Opportunities with Slippy Maps for Terrain Visualization in Virtual and Augmented Reality

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Abstract: Map tile servers using the slippy map conventions provide interactive map visualizations for web applications. This investigation describes and evaluates a viewpoint sensitive level-of-detail algorithm that mixes slippy map tiles across zoom levels to generate landscape visualizations for table top VR/AR presentation. Elevation tiles across multiple zoom levels are combined to provide a continuous terrain mesh overlaid with image data sourced from additional tiles. The resulting application robustly deals with delays in loading high resolution tiles, and integrates unobtrusively with the game loop of a VR platform. Analysis of the process questions the assumptions behind slippy map conventions and recommends refinements that are both backward compatible and would further advance use of these map tiles for VR experiences. These refinements include: introducing tiles addressed by resolution, ensuring consistency between tiles at adjacent zoom levels, utilizing zoom values between the current integer levels and extending tile representations beyond the current raster and vector formats.

1 INTRODUCTION

Slippy maps[2] are an established mechanism for interactive map browsing in online applications (Farkas, 2017). Map data is provided in the form of square tiles that allow the visible window to pan over this underlying grid of tiles. Tiles are available at different levels of magnification so that the view can be zoomed by displaying tiles from a different level. Map tiles depict traditional map representations (e.g. satellite imagery, road layouts) but can also encode other data sets. Tiles containing elevation data enable procedural generation of 3D terrain representations suitable for virtual or augmented reality applications (VR/AR) as illustrated in Figure 1. Our focus is an interactive table top VR/AR landscape visualization for collaborative seabed analysis (Campos et al., 2020) which particularly requires change of magnification and multiple levels-of-detail. This differs from VR applications where terrain is at a fixed scale relative to the user.

This paper adapts and evaluates the use of slippy map technologies applied to generating landscape representations for VR applications. The significant contributions of this work are:

1. Combining tiles of different magnification to provide a viewpoint dependent level-of-detail representation to adapt geometry complexity and data access restrictions to accommodate VR/AR. The process developed ensures that terrain presentation within a VR/AR experience cooperates with other system operations and shares essential resources. Low resolution content and incremental refinement are used to compensate for delays in tile loading.
2. Identifying opportunities for further refinement of the slippy map concept, including: challenging assumptions about tile structures and accepted parameter values (e.g. tile resolution) which define the shape of the slippy map tile pyramid, develop-

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[2] https://wiki.openstreetmap.org/wiki/Slippy_Map

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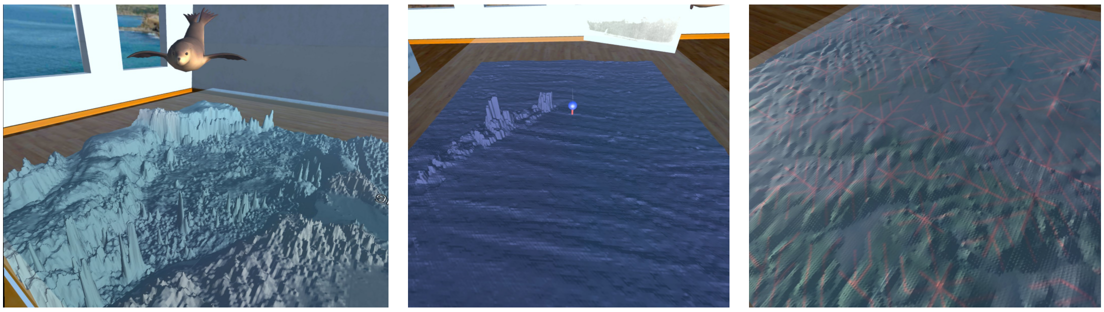

(a) (b) (c)

Figure 1: a) Land- and sea-scape visualized on a table top in VR as seen through an Oculus Quest head set (water surface removed for clarity) b) Section of high-resolution seascape showing a shipwreck c) Combining tiles across multiple levels of detail (the high resolution tile data is marked with a grid-like pattern). Two texture layers are present (blue representing the underwater regions, and red indicating key ridge/valley structures).

ing algorithms to blend tiles across zoom levels, integrating additional sources of tile content beyond raster data that would be relevant to VR/AR contexts, and extending the 2D slippy map concept to 3D. The latter includes integrating 3D content with the map surface, and using tiles to capture the volumetric region above and below this surface.

