Online Visualization of Adaptive Distributed Sensor Webs

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Abstract—Sensor webs for environmental monitoring integrate data from a large number of fixed and mobile sensors. The spatial and temporal distribution of these sensors varies with time when the network controllers adapt the operation of the sensors to detected events. The paper describes an approach for online visualization of data from such sensor webs. The visualization approach explicitly takes into account the varying resolutions of the sensor data and depicts the movement of mobile sensors. The sensor web visualization utilizes the Google Earth 3-D virtual globe software and data representation formats. This enables data from sensor webs to be made available on the Internet. Users download this data and control the visualization using their own desktop computer. The paper demonstrates the visualization approach on data collected from the New York Harbor Observing and Prediction System. The data includes oceanographic parameters collected using onshore and offshore sensors and from mobile platforms such as unmanned underwater vehicles and passing surface ships.\textsuperscript{1,2}

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1. INTRODUCTION

The New York Harbor Observing and Prediction System (NYHOPS) sensor web system consists of a hydrodynamic ocean circulation model (the ECOMSED model) that is instantiated with sensor measurements from in-situ stationary sensors [1]. The outputs of the ocean model are 48 hour forecasts of marine conditions such as salinity, temperature, water currents, and elevations. The model forecasts are useful for predicting events such as coastal surges, plumes, and the movement of oil spills. The model forecast data is published on a website for access by a variety of end users such as emergency responders and planners, and harbor boat captains. The forecast data is therefore processed to detect such events and the relevant end-users are alerted of any critical events using a paging system. The system is maintained by the Stevens Maritime Center of the Stevens Institute of Technology.

In our earlier work [2, 3] we showed how the operation of the sensors and communication infrastructure in the sensor web could be adapted to both the forecasts from the hydrodynamic model and the physical resources of the sensor web (such as communication bandwidth at distributed sensor nodes and the available energy at these nodes). We have used the framework of Model Predictive Control (MPC) [4] as the means to perform this adaptation. We showed how assimilation of measurements from in situ sensors that are controlled by the MPC framework resulted in reduction in the model forecast error. We also showed how the control framework could also be used to compute motion plans for unmanned underwater vehicles (UUVs) to augment the measurements of static sensors.

In this paper we describe our system to enable visualization of the system data outputs (model forecasts) and system control inputs (such as paths of UUVs) over the Internet using a virtual globe. Currently, the model forecast data is provided as a sequence of images on a website. The main disadvantage of this method of visualization is that the user is unable to integrate relevant information from other sources to this display. A virtual globe enables a user to overlay multiple geo-referenced datasets over a 3-D representation of the Earth’s surface. Thus the user can visualize the NYHOPS data products in the context of the surrounding geographic environment and forecasts of other related phenomena in the neighboring regions. For instance, a ship captain may be interested in water current forecasts only along the planned route of the ship. In addition, virtual globe software enables the natural visualization of time varying phenomenon as an animation.

Online visualization requires the transfer of large amounts of data over the Internet. In the case of the NYHOPS system, ECOMSED forecasts are provided at one hour intervals over a high resolution 3-D grid of the coastal and inland waters. We describe the implementation details that make it possible to transfer only relevant portions of the data set to the user at any one time. This reduces the latency of the visualization system and also reduces the computational requirements of the user’s computer.
2. OCEAN MONITORING SYSTEM

NYHOPS is a real-time, web-based estuarine and coastal ocean observing and modeling system for the waters of NY, NJ and CT currently operated as one of National Oceanic and Atmospheric Administration’s (NOAA) Integrated Ocean Observing System (IOOS) regional ocean forecasting systems [1]. The measurements from the sensors are provided to a predictive model of the environment, the ECOMSED model [5]. ECOMSED is a shallow water derivative of the Princeton Ocean Model (POM) [6]. The inputs to the model are ocean elevation (which depends on tides, offshore weather, cross-shelf elevation change), salinity and temperature at both the open boundary and within the domain of the model, and weather (air temperature, humidity, pressure, wind speed, solar radiation, cloud cover). The model outputs are elevation, salinity, temperature, and water velocity. The forecasts are presently forced from NOAA/National Weather Service (NWS)/ National Centers for Environmental Prediction (NCEP)’s Meso-scale Weather Research and Forecast (WRF) 12km atmospheric model, USGS river flow gauges, and NOAA Meteorological Development Laboratory’s (MDL) extra-tropical storm surge forecasts. Open boundary forcing is supplied by the WW3 model at 15min resolution. The model predictions are calculated over a high resolution orthogonal but curvilinear three-dimensional grid of the entire Hudson-Raritan Estuary, LI Sound, and the NJ and LI coastal ocean (Figure 1). Simulations are performed and archived on the Stevens Hydrodynamic Computational Laboratory’s high-performance computer cluster. The system is designed to automatically acquire all inputs and run every morning at 0600z.

