CYBER-EYE: Development of Integrated Cyber-Infrastructure to Support Rapid Hurricane Risk-Assessment

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ABSTRACT: Recent losses provide sobering evidence of the continued need for more effective hurricane risk assessment and mitigation that can leverage the latest developments both in the characterization of the hazard and its impacts on built environments and enable their efficient, high fidelity execution. This paper describes a virtual environment designed for this purpose called CYBER-EYE, with specific focus on the kernel that enables its rapid risk assessment framework, its computational model execution environment, and its geospatial services, all packaged for efficient execution online. Through the development of such digital workspaces that synergize existing datasets, models, simulation tools and risk assessment frameworks, this project offers the opportunity for integrated assessment of hurricane impacts on civil infrastructure to support not only research and education, but also decision making by stakeholders in coastal regions.

KEYWORDS: Hurricanes, risk assessment, surge, coastal hazards

1 INTRODUCTION

Every year, thousands of lives are lost around the world as communities are devastated by natural disasters; in our increasingly interconnected society, the effects of these events can ripple regionally and even globally. Particularly, in the case of hurricanes, the risk of future disasters continues to escalate with population shifts toward coastal areas and increased hurricane intensity, size, and frequency. In addition to these safety concerns, hurricanes threaten consumer supply chains including the production of energy, with both economic and environmental consequences, e.g., Hurricane Katrina halted production and delivery of oil from the Gulf of Mexico and caused havoc to regional ecosystems through inundation of wetlands and transport of harmful chemicals and waste products. Recent losses have made it very clear that the models used in risk assessment and loss estimation need adjustments not only to capture changes in hurricane frequency and intensity, but also to include secondary hazards like the impact of waves, storm surge and inland flooding. The reality is that research advances and our knowledge of hurricane hazards and their impacts are rapidly evolving, but are often not effectively harnessed in a manner that leverages the intellectual and computational resources and cyberinfrastructure being developed across the country. In response, the authors have embarked upon the creation of CYBER-EYE: A Cyber-Collaboratory for National Risk Modeling and Assessment to Mitigate the Impacts of Hurricanes in a Changing Climate.
This a virtual organization built around a cyber-enabled computational framework that synergizes existing models, simulation tools and risk assessment methodologies to assess the impacts of hurricanes [1]. This paper will specifically focus on the development of a scalable cyberinfrastructure to deliver an integrated platform for hazard characterization, and the capabilities it enables for users collaborating within its virtual spaces.
2 CONCEPTUAL DESIGN

The virtual environment of CYBER-EYE includes several major elements visualized in Figure 1. A rapid risk assessment framework developed for the Hawaiian Islands, discussed in Section 3, serves as the underpinning for the platform. A user interacts with this tool via a personal dashboards that can be customized by that user to offer a complete geospatial environment supporting collaboration, discussed further in Section 4. With time, users will have access to a menu of applications (widgets) and databases they can draw from and visualize within this environment. These customized user dashboards are tied to a collaboration space with permissions that regulate the collaboratory members that can have access to particular data sets or collaborative groups. Through the development of such digital workspaces that synergize existing datasets, models, simulation tools and risk assessment frameworks, this project offers the opportunity not only for higher fidelity integrated assessment of hurricane impacts on civil infrastructure, but also a collaboration environment that welcomes others to contribute to the shared resources of the portal in the true spirit of virtual organizations [2].

It is important to emphasize that, by moving into a cyber-enabled computational domain, there is the capability to incorporate wide ranging hazards and seamlessly explore their impact on any built or natural environmental system for which a model can be compactly supported. Therefore our approach to development supports progressive expansion of both the project’s scope and complexity with time and as the effort grows. However, the initial prototype has been kept purposefully narrow to encompass risk assessment for buildings being impacted by multiple hurricane hazards employing datasets and models currently possessed by the authors through existing collaborations/projects, packaged in a manner that is suitable for use not only by the research community, but also by public and private sector end users and educators. As such the portal features two interfaces, a Virtual Coast and a Virtual University, as visualized in Figure 2. The former is the subject of the current development cycle.
3 DEVELOPMENT CYCLE

The Virtual Coast is founded off of an initial prototype called Hakou, which was developed as a standalone executable for rapid hurricane risk assessment. Conventional approaches for hurricane risk assessment are based on analysis of data from historical storms or on simulation of design events. A different methodology, frequently referenced as the Joint Probability Method (JPM), relies on a simplified description of hurricane scenarios through a small number of model parameters. Characterization of the uncertainty in these parameters, through appropriate probability distributions, leads then to quantification of hurricane risk as a probabilistic integral over the uncertain parameter space. Its estimation entails then numerical evaluation of the hurricane impact for a significant number of scenarios resulting from the adopted probabilistic distributions. The Hakou prototype, described more fully in Taflanidis et al. [3], offers an efficient theoretical and computational framework for evaluation of hurricane wave and surge risk, in such a probabilistic setting, with particular emphasis on real-time risk estimation that extends to both the surge and wave impacts.