The context for this investigation is a cross-disciplinary project using VR/AR to explore a marine park environment including: the landscape below the ocean surface, how life shapes and is shaped by the environment, and the geological and external influences on the region. A significant challenge involves using VR/AR to visualize and explore a high-resolution data set scan of the sea floor generated during this project. The seafloor scan is too large to be stored, selectively accessed, or displayed in its entirety, particularly on the self-contained mobile VR/AR devices being used.

The remainder of this paper reviews key concepts and related work in section 2, presents the algorithms used in section 3 and evaluates the outcomes in section 4. Insights derived from this investigation are discussed in section 5.

2 RELATED WORK

2.1 An Overview of Slippy Maps

Slippy maps refer to an implementation of a map tile service (Open Source Geospatial Foundation, 2012; Masó, 2019), and use a coordinate system based on the Web Mercator projection (Larrick et al., 2020). Maps are assembled from square image tiles containing colour data (such as satellite images), or elevation samples. Individual tiles typically have an image resolution of 256×256, although this is not a fixed requirement. This study uses 64×64 elevation tiles.

Tiles are indexed by three coordinates. The zoom level which determines the scale of the map, or magnification level for each tile, ranges from 0 in integer steps to a limit determined by the resolution of the data. Each zoom level contains $2^{\text{zoom}} \times 2^{\text{zoom}}$ tiles. The single tile at zoom level 0 covers the entire planet. The remaining coordinates: x and y index the tile array, with the origin in the top-left corner (corresponding to the north pole, and $180°W$).

Tiles are prepared and accessed from a networked server. Clients access only the tiles required at any instant, at the zoom level required. This achieves interactive landscape visualizations even on low performance devices or mobile platforms used for VR/AR (Richardson et al., 2018; Jurado et al., 2018). The process of generating and serving tiles is also an interesting challenge but outside the scope of this paper.

2.2 Procedural Terrain Presentation

Control over terrain detail is achieved by filtering large data sets to show only selected regions or overviews of large regions (Kumar et al., 2018). A typical terrain covers a vast area and so level-of-detail algorithms are used to produce mesh representations whose complexity is proportional to the area occupied on the screen (Duchaineau et al., 1997).

Quad-trees (Kalem and Kourgli, 2015; Kang et al., 2018; Lee and Shin, 2019) and bintrees (Duchaineau et al., 1997; Cao et al., 2019) support viewpoint dependent level-of-detail. Converting quad-tree tiles into geometric meshes introduces cracks in the mesh between tiles of different resolutions. These are addressed variously through interpolation across the seams (Kang et al., 2018), forcing an equal number of vertices in neighbouring tile edges (Cao et al., 2019; Lee and Shin, 2019), creating overlapping polygons or skirts (Campos et al., 2020) or, as is used here, providing a custom triangulation along tile edges. Historically terrain meshes re-triangulate meshes directly by merging or subdividing polygons according to projected polygon area and measures of accuracy of the terrain reconstruction (Duchaineau et al., 1997; Ai et al., 2019; Lee and Shin, 2019; Li et al., 2021).

Mapzen tiles (Larrick et al., 2020) encode elevation in the colour channels of the image. Neighbouring vertices in each tile's mesh are connected to remove seams between tile regions. In contrast, geometry clipmaps (Li et al., 2021) provide a power-of-two multi-resolution pyramid of the terrain data, centered around the current viewpoint. The level-of-detail terrain mesh structure (Krämer et al., 2020) also uses an image pyramid (in the form of the Cesium quantized mesh format) for view dependent tile selection. However, this approach uses a computationally expensive process of re-triangulation to pre-generate mesh geometry in tiles, as compared to the approach presented here which dynamically generates the mesh from existing raster elevation data. A pyramid of geometry tiles constructs surfaces rapidly but introduces the challenge of ensuring surface continuity between tiles (Campos et al., 2020). Procedural mesh generation converts raster and vector tile formats into landscape geometry that can be presented in VR/AR, such as rivers and lakes (Menegais et al., 2021).