Data communication from the sensors

In the NYHOPS system, sensors that are deployed along the coast or in the NY/NJ harbor have to transmit their measurements to a central data acquisition/control computer. The distant location of the sensors with respect to this central computer requires that remote dataloggers act as an intermediate relay station. A datalogger (which is a PC) compresses data files, establishes a connection to the Internet via a local ISP, and pushes the data to the data acquisition server. The data transmission to the remote datalogger is through a line-of-sight serial radio modem system. A sensor can establish a 1200 baud, two-way simplex communication link with any of the remote dataloggers. Mobile sensors utilize serial cellular modems for data transmission to the remote logger. The throughput of the system is limited by the slow data transfer rate and the amount of airtime available to transfer data from each sensor. Currently, the data collection schedule is adjusted based on the power source and sampling requirements of the platform. Sites that are on the power grid can collect and transmit data at a high frequency. Typical sampling schedules consist of the measurement of up to 20 parameters that are retrieved every 5 minutes. Sensors that do not have access to the power grid measure an average of 10 parameters every 15 minutes and data is retrieved once every hour.

In our framework for adapting the operation of the NYHOPS sensing entities, these communication and energy constraints are taken into account along with regions of interest calculated from ECOMSED model forecasts. Our online visualization depicts the locations of the static sensors and the dataloggers. In our adaptive control framework, measurements from the in situ sensors are assimilated into the model forecasts. The user can therefore overlay the locations of the sensors along with the model predictions to understand the relationship between discrete sensor measurements and the wide area model forecast.

Movement of mobile sensors

To improve the spatial resolution of sea surface temperature (SST) and salinity in the NYHOPS domain, vessels of opportunity (NY Harbor sightseeing vessels, environmental research vessels and a commercial cruise liner) have been fitted with flow through CTD cells connected to a logger and cellular transmission system. Although providing greater spatial coverage, these mobile platforms travel repetitive courses on a fixed schedule and only cover the surface waters over small regions of the NYHOPS domain. In order to spatially sample any region of the NYHOPS domain, unmanned underwater vehicles (UUVs) are deployed. These UUVs are fitted with sensors to complement the network of static sensors. The control of the UUV-based sensors involves the use of model forecasts in real-time. The MPC resource management algorithms
can task the UUVs (along with the stationary sensors) such that specific regions of interest identified from the ECOMSED model forecasts can be sampled in greater resolution. As the energy required to moving through water is very large, the planned paths for the UUV will take advantage of favorable conditions such as a following current and avoid unfavorable conditions as far as possible. We will implement a model of the energy expenditure of the UUV that takes into account the predicted water current in the MPC to compute this optimized path. The communication between forecast model and UUV will allow for near real-time adaptive control. The paths will take the UUV into specified regions in the Harbor to examine conditions of interest identified by the ocean model and then return the UUV to its home base.

3. CURRENT DATA DISSEMINATION METHODS

The forecasts of the ECOMSED model are processed to provide advance notice of critical events such as storm surges, movement of plumes and oil spills to end-users. All NYHOPS forecasts, observations and blended present conditions are disseminated publicly through the world-wide-web as graphs, images, animations and data files. The latest predictions are displayed as images on a webpage for access by end users such as emergency responders and planners, and harbor vessel operators. Currently, the communication channels for providing these data products to the end-users are established on a case-by-case basis. Specific products and data services are directly disseminated to requesting agencies, organizations and individuals in tailored formats designed to be integrated with the disparate systems operated by each entity. For instance, NY Harbor and Bight current forecasts are served daily to the NOAA NOS Office of Response and Restoration for use in spill and/or floatable plume tracking analysis.

4. VISUALIZATION ON A VIRTUAL GLOBE

We are working on presenting the forecasts and hindcasts from the ECOMSED/POM model in a format that can be visualized by the end user over the Internet using virtual globe software. A virtual globe overlays multiple geographic data sets over a 3-D model of the Earth’s surface. These datasets are then displayed to a user on a computer monitor. The virtual software graphical user interface (GUI) allows a user to pan, zoom, and tilt the viewable area. Thus the geographic datasets can be viewed at multiple resolutions and perspectives.

