours, and so it would be useful to thin out the contours, to make the map more comprehensive, and save on the number of layers required to construct the finished map. In order to edit the layer, the attributes of the layer need to be determined. In the Layers menu, the name of the layer may be right clicked to reveal several options, including *Open Attribute Table*. Doing so will open an attribute table for the contour vectors, which may include data both on the vector shape and size, as well as elevation.



Elevation_CN20T0315_line :: Features Total: 1103, Filtered: 1103, Selected: 0

	GM_LAYER	GM_TYPE	NAME	LAYER	ELEVATION	length
1	Contour Line, M...	Contour Line, M...	360 ft	Contour Line, M...	360	715
2	Contour Line, M...	Contour Line, M...	360 ft	Contour Line, M...	360	790
3	Contour Line, M...	Contour Line, M...	360 ft	Contour Line, M...	360	2076
4	Contour Line, M...	Contour Line, M...	360 ft	Contour Line, M...	360	382
5	Contour Line, M...	Contour Line, M...	360 ft	Contour Line, M...	360	970
6	Contour Line, M...	Contour Line, M...	640 ft	Contour Line, M...	640	202
7	Contour Line, M...	Contour Line, M...	640 ft	Contour Line, M...	640	240
8	Contour Line, M...	Contour Line, M...	600 ft	Contour Line, M...	600	761

Figure 8: Attribute table for contour vector data. Elevation and vector length are included values

The attribute table for the selected contour dataset shows that the ELEVATION variable contains the value referring to the elevation of the contour vector, which can then be used to filter the dataset. The filter tool may be reached by either pressing ctrl+f while the desired dataset is selected, or by right clicking and selecting *Filter…*. The filter tool allows for datasets to be filtered by their attribute tables, utilizing appropriate logic statements. Columns from the attribute table may be included in the equations by double clicking them in the *Fields* box. For the current project, knowing that the elevation values are measured by 20’ half of them may be filtered out by putting the expression *“ELEVATION” % 40 = 0*, which will give back every other contour. In doing so, however, the contour which defined the waterline on Lake Champlain was removed, which indicates that the elevation is not 0 at the waterline. Looking back at the attribute table reveals that the waterline is at elevation 100, which we can include by changing the expression to state: *(“ELEVATION” + 100) % 40 = 0*. Pressing the *Test* button prepares a preview of what the dataset will look like under the applied filter, and returns the number of entries that are still valid in the attribute table.

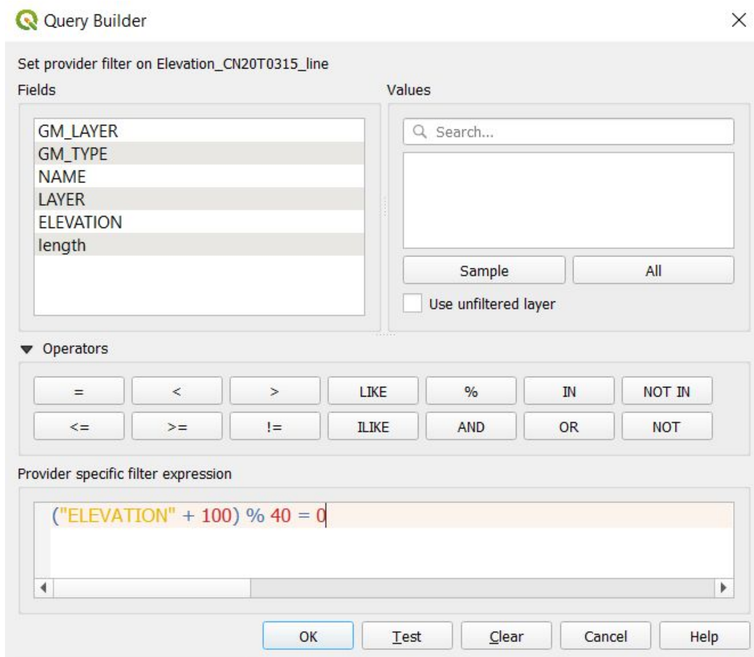


Figure 9: The Query Builder tool allows for vector datasets to be filtered based on attribute table values

The other step required to prepare the contour layer for printing is to distinguish between the different elevation levels. In order to do so, the color of the contour line can be set to vary based on the elevation value, as defined in the *"Elevation"* column. This can be done by right clicking on the contour layer, and selecting *Properties*. This opens the layer properties menu, from which select the *Symbology* tab on the left, then at the top of the tool select *Simple Line*. Clicking on the button next to *Color* will open a dropdown list, including ***Assistant***. Selecting ***Assistant*** will open the *Symbol Stroke Color* window. The Symbol Stroke Color window allows for the color of the contours to be data-defined, which in this case will be assigned based on the elevation which the contour represents. Within the new window, the variable representing the elevation of the contours is selected, which in this case is "ELEVATION". Pressing the cyclical button next to "Values from" autofills the range of the elevation, which is sufficient for this project. Finally, the color ramp indicates the specific gradient which should be used to color the vectors. Using a gradient that does not include white makes editing simpler later on, and is recommended at this step.