2.3 Terrain Representations

Geographical information can be represented in many forms, such as point cloud data (Richardson et al., 2018; Easson et al., 2019) acquired using LiDAR or photogrammetry (Jurado et al., 2018), as digital elevation maps (DEMs) (Easson et al., 2019; Lee and Shin, 2019), or in vector formats (Jurado et al., 2018). VR systems usually convert these to a polygon mesh to simplify rendering. Mesh vertices can be spaced in a regular horizontal grid matching the DEM structure, or use triangulated irregular networks (TINs) to adapt polygon density to roughness of the terrain (Easson et al., 2019; Kumar et al., 2018; Ai et al., 2019). Meshes may be pre-generated (Richardson et al., 2018), or be created on demand at run-time as described in this paper. Geographic information is not limited to terrain shape, but also includes layers such as buildings, water bodies, roads and plant cover (Kumar et al., 2018). Procedural generation of terrain trades off storage requirements by synthesizing some terrain elements during the rendering of the terrain (Galin et al., 2019; Kang et al., 2018)

3 SLIPPY MAPS FOR VR/AR LANDSCAPES

Slippy map tiles are used to provide level-of-detail for landscape representation. In the VR/AR environment the landscape is either projected onto a physical table surface, is visible through a camera/screen of a handheld device, or is fully presented within VR. Level-of-detail applies to the individual view point of each of the participants.

The landscape generation algorithm takes as input: 1) the position and size of the table top surface 2) the camera view frustum so that the geometry can be optimized for that view, and 3) the region of the map being presented. The map region is defined using three coordinates of latitude, longitude and scale. Scale is a continuous variable representing the ratio of physical distance to distance on the table top map. This abstraction removes an explicit dependency on slippy map tile coordinates inherent in many other applications.

Landscape generation uses the pipeline shown in Figure 2. These separable components are presented in the following sections.

3.1 Generate the Level-of-Detail Tree

While many web mapping applications show a single zoom level at any instant, this process mixes zoom levels using a quad-tree to provide detail in areas that are close to the viewer.

Each tree node represents a slippy map tile, with children being tiles that occupy part of the same region but at the next zoom level. Tree generation (see Algorithm 1) starts conceptually with a tile that covers the table top region. Longitude, latitude and scale coordinates identify tile coordinates: x, y and zoom for a tile, T, whose extent is comparable to the table surface area. Since tile boundaries may cut across the table a table-spanning quad-tree is created by adding two extra parent levels (see Figure 3). At level 2, this tree contains the 3×3 set of tiles consisting of T and its immediate neighbours. Level 1 merges clusters of 4 tiles. Level 0 is a single fictitious tile which may not align with an actual tile but that is a quad-tree root for the tiles at level 1. Only the tiles from level 1 down are ever utilized for terrain generation.

The tree is then selectively subdivided *based on camera distance and direction* to meet the allowed vertex budget for the terrain mesh and to manage the performance of the VR/AR application. Slippy maps are well suited to reducing detail by reverting to a lower zoom level tile. Subdivided tiles must be visible on the table, and *occupy the greatest visible screen*

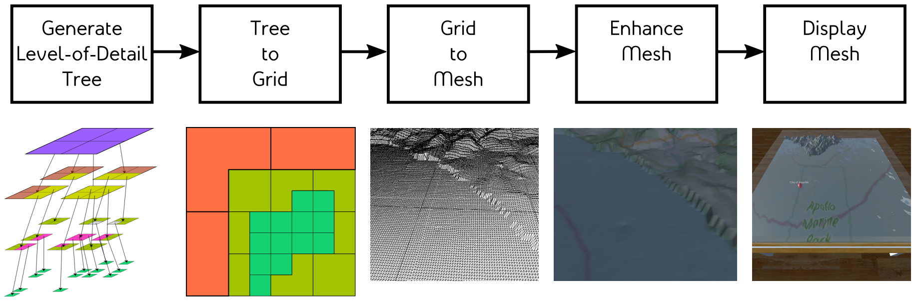

Figure 2: Landscape generation uses a quad-tree to identify tiles appropriate to the required level-of-detail. Subsequent stages render low zoom tiles first to ensure complete coverage even if higher resolution tiles are not available.

```
input  : latitude, longitude, scale, viewFrustum, table
output: Root node of quad-tree
zoom ← log2(tileSize_zoom=0/(table.size · scale));
// Identify tiles covering the table
n ← {−1,0,1};
repeat
    x,y ← LatLongToTileXY (latitude, longitude, zoom);
    tableCenter ← GetTile(x,y,zoom);
    tableCoverage ← {GetTile(x+n,y+n,zoom)};
    valid ← tilesExist (tableCoverage);
    if not valid then
        zoom ← zoom- 1 ;
    end
until zoom = 0 or valid;
// Build 2-level parent tree
a ← parentAlignmentFactor (tableCoverage);
root ← merge4(merge4(tableCoverage[n+a]));
// Subdivide for level-of-detail
while vertexCount < vertexBudget do
    tile ← biggestVisibleTile (root, viewFrustum);
    root.addToTree (largestRemainingChild (tile));
    vertexCount ← vertexCount + 3/4 × verticesPerTile;
end
return root;
```

