## 1. Overview

My research activities fall under the broad category of Smart and Connected Communities (SCC) and Cyber-Physical Systems (CPS), focusing on critical infrastructure domains of public transit, emergency response, and power grid. As such, my research lab (Fig. 1) investigates principled design, operation and optimization methods that not only consider the system operations but also consider resilience, performance and assurance.

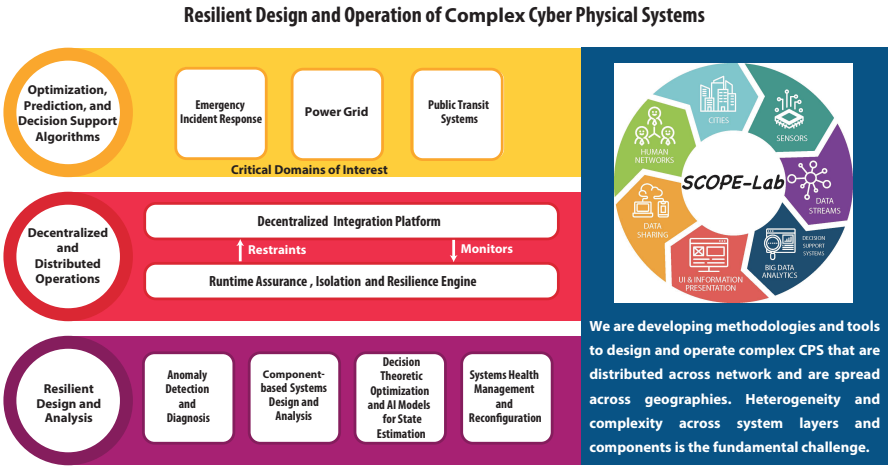


*Fig. 1: Research portfolio.*

At the core of our approach is the realization that societally important infrastructure systems are facing challenges emanating from structural problems across both the physical and cyber domains. The solution to these problems requires introspection and optimization across the layers of the system, including operating system, middleware, decision procedures, and analytics. This cross-layer focus is crucial because engineers often make unrealistic assumptions across layers that eventually lead to failures. To address the challenges, our research activities include the following: (a) Resilient design and analysis of complex CPS, including component-based abstractions, anomaly detection and fault diagnosis; (b) Decentralized and distributed operations of complex CPS; (c) Optimization, prediction, and decision support algorithms and illustrating their applicability to diverse domains such as public transit, emergency response, and power grid.

Vignettes of our work include statistical procedures that learn non-stationary incident distributions, combining multi-modal incident, traffic and weather data to improve emergency response dispatch and allocation procedures. We have also developed delay prediction, demand prediction, energy optimization, and transit scheduling algorithms for public transit systems. In addition, we have addressed the challenges of microgrid management by designing a decentralized middleware for transactive energy systems including strategies for addressing misoperation of protection equipments.

### 1.1 Research Accomplishments

The following list summarizes my key research activities to date.

- **Key Contributions**: Key contributions of my work include (a) the development and deployment of delay prediction and management system for Metropolitan Transit Authority (MTA) in Nashville, (b) design, and deployment of energy analysis and optimization framework for the Chattanooga Area Regional Transportation Authority (CARTA), (c) robust incident prediction and dispatch system developed for the Nashville Fire Department (NFD) and the Tennessee Department of Transportation (TDOT) and (d) a privacy-preserving decentralized system for energy exchange. Other contributions include middleware for online fault-detection and recovery in software-intensive distributed systems and a robust software model for building cyber-physical applications, along with spatial and temporal separation among different system components to guarantee fault isolation. Funding for these works came from grants from National Science Foundation (NSF) through CPS, SCC, and IIS programs, Department of Energy (DOE) through the Vehicle Technology Office (VTO), Advanced Research Projects Agency-Energy (ARPA-E) through their OPEN program, National Aeronautics and Space

Administration (NASA) through the Vehicle Health Management program, Defence Advanced Research Project Agency (DARPA) through programs like Assured Autonomy, System-F6, and IDAS, and industry partners like Siemens, Cisco Systems, and IBM.