We have chosen Google Earth as the virtual globe software to display forecasts of the ocean conditions from the ECOMSED model and in-situ measurements made by the sensors in the NYHOPS system. Google Earth enables datasets to be downloaded automatically from the Internet. The datasets are then overlaid over a high resolution aerial imagery of the New York coastal region. In addition, the data can be indexed with time and the user can view the changing ocean conditions as an animation.

Display of model forecast

The ECOMSED model generates 48 hour ocean condition predictions daily. These predictions are for one hour intervals and include temperature, salinity, and water currents. These parameters are available at multiple depths. The model outputs are computed at points over a high resolution grid. The spatial resolution varies with the resolution of inland water bodies being orders of magnitude higher than that of the open ocean. Two main challenges in displaying such a dataset on the Google Earth virtual globe are:

1. Mapping the range of data resolutions to fixed resolution images that will be overlaid on the virtual globe: Data that is to be overlaid on the virtual globe is provided as rendered fixed resolution images. However, the underlying dataset has widely varying resolutions. In order to enable the user to examine inland water bodies at sufficient resolution, these images should ideally be rendered at the finest resolution in the dataset. However, rendering the entire modeled area at this resolution will result in images of very large size which will increase the time to download these images over the Internet and increase the computational requirements (memory) of the user’s computer for displaying these images.

2. Mapping the range of data values to the single color map that is used in the displayed image: The ECOMSED model outputs hydrodynamic parameters for both inland water bodies and at the open ocean. Hence, the range of these parameters over the entire modeled area is large. For instance, the surface salinity varies from less than 3 psu in the freshwater streams to over 30 psu in the open ocean. As the virtual globe allows the user to seamlessly pan and zoom over the entire modeled region, a single color map has to be used to represent the entire range of parameter values. However, this results in the color map having insufficient resolution to distinguish local features.

We now describe our approach to solving the above problems. In order to represent different regions of the modeled area at different resolutions, we divide the entire area into a number of contiguous regions, where each region can be represented adequately at a single resolution. For instance, the entire open ocean region is represented at the lowest resolution, while the lower Hudson River estuary is represented at a high resolution. The limitations of Google Earth restrict each region to be rectangular. These regions are depicted in Figure 2. The resolution in these
regions and the number of grid points of the ECOMSED model that are included in each region is shown in Table 1. The image resolution used for each region is higher than the resolution of the ECOMSED model in that region in order to provide smooth interpolation.

Table 1 – Resolution of regions used to represent entire modeled area.

<table>
<thead>
<tr>
<th>Region</th>
<th>Resolution of image (m/pixel)</th>
<th>Number of ECOMSED model grid cells</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NY/NJ Harbor</td>
<td>60</td>
<td>5954</td>
<td>2099</td>
</tr>
<tr>
<td>Manhattan waters</td>
<td>19</td>
<td>1939</td>
<td>230</td>
</tr>
<tr>
<td>NY Bight apex</td>
<td>62</td>
<td>2525</td>
<td>3145</td>
</tr>
<tr>
<td>NJ coast</td>
<td>196</td>
<td>2505</td>
<td>22644</td>
</tr>
<tr>
<td>Long Island waters</td>
<td>136</td>
<td>4584</td>
<td>24390</td>
</tr>
<tr>
<td>Western Long Island Sound</td>
<td>16</td>
<td>391</td>
<td>258</td>
</tr>
<tr>
<td>Lower Hudson River estuary</td>
<td>46</td>
<td>623</td>
<td>586</td>
</tr>
<tr>
<td>Full area</td>
<td>634</td>
<td>15064</td>
<td>285224</td>
</tr>
</tbody>
</table>

Our image rendering at multiple resolutions is illustrated in Figure 3. The chief disadvantage of this approach of representing the area at multiple resolutions is the higher computational requirements for rendering the images. Note that the ECOMSED model produces one complete data set for every hour. In order to speed up the rendering of images, we pre-compute the mapping of ECOMSED model grid cells to image pixels. In this way, parameter values from an ECOMSED forecast for a particular time instant can be directly added to the pre-computed image template. Figure 4 shows an example of the depiction of sea surface salinity in the NY Harbor and Hudson River estuary regions. Figure 5 shows the corresponding SST. Note that since the same color map is used for all images, different regions are displayed seamlessly to the user.