Algorithm 1: Quad-tree generation starts by identifying a tile overlapping the table top. A synthetic parent is then created to completely cover the table. Child tiles are selected based on the screen area they occupy.

area when viewed through the camera. The visible area is approximated by projecting corners, assuming negligible height, into screen coordinates and calculating the area of this 2D shape. Comparable heuristics use estimates based on relationships between the screen-space length of a tile edge and the tile resolution (Kang et al., 2018), or use of summed-area tables to efficiently accumulate and compare error estimates for each level of refinement (Li et al., 2021).

Tiles are retrieved asynchronously from remote servers, and cached locally. Terrain generation processes are designed to fall back to lower resolution tiles in the case of delays or failures.

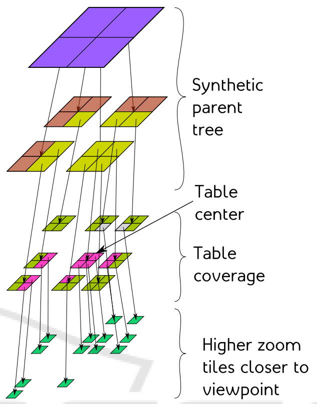

Figure 3: Quad-tree structure showing the additional two parent layers.

3.2 Tree to Grid

Quad-tree nodes may contain less than 4 children, in which case that region needs to be created using portions of the parent node combined with portions from child nodes as well as their descendants. Polygon mesh generation needs to blend across tile and partial tile boundaries. While the quad tree is able to resolve neighbour queries, in the worst case this requires a tree traversal to the root and back. Efficiency is improved by collapsing the tree (of depth d) into a square grid of size $2^d \times 2^d$ that supports constant time neighbour queries. Each node in the quad tree resolves to one or more grid entries. Each grid entry refers to the slippy map tile and the offset within the tile that the grid entry represents. The grid creation process ensures that when individual tiles are missing their grid entries contain details of parent tiles allowing a complete landscape model to be created even if portions are at a lower resolution.

3.3 Grid to Mesh

The landscape is represented geometrically using a polygon mesh boundary representation using the pro-

input : 2D array, grid, indicating tile portions used
output: Single polygon mesh

```
mesh ← ε;
foreach gridCell in grid do
    (start, end, tileData)← gridCell;
    region [gridCell] ← generateVertices (tileData,
      start, end);
end
foreach gridCell in grid do
    mesh.append (generatePolygons (region [gridCell
      ]));
    seamRight ← generateSeam (region [gridCell ],
      region [gridCell.right]);
    mesh.append (seamRight);
    seamBottom ← generateSeam (region [gridCell ],
      region [gridCell.bottom]);
    mesh.append (seamBottom);
end
return mesh;
```

Algorithm 2: Mesh generation starts by creating a set of vertices derived from the grid cell's offset, and elevation values from data sampled from the portion of tile overlapping each grid element. Neighbouring vertices are connected into polygonal faces. Neighbouring tiles that are at different vertex densities are connected by polygon seams.

cess described in Algorithm 2.

The regular array of values in an altitude tile are used to generate a polygonal mesh as a series of quadrilateral faces (or pairs of triangles) for each grid element. Meshes for each grid element are seamlessly connected by bridging boundaries with a single strip of polygons using a triangle fan topology to provide the one-to-many relationship between corresponding vertices in the two neighbouring meshes.

3.4 Enhance Mesh

Further data sets are presented as a texture image overlaid onto the terrain mesh. These textures are also provided as slippy map tiles. Tile textures from the open street map project[3] that provide location names, roads and region markers. Custom tile textures created to identify ridge and valley structures are used to identify likely travel routes for parts of the landscape that were recently submerged. Overlapping textures are blended and applied to the mesh surface.

Texture tiles are applied using a process equivalent to that used for grid generation (section 3.3). Individual tile textures are all rendered to a single texture image, T_{tex}, with a limited number (currently 1) tiles written per frame. The quad-tree is traversed breadth-first since the intermediate steps show as incremental refinement. Textures from each node are only written to their corresponding region of T_{tex}. If process is interrupted by a later terrain update T_{tex} will always contain a usable texture image. In practice polygon generation, replacement and seam removal can occur concurrently with the VR/AR experience while texture generation is performed in a shader on the GPU and must be synchronized with the VR/AR render cycle to avoid disrupting the immersive experience.

