Charlotte Visualization Center
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Technical Report CVC-UNCC-12-15
March 2012

Towards Utilizing Heterogeneous Analytics Interfaces in Coastal Infrastructure Management

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ABSTRACT

Geo-spatial data such as multiple return LIDAR terrain data, sonar data and ocean surge data play a significant role in various emergency response and planning scenarios. Such multi-planar and volumetric data is rich in geographic features; more importantly, it also contains a significant temporal component. Understanding geospatial-temporal changes is a fundamental aspect of analyzing, understanding and responding to natural phenomena (e.g. hurricane impacts, coastal infrastructure changes, and ocean surges). We are collaborating with a number of scientific colleagues on projects relating to prediction of and response to various natural disasters such as hurricanes and oil spills. These colleagues and their supporting agencies have identified several visual analytic needs relating to inspecting and cleaning up multi-return LIDAR and sonar data and volumetric ocean flows. These include the ability to provide efficient interactive display systems and user interfaces for navigating, selecting and inspecting outlier 3D points or flow vectors; the ability for multiple co-located, collaborating scientists to perform such analysis on visually dense 3D data; and the ability of the system to semi-automatically extract high-level features from large data sets and to then help the scientist construct a narrative that explains the salient temporal-spatial features in a concise textual and abstract visual form.

Keywords:.

Index Terms:

1 MOTIVATION AND RESEARCH GOAL

Managing coastal infrastructures and responding to coastal natural disasters is a multi-stage, multi-model analytics process that involves a wide range of heterogeneous geospatial data collections. Good management and emergency response policy decisions demand an effective analytics workflow that includes data acquisition, data cleaning and analytics, data visualization, and interaction. The ultimate goal is to support the human decision-making process. This is essential for coastal infrastructure management decisions that are often heavily dependent on rich geospatial features and planning. Stakeholders and emergency responders, from both government agencies and research institutes, are continuously collecting and generating heterogeneous geospatial data to support decision-making.

Geo-spatial data, such as multiple return light detection and ranging (LIDAR) terrain data, deep-ocean sonar data, and ocean surge models, play a significant role in such emergency response and planning scenarios. The scanned terrain data can include natural terrain or urban terrain that incorporates man-made infrastructure. Such multi-planar and volumetric data is rich in geographic features, and is used and analyzed to understand impacts of natural disasters and ocean dynamics. More importantly, such collected geospatial data also contains a significant temporal component. Depicting this temporal factor is an integral part of analyzing natural phenomena, (e.g. coastal terrain changes or hurricane impacts), and can help formulate responses and preventative management.

LIDAR, sonar, and flow data are generally multi-layered, if not fully volumetric. While automated algorithms will certainly be a significant part of the analytic workflow, visual analytic tools for coastal infrastructure will require a wide variety of SciVis (3D) and InfoVis (2D) interactive techniques. The 3D visualizations and their constituent interaction techniques need to account for the multi-layered and volumetric aspects of these data. In an ideal visual analytic environment, each interaction task would be performed using a display system that is best suited for the given task. When interactively cleaning LIDAR or sonar point clouds, stereoscopic displays and motion parallax can aid visual perception and understanding of the point cloud arrangement, and help with interactions such as selection. Similarly, stereoscopic displays can aid visual perception and understanding of animated, multi-layer streamlines in ocean flow or storm surge simulations. Furthermore, when selecting and removing outliers from point clouds, a multi-touch or perhaps 3D multi-finger interface might speed the interactive selection of individual points among a dense collection.

1.1 Research Goal

Given the deep heterogeneity in the coastal infrastructure data, our research addresses the design of visual analytics environments that employ a suite of heterogeneous displays to facilitate data acquisition, data cleaning and analytics, and interactive data visualization, and to support the human decision-making process.

Our system employs a suite of displays, including a semi-immersive, stereoscopic display, a high-resolution tiled display, and a multi-touch table. This creates an analytics environment that provides a powerful integration of high quality stereoscopic 3D graphics, two-handed interaction, and touch-based interaction. Our tools support analysis of terrain height changes and ocean surge as well as feature-spaces analytics that allow the user to discover structures within the data that are not easily detectable using traditional visualization or feature extraction methods. Temporal information is also represented for both terrain and feature analytics through animation. Notably, the process of collecting such geospatial data, analyzing it on multiple heterogeneous displays, and creating human-centered visual analytical environments, can be generalized across different domains.

A detailed description of the components of the display environment and the software tools with their related analysis processes are the focus of this paper.

1.2 Situation Assessment and Motivating Scenario

This research is motivated by impending sea-level rise and possible increased intensity of tropical storms and cyclones. With nearly 325 miles of coastal shoreline, the state of North Carolina has a long history of significant impacts from hurricanes and tropical storms. Recent natural disasters (e.g. Hurricane Irene flooding and Hurricane Isabel barrier island breaching) have highlighted the great vulnerability of these coastal communities.

As illustrated in recent geology research, certain barrier island segments along the Outer Banks and other NC coastal areas are clearly in danger of developing inlets in the near future. Road maintenance plans, development policies, hazard mitigation, and emergency response plans depend upon an understanding of terrain change rates.

Monitoring and adapting to infrastructure changes is critical. With advances in survey and aerial surveillance technologies, such as such as LIDAR and hyperspectral imaging, several initiatives and organizations have started collecting and sharing coastal data for analysis, modelling, and simulations. In particular, the Digital Coast project lead by National Oceanic and Atmospheric Administration (NOAA) has provided rich coastal infrastructure and natural resources data since 1997.

Unfortunately, the sheer size and heterogeneity of this data presents a hurdle for infrastructure management. According to a recent survey conducted by NOAA with a variety of coastal infrastructure experts, data collection (e.g. terrain and ocean information) and decision support (e.g. inlet monitoring and risk quantifying) are still top priorities among infrastructure-related agencies and organizations [14].

2 The Heterogeneous Display Environment

As part of the Center for Natural Disasters, Coastal Infrastructure and Emergency Management (DIEM), our team has become increasingly aware of the data analytics challenges, and consider it critical to identify the coastal resources at greatest risk before a disastrous event so that natural disaster impacts can be planned for and mitigated. Specifically, the objective of our research is intended to meet the needs of stakeholders in this regard, enhancing the effectiveness and integration of their simulation research and their analysis process.