- **Software Products:** Notable software products, jointly developed with graduate students and collaborators, include:
  1. ARINC 653 emulator - It is a Linux-based ARINC 653 emulator, which was later used in an implementation of a prototype of Future Airborne Capability Environment (FACE).
  2. CHARIOT- It is a reasoning engine for online reconfiguration of cyber-physical system software assemblies.
  3. DeepNNCar - It is a testbed for assured autonomy algorithms.
  4. ReSonAte- It is a runtime risk assessment framework for autonomous systems.
  5. TRANSAX - It is a middleware for transactive energy systems.
  6. Smart Transit - It is a software as a service cloud platform for transit agencies focusing on energy and schedule optimization.
  7. Statresp - It is a software as a service cloud platform for the state department of transportation and city emergency departments focusing on resource allocation, optimization, and dispatch.
  8. Resilient Information Architecture Platform for Smart Grid - It is a distributed middleware for smart grid application design. It is now a Linux foundation project.
  9. MODICUM - It is an online market software for enabling computational outsourcing for batch computations in smart cities.
  10. DREMS (Distributed Real-time Managed Systems) - It is a partitioned (spatio-temporal separation) application deployment operating system for fractionated satellites.
- **Publications**: I have published over 150 papers, over 120 in the Assistant Professor position (citations (>2564), h-index (27) and i10-index (59)). These publications have appeared in journals like ACM Transactions on Cyber-physical Systems, IEEE Computer, and selective conferences (acceptance rates <34%) such as AAAI, AAMAS, ICCPS, FC, IoT, SEAMS, and DEBS.
- **Patents**: One provisional patent for Method and System for Secure and Private Forward Trading Platform in Transactive Microgrids. There are two submitted and pending patents: (1) Method and System for Data-Driven Forecasting of Cascading Effects in Networked Systems and (2) Decentralized Method and System for Real-Time Anomaly Detection In Transportation Networks.
- **Research Grants:** The total grant support as a PI in the Assistant Professor position is 8.1 million dollars. The total grant support as a PI in the research scientist position was $526,294. The total grant support in the Co-PI role in the Assistant Professor position is approximately 16.6 million dollars. Cumulative grant support throughout my career as a researcher is approximately 36 million dollars. Grantors include NSF, DARPA, DOE, DOD, ARPA-E, ARL, Siemens, Cisco Systems, NASA, and AFOSR.
- **Industrial Collaboration:** My research on performance management, resilience, and platform design has led to collaborations with several companies, including IBM Research, Siemens, Marriott, and Cisco Systems. The results from my research have been applied to diverse domains, including avionics, smart grid, industrial systems, and transportation networks.
- **Professional Research Service:** I have served 14 times as a chair or co-chair for international conferences during my career and over 30 times as a program committee member. I have also frequently reviewed grants for research programs at NSF, NASA, and DOE.
- **Research in Practice:** My research has been influenced by the challenges of our communities. Accordingly, the results from our projects have been transitioned to Metro Transit Authority, Nashville Fire Department, and Chattanooga Regional Transit Authority. These research efforts have been cited in the press [6, 3, 10, 140, 40, 58, 26, 139, 144, 46, 141, 143, 142].

The following two sections detail my contributions in cyber-physical systems and smart and connected community domains of transit, emergency response, and electrical power grid. Each section has a tabulation of key innovations and a narrative statement of contributions.

## 2. Contributions to the Science of Cyber-Physical Systems

One critical challenge in cyber-physical systems (CPS) is the resilience of operations. That is, we have to ensure that the system is safe and remains operational even after failures. This challenge requires a holistic approach that investigates the problem at design time as well as during runtime. Table 1 presents a summary of my contributions in this area. A narrative of key contributions along these aspects is provided in the list that follows.

*Table 1: Summary of Innovations in Science of CPS with two representative publications.*