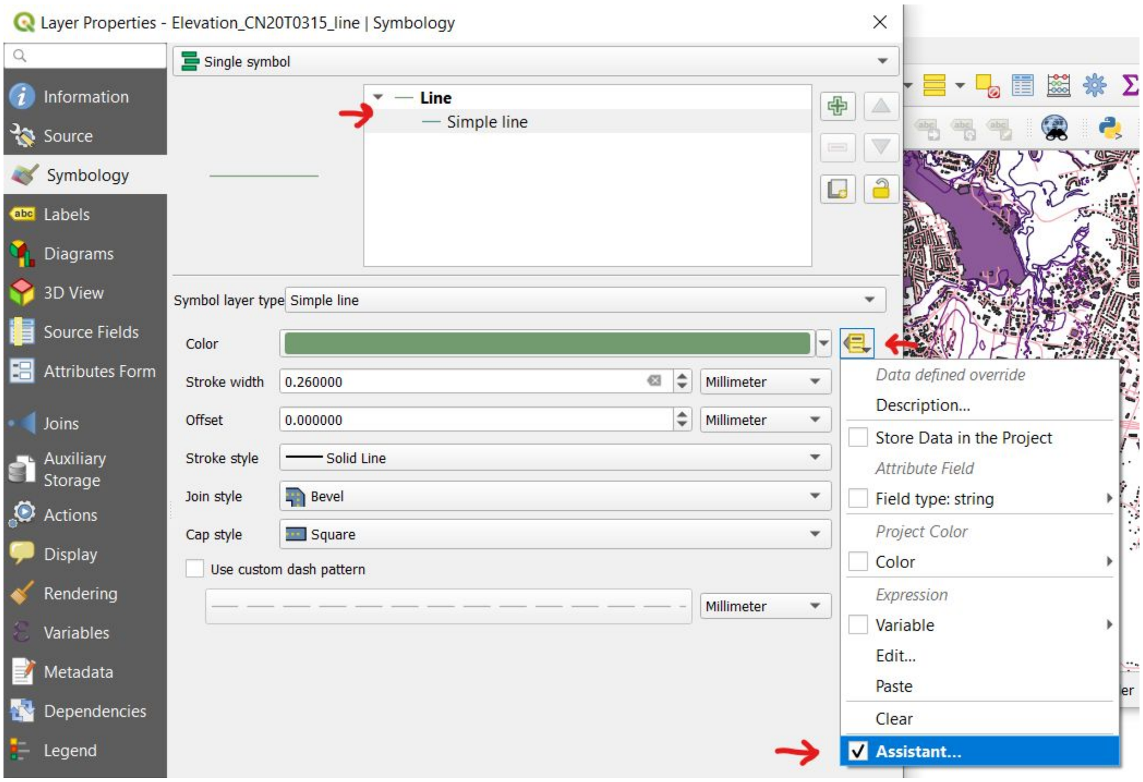


Figure 10: Select ***Assistant*** under the *Symbology* tab of the *Layer Properties* window, with "Simple line" selected

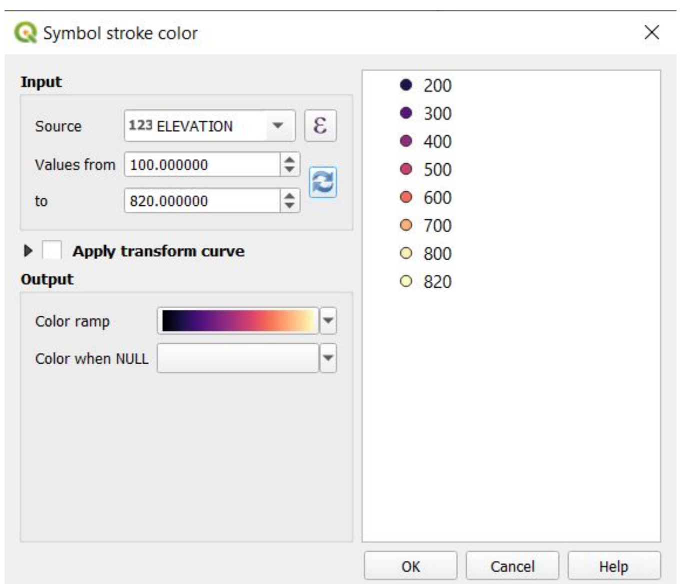


Figure 11: The Symbol stroke color window allows for data-based coloring of vector datasets

Once filtered and colored, the contour dataset is ready for export to SVG. Additional changes may be made, such as further filtering to remove small artifacts by indicating a minimum length. From this point, the rest of the work in QGIS is to prepare the other layers for engraving, which to a larger extent depends on individual design preferences and requirements. For the current project, the dataset containing building footprints also contains outlines for parks and other artifacts, and encompassed the entire state. The attribute table can be used to determine the variables which define the type of footprint as well as the county which it is contained within, which in turn allows for filtering to the desired output. When filtering variables which define strings, single quotations ‘’ are required to name the strings. For example, to filter a variable “COUNTY”, the equation would be: *“COUNTY” = ‘Chittenden’*.

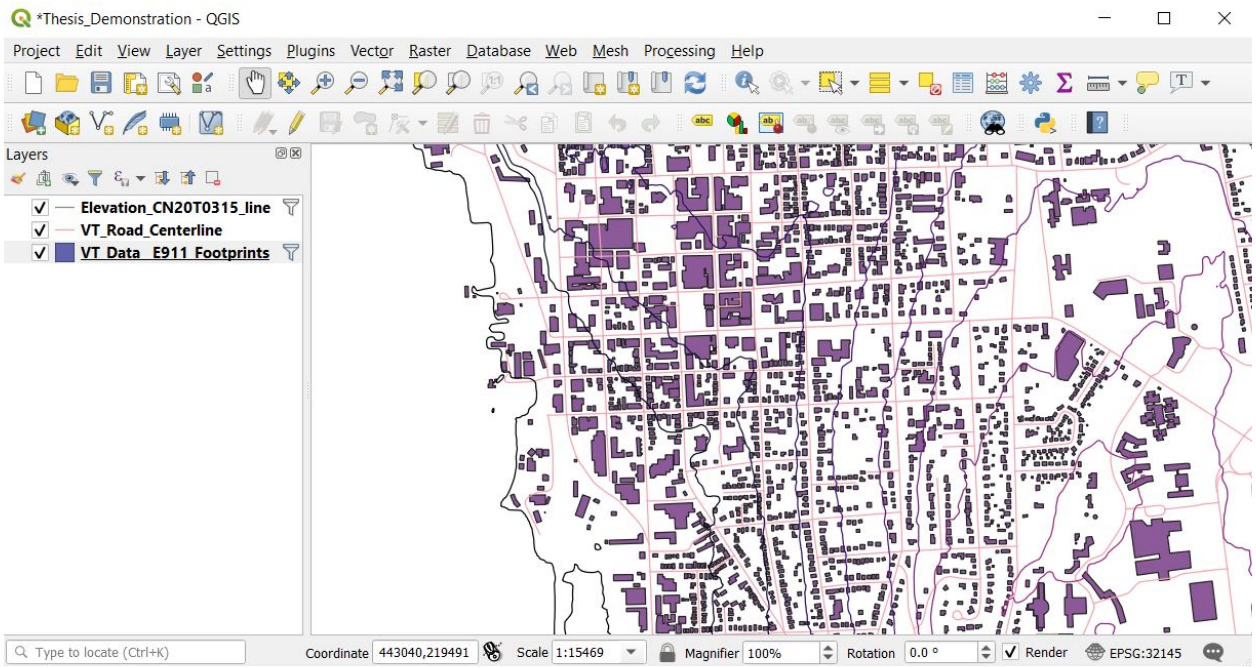


Figure 12: Final appearance in QGIS with contours, road centerlines, and building footprints

After the appearance of the layers is satisfactory, the layers can be exported from QGIS as SVG files. After zooming and panning such that the map appears roughly how the desired final result will be framed, create a new print layout either by pressing *Ctrl + P*, or by selecting *Project → New Print Layout*. Once the new layout window opens, a map object can be created on the layout by selecting *Add Item → Add Map*. After creating the map in the desired shape, press *C* to zoom and translate the map content until it is in the desired shape. A scale or north arrow may be added in the *Add Item* menu, if desired in the finished product. Once set, *Layout → Export as SVG…* may be selected in order to save, with a name that indicates that it is the contours layer. In the SVG Export options, check off the *“Export map layers as SVG Groups…”* checkbox.

