Urban-Net: A System to Understand and Analyze Critical Infrastructure Networks for Emergency Management

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ABSTRACT

Critical Infrastructure Systems (CIS) are complex interdependent systems which are vital to public life and national security. Failure of even a small part of such systems, caused by any natural or human-made disaster, can trigger widespread cascading failures impacting many other interdependent modules and disrupt the functionality of the entire system. To better manage the effects of such disruptive events, domain experts should be able to asses, in a comprehensive manner, the complex interdependencies and failure dynamics over these systems. In this project, we have developed Urban-Net[1], a CIS analysis tool, which uses heterogeneous network analysis to allow a user to: (a) visualize the nation's critical infrastructures and their complex inter-dependencies; (b) enables them to identify vulnerabilities within the network; and (c) allow fast simulations and other analysis to answer 'what-if' questions.

KEYWORDS

Critical Infrastructure Networks, Simulation, Disasters, User-Interface, Vulnerability, National-scale

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1 INTRODUCTION

Critical infrastructure systems (CIS) such as power, cyber, water, and transportation are vital to sustaining national and economic life. Recent natural and human-made disasters like hurricanes, earthquakes and cyber terrorist events show how interdependencies across these CIS components can have catastrophic effects, by enabling hazards to potentially propagate and disrupt the functionality of the entire system. As a vivid example, the massive power outage during the 2003 blackout in the north-east US cascaded to impact water-waste treatments, transportation, communication and food industries [2]. To better manage the effects of such disruptive events, domain experts need to understand the complex interdependencies and failure dynamics over these systems. This is challenging due to the several layers of multidimensional data (such as types of interdependencies, types of failures and coupling) at various temporal and spatial scales.

We present Urban-Net, a network-based interactive visualization tool to model interdependency and failure dynamics over CIS. This project is built around the idea of viewing CIS as large *heterogenous networks*. The interface can also utilize topology-based analysis and create simulations to understand consequences due to interdependencies by intentionally created perturbations.

This broad project is a collaboration between Oak Ridge National Laboratory (ORNL) and Virginia Tech (VT). This has been copyrighted by ORNL and VT, and has been successfully used by many domain experts at ORNL since the last year. We also plan to integrate Urban-Net with the US Department of Energy (DOE) situational awareness platform EAGLE-I and the Federal Emergency Management Agency (FEMA) analytical framework for emergency planning and response purposes. To the best of our knowledge, no existing system provides a software stack that performs vulnerability analysis for *national scale* CIS.

Our project adopts a large scale network-based data analysis on a US national level and also has novel formulation, modeling and algorithmic contributions for domain-based failure dynamics and identification of vulnerabilities. In addition, as mentioned before, we bring together these ideas in an interactive tool Urban-Net, using different open source technologies. From an application viewpoint, Urban-Net can significantly enhance situational awareness for emergency management and we believe will be of significant interest to the stakeholders.

Next we will briefly describe our framework in Sec. 2 and our demonstration plan using a use-case scenario in Sec. 3. More details of the project and a demo video of our tool can be found online [1].

2 URBAN-NET FRAMEWORK

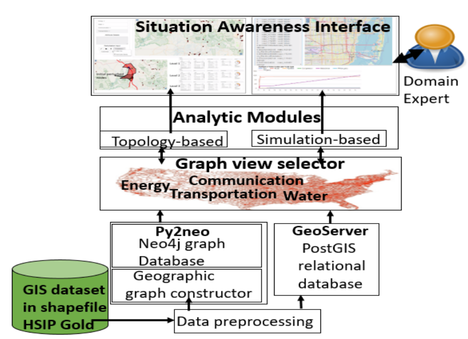

Figure 1: Urban-Net overview.

Urban-Net consists of an interactive interface which also provides an option for two types of analysis which necessitates developing two back-end analytic modules: namely a topology based

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analytic module and a simulation based analytic module. We present the workflow in the figure above. It first converts the geographic data into graph data for analysis (bottom). A domain expert interacts and selects different CIS components for vulnerability analysis (top) and send query to the server to fetch data for analysis through its modules (in the middle). Next, we discuss the three components of Urban-Net, its datasets, and our key contributions.

