High-Definition Digital Elevation Model System

Vision Paper

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ABSTRACT

Digital Elevation Modeling (DEM) has been a widely used methodology in plethora of application domains, ranging from climate and geological studies, through temporal evolution of various migration patterns, to Geographic Information Systems (GIS) broadly. However, the existing DEM methodologies and systems cannot quite straightforwardly be extended to catch up with the demands due to recent developments in autonomous driving, vehicle localization, drone and dynamically evolving high-definition smart city modeling. The new challenges are the demand of higher precision, sparse(r) elevation data compression, real-time efficient retrieval and intra-sources data integration. Motivated by this, we take a first step towards developing a tile based, multi-layer high precision DEM system, which aims at seamlessly integrating (and aligning) DEM from different sources, and enables context-driven variations in zoom levels. In addition, to further improve the efficiency of the focused-retrieval of the data necessary to construct the DEM with the desired quality assurance, our vision targets the collaborative compression among heterogeneous data sources.

KEYWORDS

Digital Elevation Model, Spatial Data Compression, Heterogeneous Data

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1 INTRODUCTION

Broadly speaking, Digital Elevation Modelling (DEM) aims at providing a digital 2D-representation that reflects 3D features – i.e., the elevation of a particular terrain. Depending on the level of details, the literature often separates between Digital Surface Modelling (DSM) which represents all the "interesting" elements along a particular region, together with the elevation data; and Digital Terrain Modelling (DSM) which only indicates the different "altitude information" of a topography of a surface – e.g., a hill, but without houses and/or roads. In terms of methodologies and implementations, currently available DEM systems represent a mature technology, capable of handling the mapping tasks that they originally targeted: land surveying, climate and geological studies, Geographic Information Systems (GIS), etc. [12, 27]. However, the requirements of these task, while demanding efficient storage and retrieval techniques, are not stringent in terms of response time. In addition, the very querying capabilities are fairly limited – a typical interaction would involve defining a (rectangular) clipping area and dragging it to the location of interest[1], possibly involving a selection of a resolution level.

Owing to the recent advances in acquisition devices, as well as networking/communication technologies, new classes of applications emerged in which the notion of meter-level (or denser) DEM is essential – like, for example, micro-environment monitoring [2, 14, 29] and vehicle localization [18, 21, 32, 34]. Moreover, some applications may demand different level of detail for different parts of a same geo-region. An example shown in Figure 1 illustrates a higher-level precision used for the elements of the road network, accompanied by very low-resolution display of the park, and a medium-level resolution used for the piers/coastline. As recently emerging applications [23]– such as autonomous driving, vehicle localization, drone-based monitoring and even transport/delivery – are becoming more and more parts of the everyday reality, several novel challenges are posed to the DEM.

1. In addition to the sheer volume of the data, a temporal bound may be imposed on the retrieval time (i.e., the time to display the required data).
2. New compression approaches will be needed to fit both DEM data itself, along with the displaying techniques, for effective use on mobile devices.
3. A varying level of detail – based on a particular context – may be acceptable and should be capitalized upon. For instance, the example in Figure 1 is actually a practical scenario of using different resolution-levels in car navigation systems, where the user/driver is not concerned much with the details of the parks and the coastal shapes.

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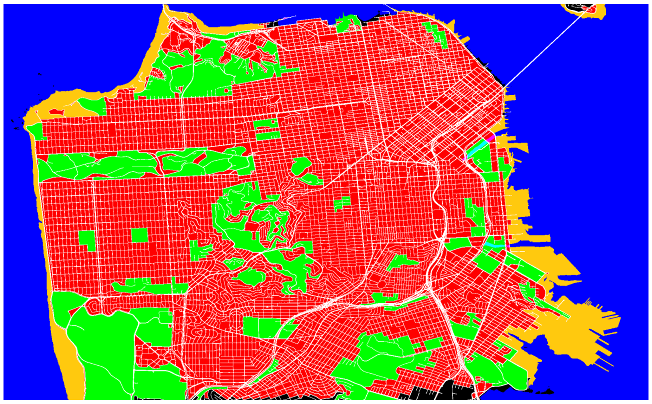
[1] cf. http://resources.arcgis.com/en/help/main/10.1/index.htmlInteractive _tools_for_terrain_datasets/005v00000023000000/



(a)

(b)

Figure 1: Visualization of areas with varying precision needs in San Francisco (color annotation: blue: water body, red: urbanized region, green: park, yellow: coastline/pier, white: road network, black: unknown) (a) and satellite image as reference from Bing Maps server ^{2}(b).