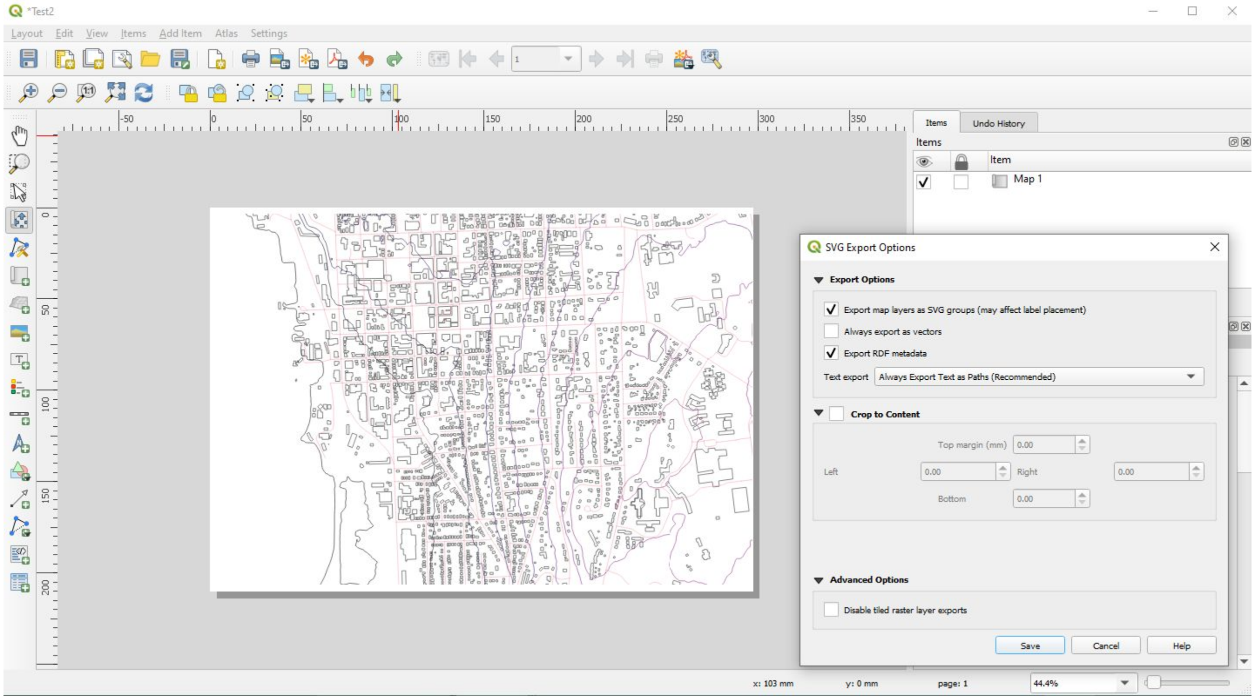


Figure 13: The print layout allows for the vector data to be exported to SVG

Vector Graphics

Once they have been exported, the SVG files can be edited using a vector graphics editor in order to ensure that they are properly cut by the laser cutter. Notably, each layer of the final model will be separate, and as such the file must reflect the contour vector and raster for each individual layer. For this demonstration, the open source program Inkscape is used, although alternative vector graphics editors such as CorelDRAW and Adobe Illustrator may also be used. Once the file is opened, each layer from the map should be seen as a separate layer in the SVG file. In the transfer process, QGIS creates several extra empty layers, which may be identified by turning on and off the visibility of each layer, by clicking the “eye” icon next to each layer in the “Layers” subwindow. If the Layers sub window is not visible, it may be opened via *Shift + Ctrl + L*. Deleting the empty layers leaves only the contours and the layers to be rastered, which for this project leaves 3 layers. The layers can be renamed by right clicking in the layer menu and selecting *Rename Layer*. It’s worth mentioning that layers with many components may be slow to render and work with, and may not show up well in the completed product. If this is the case, it’s best to add more filters in QGIS before exporting, or utilizing a different dataset.

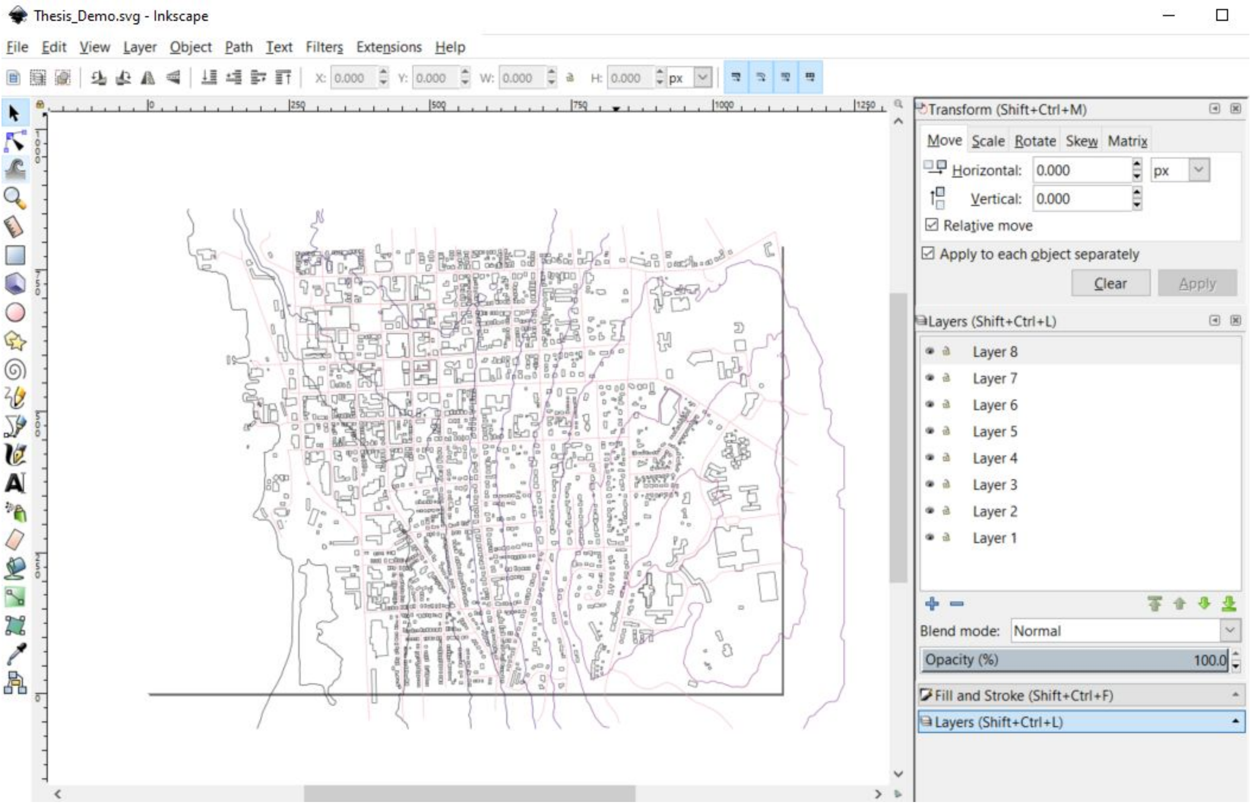


Figure 14: SVG File opened in Inkscape. Note the layers as indicated on the right.