In order to ensure that the data in each region is displayed with a color map that is sufficient to resolve local features, we render the parameters at each region using multiple color maps. This results in multiple images for each region. Our system then allows the user to select the color map that is most appropriate for his or her use. For instance, if the user is interested in the distribution of salinity in inland freshwater bodies, then a map that has higher color resolution in the 0-8 psu range can be selected. Note that only one set of images (with the user selected color map) is downloaded at a time to reduce the latency of the system.
Movement of mobile sensors

The paths of the UUVs are planned in response to regions of interest identified from the ECOMSED model forecasts [2, 3]. One of the advantages of using a virtual globe for disseminating data from a heterogeneous sensor network is that movement of mobile entities can be displayed as an animation. The multiple UUVs are depicted using symbols overlaid over the positions of the UUVs in the New York Harbor region (Figure 6). Note that the movement of UUVs can be overlaid over the ECOMSED model predictions for that period. In this way, the user can visualize the adaptation of the motion paths to model forecasts.

5. RELATED WORK

The ECOMSED/POM combination is in use by almost 1900 research groups around the world, has several deployments [7-11], and over 600 papers have been published with them as the modeling engine [12]. Data assimilation into POM has been evaluated over the Gulf Stream [13], coastal waters [14], in open boundary conditions [15], and for coastal observing systems [16]. The NYHOPS system is a unique member of the POM family of models in that it continuously assimilates observation data to improve real-time model forecasts. It is the only system presently investigating the autonomous control of UUVs by the modeling system.

In our earlier work, we had developed the basic mathematical formulation that enabled the Model Predictive Control (MPC) technique to be used for adapting the operation of a distributed sensor web to both system resources and environment model predictions [2, 3]. We showed that the MPC based adaptive control of sensor sampling rates resulted in decrease of the error in the forecasts of the ECOMSED ocean model. In this work, we describe how the results of the adaptive control framework can be visualized on a virtual globe.

Howe et al. describe a marine observation network in Puget Sound and how adaptive sampling with satellite data can be used [17]. Conover et al. describe how remotely sensed data can be assimilated into a regional Weather Research and Forecasting model [18]. In their work, the satellite data is not integrated with data from a ground-based network of sensors. Conover et al. [18] and Kedar et al. [19] also use Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) standards for information exchange. In our work, OGC standards will be used to disseminate data products to end-users with different data alert requirements.

6. CONCLUSIONS AND FUTURE WORK

We described the use of virtual globe software (Google Earth) to display both system data outputs and system control inputs of a distributed coastal environment sensor web. The system data products that are displayed on the virtual globe software are forecasts from a hydrodynamic model and the control inputs are the locations and data outputs of both static and mobile sensors. We described the steps necessary to be implemented in an operational system.
to reduce the latency of the visualization system. This includes pre-computing multiple resolution images of the underlying data and transferring only the necessary portions of this pre-rendered data to the user.

In future work, we will integrate a data communication system based on OGC standards into the online visualization system. The OGC has released a set of protocols designed to facilitate exchange of geospatial products to different types of consumers. This will enable the NYHOPS outputs to be used seamlessly by other systems and end-users.

ACKNOWLEDGEMENT

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**Biography**

Ashit Talukder graduated with a Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University in 1999. His research interests and expertise include pattern recognition, image and signal processing, machine learning, AI, controls, computer vision, optimization, and mathematics, applied to data mining, robotics, autonomous systems and sensors, sensor networks, biometrics, ATR, and human-machine interaction. He is currently a Senior Researcher (Level A) at Jet Propulsion Laboratory / NASA, California Institute of Technology, in Pasadena, California, and also holds a joint appointment as a research adjunct faculty member at University of Southern California, and Senior Researcher at Children’s Hospital Los Angeles in Los Angeles, California. He is a principal investigator and technical lead on several NASA, NIH, NSF, DoD and JPL-funded projects. He has over 50 refereed journal and conference publications and authored a book chapter. He is on the organizing committee of the Annual SPIE Defense and Security Symposium. He has a patent for a biomedical data analysis and visualization system which was nominated for the NASA software of the year, and holds a provisional patent for a remote biometric identification system. He is a recipient of the NASA Space Award and a PACE award at Iowa State University.

Anand Panangadan is a Post-doctoral Affiliate at the Jet Propulsion Laboratory and a Research Associate at the Saban Research Institute of the Children’s Hospital Los Angeles. He is developing algorithms for energy conservation in wireless sensor networks. These algorithms are to be deployed in remote human health monitoring systems and environmental sensor networks. He has also designed data compression algorithms that take into account the lossy nature of wireless transmission. Prior to joining the Childrens Hospital Los Angeles, Dr. Panangadan was a post-doctoral researcher at the Robotics Research Lab of the University of Southern California. While there, he developed probabilistic models for describing human movement and region detection algorithms for sensor networks. Dr. Panangadan received the Ph.D. degree in computer science from the University of California, Los Angeles in 2002. He received the B.Tech. degree in Computer science and Engineering from the Indian Institute of Technology, Bombay in 1996.