| | | Contributions | Select Pubs |
|---|---|---|---|
| Science of Cyber-Physical Systems | Component-based Design and Decentralization Middleware | Abstractions for spatial and temporal isolation of applications. | [48, 47] |
| | | Synthesis of runtime fault, detection and diagnosis procedures. | [5, 128] |
| | | Multi-level security and fault management across applications. | [111, 107] |
| | | Domain-specific modeling languages for reducing accidental complexity. | [24, 100] |
| | | Interaction patterns for component composition using security-labeled messages. | [110, 119] |
| | | Resilient remote deployment and configuration of applications. | [79, 99] |
| | | Analyzable component models with simplified execution semantics and inversion of control. | [39, 117] |
| | | Mechanisms to implement privacy and analyze safety tradeoff. | [4, 21] |
| | | Mechanisms for testing integration of blockchains in CPS at scale. | [61, 92] |
| | | Mechanisms for efficient market implementation using hybrid solver pattern. | [22, 66] |
| | | Strategies for setting hyperparameters of the platform to minimize cheating. | [22, 17] |
| | Fault Detection and Diagnosis | Temporal causal diagrams for managing diagnosis in systems with protection devices. | [20, 64] |
| | | Mechanisms to synthesize temporal failure propagation graphs from system assemblies. | [84, 114] |
| | | Anomaly detection for learning enabled components of CPS. | [5, 33] |
| | | Detection and study of fault cascades in transportation and electrical networks. | [19, 43] |
| | | Fast statistical procedures for anomaly detection in complex systems. | [41, 37] |
| | | Distributed diagnosis procedures for complex CPS. | [93, 125] |
| | Resilience and Risk Management | Dynamic reconfiguration problem within satisfiability modulo theory framework. | [71, 99] |
| | | Reliability driven autonomic system reconfiguration methodology. | [89, 96] |
| | | Resilience patterns and metrics for evaluation of complex system designs. | [79, 94] |
| | | Software health management methodology for real-time distributed systems. | [113, 116] |
| | | Game theoretic analysis for designing protection measures in complex CPS. | [25, 67] |
| | | Autoscaling and optimal resource allocation for cloud systems. | [131, 134] |
| | | Performance management of component-based distributed systems. | [18, 82] |
| | | Performance assessment metrics for distributed systems under uncertainty. | [109, 137] |
| | | Procedures for distributing and outsourcing computations through markets. | [22, 15] |
| | | Multi-agent distributed and decentralized planning procedures. | [8, 30] |
| | | Dynamic assurance framework for CPS with AI components. | [5, 31] |

1. **Component-based Design**: My work in this area has made several contributions, including the ARINC-653 Component Model (ACM)[127], which combines the principle of spatial and temporal partitioning with the interaction patterns derived from the CORBA Component Model (CCM). The main extension over the CCM are as follows: (a) The synchronous (call-return) and asynchronous (publish-subscribe) interfaces can be outfitted with monitors that validate pre-and post-conditions over data that is passed on the respective interface, (b) The relevant portions of the state of the component can also be observed via a dedicated state interface, enabling the monitoring of invariants, (c) The resource usage of the component can be monitored via a resource interface that component uses for allocating and releasing

resources, and (d) The timing of component execution can be observed via control interface and detect deadline violations. In summary, these extensions enable component-level monitoring that evaluates pre-and post-conditions on method invocations, verifies the state invariant, tracks the resource usage, and monitors the timing behavior of the component. This work has been extended to distributed cyber-physical systems using the DREMS (Distributed Real-Time Embedded Managed Systems) component model [78, 100, 107, 105, 115, 119], which also featured fine-grained privileges for controlling access to system services. As part of this effort, we developed a novel Multi-Level Security (MLS) information sharing policy (in collaboration with Kestrel Institute) across distributed architectures [107, 110, 112, 119].