2.1 Components

Graph construction. We import raw shapefiles of geographic CIS data into a PostGIS/PostGreSQL[2] relational database. We then convert the relational data into a graph structure (e.g., vertices and edges) and import into a Neo4j graph database using Py2neo. We use the GeoServer to host and show geographical objects stored in the PostGIS data on a map [3, 4].

Interface. We also create a map interface, to allow both an overview and detailed access of the whole or part of the CIS networks based on the user's selection to analyze the nodes. Using the map interface, the user can easily visualize an overview of the network and identify critical nodes. For a more detailed analysis of the map, we allow navigation (zoom and pan) as well as auxiliary information of the selected nodes and networks to show in the left panel. Also, to have a clear understanding about vulnerability analysis along with the network visualization, we also integrate tabular and chart interface for each type of CIS such as energy, water, communication, and transportation system.

Analytic Modules. The topology based analytic module aims to identify potentially affected entities across different CIS networks, based on different *perturbations* (say a failure). When converting shapefile data into a graph data to store into Neo4j database, we link nodes originating from different CIS based on a set of rules. For instance, we link a node that represents a power plant with a node that represents a substation that is geographically nearest to the power plant. When a user selects a node from the shown map, the module generates a graph query to find all entities that can be reached within k hops from the perturbation nodes.

The simulation-based analytic module allows users to analyze real-time consequences of CIS grid layers of a region by varying seed nodes for perturbation based on practical settings (regional, random etc). This module also considers temporal aspects along with physical interdependencies. When considering temporal aspects, we allow users to control four parameters for every CI node types: i) average time a CIS node can support before it loses control (β) ii) average time (hrs) a node takes to recover from failure (α) iii) average load for a node and iv) average capacity for a node. To create the heterogeneous network, we consider the current physical graph stored in the database. We also developed state-of-the-art tractable cascade models, which can be initialized using various user parameters (like load capacity etc) and which are based on novel *path-based* failures between the various CIS components [2].

2.2 Datasets

We chose four categories of CIS, namely energy, communication, water, and transportation based on the large non-trivial HSIP Gold data [3] of the US National Geospatial-Intelligence Agency (NGA) and Department of Homeland Security (DHS). This data includes the domestic CIS collected from different government agencies and partners and are stored in a geographic shapefile format, e.g., rivers, roads, and substation areas. The constructed graph from this dataset contains over $81M$ CI nodes.

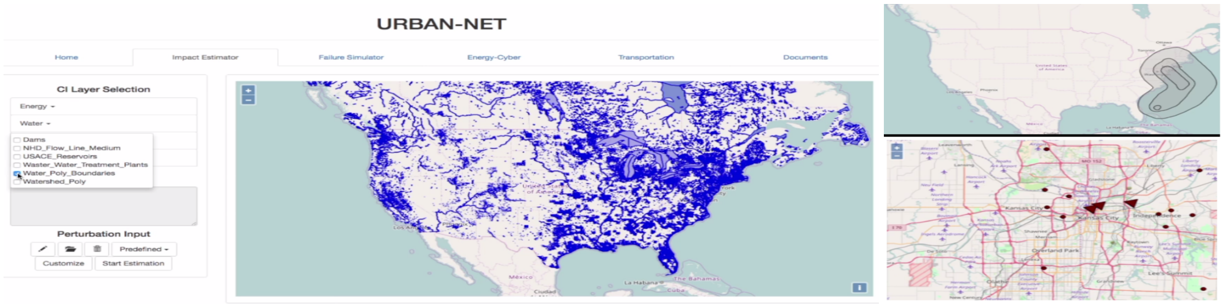
2.3 Main Innovations

Urban-Net has contributions in several dimensions. First, building CIS networks from geographic data is non-trivial as it requires handling millions of nodes and edges, coming from different data sources. Urban-Net automatically constructs a large-scale graph database from raw *shapefile* format of geographic data sets. Second, to identify vulnerabilities, Urban-Net brings both structural and more failure dynamic-based simulation based analysis. In contrast, most related work looks into only static analysis. In the topology based module, Urban-Net provides a fast, updatable computational model to determine the nearest CIS by granting the user to choose the types of CIS for understanding interdependencies and analyzing vulnerabilities. In simulation based analytic module, we developed state-of-the-art tractable heteregenous failure cascade models in collaboration with domain experts at ORNL (e.g. taking into account novel *path-based* failures between the various CIS components [2]). We have also developed new efficient algorithms to quick pinpoint vulnerable entities (the 'hotspots'). Finally, CIS consists of many complex interdependencies distributed over multiple components, which makes a simple visualization of the entire network not very useful. To handle this, Urban-Net provides an easy-to-handle interactive visualization tool which can give both overview and detailed access of CIS networks based on user preferences (See Sec. 2).