Texture rendering produces some artefacts, such as seams between images from different zoom levels. Coloured regions marking different vegetation patterns blend together reasonably well but the text labels used for place names do not as their size and positioning vary with map resolution. Potential lines of investigation (Dumont et al., 2020) include separating such meta-data to a separate class of slippy map tile, aligning labels so that they are amenable to a form of alpha blending, or modifying tiles to have more intermediate levels (i.e. a spatial tree structure that divides spatial dimensions by a factor $f < 2$). Tile pre-processing allows level-of-detail decisions to be made early and seam removal hints can be embedded in tiles.

3.5 Display Mesh

The resulting enhanced mesh is depicted on a table making use of either AR or VR technology. The landscape mesh is larger than the table surface, and is clipped to the bounds of the table by a pixel shader. Since clipping is performed for each frame, there is no additional performance overhead involved in translating and scaling the model and seeing different portions appear. Zoom and pan operations are achieved through initially translating and scaling the current model for instant response in the VR/AR experience. A new version of the terrain is concurrently generated at the designated position and scale and which takes into account the user's viewpoint to provide appropriate level of detail. A continuous flyover of the terrain can also be achieved by animating latitude, longitude and scale values between two key frames.

4 PERFORMANCE EVALUATION

This section evaluates the performance of the landscape visualization process to quantitatively assess the impact of applying the slippy map concept to control level-of-detail. A secondary goal is to identify opportunities for further refinement and investigation.

[3]https://www.openstreetmap.org/

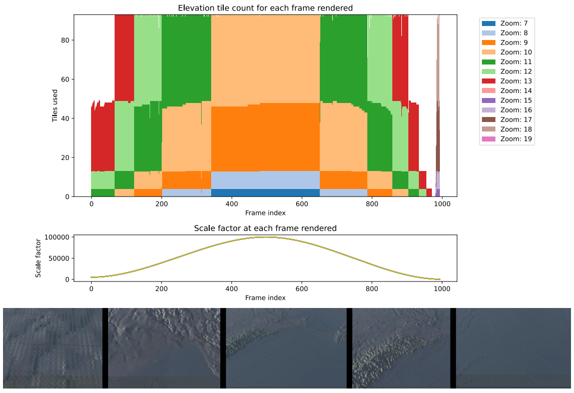

Figure 4: Tile usage patterns over 1000 frames during which the view point moves from a close up view on land, to an overview of the region and then to a high resolution sea floor area. The images at the bottom show representative samples of the terrain at key frames.

The algorithm is implemented using Unity3D[4] 2019.4.28f1 with time-dependent performance measurements taken while running completely on an Oculus Quest (v1) headset. The user pans and zooms using gestures made with the controllers. Map layers consist of elevation tiles, including the high resolution tiles (up to zoom level 19) for the marine park and up to zoom level 13 for the surrounding area. Two layers of texture tile are applied to the surface, generated from the open street map data set and an experimental layer marking ridge and valley features. A water plane is displayed at sea level, but has been disabled in some screenshots to show the sea floor.

The results of a test run forcing use of tiles across different scales are shown in Figure 4. The number of tiles required is constant since the camera was fixed during this test. Gaps in the first 50 and last 100 frames are expected failed attempts to access some tiles due to gaps in the data sets available. Missing tiles only limited the resolution of the resulting landscape mesh and in all cases a lower magnification tile is automatically substituted by the algorithm to ensure continuity and consistency of the landscape.

The client exploits spatial coherence and only ever accesses a small portion of the data on the server at any time. As an illustration, the client used for all the testing described in this paper has only ever accessed (and cached) 200 MB of unique tile data from the 23 GB currently available on the server.

The landscape quality is visually assessed using Figure 5. Different levels of detail are achieved by specifying the target vertex budget. The visible portion of the terrain represents approximately 1/9th of the mesh created as the table-center tile matches the table size, and the 3×3 table-coverage tile group is used to ensure the table top is completely covered. Panning in any direction of half the table top dimensions is possible before the edge of terrain is visible.