2. **Performance Optimization of Component-based Systems**: We have developed methods to create models that assist in performance prediction and capacity planning for components [36, 104, 106, 108, 124, 131, 132, 129, 130, 134, 137, 138, 135]. An integral part of this work is the ability to deploy sensors without affecting the performance of the rest of the system [135]. In addition, we have designed mechanisms that can adapt the system and manage performance even under degraded scenarios while ensuring that the other partitions or applications in the system are not affected [47, 78, 118, 133]. Recent works have also analyzed the effect of sensor uncertainty on the performance models [70, 88, 96, 95, 109].
3. **Decentralization**: Many distributed cyber-physical system problems can be formulated as a multi-agent and multi-stakeholder participatory problem which is especially vulnerable to data and operational disruptions common in centralized architectures. We have made progress towards the decentralization of cyber-physical systems by integrating distributed ledgers in cyber-physical systems [21] and focusing on resource allocation problems. The key innovation in our work is the hybrid solver pattern [68, 66, 69], scalable testing of IoT applications with blockchains [61, 92], ability to verify the smart contract code (developed in collaboration with Anastasia Mavridou and Aron Lazska) [21, 50, 51] and integrate it with the device using Resilient Information Architecture Platform for Smart Grid (RIAPS) middleware [68, 86, 49, 81, 80, 75]. Our platform, called TRANSAX, enables participants to trade in an energy futures market, which improves efficiency by finding possible matches for energy trades, enabling Distribution System Operators (DSO) to plan their energy needs better. TRANSAX provides privacy to participants by anonymizing their trading activity using a distributed mixing service while also enforcing constraints that limit trading activity based on safety requirements, such as keeping planned energy flow below line capacity. We have shown that TRANSAX can satisfy the seemingly conflicting requirements of efficiency, safety, and privacy [4, 17, 23]. We have recently extended this idea to provide a market for managing spot computation resources at the edge through a middleware called MODICUM [22].
4. **Anomaly Detection**: My work in this area has shown that when the data can be collected from spatial neighborhoods (transportation networks, emergency response networks, and power grids), the variance from the collective group and the time-dependence of individual parameters in a short duration can be used to detect anomalies. A proof of concept was shown in our earlier work on traffic networks [62] where we developed a statistical approach using Pythagorean mean-based metrics. However, we found that the measurement window and the size of the neighborhood highly affect the sensitivity of these metrics and, in turn, affect the precision and recall. In other recent papers, [42, 34] we were able to show that adding domain knowledge, for example, modeling the road interactions in a traffic network or the causal information from a power network, can improve the performance. Further, when past historical information is available but hard to analyze because of high dimensionality, our work has shown that we can use the latent representations learned by the variational autoencoders to detect problems. This approach has shown the ability to perform anomaly detection for AI components where the runtime data distribution may differ from the original training distributions [33, 32].
5. **Fault Diagnosis**: The focus of this research thrust is failure diagnosis, which refers to inference of root failure(s) that caused an anomaly in a downstream component of a CPS. In general, this is a difficult task for systems because it is challenging to isolate the dependencies between subsystems. Our work in this area has shown that if the CPS is constructed using the component-based design concept then the

behavior and failure propagation across the assembly can be deduced [116, 114, 123, 118, 121, 120, 122, 128, 126]. A challenge in diagnosis though is that often system topologies change over time due to design, faults, and subsequent localized protection actions. This introduces new failure modes specific to the operation or lack of operation of the protection components. We have developed an extension of Temporal Failure Propagation Graphs (TFPG) called Temporal Causal Diagrams (TCD) to resolve these challenges [64]. The key idea in the TCD is to augment the TFPG model with the possible behavior of all local observers and fault masking patterns. While TFPG and TCD address the diagnostic problem partially, they still have a shortcoming from assuming that a causal link implies the fault propagation must occur; however, in practical systems, precise causality information may be absent. To solve this problem, we have developed the notion of dynamic Uncertain Concept Graphs (UCG) with domain-specific ontology[72].

6. **Recovery and Resilience Evaluation**: My work has shown that once the fault or faults have been isolated, recovery strategies have to be used to recover the system's functionality. There are three possible strategies. The first strategy is the prescriptive methodology. This strategy uses rules to describe the sequence of failures and the corresponding mitigation actions as shown by state machine-based [136] and table-based recovery strategies [47]. However, it is difficult to define and often does not cover all combinations of losses for a dynamic system. The second strategy is the masking strategy using simplex and voter patterns. However, this also can only work for well-known failure modes and is computationally expensive to implement. The third strategy is a planning-based strategy demonstrated by my works on Software Health Management and deliberative runtime reconfiguration. The key idea in these works is to use the design space of the cyber-physical system to search for alternatives when faults occur [71, 99, 98]. The design space models encode information about resources available, known faults, system goals, and functionalities required to achieve system goals. In addition, they encode the dependency chain of the system topology and components to function mapping, all configured using domain-specific languages we developed [79, 100, 103] as part of the System-F6 and CHARIOT projects. These techniques were demonstrated on the Air Data Inertial Reference Unit (ADIRU) models of Boeing 777 [116, 114, 123, 118, 121, 120, 122, 128, 126]. Most notably, we recreated a past malfunction that led to severe in-flight turbulence and showed how our technique could help in such a situation.
7. **Risk Management at Runtime**: Traditional techniques for risk assessment focus on design-time techniques such as hazard analysis, risk reduction, and assurance cases, among others. However, these static design-time techniques do not consider the dynamic contexts and failures systems face at runtime. In [5], we introduced the ReSonAte dynamic risk estimation framework for autonomous systems. ReSonAte reasons over Bow-Tie Diagrams (BTDs), capturing information about hazard propagation paths and control strategies. The ReSonAte approach has been demonstrated in simulations using two separate autonomous system simulations: CARLA and a crewless underwater vehicle. We have also built a testbed called DeepNN-Car for experimentation and validation of these approaches [45]. Once an anomaly is detected, we use a weighted simplex strategy to transition to a safe controller. Instead of using only a single control output (as in Simplex Architecture), we designed a weighted ensemble of the two control outputs. The weights improve the balance of safety versus the performance of the system [31, 56].

