2009-06

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ACM

Web3D 2009
http://hdl.handle.net/10945/71180

X3D Earth Terrain-Tile Production Chain for Georeferenced Simulation

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Abstract

Broad needs for digital models of real environments such as 3D terrain or cyber cities are increasing. Many applications related to modeling and simulation require virtual environments constructed from real-world geospatial information in order to guarantee relevance and accuracy in the simulation. The most fundamental data for building virtual environments, terrain elevation and orthogonal imagery, is typically acquired using optical sensors mounted on satellites or airplanes. Providing interoperable and reusable digital models in 3D is important for promoting practical applications of high-resolution airborne imagery.

This paper presents research results regarding virtual-environment representations of geospatial information, especially for 3D shape and appearance of virtual terrain. It describes a framework for constructing real-time 3D models of large terrain based on high-resolution satellite imagery. This approach is also suitable for underwater bathymetry. The Extensible 3D Graphics (X3D) Geospatial Component standard is applied to produce X3D Earth models with global scope. Efficient rendering, network retrieval and data caching/removal must all be optimized simultaneously, across servers, networks and clients, in order to accomplish these goals properly. Details of this standard-based approach for providing an infrastructure for real-time 3D simulation merging high-resolution geometry and imagery are also presented. This work facilitates open interchange and interoperability across diverse simulation systems and is independently usable by governments, industry, scientists and the general public.

Keywords

Extensible 3D Graphics (X3D) Geospatial Component, X3D Earth, satellite imagery, interactive simulation interoperability

1. Introduction

High-resolution optical imagery sources that were formerly used for restricted purposes by the military sector and intelligence communities world-wide have now become widely available. Such commercial access has been enabled by the development and deployment of aerial sensor payloads capable of taking sub-meter resolution images. As the spread of commercial online mapping services has grown, the usage of high-resolution satellite imagery is also growing beyond specialty demands such as Geographical Information System (GIS) applications for environmental, agricultural and oceanographic monitoring. Furthermore, the need for geospatial data in virtual environments is increasing as shown by the economic growth of serious computer games and metaverse-style cyber worlds. The virtual environments required in the simulation of transportation, agriculture, forestry, hydrology, environment and other applications need to be built using real-world object data and accurate geospatial information such as satellite imagery. Therefore, a shared real-time 3D simulation infrastructure that can provide a base platform for simulation in these various areas is needed to promote utilization of high-resolution satellite imagery.

Providing an open, royalty free, Web-based infrastructure for utilization of such imagery in 3D environments can be accomplished using the Extensible 3D (X3D) standard, maintained by the Web3D Consortium and ratified by the International Organization for Standardization (ISO). This approach provides a compatible complement to existing GIS standards produced by the Open Geospatial Consortium (OGC), and the Web Architecture championed by the World Wide Web Consortium (W3C 2004).

This paper describes a terrain-tile production chain that was developed to provide an infrastructure for building virtual terrain models for real-time 3D simulation based on high-resolution satellite imagery. Moreover, relevant standards for geospatial data representation and interchange are evaluated, and an open standards-based framework is validated through experimental testing. Since this open infrastructure is not dependent on any proprietary or royalty-burdened technology, this solution benefits governments, scientists and the public by establishing a long-term foundation for vigorous, diverse and interoperable use of 3D geospatial information.

The next section of this paper explains related work on simulation tools utilizing geospatial information, demonstrating some limitations of existing tools and showing the direction of this approach. Section 3 evaluates technical requirements for the infrastructure described in following sections and compares candidate standards as possible solutions for these requirements. Section 4 proposes an approach to represent geospatial information using the X3D standard within a content-production framework. Section 5 discusses how to best apply the geospatial

Web3D 2009, Darmstadt, Germany, June 16 – 17, 2009.
© 2009 ACM ISBN 978-1-60558-432-4/09/0006 $10.00

component of the X3D standard to represent georeferenced 3D objects with simulation capabilities. Section 6 describes the issues encountered while implementing the proposed approach. Section 7 presents several experiments and evaluates the sufficiency of the proposed approach with respect to the identified requirements. Section 8 presents further successful web-based experiments. Sections 9 and 10 discuss results and directions for improvement.