To do this we must develop tools to examine and analyze heterogeneous, time-dependent datasets with rich and effective visualization and interaction technologies. By the report of this paper, we have developed several tools targeted at data related to storm surges, hurricanes, flooding, and critical infrastructure models. Such tools will be of significance to a variety of stakeholders, including emergency planners and infrastructure managers.

Our tools leverage a variety of displays and spatial input devices. There are many tradeoffs among display technologies in particular for 3D user interfaces (3DUI) ranging from common desktop WIMP based 3DUI to fully immersive systems [2]. Two significant dimensions are resolution and levels of immersion. Immersion is generally increased by wider fields-of-view and fields-of-regard, and the addition of stereoscopy and head-coupled motion parallax. Stereoscopy and motion parallax can improve spatial understanding and interaction with spatially dense geometric data sets. This is significant to CIM because LIDAR, sonar, and ocean current data have this property. Similarly, when analyzing and interacting with point clouds and volumetric data, having effective and efficient 3D user interface techniques for precise manipulation and selection data subsets is necessary. 3D user interface techniques based on a variety of physical input devices are available. Our tools leverage a variety of technologies including 6 degree-of-freedom, two-handed tracked input devices, multi-touch and direct 3D finger tracking.

While high-resolution, unencumbered stereoscopic, head-tracked displays have been demonstrated [15], current commercial, high-resolution displays, such as tiled-displays, generally do not provide unencumbered stereo and head-tracking, in particular for multiple simultaneous users. Hence for an emergency response task that requires multiple, co-located stakeholders to view a common display, commercial immersive display technology is less appropriate. For co-located collaboration, a large tiled-display, perhaps coupled with a multi-user, multi-touch table, can avoid users crowding around a single desktop display.

In section 4, we present our set of tools using the following systems:

- *a stereoscopic 3D finger tracked system* – this system is designed for interactive inspective and cleaning of dense, scanned point cloud data. Stereo display improves depth perception of the dense point cloud while the 3D finger tracking provides a high-DOF input device for selecting and partitioning small sets of points amidst a dense cloud.
- *a high-resolution desktop system* – this system uses a WIMP 3D UI on a high-resolution display for exploring changes to LIDAR scanned terrain along the N.C. coast.
- *a stereoscopic desktop VR system using a two 6DOF input devices* – this system allows the inspection of N.C. coast LIDAR terrain and interactive exploration of a feature space view of the terrain along side a 3D view.
- *a stereoscopic, multi-touch system* – this system visualizes ocean currents and the insertion of virtual dyes that generate various types of flow lines. Stereo display greatly enhances the depth perception of the volumetric flow. A novel multi-touch input mechanism is created for controlling position of the dye emitters.

3 Situation Assessment and Characterization

According to NOAA's mission statement, the standard workflow for Coastal Infrastructure Management involves a varied and large amount of scientific, engineering, as well as information analytics. Within this broad scope, we have collaborated with coastal infrastructure managers and planners to enhance the digital coastal resilience and emergency management technologies. The partnership focuses on the improvement of the information analytics aspect, with the goal of providing improved visual interfaces that support the analytic workflows that yield more accurate and effective results.

Based on our discussions during our three-year collaboration, it has become clear to us that, at a high-level, coastal infrastructure management (CIM) involves three major challenges.

First, available tools for planning, situation assessment, and change detections are inadequate for analyzing and managing existing coastal infrastructure. Based on a survey conducted by NOAA, 57 out of 198 managers are not satisfied with their current tools [14]. Most of the participants in this survey showed interest and need for decision-support systems. The geospatial data used by these systems includes terrain, weather and oceanic data (currents, temperature gradients, etc.). Here, the term *terrain* refers to both natural terrain as well as urban terrain. Currently, LIDAR scans are the technology of choice for digitizing terrain geometry. Based on our collaborations, we determined that for CIM systems the three major tasks are data cleaning, geospatial change detection, and interactive analysis. The densely sampled sensor derived data must be cleaned by a combination of automated and semi-automated techniques to deal with noise and errors.

A second major CIM challenge is that changes in the coastal infrastructure environment are increasing the potential impact of existing hazards. Depicting temporal patterns and terrain changes caused by natural disasters are the two main aspects of this challenge. This requires the ability to semi-automatically detect changes in the geospatial geometry over time, and to characterize the geometric features of identified change segments of the geometry that were affected by an earlier disaster.

A final CIM requirement is the ability for collaborating stakeholders to be able naturally converse in an unencumbered fashion while viewing and interacting with the collected data. The ability to navigate, select, and manipulate densely sampled geo-spatial datasets is important to two components. First, the data cleaning process—where you want find, select, and investigate outliers perhaps at the level of individual points. And second, to the process of detecting, investigating, and characterizing geometry change features in the data set (e.g. a house in a LIDAR terrain scan that gets washed away in a hurricane storm surge).

To meet these challenges, the coastal emergency management system requires a top to bottom review. There is a clear need to build a resilient and sustainable coast, able to successfully adapt to twenty-first century challenges posed by natural hazards and growth on the coastal urban interface. Effective adaptation strategies require a far-reaching transformation in coastal management plans, tools, and institutions.

4 Our Design and Analytics Solution

Based on our domain characterization and design assessment, below we describe our applications that use the following types of display systems: two desktop Windows-Icon-Menu-Pointer (WIMP) systems, a desktop VR system, a multi-touch systems, a hybrid multi-touch desktop VR setup with camera based full hand tracking, a tiled-display application, a hybrid multi-touch table + tiled-display system.