The new set of challenges for High Definition (HD) DEM are especially accentuated in the field of autonomous driving. Currently available HD Map sources, along with the corresponding editing tools and processing algorithms, exploit certain features that are constrained by the underlying technology – for example: point cloud, aerial and perspective image. The corresponding data is then projected on a local 2D (tangent) plane to reduce overheads associated with the very process of editing, along with the cost of the corresponding computation [12]. One specific scenario/application where the state of the art needs improvement is the image based HD road modeling [5, 11, 24]. The impact is that all the key points of small segments of a certain road are located in a single-valued elevation (commonly known as *elevation missing* in maps-industry) – which can cause "stair-case" effect when displaying consecutive portions of road segments. But one example: certain mountain roads have even more than 1 meter elevation differential, when comparing the leftmost and rightmost lanes in a segment (cf. Figure 2), known as (large) *bank* angle. In this particular setting, the solution amounts to assigning a correct elevation information to each control point of the corresponding spline used to represent the segment in the HD Map.

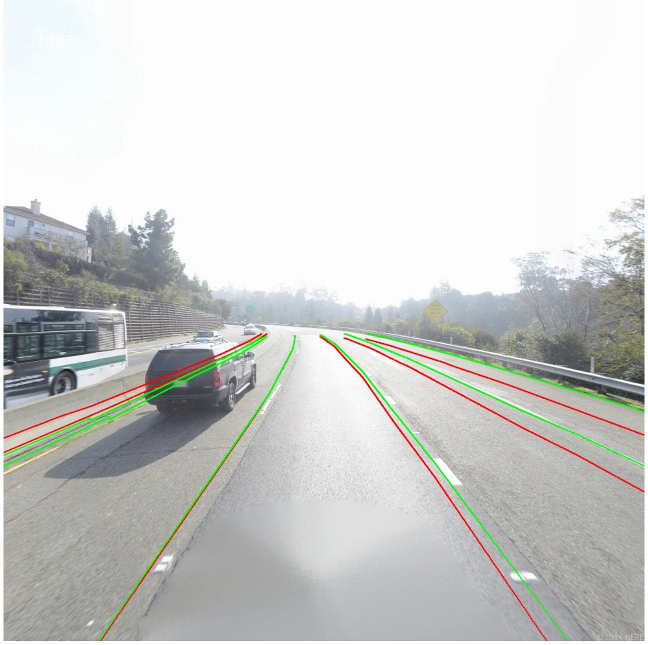


Figure 2: Manual edited HD Map without elevation correction (red lines) and with elevation correction (green lines) from HD DEM.

However, in reality, a particular data source may be limited in its precision and/or other features (e.g., context provided by DSM vs. "pure" DTM) and, if an application so demands, data from multiple sources will need to be integrated [25]. Even for a homogeneous data (e.g., polylines) different sources of DEM may vary in their granularity. There are three basic categories/levels of precision among the data sources used in practice: ten-meter-level, meter-level and sub-meter level (i.e., within (tens of) centimeters).

In the ten-meter-level category, most providers – for example, U.S. Geological Survey (USGS) and Earth Remote Sensing Data Analysis Center (ERDAC), National Oceanic and Atmospheric Administration (NOAA) – use flying platforms such as remote sensing satellites and airborne laser scanner to survey a large area from a county to a country. However, these approaches yield low data precision and exhibit higher measurement errors. Ten-meter-level DEM covers the entire world, and can be used for querying enabled by most of the corresponding providers – for example, 1-minute resolution (approximate 90 meters) sources can be found at NOAA Grid Extract [15], USGS Earth Explorer [28] and WebGIS Terrain Data [30]. All of these open source providers support bounding box query and will return gridded data in a particular format, such as GeoTIFF.

