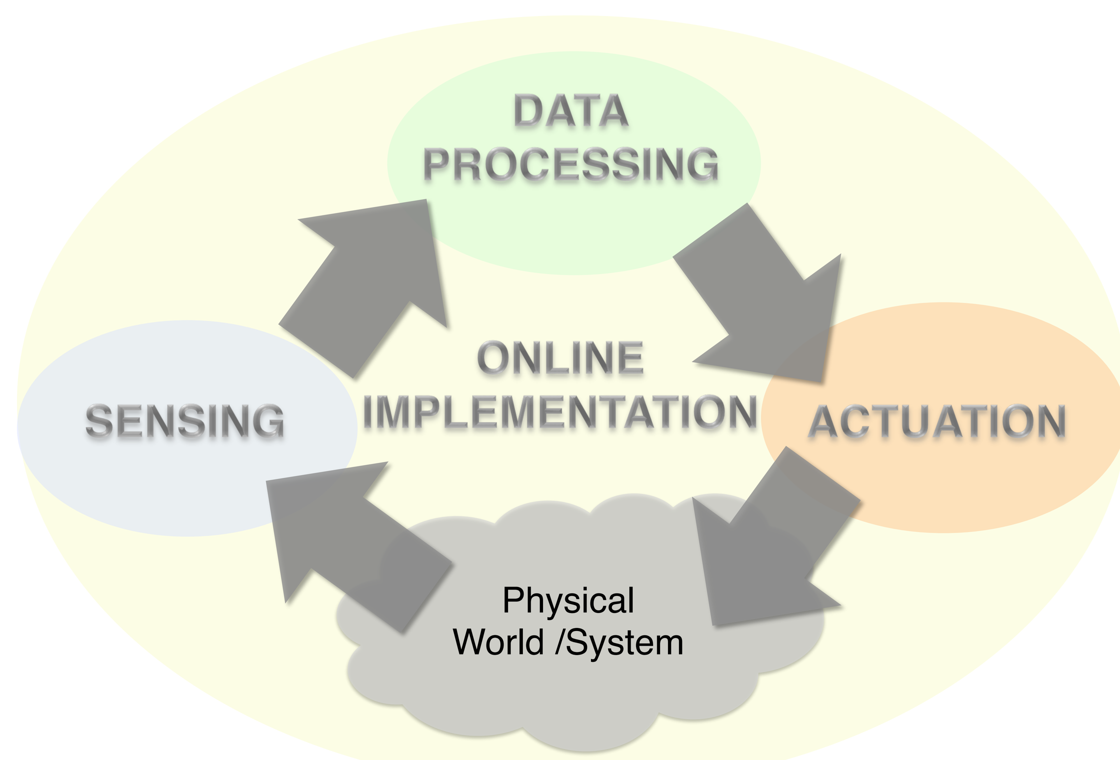
Achieving High-Resolution Situational Awareness in Ultra-Wide-Area Cyber-Physical Systems

PIs: Hairong Qi (PI), Qing Charles Cao (co-PI), Yilu Liu (co-PI), Leon Tolbert (co-PI)

Students: Brandon Johnson, Liu Liu, Yang Song, Wei Wang, Sisi Xiong, Yanjun Yao, Lingwei Zhan, Jiecheng Zhao

MOTIVATION

The proposed work employs the power grid as a target application and develops a high-resolution, ultra-wide-area situational awareness system that synergistically integrates sensing, processing, and actuation. The objective is to turn a large volume of real-time data into actionable information and help prevent potential outages from happening.



SENSING TOWARDS THE EDGE

Innovation: Make accurate frequency measurement from low voltage distribution systems through the wide deployment of Frequency Disturbance Recorders (FDRs). The uniquess of FDR is that it can measure essential transmission level information at the distribution level using low-cost sensors.

Challenges: At the distribution level, the SNR is much smaller than that at the transmission level. Existing frequency and phasor estimation algorithms are not robust to noise. They only show accurate estimation in steady-state test, the errors arise when the power system is operating at off-nominal frequency, or when the testing is under distortion of phase modulation or harmonics.

Year 1,2 Findings: Developed frequency estimation by curve fitting and voltage denoising by digital filtering. Studied the theoretical limit of measurement accuracy. Designed the Universal Grid Analyzers (UGAs) to enhance the situation awareness of power grids and contribute to the measurement accuracy improvement.

Year 3 Achievements: Analyzed the distortion of the power grid signals at the distribution level and studied the effect of the distortion on phasor measurement accuracy. Developed a new DFT-based phase and frequency estimation algorithm for synchrophasor measurement at the distribution level. The algorithm is able to output accurate measurement result under the conditions of off-nominal frequency, phase modulation, noise, and harmonics distortion.