2. Related work

3D geospatial data and satellite images are becoming more widely used thanks to the continued improvement of geobrowser applications (Butler, 2006; Nature, 2006). Support for the digital earth advocated ten years ago (Gore, 1998) has progressed. Grossner also defined a vision of the digital earth, comparing Google Earth and the digital earth (Grossner and Clarke, 2007). Google Earth, Microsoft Virtual Earth, NASA World Wind and ESRI ArcGIS Explorer are well-known geobrowsers. Additionally there are many 3D virtual earth applications providing satellite imagery display including Geosoft Dapple, Lunar Software EarthBrowser, Skyline TerraExplorer, GeoFusion GeoPlayer, Poly9 FreeEarth, etc. Overlays are also becoming more prevalent. Google Earth (Ertac, 2008) and ArcGIS Explorer let the user add data layers to the original map and imagery. ArcGIS Explorer allows user analysis with simple tasks (Lund and Macklin, 2007; Kienberger and Tiede, 2008).

Georeferenced application output may be overlaid on the Earth surface in some geobrowsers. Nevertheless integration and fusion of data and simulation models from multiple disparate sources is rarely possible within the applications themselves (Grossner and Clarke, 2007). For example, although NASA's World Wind for Java provides an advanced system architecture implemented in an open-source code base, it does not provide generalized simulation functionality and requires Java developers to embed World Wind in their own applications. Other applications present similar limitations, even more so in immersive virtual reality (VR) environments (Polys et al. 2008). The closed, proprietary or unique nature of these various applications often means that they require a similarly specialized approach to 3D object modeling and simulation, thereby discouraging broader interoperability.

3. Requirements and solution

A general and open real-time 3D simulation infrastructure is needed for practical applications utilizing satellite imagery and diverse geodata resources. The following technical requirements are considered for such a real-time 3D simulation infrastructure.

While there are many geospatial data formats available, this comparison focuses on a select number of widely used standards. The goal is to determine a single best-fit standard that supports a mix of both geospatial information and real-time simulation. Group evaluation led to the following primary requirements:

- Interoperability with different formats and data sources
- Open architecture permitting diverse application uses
- Real-time 3D graphics and interactive responsiveness
- Distributed simulation support

Secondary requirements include:

- Metadata annotation embedded within (or linked to) data
- Computer aided design (CAD) model layer
- User interaction, sensing and event scripting
- Extensibility for new models and capabilities
- Support for advanced 3D graphics rendering techniques

In order to find a satisfactory 3D solution for the defined requirements, a comparative study of existing standards was conducted for representation and interchange of geospatial data.

Table 1 shows the comparative result among selected standards: GML (OGC, 2007), CityGML (Kolbe et al., 2005; OGC, 2008b), KML (OGC, 2008a), X3D (Daly and Brutzman, 2007), SEDRIS (SEDRIS, 2007), SDTS (USGS, 2007), and DXF (Autodesk, 2008). The websites and papers cited in this research were used as informative references. Considering the stated primary requirements, X3D provides the largest number of competitive features in a royalty-free open standards format and run-time architecture that can represent 3D scenes and objects using XML.

(Crews 2008) also conducted a comparative study of related 3D graphics capabilities among open, free to use standard formats that are preferably based on XML, evaluating 42 graphics file formats according to requirements for publishing 3D models. Taking the stated objectives for each 3D format into consideration relevant to his study requirements, X3D again provides the most comprehensive solution when using reasonably sized memory and file storage. These study requirements are roughly equivalent to the stated secondary requirements above, and can be considered fairly extensive especially with respect to 3D graphics capabilities.

X3D is a well-known standard and formally collaborates with the Open Geospatial Consortium (OGC) and the Collada community in the Khronos Group. According to each of these two comparative studies examining the most dominant information standards, geospatial standards and 3D graphics standards, X3D provides the best fit solution for the defined requirements.