In this approach, each hurricane event is approximately described by only five variables, all corresponding to its characteristics at landfall: (i) the location; (ii) the track heading; (iii) the central pressure; (iv) the forward speed; and (v) the radius of maximum winds. The hurricane impact (response) for a specific scenario, described by the model parameter vector, is then accurately estimated through numerical simulation by adopting an appropriate high-fidelity model (ADCIRC+SWAN). Such models have significant associated computational costs that are alleviated in the risk evaluation through a response surface surrogate modeling approach. The surrogate model is based on information provided by a number of evaluations of the computationally intensive high-fidelity model (called support points), and ultimately establishes an efficient approximation to the entire coastal impact for each scenario. A moving least squares response surface methodology was adopted for this purpose, as it provides greater versatility in characterizing multiple response quantities.

Figure 3. Graphical user interface for Hakou prototype.
Through a collaboration with the Army Corp of Engineers, the first application of Hakou was for the Hawaiian Islands and resulted in Hakou, the standalone assessment tool with a Graphical User Interface (GUI) suitable for operation on machines with minimum computational resources. Figure 3 shows this GUI that allows the user to define track and strength characteristics and then request evaluation of the response. \( N=2000 \) evaluations of the surrogate model are used for estimation of risk based on Monte Carlo, requiring 6 min on a 3.2 GHz single core processor with 4 GB of RAM. This corresponds to a tremendous reduction of computational time compared to the high-fidelity model, which required over 1500 hours for analyzing a single hurricane scenario. The outputs from the risk estimation are graphically presented as contours for the surge and wave run-up inundation as well as contours for the significant wave height. Ultimately this framework is the foundation that allows for the real-time risk assessment that underpins CYBER-EYE.

While this framework provided the capability for rapid risk assessment, GIS visualization of inundated zones could not be seamlessly achieved within the MATLAB-based GUI shown in Figure 3 and required the generation of output files for subsequent visualization within Google Earth. Moreover, as a standalone tool, access is limited to machines that host the executable, limiting its ability to easily scale and offer the potential for real time collaboration between end users, and was constrained by the computational resources of each machine hosting the executable. Therefore translating this framework into a cyberplatform was Phase I of the CYBER-EYE development cycle shown in Figure 2.

Phase II, which is currently underway, is now integrating the wind field hazard characterization and introducing layers to allow impact to constructed systems to be evaluated. These include an automated infrastructure digitization framework described in LaBarge and Kijewski-Correa [4] and an automated damage assessment framework employing aerial images detailed in Thomas et al. [5]. Phase III will accept field data, including self-reported datasets uploaded through the portal or directly from the field via mobile applications. Given the demand for data curation and graphical display of assessments in the wake of recent storms like Sandy, data handling features to support robust curation of the community’s post-storm damage databases are now being brought online in parallel with Phase II. The design of the cyberinfrastructure enabling these capabilities is now described.

4 CYBERINFRASTRUCTURE OVERVIEW

The goal of the CYBER-EYE is to build an adaptable, web-based framework to rapidly create collaborative web applications that encapsulate and provide interfaces to computational models as well as facilitating heterogeneous, geospatial data exploration. Python and the Django high-level python web development framework were chosen as the main development platform. Django [6] has a reputation in the web development community for its ability to facilitate rapid development of high-quality web applications and also provides tools, development patterns and code abstractions that yield maintainable, production-quality code. The main design philosophy for the CYBER-EYE framework, depicted in Figure 4, is the client-server model, where views of the data (applications) are separated from the details of the data storage and organization. The server-oriented data infrastructure within CYBER-EYE uses a Service Oriented Architecture (SOA) employing the web standard Representational State Transfer (REST) as an implementation medium. The RESTful architecture also gives flexibility to build applications on mobile platforms for the collection and submission of damage assessment data.
Figure 4. Open-source frameworks utilized in CYBER-EYE
CYBER-EYE also utilizes open-source, modular components developed at the Renaissance Computing Institute (RENCI) as part of their Django-based GeoAnalytics [7] framework. Geo-Analytics provides lightweight components connecting to existing open-source data storage frameworks such as PostGIS, mongoDB, and iRODS. This gives developers flexibility to include only those components and frameworks necessary for application construction, decreasing complexity and increasing maintainability of these applications. CYBER-EYE extends geospatial collaborative tools developed as part of Geoanalytics using them as “components” inside of a data exploration dashboard. This dashboard facilitates sets of tools to be encapsulated and used in coordination with one another through a web interface. The dashboard also provides the basis of a collaborative toolset that allows users to annotate maps and provides collaborative conferencing over map-based data.