## 3. Contributions to the Science of Smart Cities

Smart cities are a challenging extension to cyber-physical systems characterized by integration of humans in the feedback loop and interactions of multi-agent and multi-domain subsystems. Challenges include data distribution, data preparation, and design of decision support systems while solving the problems of scalability, resilience, and robustness. Driven by our research into CPS, we have been able to tackle problems of three domains: public transportation systems, emergency response systems, and power grids. Table 2 presents a summary of my contributions in this area. A narrative of key contributions along these aspects is provided in the list that follows.

*Table 2: Summary of Innovations in Smart and Connected Community Domains with two representative publications.*

| | | Contributions | Select Pubs |
|---|---|---|---|
| Smart and Connected Community Applications | Electric Power Grid | Decentralized transactive energy system platform with support for privacy-preserving futures trading at distribution level. | [4, 21] |
| | | Machine learning algorithms for data-driven anomaly detection and event-classification. | [34, 1] |
| | | Mechanisms for power systems defense against dynamic cyber-attacks. | [25, 67] |
| | | Framework for studying IoT based transactive systems with Gridlab-D and Opal RT. | [4, 63] |
| | | Study of privacy and safety tradeoffs for transactive energy systems. | [4, 17] |
| | | Resilient Information Architecture Platform for Smart Grid for designing distributed microgrid applications. | [39, 80] |
| | | Temporal causal diagrams that can efficiently model fault progression path considering protection relay failures. | [20, 64] |
| | | N-k contingency analysis procedures for distribution systems. | [83, 2] |
| | | Decision theoretic analysis and optimization of transit electrical vehicle charging schedule considering impact on smart grid. | [29] |
| | | Integrated Energy and transportation simulation for public transit fleets with electrical vechicles. | [14, 11] |
| | Emergency Response Systems | Mechanisms for analyzing the factors affecting incidents on road networks and highways. | [13, 28] |
| | | High resolution prediction of likelihood of accidents across the state of Tennessee and the city of Nashville considering information sparsity. | [13] |
| | | Integration of social media data considering uncertainty to help in incident and demand detection. | [35, 72] |
| | | Algorithms for optimizing the dispatch strategies using the incident prediction models. | [52, 87] |
| | | Fast Multi-agent distributed, hierarchical and decentralized planning procedures for proactive stationing of emergency response resources. | [8, 30] |
| | | Uncertain concept graph (UCG) to model the uncertainty in knowledge of state in dispatch operations. | [72] |
| | Public Transportation Systems | Analysis and prediction of long-term, short-term and real-time delays in sparse public transit networks. | [59, 53] |
| | | Algorithms for optimizing the schedule of public transit considering seasonal delays. | [44, 91] |
| | | Modular trip planner and social routing policies for multimodal transportation options. | [57, 73] |
| | | Data-driven analysis and forecasting of cascading effects of congestion. | [43, 42] |
| | | Mechanisms for analyzing and predicting the energy costs for public transit. | [14, 16] |
| | | Data-driven simulator for assessing usage and energy consumption of public transit. | [12, 57] |
| | | Low-resolution camera based traffic density and pedestrian density estimation. | [55] |
| | | AI-based scheduling systems to solve the problem of allocating vehicles and drivers to transit services. | [11] |
| | | Analysis and optimization of electrical vehicle usage by public transit agencies. | [29, 16] |
| | | Anomaly detection and data imputation for large scale real-time transportation data collected in cities. | [41, 62] |
| | | Design of resilient architecture for managing multi-modal transportation data for cities. | [15, 38] |