Table 1. Requirements comparison table of open standards for geospatial data representation and interchange (Yoo et al., 2008)

	GML/CityGML	KML	X3D	SEDRIS	SDTS	DXF
Geospatial Component	Feature	Feature	Geospatial Component	Environmental Data	Profile	Geodata object
Standards Organization	OGC, ISO	ISO, OGC, Google	ISO, Web3D.org	ISO, SEDRIS.org	USGS	Commercial (Autodesk)
Interoperability	Yes	Yes	Yes	Yes	Weak	Weak
Simulation Capabilities	N/A	Limited, simple task	Interactive profile	Yes	N/A	N/A
Real-Time 3D	Limited	Embeddable	Yes	Limited	Limited	Limited
Multimedia	N/A	Limited	Yes	N/A	N/A	N/A
Run-time Architecture	Limited	Google Earth, geobrowsers	Multiple implementations	Limited	N/A	N/A
Advanced 3D rendering	N/A	N/A	Shaders, etc.	N/A	N/A	N/A

4. Terrain-tile production chain

Content authoring of high-fidelity terrain or bathymetry for virtual environments is typically a laborious but essential process. It is a challenging task to reliably create high-quality geospatial assets for 3D simulation. A key motivator in this work is to reduce the troublesome and repetitive aspects of geodata processing, automating time-consuming processes to consistently generate virtual 3D terrain. Thus a standards-based content production framework – terrain-tile production chain – was developed. Details follow. Reusability for recurring reproduction of virtual terrain is also considered in the design of this framework, since geospatial data sources may be frequently updated and a variety of application requirements continue to emerge.

The overall terrain-tile production chain process is shown in Figure 1, with details available online (Yoo, 2009) as well. The interoperability of the terrain model shown in the proposed framework is based on the design of the Geospatial Component in the X3D standard. The process generates multi-resolution terrain models in valid X3D format from geospatial information including high-resolution satellite imagery, thus supporting real-time interactive X3D visualization while simulation applications are running. This processing framework has been successfully validated numerous times by graduate students of the Naval Postgraduate School, who each individually generated X3D terrain-tile scenes for locales of their own geographical interest.

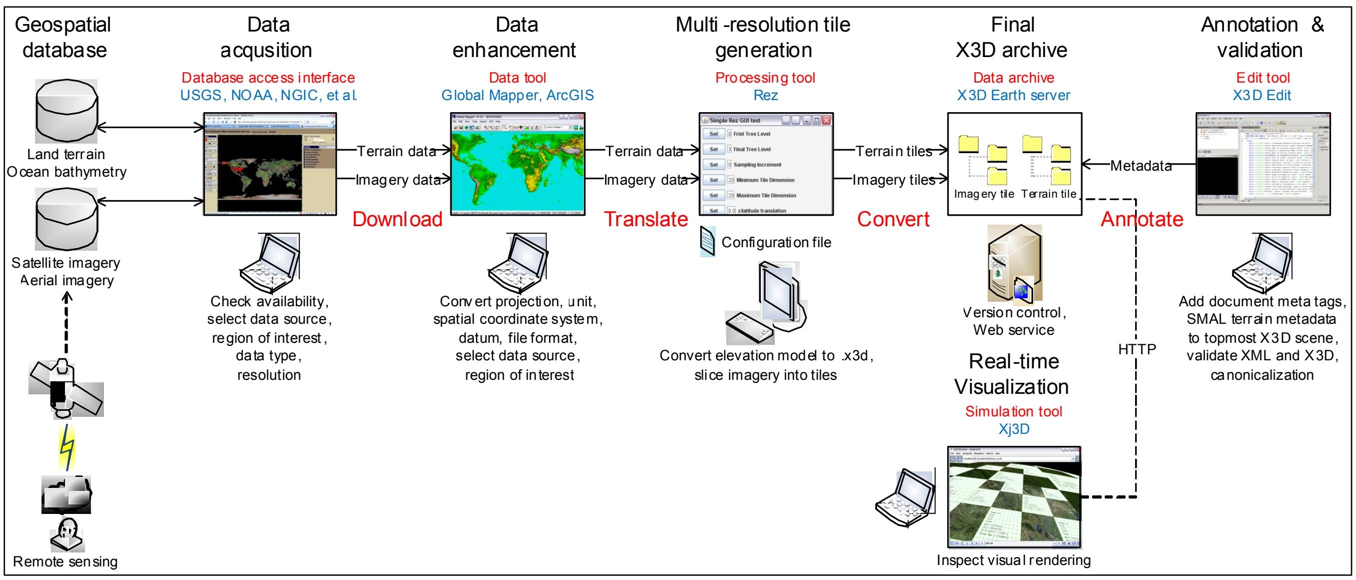

Figure 1. X3D terrain-tile production chain generates multi-resolution file sets from geospatial data (Yoo, 2008)

The terrain-tile production chain process for generating multi-resolution terrain tiles includes the following steps. Top-level decisions are by human users, while most tasks are performed by individual software components.