Different types of displays and associated user interfaces can best take advantage of the human perceptual system for these three tasks. For data cleaning the user needs to be able to quickly navigate through the spatial data set, to spot, select and investigate outliers. For dense LIDAR point clouds or Doppler radar weather data, being able to visually distinguish shape and details—down to the individual sample point level—can be a perceptual challenge. For these types of data that have lots of occlusion and dense geometry, motion parallax and stereoscopic display can improve understanding of the geometry [20]. Further being able to quickly change the viewpoint via 6 degree-of-freedom adjustments is also important. With the addition of stereoscopic display, head motion parallax and/or direct 3D (6DOF) manipulation the view scale factor must be further adjusted as a 7^{th} degree-of-freedom [21] . Further if one wants to be able to quickly navigate (controlling up to 7 DOFs) and to perform selection of small subsets of densely sampled data—in particular volumetric data—being able to interact with both hands is engages far more of human motor system than a standard mouse interface. This can be done either through a two-handed 6DOF interfaces [8] or a multi-touch interface or a hybrid approach [1].

Some types of data are best viewed with 2D, InfoVis visualizations while others are best viewed using 3D graphics. Within 3D graphics, under some circumstances stereoscopic display and/or head-position dependent 3D (commonly done with head-tracking) are beneficial. Correspondingly input devices could range from the standard mouse and keyboard, to multi-touch, to 3D 6-degree-of-freedom input devices and camera based body tracking. An ER environment could include mobile display systems, small form factor desktop technologies and large scale command centers containing high-resolution tiled-displays, VR technologies (preferably, of course, auto-stereoscopic with unencumbered tracking), etc. In this paper, however, we focus the non-mobile components, as might be found in a command-and-control (C&C) center, while acknowledging that a complete, deployed ER software suite would include mobile systems for the "in-the-field" first responders.

4.1 Data Acquisition and Batch Processing

A B

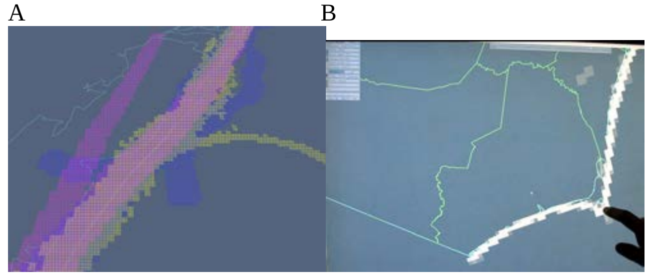

Figure 1: (A) Overlapping flight paths from aerial LIDAR scans (B) Data processed into tiles. Tile opacity indicates number of flight paths that crossed each tile.

NOAA's digital coast contains LIDAR surveys of the NC coast from multiple dates and the surveys overlap in irregular ways (Figure 1A). These datasets are very high resolution, often with sub-foot sample point spacing, leading to terabytes of storage that exceed a workstation's memory capacity. The individual survey files are in multiple formats and organized in multiple space-dividing schemes (e.g. gridded chunks, flight swaths, etc.) To efficiently visualize this heterogeneous collection, our software pipeline standardizes the storage and organization. Our automated pipeline sorts the multiple datasets sample points into an organized grid-based file structure (Figure 1B). This provides an efficient mapping between geographic area and the original survey files. In our application (Figure 1B), the user selects which grid tile to load and analyze further. This interactive data catalog is integrated into the system we describe in Section 4.3. The data files themselves are currently also read directly by the system we describe in Section 4.4. The experimental data cleaning tool described next (Section 4.2), currently loads sonar point cloud file format but can be trivially modified to also read from our coastal LIDAR dataset.

4.2 3D Semi-Immersive Display for Data and Cleaning

Traditionally, point cloud data cleaning tasks involve a semi-automated but repetitive and tedious process of navigating the dataset, rotating it in such a way as to make the bad points visually separated from the good points, then carefully selecting them for removal with the mouse. However, by employing virtual hand models as "cutting plane" type tools, the user can quickly position them between good and bad data points, marking those that should be removed.

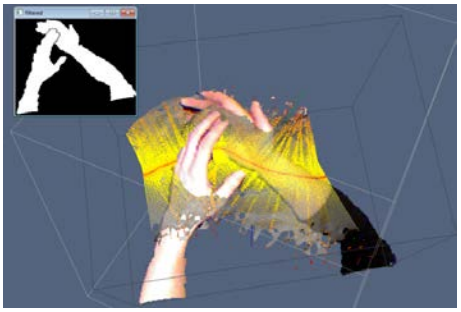

Figure 2: Screenshot from an experimental sonar/LIDAR data cleaning tool that uses a Kinect to capture the user's arms, then reconstructs them as textured 3D models, that are projected into the data space to be used as virtual tools.

By using an inexpensive Kinect depth camera, we can capture both color video and depth measurements of the user's hands in front of the display(s) [5]. Through image processing and 3D segmentation algorithms, the individual arms/hands/fingers can be extracted and transformed into 3D triangulated mesh models, textured with the corresponding color imagery. The result is a set of live virtual hand models with true 3D structure that can be directly inserted into the 3D world onscreen (Figure 2). These can be used to directly manipulate the items in the virtual world. In particular, in our data cleaning tool this virtual hands are used for selecting and distinguishing points in dense sonar and LIDAR data sets.

In contrast to the flat, rigidly defined cutting planes that can be defined by a single 6DOF device, the user can easily manipulate their hands to form complex curves that conform to the irregular distributions of noisy data. Conducting this interaction with a stereoscopic display provides highly realistic visual feedback that exploits the user's natural hand-eye-coordination skills.

4.2.1 Implementation Details

The Kinect (and the PrimeSense design it is based on) consists of a standard RGB camera, a laser-based projector that emits infrared light in a known, static dot-pattern, and a monochrome camera with an infrared pass filter that captures the reflection of the dot-pattern from the scene. The device calculates a depth image from the distortions observed in the reflected pattern.

We reviewed the methods used by other researchers to extract useful tracking information from these depth images and found that most suffer from a few shared limitations due to assumptions or constraints in their image processing. Exact placement or orientation of the depth camera relative to the display or user is not necessary. The sensor does not need to actually view the display surface; it only needs to see a finger-tip touching each corner of the display surface. The optimal setup for tracking hands interacting with a display is to place the sensor directly above the workspace.

After calibration for a particular display surface, one then defines an interaction volume in front of that display, within which hands/touches are detected and segmented for processing as touches or gestures.

The simplest method to construct an interaction volume is to extrude the display screen into a cuboid. This can be done by translating each of the corner points a set distance along the screen's normal vector. The choice of distance to translate/extrude controls the depth of the interaction volume, and is directly determined by the desired interaction one wishes to capture.