After the empty layers are deleted, and the remaining layers are renamed, create a new layer by pressing the *"+"* button in the Layers subwindow. After clicking on the new layer to make sure that editing is happening in the new layer only, a rectangle can be created either by selecting the "*Create Rectangles and Squares*" button on the left hand side of the main window, or by pressing f4. A rectangle should be drawn where the desired eventual edges of the map will be. This may leave parts of other layers outside of the rectangle, which will be accommodated for later. Notably, the shape of the final map is not limited to being rectangular, and could take the shape of a circle, a natural contour shape, or otherwise. As a default, drawn rectangles have a solid fill and no border, which can be rectified by going to the "*Fill and Stroke*" menu in the right subwindow, or by pressing *Shift + Ctrl + F*. Selecting the leftmost icon in the shape of an 'X' for the "*Fill*" will make the rectangle transparent. In "*Stroke Paint*", the color of the rectangle can be defined, and finally in "*Stroke Style*", the thickness of the border may be set. The latter two settings should be altered such that the border is visible.

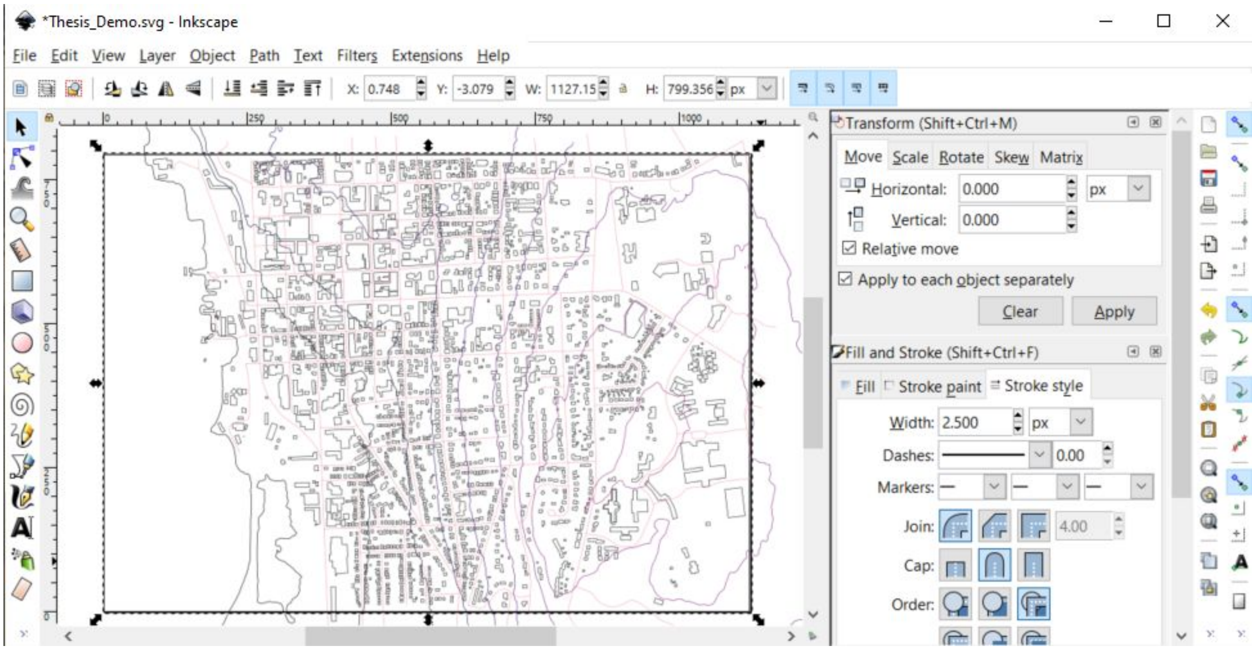


Figure 15: The *Fill and Stroke* menu allows for the fill, stroke, and stroke color to be customized

The next step is to separate the contour lines into individual layers, such that they may each be individually cut on the laser cutter. In order to do so, first determine the number of layers that will be required in the final model. This can be done by summing the number of different contour levels. If having difficulty determining the number of layers, contours may be grouped by right clicking on a contour, clicking "*Select Same → Stroke Color*", and grouping them together by selecting "*Object → Group*", or pressing *Ctrl + G*. Once the number is determined, make that many copies of the layer that contains only the rectangle by right clicking on the layer, and selecting "*Duplicate Layer*". Each layer should be renamed numerically, such that when complete there are as many numbered layers as there will be layers in the final model, plus the original rectangle layer, which can be renamed "Base" or something similar. With only the contour layer and the newly created layers visible, the lowest contour should be selected. Right click and select "*Select Same → Stroke Color*". Right click again in order to move the selection to the associated numbered layer using "*Move to Layer…*".