- **Data survey and acquisition**:
  Survey and access available public and/or commercial geospatial databases for acquisition of geospatial information. Heterogeneous datasets from multiple sources are sometimes needed due to the range of coverage and resolution provided by each source. Select and download terrain-height data and corresponding imagery according to the relevant region of interest, using the maximum resolution desired (or available).
- **Preprocessing and data enhancement**:
  Adjust projection, units, spatial coordinate system and datum as needed for data consistency during processing. Convert and merge datasets from multiple data sources when different data types are encountered. Select range of interest and crop to fit area of interest. Translate file formats if needed for import by terrain-tile processing tool.
- **Multi-resolution tile generation**:
  Define ultimate depth of level of detail (LOD) for multi-resolution terrain-tile generation, based on available data sources and simulation goals. Slice and dice highest-fidelity source terrain and imagery data into multi-resolution X3D terrain-tile sets using Rez and ImageSlicer tools. Fidelity is reduced by a factor of 4 when producing each higher level. Terrain data is converted into elevation grids with matching image textures draped on top.
- **Annotation and validation**:
  The X3D archive is finalized by creating the top-level scene with metadata documenting the geospatial context. Validate all X3D scenes generated by the processing tools. The X3D-Edit authoring tool (Brutzman 2009a) includes Geospatial Component support and all necessary features for performing such steps manually.
- **Archiving and application**:
  Check results into X3D Earth server for version control. Verify the X3D scene by visual inspection using a standards-compliant X3D browser that is capable of rendering X3D geospatial nodes.

As might be expected, there are several issues that need to be taken into account during each step of the process. Maintaining consistency of the geospatial context throughout the data-manipulation process is the most sensitive issue in the overall production chain, and is discussed further in section 6.

5. X3D geospatial component

The Web3D Consortium's X3D Earth working group uses the Web architecture, XML languages, and open protocols to build a standards-based X3D Earth specification usable by governments, industry, scientists, academia, and the general public (Brutzman et al., 2007). The X3D Geospatial Component provides support for geographic and geospatial applications including the ability to embed geospatial coordinates in certain X3D nodes, to support high-precision geospatial modeling, and to handle large multi-resolution terrain databases. Together these design criteria provide a rich set of functionality for tandem client-side and server-side development of X3D Earth solutions.

In the terrain-tile production chain, X3D geospatial component nodes are carefully applied in a regularly repeating design pattern that can represent the overall terrain model at multiple levels of fidelity without loss of geospatial context. The terrain-tile production chain uses the following X3D geospatial component nodes for representation of the multi-resolution terrain tile:

- GeoCoordinate
- GeoElevationGrid
- GeoLOD
- GeoMetadata
- GeoOrigin

Detailed descriptions of each node of the geospatial component are described in the X3D specification document (Web3D, 2008). For reduced network loading and best rendering performance in real-time simulation applications, GeoLOD nodes are used in each terrain tile of the production chain. An example file structure for a typical X3D tile scene (with height values replaced by ellipsis …) is illustrated in the following example excerpt (Code 1).

```
<GeoLOD
    child1Url='l00g.x3d'
    child2Url='l01g.x3d'
    child3Url='l02g.x3d'
    child4Url='l03g.x3d'>
  <Group DEF='TerrainForThisLevel'>
    <Shape>
      <Appearance>
        <ImageTexture url="0g.png"/>
      </Appearance>
      <GeoElevationGrid
        geoGridOrigin ="-90 -180 0"
        yScale ='1.0'
        xDimension='21'
        xSpacing='18'
        zDimension='21'
        zSpacing='9'
        height="...">
      </GeoElevationGrid>
    </Shape>
  </Group>
</GeoLOD>
```

Code 1. Example X3D scene excerpt using the XML encoding (tilename.x3d) within a multi-resolution terrain tile.