For example, if one wants to simply emulate a multi-touch overlay on a display surface, and thus only wants to watch for fingers entering the area directly in front of the display, one would only need to extrude a small amount (~3cm). In order to capture the entire hand, (e.g. to get pose information related to touch points,) the screen should be extruded outward far more, ~30cm.

In these simple extrusion cases, the four original corners and the four extruded corners are used to calculate six planes that define the boundaries of the cuboid interaction volume. As data is received from the camera, it is converted to a 3D point cloud and the points are filtered using a common point-in-box clipping algorithm. This method of filtering points using is superior other depth image processing methods such as depth thresholding and background subtraction. The former can only filter against planes parallel to the camera image plane and latter will fail if the background changes--for instance if a coffee mug were placed on the desk below the monitor.

4.3 Hi-Res Display for Change Detection and Characterization

We developed an interactive visualization program for detecting and exploring temporal surface changes and we developed a data processing software pipeline for ingesting terrain data from NOAA's digital coast. This application uses the common Windows-Icons-Menu-Pointer (WIMP) interface. NOAA's digital coast contains LIDAR surveys of the NC coast from multiple dates and the surveys overlap in irregular ways. These datasets are very high resolution, often with sub-foot sample point spacing, leading to terabytes of storage that exceed a workstation's memory capacity. The individual survey files are in multiple formats and organized in multiple space-dividing schemes (e.g. gridded chunks, flight swaths, etc.) To efficiently visualize this heterogeneous collection, our software pipeline standardizes the storage and organization. Our automated pipeline sorts the multiple datasets sample points into an organized grid-based file structure. This provides an efficient mapping between geographic area and original survey files.

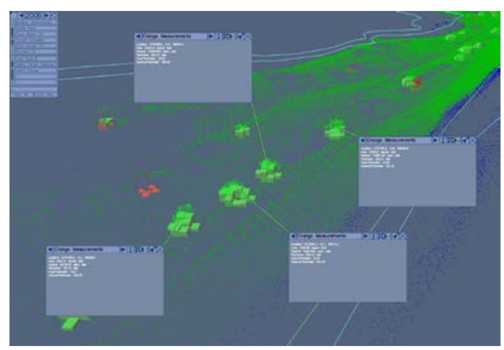

Figure 3: Point cloud and extract change models as extruded rasters.

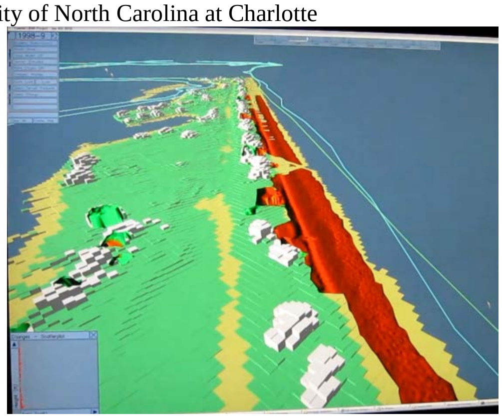

Figure 4: Extracted change models as polygon mesh (red).

Our 3D visualization program presents to the user the extents of the LIDAR datasets available in the grid-based file structure. The user picks a region to focus on, and the software retrieves those portions of the datasets from disk. Using these retrieved point sets, our software extracts terrain models for both visual exploration and change detection. The software displays a number of different terrain model options, including the raw point clouds (Figure 3), extruded rasters, and triangulated meshes (Figure 4). Overlapping regions that have been sampled during multiple LIDAR surveys are automatically compared against each other. An image processing based algorithm identifies those areas containing significant changes, and then the raw data points for each these areas are utilized for reconstruction of a 3D change model. This change model object consists of two 3D models showing the before and after physical structures of the change, as well as measurements and characteristics extracted from the data. These measurements and characteristics are then employed within the application to classify and filter changes

We significantly increased the speed of our change detection algorithm by adopting image processing based operations using OpenCV. Previously we pre-processed our datasets to extract changes geometrically before interactive analysis [3] . The new algorithm provides results quickly enough (within a few seconds) to be done during run-time. This allows the user to not only see the results of change detection, but to interactively adjust the change-detection parameters and quickly see the effects of their adjustments. This facilitates detecting and extracting challenging subtle features, as well as facilitating consistent detection across datasets of varying quality. In Figure 3, the green and blue dots are the LIDAR point cloud (green is above sea-level and blue below). The green extruded raster shapes are additive changes detected by our raster change detection. These shapes correspond to newly built houses. The red extruded raster shapes are subtractive changes. By controlling the raster resolution, the user can generate quicker, more approximate change detection, and then zoom in to inspect the original LIDAR points that cover the extent of the raster change objects. We are applying our probe based interfaces [3] to our new change detection software (Figure 3). Each probe window is associated with one change object and displays information regarding the change object.

In addition to LIDAR derived terrain and change models, our application imports vector data in standard Shapefile format. We include multiple representations of the NC border/coast and the state's transportation network (red in Figure 5A). Any number of other readily available GIS data can be easily imported. This could include data detailing the locations and attributes of critical infrastructure, evacuation routes, etc.

A B

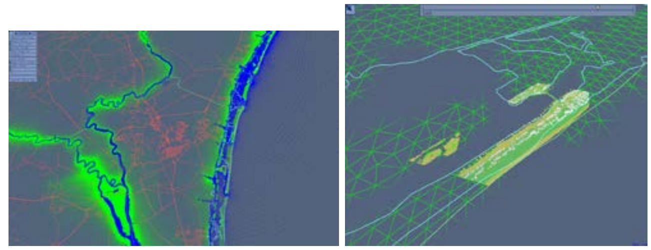

Figure 5: (A) Integrated simulation grid (B) Comparison of grids.