3 DEMONSTRATION SCENARIOS

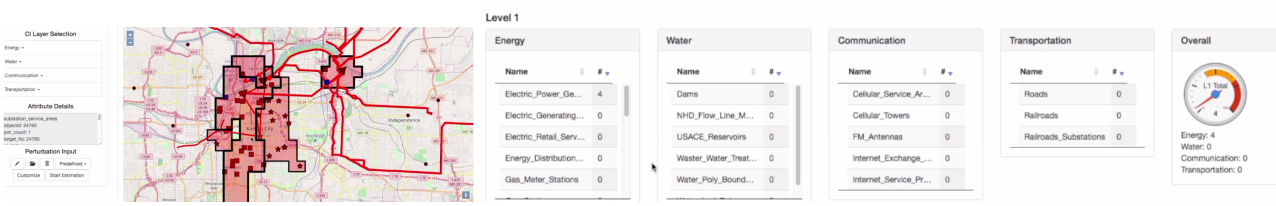
We plan to invite the attendees to interact with Urban-Net and try out its capabilities with both the modules. We will showcase a real-life use case for both the analytic modules for identifying vulnerabilites in interdependent networks. We show the screen-shots of our tool in Fig. 2 how topology-based analytic module looks, how user can choose pertubed nodes, and how it presents the affected CIS. Simulation-based analytic module is similar as shown in Fig. 3(b). Note that we chose only a few categories of CIS within a small area here only for demonstration purposes, while a user can interact with any/all four types of CIS in the original Urban-Net tool. We use a representative usecase for topology-based module. We will identify the impacts of hurricane Harvey 2017 by knocking down the affected electric power plants. Since most of the damage due to hurricane Harvey is in Houston, we selected three power plants for two different independent analysis. In Fig. 3(a), we selected three power generation plants near Southern Houston which effects 38 electrical nodes (gas stations, substations, transmissions, substation service areas) in total and 12 water treatment plants. To showcase the simulation-based module, we considered the state Florida, the most affected state during hurricane Irma. We selected some random nodes centered around the hurricane area and ran the simulation for three mins. Bottom Fig. 3(b) shows the initial seed nodes (red) where majority of them are gas power plant generators. The last cascade of the simulation after 3 minutes shows that the failure cascade heavily damaged the road networks, when failure

[2] https://postgis.net/,https://neo4j.com/,https://py2neo.org/v4/,http://geoserver.org/
[3] https://gii.dhs.gov/HIFLD/hsip-guest



(a) Topology-based analytic module

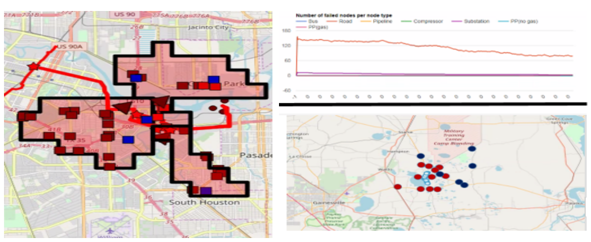
(b) Selecting perturbation based on historical hurricane study (top) and user's choice (bottom)



(c) Affected region

(d) Affected CIS types in tabular form

Figure 2: Screen-shots of different parts of topology-based analytic module (named as impact estimator).



(a) Scenario 1

(b) graph and map visualization of failed Nodes in real time.

Figure 3: (a) An example of topology-based analytic module: we can quickly estimate how perturbing a set of power plants (red triangle) affect some other electric plants and water treatment plants (blue rectangle). (b) An example of simulation-based analytic module: we can simulate how some initial seed/failed nodes (red) (bottom Fig.) can affect multiple CIS types with heavily damaged the road network (top Fig.).

of all other nodes reduced (Top Fig. 3(b)). This implies the end time of the hurricane.

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