1. **Proactive Spatio Temporal Resource Matching**: These procedures foresee how the system will evolve, capture the long-term value of actions, and make decisions that optimize the expected long-term utility of the CPS. Proactive management requires an integrated pipeline of components to (1) detect demand in real-time from heterogeneous data streams (demand detection), (2) forecast how demand distributions and the environment will evolve in the future (demand prediction), and (3) integrate the above information to plan proactive and adaptive allocation decisions that serve current demand while foreseeing their effect in the future (adaptive planning). We have applied these methods to decentralized energy allocations, electric vehicle allocations, computation resource matching, and emergency response allocations [21, 4, 22, 8, 30, 29, 52].
2. **Multi-agent Decision Support Systems**: We have developed adaptive multi-agent anytime decision-making algorithms that use the upstream prediction models for resource allocation to improve system performance using a predict and optimize framework. We formulate the problem as a semi-markovian decision process (SMDP). Often, it is not possible to do this in real-time due to the size of the decision space. Therefore, we use the Monte-Carlo Tree Search (MCTS) family of algorithms, which evaluate actions by sampling from many possible scenarios [52]. To account for communication failures and further scalability challenges, we have also developed a decentralized multi-agent MCTS (MMCTS) approach. In MMCTS, individual agents build separate trees focused on their actions rather than having one mono-

lithic centralized tree, dramatically reducing their search space. Our innovation lies in adding the concept of action filtering to the standard MCTS approach to resolve global conflicts. To scale these methods further, we have designed hierarchical planning [8] procedures based on available communication resources and real-time situational awareness.

3. **Emergency Response Systems (ERS)**: Planning and preparation in anticipation of urban emergency incidents are critical because of the alarming extent of the damage such incidents cause and the sheer frequency of their occurrence. Our research on algorithmic approaches to ERS spanning the past six years has has led to the development of principled proactive stationing and dispatch strategies that reduce overall response times [7, 27]. As such, we have tackled several fundamental problems in the area of multi-agent systems and machine learning in the context of proactive and principled emergency response [30, 52, 54, 72, 87, 90]. The key contributions include mechanisms for analyzing the factors affecting incidents on road networks and highways, robust prediction of the likelihood of accidents in a large metropolitan area using online survival analysis and Long Short-Term Memory (LSTM) networks, algorithms for optimizing the dispatch and stationing strategies using the optimization under uncertainty, and development of an uncertain concept graph (UCG) to model the uncertainty in the knowledge of state in dispatch operations.
4. **Public Transit System Delay Management**: We built an analytics module to identify historical bus delay patterns and locate the bottlenecks in the transit network by measuring transit performance for the city of Nashville [53, 74]. This model was subsequently used to develop a genetic algorithm for optimizing the transit schedule and adjust it seasonally [44]. This work was integrated into the transit hub platform [59] and deployed for Nashville as part of the Global Cities Team Challenge in 2016 and 2017.
5. **Energy and Scheduling Efficiency of Public Transit Systems**: Working with Chattanooga Area Regional Transit Authority (CARTA), we have developed methods to develop data-driven predictors of energy consumption for various routes and schedules using deep neural networks [16, 9]. Additionally, we developed optimization procedures to generate trip rosters that reduce the overall energy consumption [11]. The critical contribution of the work is the design of the distributed data store, real-time data merge procedures, and subsequently, the creation of multi-task learning (MTL) models to generalize the energy model training across different vehicle classes. We have shown that the MTL models perform better than traditional baseline models trained for each vehicle class separately. Further, in the case where there is a significant variation in vehicles in each category, we use inductive transfer learning (ITL) to improve predictive accuracy for vehicle class models with insufficient data [14]. We are currently investigating the scheduling efficiency problems of public transit as part of a NSF grant.
6. **Power Grid**: Power systems are designed to be $N-1$ failure tolerant. However, multiple failures, specifically cascaded failures, occur and result in systemic damage as shown by our analysis [2, 25, 67, 83]. Traditional approaches find it hard to analyze fault protection modes because of the complexity of mode switches caused by misoperation of protection devices. We have developed a fault modeling approach called Temporal Causal Diagrams that can model fault progression paths in power systems that have built-in automatic fault-protection devices like protection relays [64, 65, 77, 76, 93, 102, 101]. Further, we have developed a novel platform called Resilient Information Architecture Platform for Smart Grid (developed in collaboration with Prof. Karsai and Prof. Lukic and Prof. Srivastava) for deploying robust decentralized applications for smart grid [60]. This platform has enabled the development of portable and modular device access protocols [48].
7. **Transactive Energy**: We have developed a decentralized transactive energy platform called TRANSAX (provisionally patented) [4, 21, 50, 63, 68, 66, 69, 80, 86, 75, 92, 85, 97]. It enables participants to trade in an energy futures market, which improves efficiency by finding possible matches for energy trades, thereby reducing the load on the distribution system operator. It provides privacy to participants by anonymizing their trading activity using a distributed mixing service while also enforcing constraints that

limit trading activity based on safety requirements, such as keeping power flow below line capacity. One of the critical innovations in TRANSAX was developing a novel hybrid solver concept that combines the trustworthiness of distributed ledgers with the efficiency of conventional computational platforms. This hybrid architecture ensures the integrity of data and computational results as long as most ledger nodes are secure and allow the complex computation to be performed by a set of redundant and efficient solvers.