We also integrated the terrain/bathymetric data model utilized in the storm-surge inundation simulation by our collaborators (blue and green sample points in Figure 5 A). While this model's sampling rate grows denser along the coast, comparison of this model the latest high-resolution LIDAR survey data proves difficult. The resolution of the LIDAR data is orders of magnitude higher than the inundation model. For instance, Figure 5 B shows the inundation model samples compared to the extruded raster version of the LIDAR based strip of beach. In Figure 3, this same length of beach is shown, but the point cloud is from the LIDAR data rather than the inundation model. The inundation model has one sample point every 8-10 houses along a beach while the LIDAR has hundreds of sample points covering each roof.

We discussed with our collaborators adding additional statistical information to the inundation model during its generation from its original higher resolution source data. This information could make change detection between datasets of otherwise vastly different resolutions more meaningful. Further, such information might allow faster calculations of on the lower-resolution data while retaining greater accuracy. For instance, we could calculate the minimum height that a storm surge would have to reach in order to flow over/through a region associated with a sparse sample point. This might allow an approximate simulation to run at interactive speeds while retaining some error information.

We are also developing methods to extend our probe-based interaction techniques into the domain of 3D, time-varying terrain models [3]. We demonstrated usefulness of probes for exploratory analysis in other applications and will extend them with new techniques for the analysis of natural terrain features. These features are more challenging to delineate, extract, and select than urban features, such as buildings. These feature based probes should permit the user to interactively experiment with different combinations of region-growing algorithms and shape metrics in pursuit of developing better automatic feature extraction criteria. This would then be applied to the entire coastal catalog providing a "search by example" functionality.

4.4 Desktop VR Immersive Environment for Statistical Feature Space Analytics and Interaction

Equally important to terrain change detection is characterizing the terrain regions that were impacted by various coastal hazards and predicting which terrain regions are most susceptible to similar future impacts. These predictive models must ultimately be physics based, not just geometry based. However, having a fast, interactive exploratory tool for determining the statistical geometric features of affected regions is an important step. Based on our discussions with NOAA experts, current tools are limited to a small set of geometric feature characteristics with which they can interactively query and search the terrain data. The feature characteristics are largely determined by isolated geometric factors or pre-defined segmentation algorithms. Further, the user interface for creating feature descriptions and using them to explore terrain data does not directly support time-varying terrain.

We have developed a tool to address these issues. The tool supports interactive exploration of the rich statistical feature spaces of LIDAR terrain data. It provides an integrated environment for exploring terrain features using a concept called linked feature spaces [9] that allow users to make regular, conjunctive and disjunctive queries of the LIDAR data by interacting with multi-dimensional scatter-plots. The goal for this application is to integrate terrain feature space with our previous terrain analysis system for detecting the terrain changes that are the impacts of natural disasters (e.g., hurricane, storm surge, and flooding).

Our software uses a semi-immersive, desktop VR system [18][6][2]. The system uses a commodity stereoscopic display with head-tracking plus a secondary monoscopic display and two 6 degree-of-freedom button-ball input devices. The standard keyboard and mouse remain available. The user views a 3D model of a patch of terrain and he navigates using the button-ball devices using the scene-in-hand technique. The terrain patch is assumed to be a height-field, tessellated using a non-uniform triangular mesh. The height-field assumption simplifies the calculation of geometric statistics such as average local slope, degree of roughness, maximum local slope, etc. The button-balls each have a virtual 3D cursor representation. The user can set an offset between the physical location of the button-ball and the 3D cursor in order to maintain a comfortable resting arm position [16].

The user can add and delete multiple scatter-plots whose plot points each correspond to a terrain point. Each plot point x-y location is determined by a geometric characteristic of the associated terrain point such as the terrain point's average local slope, local degree of roughness, etc. In other words, each original terrain point has several additional geometric characteristics associated with it and by creating scatter-plots along these dimensions, the user can view the terrain in a different feature space such as plotting local degree of roughness versus elevation.

Within user interface, the scatter-plots are 3D objects but are constrained to view plane and can be repositioned manually or automatically. They generally appear in front of the terrain patch at the screen center. When a 3D cursor occludes the scatter-plot boundary, icons along the x or y axes appear allowing selection of which statistic will be plotted on the given axis. Various statistics such as average gradient, maximum gradient, local standard deviation can be selected. A KD-tree is used to accelerate finding of neighbouring terrain points for these computations.

Users can brush points in the scatter-plot using the 3D cursor. Brushing occurs by creating a rectangular selection region using selection-by-occlusion. The selected points are highlighted on the terrain surface using the color pre-assigned to the scatter-plot. Users can optionally enable the display of lines connecting the scatter-plot points and the terrain points. This gives a stronger visual impression of how the brushed scatter-plot points are spatially distributed on the terrain. (For performance, only a randomly chosen subset of the connecting lines is drawn). Understanding the spatial structure of this net of lines is greatly enhanced by the stereoscopic display. It has some conceptual similarities with traditional 2D parallel coordinates. Figure 6 A, shows three scatter-plots with line nets connection their brushed regions to the terrain points. In Figure 6 B, the scatter-plot in the lower-left plots elevation versus local gradient. The brown selection region is selecting for relatively low elevations with minimal gradient. This causes mostly home roofs to be high-lighted in the terrain point cloud view.

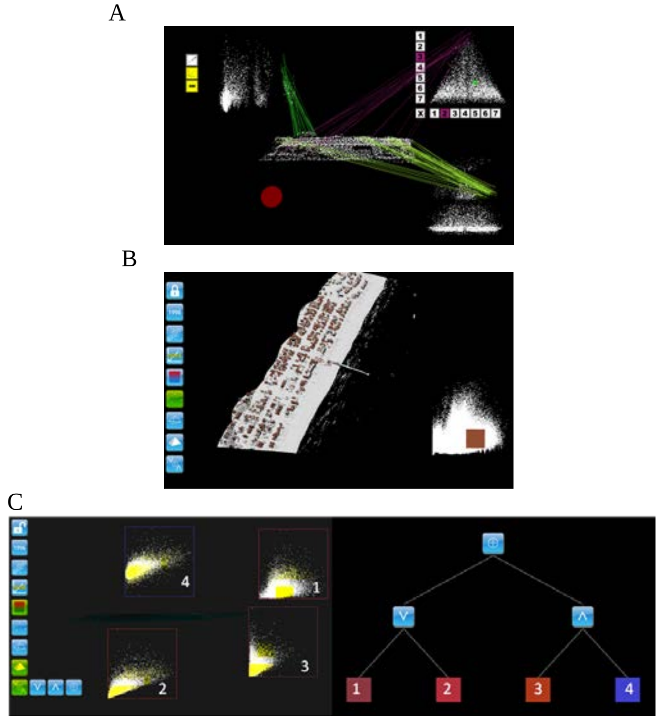

Figure 6: (A) 3 scatter-plots with line nets (B) brush of scatter-plot selects roof tops (C) creation of Boolean query expression to combine 4 selections.