In the category of meter-level resolution, the elevation data is acquired with a much higher precision – typically limited in coverage to a smaller geographic region, and associated with a specific phenomenon (e.g., pollution, micro-climate variability), which covers the most cities worldwide [3] and limited areas [4].

On the highest resolution-end, the DEM data can be generated from ground based LiDAR [33]. Compared to airborne-based data (i.e., satellite imaging, remote sensing, or even drone-based LiDAR), ground based LiDAR has the advantage of a much higher precision – however, it suffers from much smaller coverage and at a higher cost. Ground based LiDAR sources have the highest demand in Autonomous Driving industry [18] – however, different sources may vary in their precision [23].

Yet another source of elevation information comes from single point surveying datasets like, for example, Survey Marks and Datasheets [5]. Such data sources have the highest precision – equivalently, lowest measurement and system errors – however, they also have highest costs and always cover very small geographic regions. Typically, the cost of *(latitude, longitude, elevation)* data covering 0.1m^2 is within the range of a few hundred US dollars – in contrast with \$ 100 USD for 1km^2 area but at meter-level resolution from commercial solution provides [6] [7].

In this paper, we take a first step towards providing a methodology for generating globally aligned HD DEM system using elevation information from different sources and resolutions, and present our vision and initial approaches towards the problem, based on designing a tile based [22] spatial representation to cater to varying accuracies. The proposed methodologies aim at automatically integrating and aligning new/incoming DEM at any level within a database, and retrieving elevation information by: single point; bounding box; trajectory; as well as other possible (spatial/temporal) inputs with different resolution requirements.

The main components of the proposed system are:

(1) Same Level DEM Alignment.
(2) Cross Level DEM Alignment.
(3) Multi-Level DEM Compression.
(4) DEM Query.

The main components of the system, along with their dependencies/workflow are illustrated in Figure 3. In the rest of this paper we describe in a greater detail the main aspects of the system, along with the corresponding methodologies serving as bases for implementation.

2 SAME AND CROSS LEVEL DEM ALIGNMENT

Measurement errors, as well as other system-generated errors (e.g., unsynchronized clocks) are inevitable – thus, one needs to accept the fact that there is a high possibility for misalignment between any two DEM sources. Those can be reflected in the mere coordinate-values, as well as scale, rotation and shift in 3D space. Misalignment are also caused by the variations inherent to different datum/geodetic systems and their representation-model of the earth (SAD69, GRS80, NAD83, WGS84, etc.) [17], to the discrepancy in the elementary types and data structures used.

An effective alignment process is the essential component of combining multiple data sources in a unified coordinate system – however, considering the differences of resolution and data source, there can be no "universal" alignment methods.

2.1 Same Level DEM Alignment

Same level DEM alignment at lower resolutions is computationally less demanding than the case of aligning two DEM data sources with high resolution. Typically, a DEM is represented as a 2D array of pixels, where each element of the array (i.e., a pixel) will have a specific value, representing the recording obtained through a given surveying tool. Lower resolution DEMs are acquired for large area and, more often than not, they are continuous – in the sense that every pixel has a well-defined value. In other words, there is likely to be a "continuity" between neighboring pixels. When it comes to higher resolution DEM data, given the narrower area of sampling, it may be the case that the DEM array corresponding to a larger area may have pixels with undefined values.

Different from DEM validation [7, 13, 19, 20] and fusion [31], the goal of Same Level DEM Alignment is to transform (at least one of) the two datasets so that they be represented in a unified coordinate system values/boundaries, and then fuse the data from both sources at each unique pixel. A commonly used idea when aligning DEM is to apply Iterative Closest Points (ICP) matching algorithm [8, 36].

On the high resolution end, one may often end up with sparsity in the datasets (cf. Figure 4). There are different causes for this – but few examples being: object occlusion, LiDAR density and other influencing factors [10], as shown in Figure 4. The higher the speed of motion of the ground based LiDAR device, the sparser the DSM will be. Thus, the classic ICP approach may not be suitable for this task. As a part of our work, we are planning to address the HD DEM Generate from ground based point cloud as a separate project – with the main idea of generating an interpolated HD DEM via probability map. Then, we envision a weighted ICP approach to be designed to handle this task.