The full X3D terrain-tile set of GeoLOD files is typically generated via the production chain illustrated in Figure 2. Both terrain-tile sets and corresponding imagery tile sets must be constructed at each level of the GeoLOD-based scene archive. Tile file-naming conventions indicate sector locations, quad-tree indices and resolution level to facilitate direct access on demand.

As noted in (McCann 2009) elsewhere in these proceedings, the GeoOrigin node is now deprecated and will not be needed in future versions of this design pattern since the contained information can lead to interoperability difficulties and is essentially redundant. As described in that reference, we expect the tile template to change further to accommodate use of the proposed GeoTerrrainLOD node as a superior, more tightly constrained replacement for the GeoLOD node. Such modifications are slight and do not affect the fundamental functionality or design pattern for these terrain-tile scenes.

6. Geospatial consistency management

Within the series of processing-chain steps for tile production, there are a number of conversions and translations of projection type, unit, spatial coordinate system, datum, and file format in preprocessing and tile generation process. The consistency of geospatial context during the data processing through the overall production chain must be managed consistently or else spatial distortions and mismatch errors will occur. Potential errors and essential correlations of geospatial context that need to be considered during the terrain-tile production chain are as follows:

- **Consistency between terrain data and imagery data**: Coverage, projection, spatial coordinate system, datum and units for each retrieved dataset are usually different. These must be matched through correlation conversions in the data enhancement process of the production chain.
- **Format consistency between feeding data and parsing scheme of tile generation tool**: The Rez tool needs to be able to parse input data with correct understanding of the geodata format.
- **Conformance of X3D tile-generation output**: Output X3D tile sets from the Rez tool need to conform to X3D Earth specification requirements. This step is usually accomplished via XML well-formedness checks along with DTD and X3D Schema validation. Further quality assurance (QA) is also possible through application of X3D Schematron rules (Brutzman 2009b).
- **Conformance of geospatial X3D browsers**: While experimenting with the geospatial component of X3D Earth specification, correctness and conformance of browser implementations must also be considered. Three players currently provide X3D geospatial support.
- **Consistency of adjacent tiles in either the same or different levels of LOD**: Coverage, location of the GeoGridOrigin and direction of GeoElevationGrid field values in a tile set at each arbitrary level must be correlated with adjacent imagery tiles within the same-LOD tile set. An illustration showing corresponding tile sets is shown in Figure 2.
- **Consistency between naming convention of GeoLOD tiles and contents**: The naming convention of terrain-tile and imagery tile must be correlated. Naming convention and direction of order for contents of each tile should match.
- **GeoOrigin in an X3D scene and each tile**: GeoOrigin is intended for high precision of geospatial location in run-time architectures, but multiple different GeoOrigin values lead to inconsistency problems. The X3D terrain-tile set should have a single GeoOrigin or else no GeoOrigin (since that node is now deprecated).

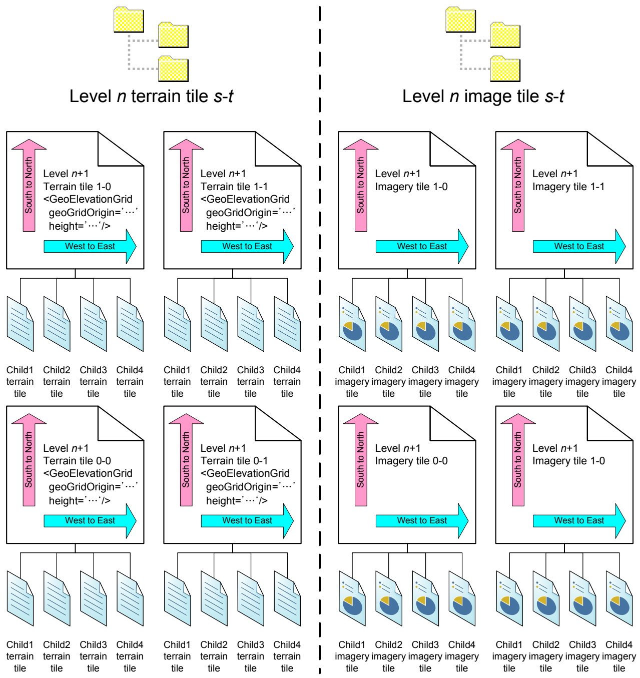

Figure 2. Consistency of georeferenced information of terrain-tile set and corresponding imagery-tile set at arbitrary levels of detail in X3D multi-resolution scenes.