Test	Reference signal	Qps-DFT algorithm		Avg_Avg2Comp DFT algorithm		PMU Standard C37.118.1(a)	
		Angle error in degree/aTVE	Frequency error in mHz	Angle error in degree/aTVE	Frequency error in mHz	TVE	Frequency in mHz
Noise	$1\cos(2\pi f_0 t)$+ 60dB noise	0.033/0.06%	1.1	0.005/0.009%	1.3	NA	NA
Frequency range	$1\cos(2\pi f t)$ $55 \le f \le 65$	0.05/0.09%	1.8	0.04/0.07%	0.25	1%	5
Harmonics	$\cos(2\pi 59.5t) + 0.1\cos(2\pi i 59.5t)$ $2 \le i \le 50$	0.023/0.04%	0.528	0.004/0.007%	0.315	NA	NA
	$\cos(2\pi 60t) + 0.1\cos(2\pi i 60t)$ $2 \le i \le 50$	6.1×10^{-13}/0%	7.1×10^{-12}	0.003/0.005%	2.8×10^{-11}	1%	25
	$\cos(2\pi 60.5t) + 0.1\cos(2\pi i 60.5t)$ $2 \le i \le 50$	0.025/0.04%	0.485	0.003/0.005%	0.184	NA	NA
Frequency ramp	$1\cos(2\pi(55 + 1t)t)$ $0 \le t \le 10$	0.19/0.33%	7.4	0.022/0.04%	0.268	1%	10
Magnitude modulation	$(1 + 0.1\cos(2\pi f_m t)) * \cos(2\pi f_0 t)$ $f_m = 1,2,3,4,5$	0.026/0.05%	0.38	3.6×10^{-3}/0.006 %	0.35	3%	300
Phase modulation	$1\cos(2\pi f_0 t + 0.1\cos(2\pi f_a t - \pi))$ $f_a = 1,2,3,4,5$	1.58/2.76%	116	2×10^{-3}/0.004%	1.5	3%	300
Artificial signal	$1\cos(2\pi 59.95t)+\sum_{i=2}^{50} v_h \cos(2\pi \times i \times 59.95t + \theta(i))$+60dB noise	0.04	1.27	0.005	1.49	NA	NA

Testing & comparison of proposed algorithm

DATA ANALYSIS THROUGH EVENT UNMIXING

Innovation: A new conceptual framework, referred to as event unmixing, is proposed, where we consider real-world events as mixtures of more than one constituent root event. This concept is a key enabler for analysis of events to go beyond what are immediately detectable in a system, providing high-resolution data understanding at a finer scale.

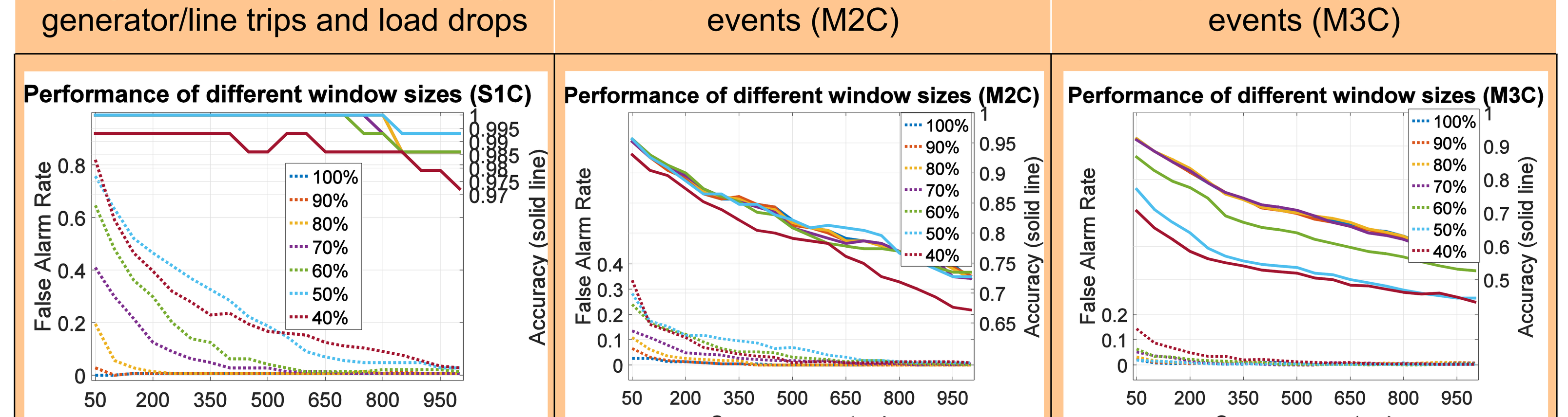
Challenges: When multiple events occur in cascading fashion, the measurement taken at an FDR would more than likely be a "mixture". Existing approaches can only detect the initial event.