2.2 Cross Level DEM Alignment

Cross Level DEM Alignment aims at aligning DEMs from data sources with different resolutions – as shown in Figure 5, illustrating the fusion of visual data from satellite images on level 15, 17 and 19. Clearly, this step also implies aligning to a (now, high resolution DEMs) to some kind of a global coordinate. However, there is a distinct challenge of this process – which is, how to reduce the cross-level error. To illustrate, assume that there are two DEMs at level n and $n + k$, where $n \subset [0, 17]$ and $k \subset [1, 5]$. A particular tile at level n contains 2^k tiles from $n + k$ level which implies that (according to [22]), the shift error will be

$$\frac{cos(latitude * \frac{pi}{180}) * 2 * pi * 6378137}{256 * 2^n}$$

This, in turn, equals to the ground resolution at level n, if we align two DEMs directly.

We note that, in the settings in which a survey point from a third party single point surveying is available, that point will be considered

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[3] http://www.landinfo.com/LandInfoRussianCP.pdf
[4] National Elevation Dataset (NED). USGS. https://lta.cr.usgs.gov/NED
[5] Survey Marks and Datasheets. NOAA. https://www.ngs.noaa.gov/datasheets/
[6] LAND INFO. http://www.landinfo.com/coverage.html
[7] AW3D. http://aw3d.jp/en/index.html

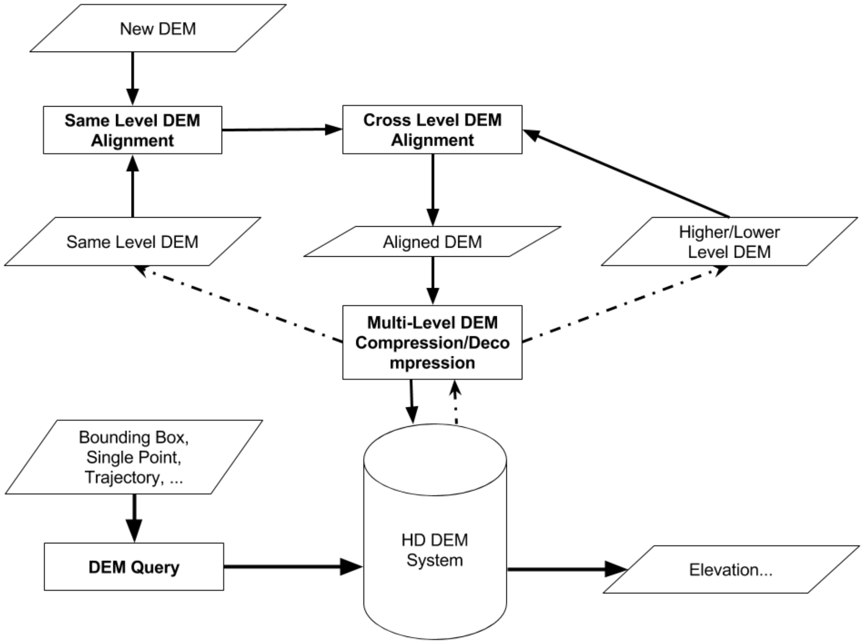
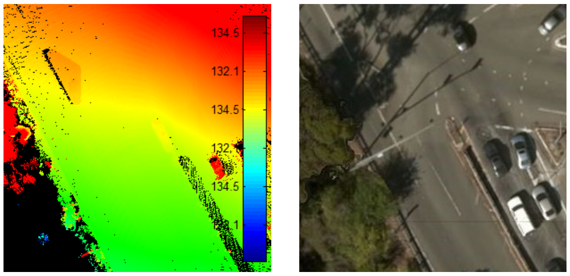


Figure 3: System components



(a) (b)

Figure 4: An example of original sparse DSM at level 20 near [37.8511 -122.2328] (a); and corresponding satellite image at same resolution (b).

as a ground truth, and the entire DEM system will then have to be adjusted to align to this point. Clearly, a fine-grained single point survey can only be aligned with the high resolution DEM – in other words, we may not know where to place the single point in the lower resolution (but covering wider area) DEMs. However, we can then iterate and use the "revised" higher resolution data to further improve the alignment at lower resolution layers.