The Rez tool (Thorne, 2007b) is open-source software for translating gridded data to different formats. Rez was modified and improved for the terrain-tile production chain. The consistency of geospatial context and support for X3D geospatial component are improved. Most improvements are related to the X3D Earth specification. The former GeoVRML output filter was modified to satisfy X3D Earth conformance. Validation on three tiers (X3D scene generator, X3D contents and X3D browser) is conducted simultaneously to maximize quality assurance.

7. Experimental results

Using the proposed terrain-tile production chain, several experiments were conducted for validation of the framework. The most basic experiment is the generation of multi-resolution X3D tiles from high-resolution satellite imagery and elevation grids. LANSAT7 satellite images and USGS high-resolution orthoimages are used for this experiment. The highest resolution orthoimage is 0.3m per grid of pixel. Figure 3 shows different GeoLOD levels of the generated X3D tile set. It is composed with 20 GeoLOD levels with binary tree structure. Smooth transition between GeoLOD nodes depending on the distance from terrain surface to the viewpoint, real-time 3D EXAMINE and FLY navigation, georeferenced viewpoint handling with geographic coordinates, and performance measurements of the X3D run-time architecture were all evaluated during the experiments.

The interactive animation capability of 3D objects was further tested by adding a 3D cargo ship model to the X3D terrain-tile set. In this example scene all 3D objects are positioned via GeoLocation nodes, thus providing the ability to georeference any inlined X3D model as shown in Figure 4. Additional track information for the cargo ship was overlaid on the terrain-tile using a GeoTransform node which allowed for the translation and orientation of geometry built using GeoCoordinate nodes within the world coordinate system. The terrain model used in the second experiment is composed of 5 GeoLOD levels of quad-tree structure for multi-resolution terrain-tiles of the Straits of Malacca.

Finally the simulation capability of X3D terrain-tiles, generated with the proposed terrain-tile production chain, was successfully demonstrated with an experiment of coverage simulation of radio towers in Algeria as shown in Figure 5. The Algeria scene is composed of 7 GeoLOD levels in the quad-tree tile set.

8. Web server PHP script, Web Service support

In order to test an initial server-side architecture for X3D-Earth, a self-referring PHP script implementation was created which generates X3D terrain-tile sets on-the-fly. The server receives an initial query for location, and then constructs an X3D scene that includes top-level GeoElevationGrid height data with appropriate draped ImageTexture imagery, along with child url links to the next-lower quadtree of similarly constructed scenes. The PHP script is then used repeatedly to query, generate and link terrain-tile files dynamically for each subsequent Inline quadtree child.

Interestingly, when considered from the client perspective, the PHP approach appears identical to that produced by preprocessed X3D Earth retrieval. Terrain height data, bathymetry altitude data, cartography, satellite imagery or aerial photography of interest is retrieved as needed to produce tiled structures for multi-resolution terrain. The script checks if the server has cached imagery and serves the imagery matching the appropriate location, dimensions and pixel resolution. Otherwise the script generates artificial imagery indicating the geospatial metadata of the missing image tile. This approach was adapted to work with several geospatial web services including OpenAerialMap and OpenStreetMap.

X3D Earth top-level scene: http://x3d-earth.nps.edu/d0.x3d
Open Street Map X3D scene: http://x3d-earth.nps.edu/osmb0.x3d
Open Aerial Map X3D scene: http://x3d-earth.nps.edu/oamb0.x3d

This image-retrieval approach was first prototyped in the PHP script was then further generalized using Web Services applying the OGC Web Mapping Service (WMS).

http://x3d-earth.nps.edu/service/geocode.html

A detailed demonstration of this functionality is provided in the following online video.

http://x3d-earth.nps.edu/video/X3D-EarthVideoWide1280x720(2008.11.25).wmv

9. Discussion and future directions

Geospatial information is pervasively used in Web environments. This remarkable growth of geospatial web services is enabled by a rich and free infrastructure along with easy-to-use geospatial APIs for web development and mashup capability. It allows people who utilize geospatial web services to become GIS users (and even contributors) intuitively without special training or knowledge. In the same manner, we believe that the royalty-free infrastructure for building an interoperable, real-time 3D simulation environment of geospatial information will influence the growth of georeferenced scientific simulation, education and analysis.