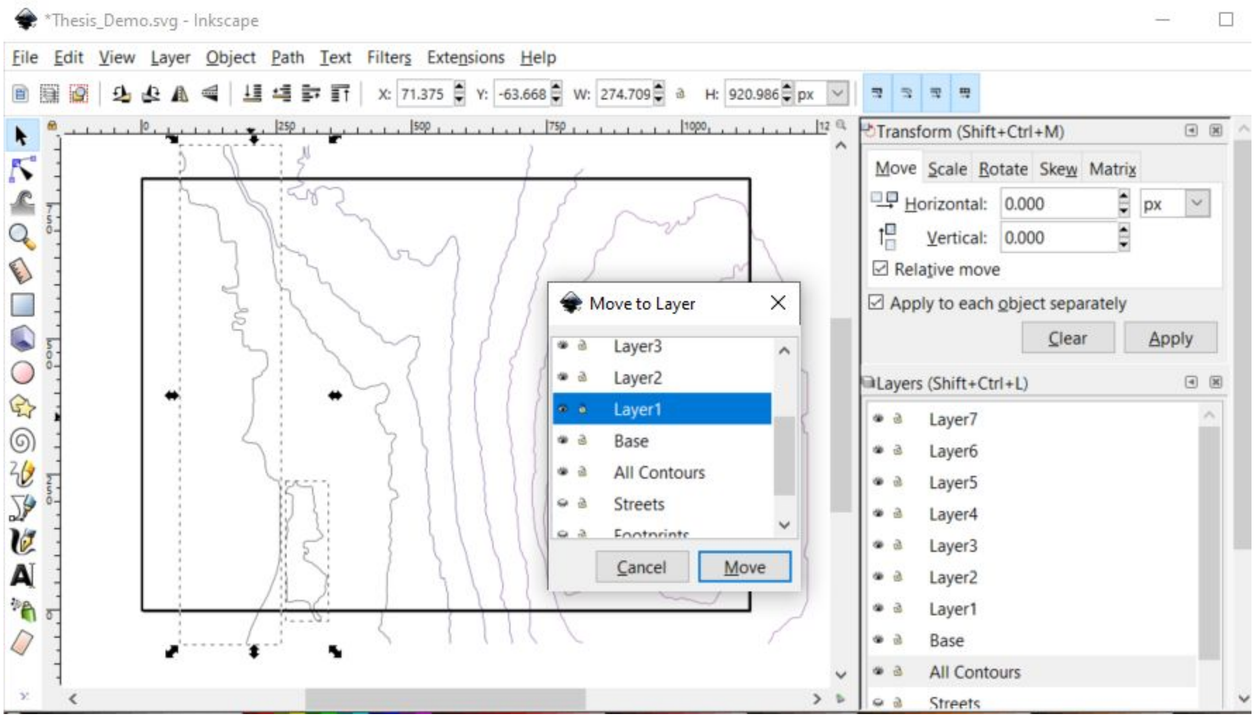


Figure 16: Use the *Move to Layer* command to move the selected contour to the new layer.

Repeat the above process for each layer, such that when complete the original contour layer should be empty, and each numbered layer should contain a single contour level. Hiding the completed numbered layers as each is completed can help to make the process simpler. Utilizing the *Select Same Stroke* tool each time ensures that every part of the contour is selected, regardless of whether it is a single vector or not. With the contour levels separated, the next step is to prepare the file for laser cutting. Depending on the laser cutter being used, the symbology to denote which lines are to be cut, and which lines are to be engraved can vary. Regardless of the specifics, each contour and surrounding rectangle (or alternative border shape) can be assigned the symbology for cutting. The same can be done for the layers to be engraved, such that they are correctly formatted to be interpreted by the laser cutter as rasterized layers. For the laser utilized in this project, the laser interprets blue lines as vectors to be cut, and red lines as lines to be rastered. The manual may be checked for the laser cutter being used to determine the correct symbology.

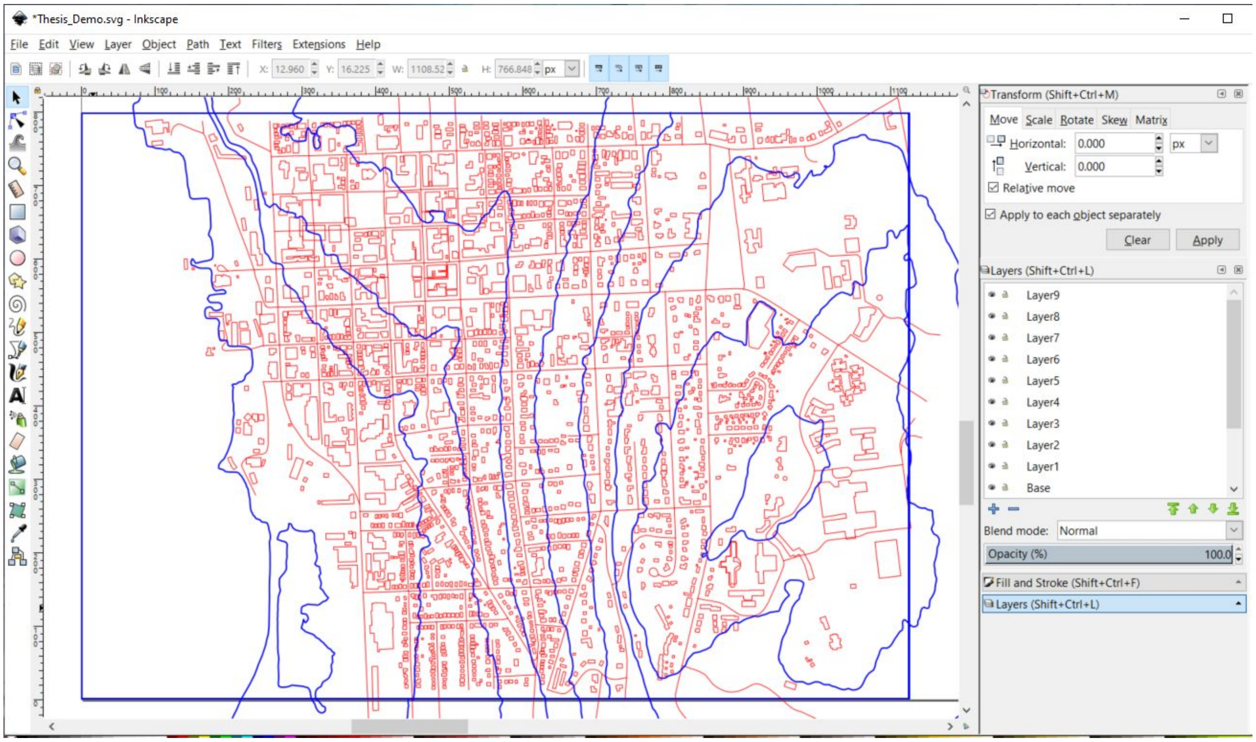


Figure 17: All layers visible with contours colored blue to be cut, and streets/footprints red to be rastered.

Looking at the map, there are some artifacts in both the contours and raster layers which will need to be altered before cutting. To delete individual vectors, select the layer in question, and ungroup all of the objects by going to "*Object → Ungroup*" or by pressing *Ctrl + Shift + G*. Once ungrouped, the individual vector lines may be selected and deleted or moved as required. With the file nearly ready to be cut, it is an appropriate time for any additional features or decorations to be added to the map. With one of the raster layers selected, text or other features may be added. For this project, a label and a north arrow are added. Directions for how to utilize the text tool and pen tool can be found in the software documentation, as well as instructions on how to add other features to the file. The most complex part of the vector graphics editing process is separating the raster layers such that only the content which is to appear on each layer gets rastered with that layer. While it isn't strictly required in order to complete the project, not doing so will result in engraving the entire map on each layer, which will significantly increase the amount of time required to cut the finished product. The simplest way to do this is to first create a combined layer of all the rastered layers, which can be done by ensuring that the rastered layers are all adjacent in the Layers window, selecting all items in the top layer, and using the "*Layer → Move Selection to Layer Below*" tool, or *Shift + Page Up*. The process is repeated for all of the raster layers. All of the elements in the resulting layer should be ungrouped by pressing *Ctrl* + *A*, then ungrouped as above. (*Ctrl* + *Shift* + *G*) The merged layer should be renamed, and then duplicated as many times as there are layers and the duplicates named numerically. (Raster1, Raster2, ...)

