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

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Background

- Critical infrastructure Systems (CIS) are crucial for sustaining day-to-day commodity flows vital to national security (e.g., Energy, water, transportation)

- An extreme weather event or a human-caused incident can trigger widespread cascading failures


Fig: 2003 NorthEast Balckout cascading effect
Motivation

- CIS are mutually interconnected, interdependent in complex ways
- Several layers of multidimensional data
- CIS Interdependencies can act as risk multipliers
Our Idea

View CIS as large heterogeneous networks with nodes representing different CIS components and links representing the physical and relational connections among them.

WHY?

- More general: can be applied for different systems
- Require less domain knowledge
- Not as high fidelity, but great for quick understanding and decisions
- Serve as input to more high fidelity frameworks
Challenges

- **Convert geographic data into graph**: need to handle millions of nodes and edges.

- **Components have recovery/failures**: network needs to be flexible to add/remove a component.

- **Effect and conditions of failures vary**: need analysis and tractable simulation with dynamically change of inputs based on topology and temporal dependencies.
Urban-Net Tool

A network based interactive visualization and automated decision-support tool to model interdependency and failure dynamics over CIS.

Core Capabilities
✓ Visualizing complex CIS interdependencies
✓ Identifying vulnerable components in CIS
✓ Predicting potential propagating impacts under certain scenarios

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Architecture/Workflow

Situation Awareness Interface

HomeLand Security Infrastructure Program (HSIP) Gold Dataset

<table>
<thead>
<tr>
<th>Information</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Nodes</td>
<td>~82M</td>
</tr>
<tr>
<td>No of edges</td>
<td>~83M</td>
</tr>
<tr>
<td>No of node types</td>
<td>32</td>
</tr>
<tr>
<td>No of edge types</td>
<td>31</td>
</tr>
</tbody>
</table>

Graph View Selector

Graph Database
- Py2neo
- Neo4j Graph Database

Geographic Database
- GeoServer
- PostGIS
- Postgres Database

Geographic Graph Constructor

Domain Expert
Analytic modules: Topology-based

Identify potentially affected entities across different CIS when one/more perturbation entities are selected from a CIS network

To understand

✓ How efficient is the CIS network as a whole?

✓ What are the most important nodes/edges in the network whose malfunctioning cause largest impact?

✓ What are the consequences of a given perturbation event (e.g., hurricane, earthquake)?

Fig: The whole CIS network of US

Difficult to understand anything from this visualization

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Topography-based module: Steps

Converting shapefile to graph

How to link nodes of different CIS in network?

Shapefile → Neo4j Graph database

Geo-logically nearest substation which are located in k-edge distance

Converting shapefile to graph

How to link nodes of different CIS in network?

Converting shapefile to graph

How to link nodes of different CIS in network?
Selecting initial failures (perturbation)

1. Random selection

2. Case study region-based selection

Topology-based module: Steps

Affected entities in 2k (15) edge distance

Map View

Three level detail view

Hurricane Sandy region

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Analytic modules: Simulation-based

Very important to understand the impacts of failure cascade based on temporal delay (e.g., recovery period)

To understand
✓ Real-time consequences of CIS grid layers
✓ Temporal aspects along with physical interdependencies
✓ Identify critical facilities that may largely impact the entire CIS

Snap-shot of simulation-based module
Simulation-based module: Steps

Model failure cascade (F-CAS) on heterogeneous CIS energy network

- Proposed F-CAS Model:
  - If a substation has no path in the trans. network to any power plant, it fails.
Simulation-based module: Steps

- Proposed F-CAS Model:

  - If a substation has no path in the trans. network to any power plant, it fails
  - If a natural gas compressor’s associated substation fails, it fails
Simulation-based module: Steps

Proposed F-CAS Model:

• If a substation has no path in the trans. network to any power plant, it fails.
• If a natural gas compressor’s associated substation fails, it fails.
• If a power plant’s reachable natural gas compressor fails, it fails
Simulation-based module: Steps

Selecting Initial failures (a what-if scenario)

Every type of node has four user-control parameters

\( \alpha \): recovery time
\( \beta \): time to lose control before turning into inactive node
\( L \): load
\( C \): capacity

By State

Randomly sample nodes from the selected state

By Point

All nodes in 10km radius

Center node
Simulation-based module: Steps

Iteration (At each cascade):

✓ Identify and enlist the failed nodes due to current cascade whose L>C
✓ Schedule recovery time for each failed node
✓ Distribute load of failed nodes to the connected components

End simulation:
When all node becomes active
   Or
Recovery time of all failed nodes reaches its maximum
Scenarios: Topology-based

**Initial selection:** Two electric power-plant generator to fail

**Consequence:**
- Failures affect components in multiple layers
- Cascading impact components which are located geographically far
Scenarios: Topology-based

**Initial selection:** Three electric power-plant generator in Southern Houston (the *most affected area* during hurricane Harvey)

**Consequence**
- Identifies which subset can affect largest CIS components
- Affects 68 energy nodes within this smaller area

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Scenarios: Simulation-based

Initial selection: State Florida (the most affected state during Hurricane Irma)

Consequence:
✓ Heavily damaged road networks at the end of hurricane
Future Plan

Explore our avenue of research for

✓ Cyber

✓ Water

✓ Transportation
Importance of Urban-Net

- For emergency planning by DOE for their emergency support framework
- A national scale tool, can simulate any scenario at any place
- Can show the components having largest impacts along with the cause of these impacts
- Licensed by VT and ORNL, for use at utilities
References


Thank you

Questions??