After creating multiple scatter plots and brushing different regions in each scatter plot, the user can construct a boolean expression that combines the different selections. Only the terrain points that satisfy the boolean expression are highlighted in the terrain view. The secondary monitor shows the tree structure of the Boolean expression. Figure 6 C shows a logical expression of (1 AND 2) XOR (3 OR 4). Numeric labels map elements of the expression to the scatter plot. After saving the expression, an icon appears on left top of the secondary monitor to record the expression. Users can delete, select or modify prior saved expression with the button-ball using selection-by-occlusion.

We refer to these expressions as *features* because they are criteria that select particular subset of the terrain data. For example an expression that selects a lower elevation range and lower roughness characteristic will tend to select beaches. In our system, the user can explore the terrain in either the feature space or the terrain space, and can see the effects of the interaction and selection on one space on the other. The goal is to allow the user to find features of the terrain that correlate with significant events such as flooding or erosion. Once determined these feature criteria can be used to search for other terrain regions that match the same criteria. These matching terrain regions would then be subject to further expert evaluation to determine if they were at risk for similar events.

As an example, exploration of a terrain data set might reveal that empirically low-lying areas with certain roughness characteristics were correlated with flash flooding during a hurricane storm surge during a given storm event. The feature characteristic could then be used to identify other similar areas of terrain that might be prone to flooding in future storms.

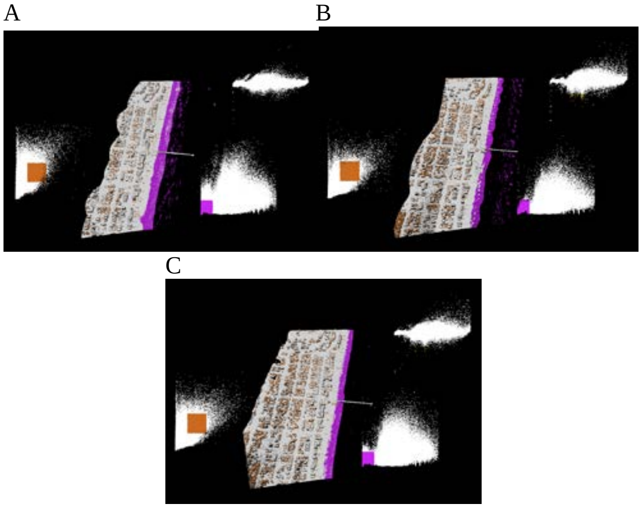

Figure 7: Time sequence of terrain from 1998 through 1999 with same Boolean feature expression.

The application loads one point cloud tile from our data catalog described in Section 4.1. The catalog includes data between 1996 and 2005. Users can switch between different years for the loaded tile or the system can automatically cycle through the years. This 'cycling' function changes the dataset year every 5 seconds while highlighting the terrain points based on the current active feature expression. The image sequence in Figure 7 shows the same tile across three scans: 1998 and two scans during 1999 after hurricanes Dennis and Floyd. The scatter-plots' axes are: average gradient vs. neighborhood standard deviation (left), difference from mean vs. elevation (top-right) and elevation vs. average gradient (bottom-right). Note, the beach is on the right and the third selection criterion is fairly stable at selecting the beach area. Also note, the left edge of the terrain varies from year to year, but this is only due to the limited extent of the LIDAR scans. We demonstrated this software to CIM experts from NOAA and collected an initial round of informal feedback.

4.5 Multi-Touch 3D Display for Ocean Current Simulation Analytics

Equally important to CIM as terrain analysis is ocean and storm surge analysis. The currents and flow patterns in a body of water can vary significantly with depth. Therefore, visualization of these water bodies is best performed in 3D, as viewing any one particular layer at a time causes the viewer to lose the overall context. Often, 3D flow visualizations will utilize large numbers of small visual indictors to illustrate the currents and flows present. Due to issues of depth ambiguity, this can pose significant confusion for the viewer, as it is hard to tell which items are in front of, or behind others. Stereoscopic displays can overcome these issues by providing proper disparity-based depth cues that ensure correct perception of the relative distances between visual features.

For these types of 3D visualizations, there can be significant burden on the user in terms of the complexity of interactions needed to reposition their view of the model, select regions of interest, and manipulate 3D tools within the data. A standard mouse interface, with only two degrees of freedom, begins to show its limitations as geospatial applications move from 2D to 3D. Dimensions must be adjusted iteratively, and the user often must reposition their view to enable data items of interest to be selected without being obscured by, or including other surrounding items.

A multi-touch interface can address the need for higher degree of freedom input, as well as offer potential advantages over true 3D positioning devices in some situations. While each individual touch has the same input dimensionality as a mouse, you get many additional degrees of freedom when additional fingers are used for a particular interaction. For example, the "pantograph" technique [5] requires only two fingers (thumb and index), but enables smooth positioning in a 3D environment. It does this by mapping the x,y value of a 3D cursor to the midpoint of the two fingers, and then mapping the z value (into the screen) to the separation of the two fingers. By pinching the fingers together the user brings the cursor closer to themselves, by spreading their fingers apart, the cursor can be moved away, into the screen. A fourth degree of freedom can be further extracted from this gesture, the angle or "pose" of the hand. By comparing the angle of the inter-finger vector to vertical, a 4^{th} value is determined. This can be used, for example, to set the desired speed when placing waypoints for a planned underwater vehicle's path, or to adjust the size of a volumetric cursor for selection within a point cloud. An implementation of this particular technique can be seen in Figure 8.