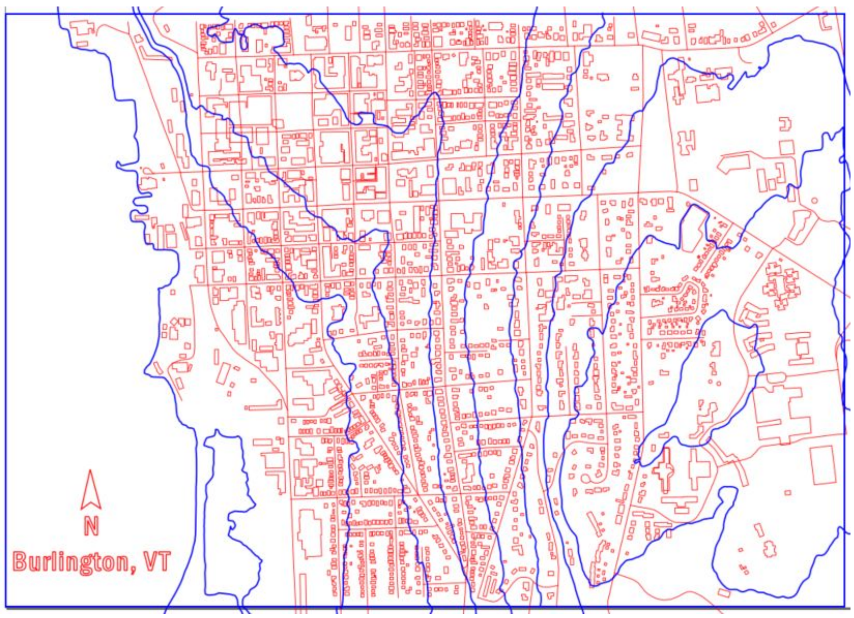


Figure 18: Completed map with added icons, faulty artifacts removed, and raster layers merged.

Next, for each contour layer, only the current contour, the contour below it, and the associated merged raster layer should be made visible. The components which do not fall inside the layer should be deleted, although precision isn't necessary. Having some raster lines which extend past the layer will serve to make aligning the cut layers easier later on. Repeat the process with each contour layer, including the base layer. At this point the file can be cut and assembled.

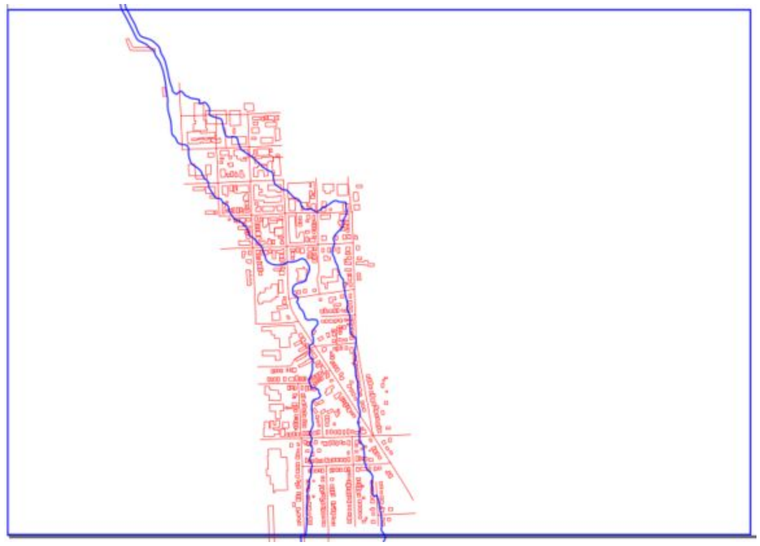


Figure 19: Selection of single contour and contour below, with only required raster visible.

Physical Manufacturing

Due to limitations on travel and access to outside resources during the development of this thesis, a physical model has not been made of the demonstrational project. The steps below are generalized for this reason, but should be functional enough for completion of the project.

Once the file has been properly prepared, the process of cutting is relatively simple. The material to be cut can vary, however for best results take into consideration the number of layers and the height of the material in question, as well as the final usage of the project. Prior testing has shown that both wood, in the form of plywood, as well as cardboard can be used to great effect. Ensure that enough material is available to cut each layer, and that the material has been sized appropriately to fit into the available laser cutter. If the project needs to be resized, be sure to make all layers unlocked and visible, and use "*Edit → Select All in All Layers*", or alternatively press *Ctrl + Alt + A*. Doing so ensures that the layers remain in proportion to each other. To cut each layer, toggle the visibility of the layers such that only the contour layer and the raster layer are visible, then save the file and print. Depending on the extent of the raster layer, it can be useful to include the above contour level as a raster, by making the layer visible and changing the symbology temporarily such that it is rastered. Pressing print will open the print preferences, which need to be configured for the material being utilized. It is advised to test out the print settings before working with the actual file. Once the print settings are tuned, the file may be submitted and cut on the laser cutter.

After all of the layers are cut out and engraved, they may be stacked to ensure that the raster layer lines up appropriately. If the project is to be stained, painted, or otherwise decorated, it should be done before the layers are adhered together, with the exception of wood sealers and finishes, which are best left until after. Depending on the material used the adhesive will vary, but regardless each layer should be adhered one at a time, starting from the bottom up. The instructions can be followed from the adhesive in question, and clamping is advised to ensure that the layers do not slip. Once dry, the model is complete.