## 4. Future Research Plan

For the next several years, I plan to emphasize research into the following listed topics as part of my goal towards developing methods to improve the performance, and resilience of cyber-physical systems, including smart cities.

- **Realistic Covariate Simulation:** Investigating solutions to the challenges of real-world deployed systems found in cities is generally infeasible due to access issues and the inability to tinker with production systems. Thus, simulation including hardware-in-the-loop and emulation are attractive options. However, instead of just focusing on the plant dynamics, we need to investigate fast and reliable covariate simulators to predict future environmental conditions such as traffic congestion that can be eventually used in other analytic procedures.
- **Online Scalable Anomaly Detection and Fast Diagnosis Procedures:** The temporal failure propagation graphs [114] assume that a causal link implies that the fault propagation must occur; however, in practical systems, precise causality information may be absent. Anomaly detection is also challenging due to the dimensionality of real-world data, especially for transient and streaming observations. We are investigating generative approaches to learn distributions over reduced-order abstract space as shown in our work with images [33]. This approach can provide tractable density estimation because the reduced order space can be efficiently used to flag anomalies. Further, we can use the reconstruction methods to generate synthetic anomalies, which can be used to train human operators.
- **Reusable Design Models:** There is a lack of suitable design tools that enable the researchers and engineers to work with large-scale data, train machine learning models, manage cloud complexity, and develop assurance cases and runtime monitors. I have developed such modeling toolchains with my collaborators [100, 24] and this has enabled us to design and deploy the weighted simplex architecture for the DeepNNCar [31]. However, this system needs to be extended with design patterns in the toolchain to codify the common concepts that can be used to make the systems resilient. These patterns are essential because many techniques for resilient systems (e.g., primary/backup and triple-modular redundancy) cannot be captured as components and often not even as a distinct construct in a modeling language. Effectively, it has to be modeled as a transformation pattern, validated, and applied to the system design.
- **Scheduling and Dispatch for Public Transit:** Transit agencies struggle to maintain transit accessibility with reduced resources, changing ridership patterns, and vehicle capacity constraints. We are working to (1) design AI-based scheduling systems to solve the problem of allocating vehicles and drivers to transit services, (2) schedule vehicle maintenance and electric vehicle charging, and (3) proactively station and dispatch vehicles for fixed-line service to mitigate unscheduled maintenance and unmet transit demand.
- **Emergency Response and Dispatch for Interstate Network:** We are working to develop and pilot a decision support system that addresses the following challenges for the Tennessee Department of Transportation: (1) Dynamics and variability of incidents; (2) Multi-variate data integration at scale; (3) A resilient incident response that can handle complex issues such as communication breakdowns; (4) Community-driven impact criteria that are used to process and build the response procedures – for example, it is vital to consider the impact on future congestion when deciding response on interstate networks and understand the impact of congestion on travel delays; (5) Effective coordination with local agencies to provide the most efficient use of resources; and (6) Enabling early incident detection using multiple data channels.

- **PowerKeeper: A comprehensive online management tool to detect, diagnose and mitigate anomalies in Power Systems:** National power grid is going through transformational reform fueled by advancement in Distributed Energy Resources (DERs) such as solar and wind farms. However, recent widespread outages caused by natural phenomena (adverse weather conditions) and cyber-attacks have exposed numerous weaknesses in the existing infrastructure. These weaknesses stem from degrading power equipment, vulnerable embedded control algorithms, and inadequate security compliance. Our approach to this problem is to formulate the challenge as a non-cooperative multi-agent planning problem that can be solved with some of the decision approaches we have developed in the emergency response domain.

## 5. Graduate Students, Postdocs, and Research Scientists

This work has been made possible by the postdocs, research scientists, graduate students, and undergraduate researchers who have worked with me over the years.