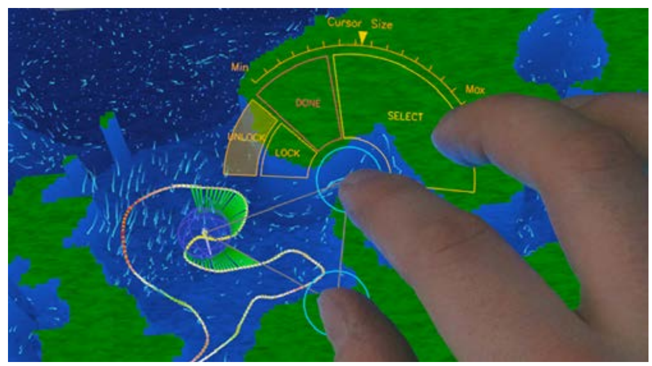

Figure 8: Editing a planned underwater vehicle path using the pantograph multi-touch technique to control a dynamically sized volumetric cursor.

In contrast to many other high-DOF input devices, multi-touch displays have no special space requirements or wired devices that can encumber users. This allows them to be immediately used by anyone approaching them, making them ideal for heterogeneous workspaces where analysts are likely to move between stations. A further benefit over hand held devices is the steadying effect gained by the physical contact with the display; it can be tiring to hold one's arms out in mid air for even relatively short periods of time, and this can cause significant inaccuracies when precise and steady positioning is desired.

Butkiewicz [5] use this combination of stereoscopic monitor and multi-touch overlay to provide an environment for highly interactive exploratory visual analysis of 4D ocean flow simulation output. Their system supports the loading of large flow models in the common NetCDF format, from which it produces a 3D terrain model. The system uses a particle system to illustrate flows. As each particle traces out a path through the flow model, it is visually represented by a pathlet. The pathlet is drawn as a line segment connecting recent positions and uses opacity as an effective indicator of direction. The speed of a particle determines the length of the pathlet, and thus the visual weighting. Fast, major currents become dense, striated ribbons, while still waters appear sparse and shimmering as pathlets slowly drift around.

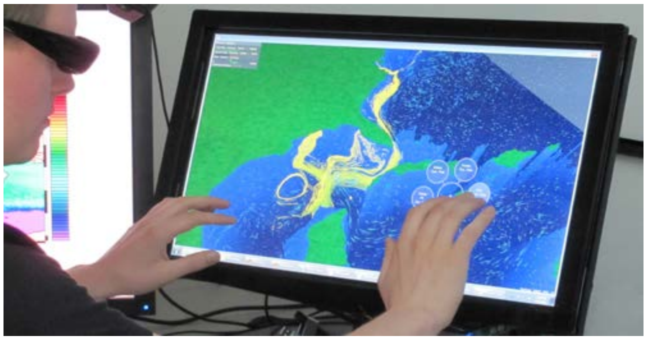

Figure 9: Butkiewicz and Ware's stereoscopic multi-touch system being used to analyze an oil spill scenario in the Gulf of Mexico.

To provide overall context and give the user a starting point for their analyses, the general flow patterns and major currents in a model are illustrated by a collection of particles that are continuously seeded at random throughout the model. When the user finds a region they wish to investigate, they can use a number of tools provided to introduce special dye particles into the model. These dye particles all them to isolate and illustrate flow patterns of interest.

The user can place point-source dye emitters, or dye-pots, either temporarily for exploration, or anchored for sustained release. A more flexible dye release tool, the dye-pole, allows for dynamic configurations of any number of particle emitters along a vertical pole from the seabed to the surface. Associated control panels allow the user to add/remove/split emitters and change how and where they release dye particles. The particles emitted can be customized in terms of both their visual characteristics and their physics-based behaviors.

By allowing the user to configure particles properties, such as density, lifetime, etc., their system allows for simulation of scenarios such as marine pollutant releases. For example, during the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, scientists were struggling to locate the deep plume of oil that was rising from the well-head. This system can allow a user to predict such a plume's path by loading a flow model for that region and time, creating a dye release point at the well head, and configuring the properties of the particles being released to have a density/temperature such that they will rise with respect to the surrounding waters in a similar manner as the real life oil. Through this process, a simulated plume can be illustrated, that could be used to give scientists a better idea of where to take measurements to confirm, and where responders should concentrate their containment efforts. Due to the large number of small swirling particles, the stereoscopic rendering is crucial in overcoming depth ambiguity and ensuring correct perception of the complex 3D shape of these types of plumes.

5 USAGE CASES: FLOOD WATER DRIVEN POLLUTION

Beyond the physically destructive forces of flooding, there is also a serious danger posed by pollutants that are released by and carried in the flood-waters. For example, Hurricane Floyd (1999) caused massive flooding in Eastern/coastal North Carolina. Hog farming is common in this region, with these farms using large lagoons to store immense quantities of faces and other waste. Floodwaters inundated these lagoons, carrying the toxic contents into nearby waterways, and depositing the waste over large areas, including residential neighborhoods. In addition to farms, municipal human sewage treatment plants, industrial sites, fuel storage tanks, and chemical production facilities can also be significant sources of flood water contamination.

While storm surge modelers primarily concentrate on the output of water heights from their simulations, they could also include flow vectors. With this additional data, one could then apply existing flow analysis software, that, while designed for analysis of permanent water bodies (such as oceans or estuaries), can be easily adapted to handle storm surge and other flooding scenarios.

For example, Butkiewicz [5] present a system for exploratory analysis of large ocean flow models, which is designed to utilize an interface consisting of a tightly integrated high-resolution stereoscopic monitor and multi-touch overlay. The stereoscopic rendering provides the disparity based visual cues needed to ensure proper perception of the 3D nature of the datasets, while the multi-touch overlay enables quick, natural interaction and direct manipulation of onscreen visualization tools. The system uses a particle system to illustrate flow patterns and provides interactive tools that allow the user to introduce dye particle in different ways, to explore and isolate specific flows and currents of interest.