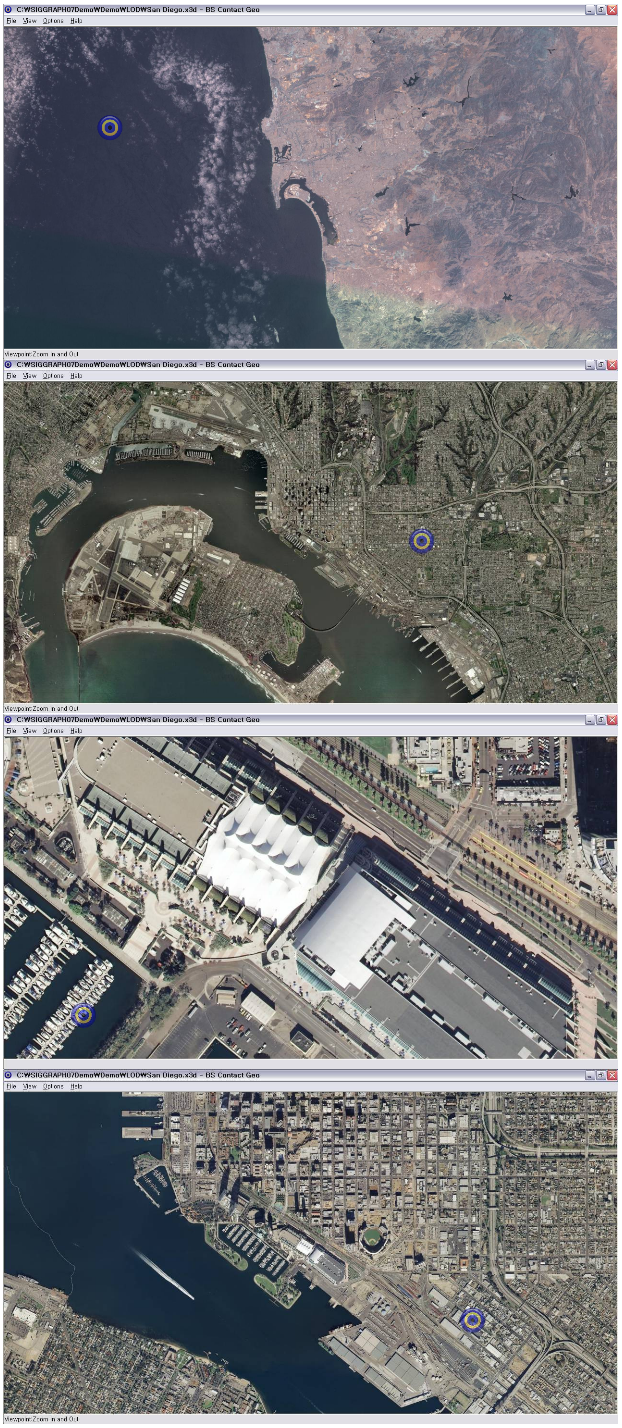

Figure 3. Multi-resolution X3D terrain-tile set of San Diego California generated using the terrain-tile production chain (Yoo et al., 2008)