4.1 Spatial Services in CYBER-EYE

OpenLayers [8] is a javascript library used to present maps in most modern web browsers. OpenLayers allows the user to zoom in, zoom out, pan and turn map layers on and off. A number
of static map layers were prepared to provide base layer information for OpenLayers presentation. These base layers provide political boundaries, road and other physical infrastructure information. The data for these layers utilizes either the ERSI Shapefile vector format or the GeoTIFF raster data format. Map data is served to OpenLayers using the open-source spatial data framework MapServer [9]. MapServer is used to combine requested layers into a single image for the requested area/zoom level and serve it via the Open Geospatial Consortium Web Map Service (WMS) [10]. In addition to using MapServer to serve map layers, a utility called TileCache [11] is used to cache requests to reduce server load and response time. Additional map base layer data is provided by Open Street Map [12]. OpenLayers is encapsulated into the overall Django web frameworks by the Django templating architecture. Django also provides connectors and data model abstractions necessary to store and query spatial data. CYBER-EYE utilizes PostGIS as its primary spatial database, employing some open-source connectors provided by the Geoanalytics framework. User-submitted content such as damage assessment information is stored using this method. The data may then be aggregated and queried using Django models as well as direct database query operations. Geoanalytics also provides a framework called The Big Board that enables Teleconferencing over maps. CYBER-EYE uses the map data services associated with the Big Board to provide teleconferencing capabilities to the dashboard data explorer, shown in Figure 5. This allows users to explore, share and annotate map data as well as share data provided by other tools, e.g., using the Damage Assessment Data Exploration tool, all from within the dashboard environment.

4.2 Computational Model Execution Environment

The CYBER-EYE cyberinfrastructure also provides an environment for computational models to be executed and results visualized using the dashboard map tools. The Hakou prototype introduced in Section 3 is implemented as a hybrid c++ application with a python interface encapsulated as a Django application. Hakou utilizes Grass 7 [13] for spatial interpolation and generation of inundation map contours. A digital elevation model (DEM), a Boolean mask of the area flooded, and the output of Hakou are placed into a temporary file system location. The Grass r.surf.idw2 module is used to interpolate over the blank area of the island in the wave map. This interpolation module uses the values of the n-closest non-zero cells in a weighted averaging technique. The interpolated map is then resampled up to the resolution of the DEM using r.resamp.interp and the bilinear method. Vector representation of the contours is provided by the python plotting library matplotlib [14] producing GeoTIFF’s that can then be presented as a layer within the OpenLayers map. HAKOU model computation scheduling is provided by the Celery Distributed Task Queue [15] facilitating job queuing and task execution.

Figure 6a shows the Wave Contour Calculator Interface, which replicates the basic functions of the original Hakou GUI shown previously in Figure 3 within the CYBER-EYE web environment. This user interface capability for both manual entry of the parameters used to characterize the hurricane, as well as interactive input tools that allow users to specify landfall location and angle graphically. A results browser in Figure 6b then allows the surge and wave contours (both deterministic or probabilistic) generated from the user-input run to be visualized within the fully interactive GIS environment, where additional layers can be added and manipulated to reveal the impacts to various critical assets.
Figure 6. Screen shots of the (a) Wave Contour Calculator user interface and (b) visualization of wave heights around the Hawaiian Islands.

5 CONCLUSIONS

CYBER-EYE represents an effort that is designed not to replicate the infrastructure and resources at other universities and agencies but rather to pool and integrate these resources in the spirit of collaboration to maximize the impact of all the investments made not only by the authors and their institution but by others in the field of hurricane risk assessment and mitigation. This paper discusses the development of a scalable cyberinfrastructure to support this vision by providing a platform for hazard characterization and system vulnerability assessment and a virtual collaboration space for researchers allied in the common goal of mitigating the losses due to
hurricanes. Major elements of the platform were described: the rapid risk assessment framework developed for the Hawaiian Islands that serves as the underpinning for the platform and its computational model execution environment, as well as the customizable personal dashboards that support spatial services within the platform. These customized user dashboards are tied to a collaboration space with permissions that regulate access to particular data sets or collaborative groups. Through the development of such digital workspaces that synergize existing datasets, models, simulation tools and risk assessment frameworks, this project offers the opportunity for integrated assessment of hurricane impacts on civil infrastructure to support not only research and education, but also decision making by stakeholders in coastal regions.

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7 REFERENCES

6 https://www.djangoproject.com
7 http://geoanalytics.renci.org
8 http://openlayers.org
9 http://mapserver.org
10 http://www.opengeospatial.org/standards/wms
11 http://tilecache.org/
12 http://www.openstreetmap.org
13 http://grass.osgeo.org
14 http://matplotlib.org
15 http://www.celeryproject.org