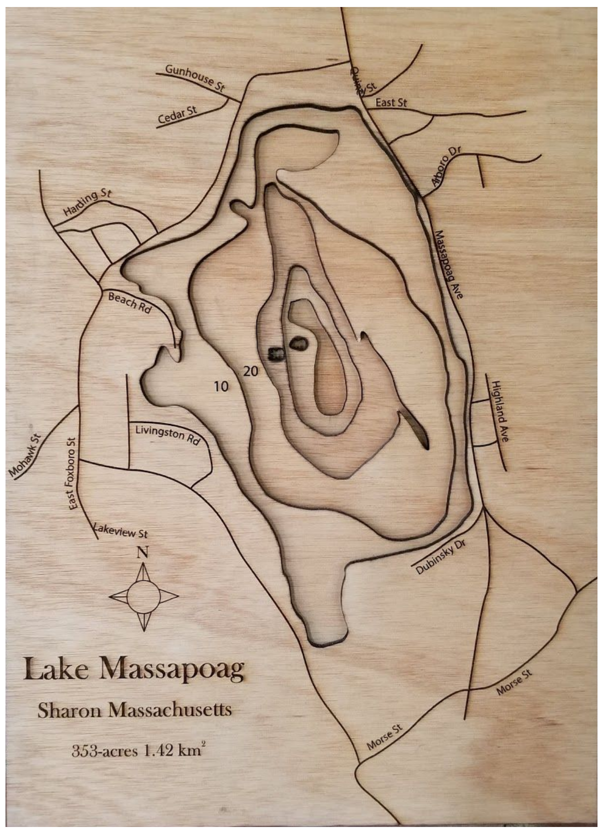


Figure 20: Example of bathymetric lake model made from laser cut plywood

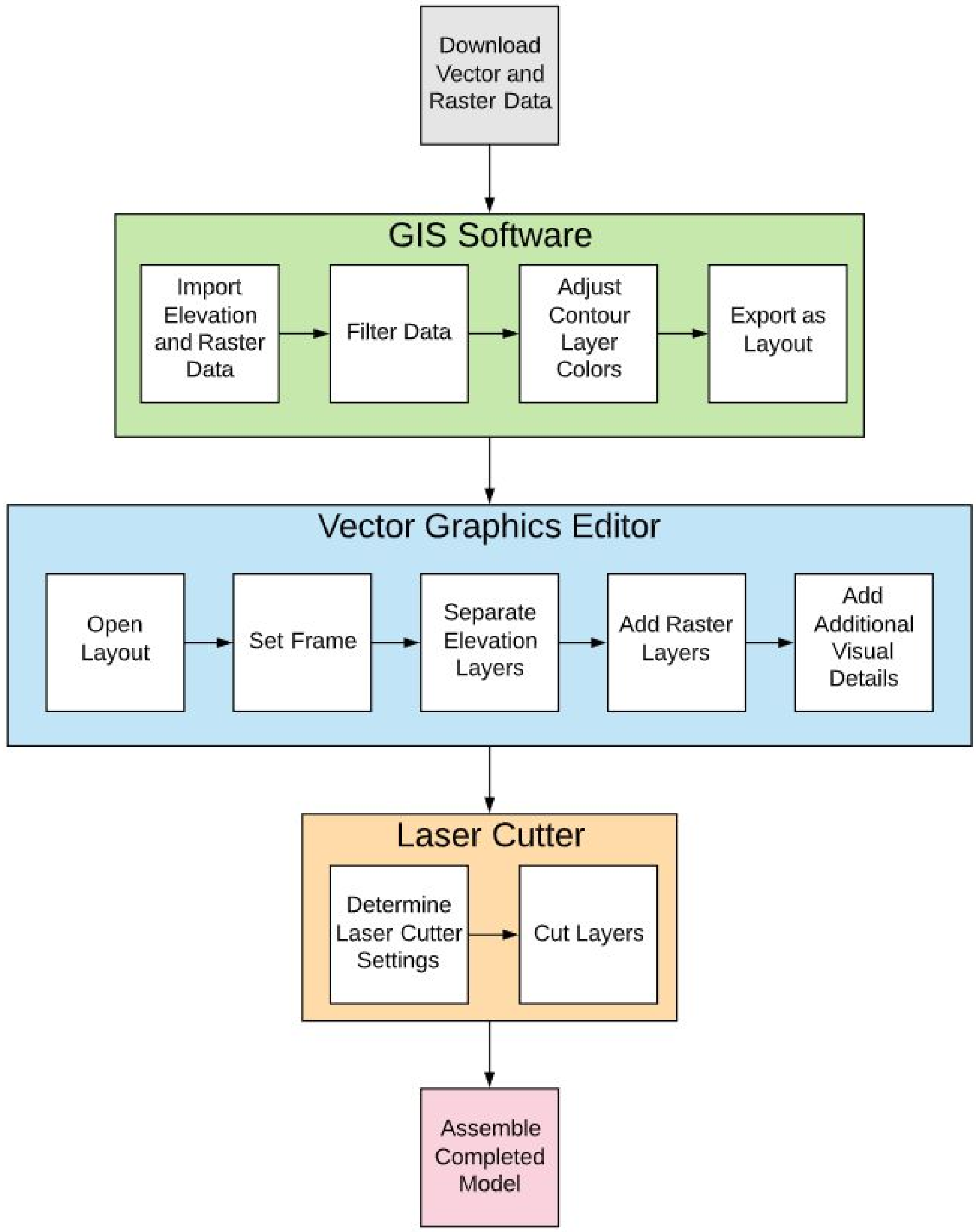


Figure 21: High-level overview of workflow

4. Discussion

The main goal for this project was to determine a process of creating laser cut elevation models in a way that was both functional and accessible beyond my own personal workflow. While the initial plan to accomplish this was to encapsulate those ideas into an independent software program, it quickly became clear that doing so would not only limit the capabilities of the final product, but much of the desired functionality could be completed with existing open source software. The results accomplish this well, as the software utilised are cross-platform and well-documented, and give a great degree of functionality at the cost of somewhat reduced accessibility to individuals unfamiliar with GIS or vector graphics editors. Previous efforts at making comparable models took upwards of 15 hours of work, whereas with the established methodology a model was prepared in under 2 hours, not including the time required for assembly. Moving forwards, if possible an individual with minimal background knowledge should be asked to complete the process to determine weak spots and potential spots for improvement.

A topic not discussed in the results is utilizing bathymetry data, which captures the depth of a body of water. The methods utilized may easily be utilized to create comparable maps with such data, or combined with elevation data to create models that exhibit elevation above and below water level.

Applications

As of today, most 3D topology maps of significant scale can be found being utilized in museums and national parks for educational purposes, and for civil engineering and landscaping projects. Laser cut topology maps have mostly been produced as artistic pieces without much practical purpose, in part due to the difficulty of creating such a map without extensive background knowledge. Increasing the accessibility of creating laser cut 3D maps opens up a number of potential niches which may be filled.

For generating educational content, physical maps offer the possibility to appeal to kinesthetic learners. In neuro-linguistic psychology, the Visual Auditory Kinesthetic theory

(VAK) proposes that people fall under one of the three learning styles, and learn best when they are presented educational material in the format of preference. Multimodality improves learning, such that people are shown to better retain material when presented with multiple options (Rourke 2002). Providing a physical model has the potential to allow for greater comprehension and retention among students, such that laser cut maps could be a cheap and effective way to improve educational content. Outside of the classroom topology maps are commonplace in the outdoor industry, as a variety of outdoor recreational activities are dependent on knowing elevation across a natural area, such as hiking or skiing. While some locations with significant financial backing have the means to commision custom 3D maps, most rely on 2D topological maps or aerial photography. Providing a means for the creation of inexpensive 3D maps allows for smaller operations and public natural areas to gain the advantage of having physical elevation maps, allowing for easier comprehension and lower risk of visitors misinterpreting a topology map.