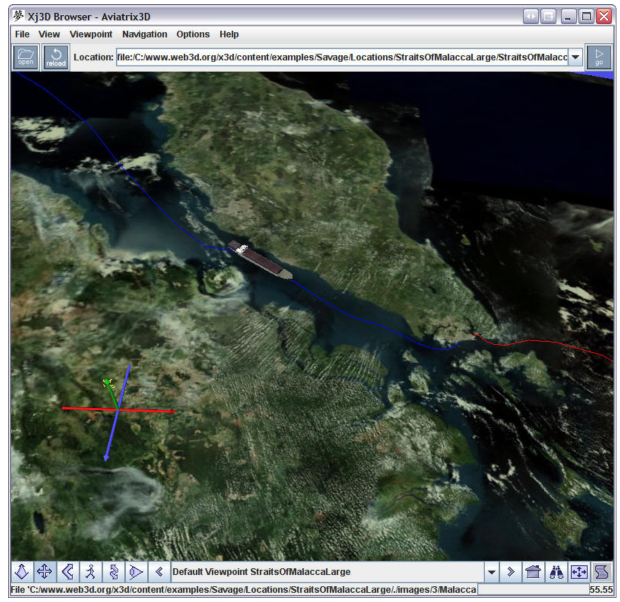

Figure 4. X3D scene of Straits of Malacca with animating 3D objects, a cargo ship following a geospatially referenced track

A natural evolutionary path for the terrain-tile production chain is to utilize flexible preprocessing tools in the public domain instead of current commercial tools such as GlobalMapper and ArcGIS. Another approach is to improve the processing tool for more robust and scalable memory management during tile generation. The current version of the Rez tool can handle several hundred million pixels in a single process.

Another strategic goal is to build a fully detailed X3D model of planet Earth using X3D Earth, both in preprocessed versions and via Web services. Such public assets might enable new geospatial capabilities including 3D publication for visual correlation of climate-change models and data. Arbitrary sources of overhead imagery might contribute to building such standards-based globe models. Individual governments and diverse communities can each create X3D Earth models without technical or licensing restrictions, working either independently in isolation or together in concert on multiple sets of interoperable X3D Earths. Great opportunities await.

10. Conclusions

We have shown that X3D terrain-tile production from geospatial information can be routinely constructed for various applications. This work was based on goals set forth in the original X3D Earth Technical Requirements workshop, and also motivated by evaluations of a variety of existing geospatial and 3D graphics standards. Experimental results demonstrate that the technical details of a standards-based X3D Earth approach provides excellent infrastructure for real-time 3D simulation using high-resolution overhead imagery. This approach facilitates broad interchange and interoperability across diverse systems, and continues to improve thanks to the dedicated efforts of X3D Earth Working Group contributors in the Web3D Consortium.

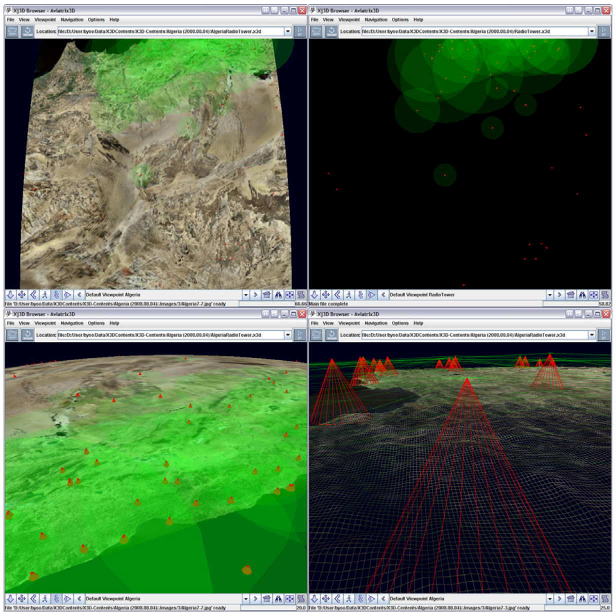

Figure 5. An experimental simulation using X3D Earth for Algeria showing a notional scene for radio-tower coverage.

Acknowledgements

This work was supported in part by the Web3D Consortium as a part of the first Web3D Fellow Program. It was also supported by the KOMPSAT-3 satellite development program promoted by the National Space Program of the Korean Government (MEST). We gratefully thank Mike McCann of MBARI, Dr. Chris Thorne of VRshed.com, Rex Melton and Alan Hudson of Yumetech Inc., Doug Maxwell of Naval Undersea Warfare Center (NUWC) Newport Rhode Island, Dr. Richard Puk of Intelligraphics, and John Stewart of CRC Canada for collaboration throughout the design and implementation of this work. Nathan Crews provided several interesting ideas, particularly with regard to LandXml.org. We also thank the many NPS graduate students studying Advanced X3D who successfully tested and improved this process.

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