(a) Vertex target: 10,000

(b) Vertex target: 100,000

(c) Vertex target: 1,000,000

Figure 5: Views of the landscape visualizations created with different vertex targets. The actual vertex counts are: a) 176218 (target 10,000) b) 262144 (target 100,000) c) 1159168 (target 1,000,000) although only a portion are visible within the region above the table. Changes to the text labels are visible in the most detailed image.

Interactive level-of-detail refinement takes place continuously during the VR experience. Figure 1c shows the region closest to the viewer (bottom of the image) accessing tiles at a higher zoom level than the region of the terrain further from the viewer (at the top of the image). The high zoom tiles have a grid-like sampling artefact embedded in the tiles. The landscape mesh is regenerated automatically based on the current position and direction of the viewer. On an Oculus Quest headset it takes 0.25 s to recreate a terrain with a vertex target of 1,000,000 (the resulting mesh actually contains 1.15×10^6 vertices). This ensures that any region that the viewer pauses to look at is then rendered with higher detail. Rendering of

[4]https://unity.com/

the mesh does not significantly impact the responsiveness of the VR application as mesh generation is performed asynchronously.

5 DISCUSSION AND OPPORTUNITIES

Slippy maps enable standardization of coordinate systems, multiple sources of quality tile sets that provide vegetation coverage, roads and buildings, and altitude data, as well as a range of online services providing access to these tiles. A slippy map philosophy assumes unlimited server tile storage traded against client performance and spatial locality. The second focus of this investigation is to identify opportunities to adapt and extend the slippy map concepts through consideration of the VR/AR mapping context.

The quad-tree structure and slippy map tile pyramid provide control of level-of-detail. Dynamic control of tile resolution would provide finer grained control over vertex budgets, using extra tiles pregenerated on the server and accessed using an additional tile coordinate. The quad-tree is always constructed to fully cover the table top region to ensure that change of viewpoint, common is VR, never shows a partial landscape while the terrain mesh is regenerated. The quad-tree is adaptively refined based on the view frustum so extra detail is still provided based on the camera proximity and direction. The raster rendering approach used in the algorithms presented in section 3, that collapse the tile tree to a grid and render of texture tiles to a single texture image, ensures that low zoom tiles are automatically used to replace any missing tiles at a higher zoom level. This also enables the VR experience to be relevant and responsive even while additional tiles are being transferred from the server.

Altitude tiles encourage the use of boundary representation terrain models. In this context, the underwater environment contains a usable volume between sea floor and water surface that is actively inhabited and utilized and could, for example, make use of a voxel based tile (Galin et al., 2019) to extend up and down (Jurado et al., 2018) and include data from other fields and disciplines (Christophe, 2020). Slippy tile coordinates could be made continuous in ways that support blending of tile textures across different zoom levels, or to reducing seams. Slippy map tiles tend to focus on bitmaps. Other tile formats are already being explored that allow representation of overhangs (Kumar et al., 2018), and produce progressive TINs suited to slippy map tile structures (Ai et al., 2019; Campos et al., 2020).

Many of these ideas could be introduced while remaining backward compatible with existing slippy tile clients while providing opportunities to enhance VR/AR terrain presentation.

6 CONCLUSION

This paper presents the viewpoint sensitive level-of-detail algorithm that mixes slippy map tiles across zoom levels to generate landscape visualizations for table top VR/AR presentation. The process benefits from slippy map characteristics: the ability to use low zoom tiles to unobtrusively provide a rapid early approximation even while loading higher resolution tiles and responsiveness through caching tiles for the local view area. Further opportunities that are identified and exploited include instant localized pan and zoom by invisibly managing a mesh larger than the table, and ways to integrate the process into the game loop pattern employed in VR/AR applications on mobile platforms.

This research is a stage in an ongoing process of applied cross-disciplinary research. The immediate outcome: a responsive landscape for VR/AR provides an artefact that is immediately usable by collaborators from other disciplines. Opportunities are identified for further enhancing the process and augmenting slippy map concepts by varying properties currently kept constant, adapting the shape of the tile pyramid, extending the type of information stored in a tile and what it represents, and constraining the relationships between tiles at adjacent zoom levels. These opportunities are achieved through the systematic derivation of the algorithm presented which would be lost when using third party implementations and focusing only on the evaluation of the system.

It is rewarding that even with a well-established problem of providing adaptive level-of-detail in landscape visualization, and while using the established technology of slippy maps, that opportunities can still be identified to investigate new directions and to further refine these industry standards.

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