Another common usage of three dimensional maps today is in construction prototyping, as models are often built both for testing and public display by civil engineers, architects, and landscapers. With the advancement of physics simulators and computer aided design programs, creating physical models has become less common, with computer generated models often taking their place. Part of the reason for this change is the historical inability to rapidly prototype at scale,as the size and complexity requirements of large scale infrastructure and landscaping projects have limited model making significantly. Laser cutting has the potential to at least partially address this issue, as models may be quickly generated at scale. While not appropriate for every project, a tangible prototype has the benefit of being utilized and manipulated by people without a technical background, can be integrated with other existing components, and can help to bridge the gap between simulation and reality.

With easier access, laser cut topology maps may see more usage beyond the traditional uses of 3D maps. Organizations such as Open Street Maps humanitarian team utilize geographic data in order to provide assistance to humanitarian efforts, including providing first responders accurate maps in the wake of natural disasters, and directing humanitarian aid to locations in need. Accessible and rapid 3D mapping could enhance such projects and others, allowing for information rich maps that may be read independently of technology and cartography expertise. Artists could further utilize the technology to improve data visualizations, create models of fictional landscapes, or prototype large scale sculptures and earth art.

Limitations

Initially, the hope for this project was to develop a singular piece of software for the purpose of creating files capable of being utilized with a laser cutter to create topological maps. While the end goal has remained the same, for several reasons the project has shifted from independently written software to a defined methodology that capitalizes on existing open source software. One of the central aspects of this project was to ensure that the final models could utilize both vector and raster data, which meant pulling data from multiple sources to create the final model. This inevitably ran into the issue of alignment and map projection. Ensuring that the engraved raster was accurately aligned to the underlying vector cuts was difficult in its own regard, and several potential solutions arose, including requiring that coordinates be predefined, or allowing for user-defined alignment. However, the initial plan neglected to take into consideration the problem of coordinate reference systems, which is the way that maps are adapted to 2D given the 3D nature of our physical planet. Doing so requires an accurate transformation of the latitudes and longitudes of every location across the surface of the mapped area into locations onto a plane, which is done in various ways depending on the map in question. While it is possible to solve this issue with the appropriate software, the task felt extensive given the resources for this project, and instead a preexisting software tool was found which would enable accuracy across projections with QGIS. This issue simultaneously solved the issue of file formatting, as much of the publicly available geographic information is stored in GIS specific file formats such as GeoTIFF and GeoJSON, which then require a change in file type in order to be utilized by a laser cutter, which primarily utilize SVG files as input.

In theory, the process could be simplified further, using plugins for the selected software programs written with python to automate specific tasks required to make such maps, such as the filtering of the inputted data to only show data within the desired area, or the separation of the layers within the vector graphics editor. Using such software would limit the workflow exclusively to the specific software highlighted, as opposed to the current system which can theoretically utilize any GIS software and vector graphics editor. While not in the scope of this paper, programming such plugins would require an advanced familiarity with the API systems of the selected software programs. The separation and preparation of the individual layers in the vector graphics editor is currently the longest part of the workflow, and as such stands to benefit most from automation. Such software would need to be able to distinguish the contour vectors from any existing raster vectors, generate new layers, then transfer the contour layers and the raster layers to the appropriate layer. The difficulty in this algorithm is accurate separation, considering that the contours and rasters are separated by color, and not all contours are closed shapes.

In comparison to a 3D printed or CNC routed topology, the generated models have a significantly lower vertical resolution. For the intents of contour modeling this ends up working well with the limitations of a laser cutter, however limits laser cut topology maps from applications which require high levels of resolution, an issue which may be further compounded by the introduction of human error in the assembly process. Topological contour models can be misunderstood by people who are unfamiliar with how they work, and have the potential for misinformation. This issue is reduced by the fact that the physical models have actual 3D elevation, however the problem is not completely solved.

As it stands, the devised methodology from data gathering to manufacturing still has a considerable amount of manual work involved, which could be difficult especially for individuals with limited or no prior experience in geographic information systems, vector graphics editing, or laser cutting.

Future Work

One means of addressing the aforementioned limitations may be to expedite the software work by creating scripts that work with the GIS and vector graphics editing software. There are numerous potential applications of automation throughout the process as it stands, which could increase both accessibility and versatility. For GIS work, contour data could potentially be downloaded automatically from a national or state database given a specified input, as well as corresponding datasets such as road centerlines, land usage, or building footprints. Such an application would need to account for variation in map projections, as well as the issue of file sizes when it comes to larger datasets. Another avenue of automation may apply to the vector graphics work, by automatically recognizing topographic layers within the associated layer of the file, and separating them into independent layers for cutting along with the appropriate raster data. As much of the process involved in the production requires user input, the amount of automation possible is limited without removing a significant portion of the versatility available.

For the purposes of conserving resources and shortening the duration of time required to cut and raster such projects, a system or application could be developed to efficiently pack smaller layers together such that multiple layers could be cut at once. Advanced research into this field may utilize solutions to the 2D packing problem, in order to optimize the usage of material. Further research may also look into how the maps generated by the method described in this paper compare to flat and 3D printed topology maps for the purpose of navigation and comprehension of elevation data, as well as applications in humanitarian mapping and education.

5. Conclusion

This research aimed to improve the accessibility of laser cut topology models by developing a defined model creation process to aid in the creation of topology maps using a laser cutting machine, and further establishing where laser cutting offers benefits over alternative rapid prototyping processes for mapping purposes. Work was conducted to determine the best means of creating such a model, and was defined with the use of a geographic information system and vector graphics editing program. Data collection methods were standardized to fit the requirements of the new paradigm, and the completed result is an accessible means to translate geographic data into a physical laser cut model. The results show that the methodology significantly reduced the amount of time and human effort required to do so, while resulting in a comparable, if not improved end result.

In the study and advancement of rapid prototyping, laser cutting is frequently overlooked due to a variety of factors, however it clearly has individual strengths which may be utilized for specific tasks. Developing novel uses of technology can certainly provide up new solutions to problems which otherwise may seem unrelated. The research undertaken shows that there is certainly a utility for the creation of topology models using laser cutting technology, and in some cases is the best option over other means of manufacturing. In order to further promote the utility of alternative rapid prototyping techniques, the main focus should be determining means of increasing accessibility, and exploring strengths as opposed to focusing on limitations.

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Map Data from OpenStreetMap contributors and available at https://www.openstreetmap.org