Similarly, this process could be applied to planning and response for pollutant release and spread during storm surge and flooding scenarios. This would begin with placing large groups of particles configured to represent different pollutants at known storage locations, e.g. manure lagoons, sewage treatment plants, etc. A time-varying flow model of the floodwaters would be applied, which could be either a forecast scenario for planning purposes, or a now-cast model based on real-time observations for emergency response. When a storm surge inundates the particles, they would be picked up and carried further inland. Then, as waters recede, the particles would move downstream, being deposited across the region based on predefined precipitation rates. These deposition records could be used to identify at risk regions and provide evidence for decision making regarding existing and proposed storage facilities in low lying areas. Finally, because the system was designed to run at interactive speeds for exploratory analysis, tools could allow the user to quickly experiment with adding flood control countermeasures, such as sandbags or levees, around at-risk locations.

6 USER FEEDBACK AND FUTURE WORK

Thoroughly evaluating a tool set that runs across a heterogeneous display environment has many additional challenges beyond evaluating a tool set that executes on a single workstation. This evaluation process requires experts from multiple research domains working on a collaborative task. Due to the limited availability of domain experts, we have only sought feedback from experts on the individual tools that we presented in this paper.

In this section, we report user feedback from our interactions with three groups of experts during DIEM annual meetings and during on-site visits from our collaborators. During this outreach, we demonstrated our systems to multiple users, including US Coast Guard (2 experts), NOAA storm-surge managers (3 experts) and storm-surge simulation experts (2 experts). These evaluations were conducted to assess the functionality, affordability and effectiveness of these interfaces in supporting the coastal infrastructure management process, such as the individual use cased presented earlier.

While the evaluations were conducted informally, these outreach activities allowed us to introduce the software tools presented above and to gather expert feedback. First we presented our system by demonstrating the investigative scenarios described in the previous section. Then the experts were given some time to ask questions regarding the system and the interface. Finally, we asked for constructive feedback and comments. In general, the expert feedback suggested that our methods of utilizing heterogeneous displays could contribute to the coastal infrastructure management process in the following respects.

6.1 The Benefit of Utilizing Heterogeneous Displays

One of the benefits that most of these experts see in our analysis environment is its ability to depict the heterogeneous datasets related to coastal infrastructure management. Especially to US coast guards, who are responsible for monitoring overall development of coastal changes on a daily basis, the capability to identify and interactively examine their data is of great value. One of the chief analysts mentioned that, "this analysis setup provides new innovative approaches in monitoring the coastal infrastructure changes." He further commented that, "it would provide the coast guards with an effective and efficient integration to understand the ***oceanic development*** from multiple aspects."

As one of the simulation experts pointed out, however, a drawback that requires our development is on the extensibility and scalability of our visualization tools and display setups. Given the different granularity of domain simulations, the expert expressed his concerns regarding our systems ability to connect multiple simulation results. Such extensibility and scalability is certainly a crucial future direction as we continue enriching our systems. Collaborating with these experts, we are further investigating methods to facilitate their analysis needs.

6.2 Feature Tracking Enriches CIM analysis

The Feature Tracking capability brings a unique analysis angle when examining the coastal infrastructure domain. Many experts, including NOAA managers, expressed their interests in utilizing our approach with their more specific data. The ability for them to look into ensembles of different geospatial data and hydrology data is of great importance. As one of the managers indicated "the ability to isolate the dune structures along the coastal shoreline and visually track its development before and after a storm surge means great deal for planning." One use case they imagined our system being applied to is for proactive planning scenarios, connecting their storm surge simulations with our feature tracking analysis tool.

One of the terrain researchers suggested that topology based feature extraction should be taken into consideration. In particular, he is interested in learning how we could effectively combine both geometry and topology feature extraction methods to enrich the tracking analysis. We are working collaboratively on combining both feature approaches into a hybrid method.

7 Related Work

The concept of heterogeneous display environment is not new. First, control systems for complex vehicles, such as aircraft, ships, tanks, etc., and complex industrial systems, such as nuclear reactors and power stations, all involve multiple displays with multiple types of input devices. Hence these could be considered heterogeneous display environments to some degree. However, more typically, the *heterogeneous display environment* refers to one in which the heterogeneous displays are display the same dataset, or subsets of the same data, and where a single user can smoothly switch between interacting on one display to interacting with another co-located display to view the same data from a different perspective or style of visualization. We do not attempt a complete literature review here, but instead summarize a select few related works. An early heterogeneous display environment example is Donelson's early Spatial Management System [7] that integrated large and small screen displays, pen, joystick and touch screen input and sound. Co-located collaboration is also typically assumed or supported when discussing heterogeneous display environments. UNC Chapel Hill's "Office of the Future" concept [8], used projectors to place pixels on every and any possible display surface supporting 2D, 3D and stereoscopic 3D displays within a single shared room. Various software architectures have been developed to support integrating, co-located heterogeneous displays. Roomware [11] describes a design framework, software architecture and multiple deployed systems that allow spontaneous integration of both mobile and non-mobile display systems. Scape [12] is a software system that supports the idea of putting pixels on every surface but uses a particular technology, projected-head-mounted displays, to do so. Implicitly the system can support displays of all shapes and sizes, mobile and non-mobile. Wigdor et al [13] describe a year long ethnographic study of WeSpace, a system combining a multi-touch display, a tiled display and laptops used by scientists.

8 Conclusion

In this paper, we presented our research in utilizing heterogeneous displays to facilitate the analysis process in the coastal infrastructure management domain. To capture the rich insights of the widely used geo-spatial data, we developed a suite of heterogeneous displays to facilitate data acquisition, data cleaning and analytics, and interactive data visualization, and to support the human decision-making process. Multiple complementary display setups, such as a semi-immersive, stereoscopic display, a high-resolution tiled display, and a multi-touch table, are utilized to create an interactive analytics environment. Our approach provides a powerful integration of high quality stereoscopic 3D graphics, two-handed interaction, and touch-based interaction, and further support analysis of terrain height changes and ocean surges as well as feature-space analytics that allow the user to discover structures within the data that are not easily detectable using traditional visualization or feature extraction methods.

Acknowledgements

The work at UNCC was supported in part by grants W911NF0910241 (PN 55836MA) from The U.S. Army Research Office and grant PN 5-36440 from Coastal Hazards Center of Excellence at Chapel Hill (DHS, S&T). The work at CCOM UNH was supported in part by NOAA grants NA05NOS4001153 and NA10NOS4000073.

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