3 HD DEM COMPRESSION AND RETRIEVAL

We re-iterate that, different from image based tile systems or current DEM systems, some pixels from the tiles at higher resolution may be empty which, in turn, makes the data sparse at this level. Also, level n is a coarser representation of level $n + 1$ – however, some

Figure 5: Level 19 satellite image in red bounding box, level 17 satellite image between red and blue bounding boxes and level 15 satellite image.

DEM compression methods [6, 26, 35] designed for a single layer DEM may not be suitable for multi-layer DEM structure.

As an illustration:

- The total of urban area coverage in the US is $275,538.47$ square kilometers, which is 3.60% of land area according to the US Bureau of the Census [16]. These are the regions which need meter-level resolution of DEM data, because of various modelling purposes in the context of the smart-cities initiative [23] and other purposes [2].
- 0.61% of the land area in the US is covered by roads of all kinds according to [1, 4], which need sub-meter-level DEM.

The number of valid tiles from different levels can be estimated for the data sources above. Adopting the gradation (or, tile-levels) used by HERE [8] and Tom-Tom [9], $0-12$ levels are at low resolution (i.e., above 10m level per pixel); levels $13-16$ have meter-level resolution; and the levels 17 and above have extremely high precision, within few (tens of) cm per pixel[10]. Having this in mind, the percentages of valid tile are 100% at levels $0-12$; 3.6% at levels $13-16$; and only 0.6% at levels 17 or higher. In San Francisco, the needs of sub-meter-level is 19.73% [33] at level 17 and shown in Figure 1. These numbers show the tile data is very sparse. An example of highway in rural area is shown in Figure 6, the tile pixels with valid elevation information are sparser with the increasing of tile level.

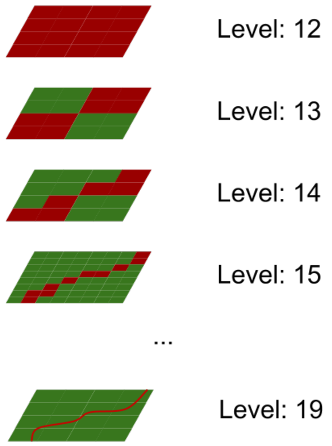


Figure 6: Data is sparse at higher level: valid elevation information pixel in red and empty pixel in green at certain level.

4 CONCLUDING REMARKS

This paper described the preliminary ideas and the envisioned approaches for developing HD DEM system that can integrate data from heterogeneous sources and at different resolution/precision levels. Compared to the state of the art in DEM systems, our solution is expected to yield much more flexible query processing approaches, and different trade-offs between compression, precision and the processing time. These types of trade-offs are extremely important when one needs to seamlessly shift between devices with different capabilities – e.g., from driving (and using in-car navigation – or, in the near future, an integrated system for autonomous driving) to walking and using a smart phone with a smaller display and available memory to pre-fetch data.

At the time being, we have completed the same level alignment for low resolution DEMs from USGS and WebGIS, and the following are the major tasks that we are currently addressing:

1. Integrate open source and low resolution DEMs, establish our tile based query server and build web based interface for specifying the queries, similar to MinnesotaTG: Web-based U.S. Road Traffic Generator [3].
2. Align cross resolution DEMs from open source (i.e., varying between middle resolution DEMs to low resolution DEMs).
3. Develop compression methodologies for different granularity and properly place the sparse DEM tiles in each.

Generally speaking, our HD DEM system will be beneficial for various tasks in GIS-related industries because of its cross-validated DEM data and offering a flexible query methodology. Specifically, in Autonomous Driving industry, HD DEM system will make the storage of large quantities of elevation data available for portable devices, so that it can contribute to the vehicle self-localization. In a broader sense/scope of the HD Map industry, our DEM system will help the road model automation program calculate correct elevation values without repetitive computation and with adaptable amount of storage. Furthermore, this tile-wise solution can also be extended to store/represent occupancy grids (i.e. Road DNA [11]) for vehicle self-localization purpose [9], by replacing 2D tile structure with multi-layer 2D or 3D tile structure.

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