1. Graduated
   (a) **Scott Eisele, PhD. EE (2020)** (Primary Advisor): Challenges in Multi-Stakeholder CPS Using Distributed Ledgers (Doctoral dissertation, Vanderbilt University).
   (b) **Matthew Burruss, MS. CS (2020)** (Dual BS/MS) (Primary Advisor): Matthew is researching methods to improve the robustness of neural network classifiers, and his research is aligned with the assurance horizontal.
   (c) **Sanchita Basak, MS. EE (2020)** (Primary Advisor): Anomaly Detection and Prediction of Anomaly Propagation Path Using LSTM Networks (MS Thesis, Vanderbilt University).
   (d) **Chinmaya Samal, MS. CS (2019)** (Primary Advisor): Time-dependent and Privacy- Preserving Decentralized Routing using Federated Learning (MS Thesis, Vanderbilt University).
   (e) **Fangzhou Sun, PhD. CS (2018)** (Co-Advisor): co-advised with Jules White, 2018. Algorithms for Context-Sensitive Prediction, Optimization and Anomaly Detection in Urban Mobility (Doctoral dissertation, Vanderbilt University). The research undertaken was directly under my supervision and guidance.
   (f) **Pradhan, Subhav, PhD. CS (2017)** (Co-Advisor): co-advised with Aniruddha Gokhale. Algorithms and Techniques for Managing Extensibility in Cyber-Physical Systems (Doctoral dissertation, Vanderbilt University). The research undertaken was directly under my supervision and guidance.
2. Current students:
   (a) **Shreyas Ramakrishnan, PhD. EE** (Primary Advisor): Shreyas's research interests are in the system assurance area. He is developing the weighted simplex strategy and anomaly detection methods for neural networks.
   (b) **Geoffrey Pettet, PhD. CS** (Primary Advisor): Geoffrey works on the emergency response vertical and develops the coordination algorithms
   (c) **Michael Wilbur, PhD. CS** (Primary Advisor): Michael works in the performance management area and develops energy prediction and optimization algorithms for smart transit systems.
   (d) **Nithin Guruswamy, MS CS** (Primary Advisor): Nithin works in the system resilience area and is developing AI-based fault diagnosis methods for edge cloud systems.
3. In addition I have mentored the following students and supported them as a research supervisor on my grants during their research.
   (a) **Mike Walker, MS CS**
   (b) **William Emfinger, PhD. EE**
   (c) **Pranav S. Kumar, PhD. EE**
   (d) **Akshay Dabholkar, PhD. CS**

(e) **Timothy Krentz, PhD. CS**
(f) **Zhuangwei Kang, PhD. CS**
(g) **Purboday Ghosh, PhD. CS**
(h) **Shweta Khare, PhD. CS**
(i) **Ajay Chokra, PhD. EE**
(j) **Saqib Hasan, PhD. EE**

4. Postdoctoral scholars.
   (a) **Sayyed Vazirizade** (current postdoc)
   (b) **Saideep Nannapaneni**
   (c) **William Emfinger**
5. Research Scientist.
   - **Dr. Ayan Mukhopdhyay**

## 6. Undergraduate Researchers Supervised

I have supervised the following undergraduate students during their research work.

1. **Rongze Gui, CS (2020,2021)**: Transit Simulation Statistical Analysis and Visualization for Emergency Response Systems
2. **Abhiram Vadali, CS (2020)**: Big Data Analytics for Smart Transit Systems
3. **Riyan Kabir, CS (2020,2021)**: Big Data Analytics for Smart Transit Systems
4. **Hunter Wang, CS (2020)**: Assured Autonomy
5. **Shriya Karam, CS (2020)**: Big Data Analytics for Smart Transit Systems
6. **Teo Lee, CS (2020)**: Predictive Models for Emergency Response Systems
7. **Anna Ouyang, Psychology (2020)**: Predictive Models for Emergency Response Systems
8. **Keegan Campanelli, EE (2019,2020)**: Transactive Energy and Electric Grid
9. **Matthew Buruss, CS (2018, 2019)**: Assured Autonomy
10. **Li Haoyu, CS (2019)**: Data Analytics for Emergency Response
11. **Brian Xu, CS (2019)**: Data Analytics for Emergency Response
12. **Rounak Salim, CS (2017, 2018)**: Indoor Localization
13. **Hoyos Juan Sebastian, CS ( 2017)**: Secure Operating Systems
14. **Nicholas Lewis, CS ( 2017)**: Internet of Things
15. **Aaron Smith, CS (2017)**: Virtual Reality
16. **Anne Zou, CS (2017)**:Mobility Application for Cities

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