Year 1,2 Findings: Designed and developed the nonnegative sparse event unmixing (NSEU) algorithm and its improved version, group-based NSEU, for simultaneously event detection, recognition, and temporal localization. Superior performance have been achieved, as compared to the state-of-the-art, in both large-scale simulations and real-case analysis using FNET data.

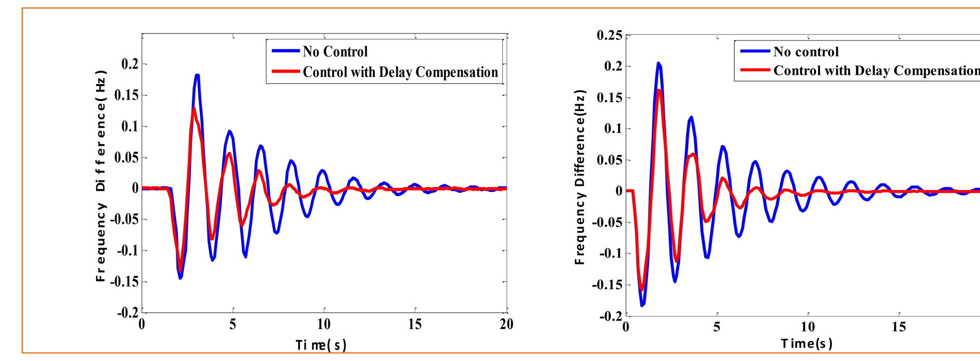
Year 3 Achievements: Developed a dictionary reduction approach that takes advantage of the geometric structure of the data as well as classification error to derive a high-fidelity dictionary with much smaller size while at the same time maintaining competitive recognition performance. The algorithm can also help shorten the size of the detection window such that a response can be generated even before the entire event is finished.

Effect of window size (100% ~ 40%) on detection accuracy and false alarm rate

Single event detection including generator/line trips and load drops	Multiple event analysis with two events (M2C)	Multiple event analysis with three events (M3C)



Single event window size reduction potential = 60%	M2C window size reduction potential =50%	M3C window size reduction potential = 30%



Control Effect Comparison
The damping controller based on measurement model can provide better damping ratio to suppress low-frequency oscillations.
Case 1: Generation trip (left)
Case 2: Load increase (right)

ACTUATION BASED ON MEASUREMENT MODEL

Innovation: A measurement-based model doesn't rely on the dynamic model of each component and can be easily updated in real time to reflect the changes in power system operating conditions. It is more accurate than a system circuit model and is a good candidate for oscillation control design.

Challenges: The identified model using pure measurement may not depict the system oscillatory behaviors for damping control.

Modeling: The AutoRegressive Exogenous (ARX) model is utilized to represent system dynamics. Before designing damping controller, the identified model is validated in time and frequency domain.

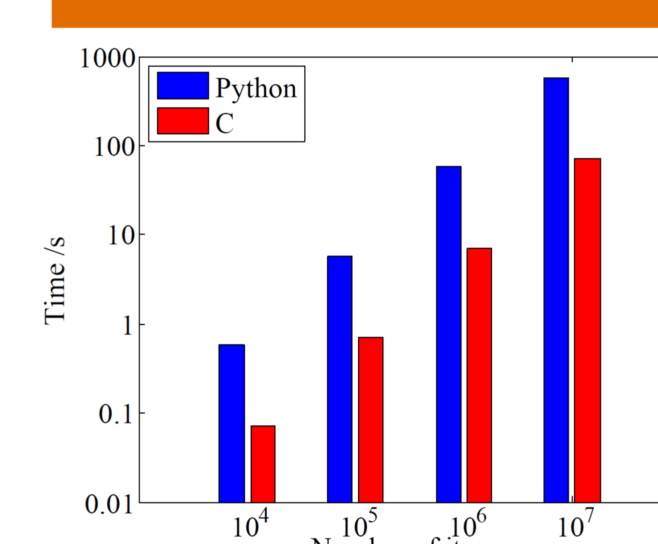
ONLINE PROGRAMMING BY APPROXIMATION

Innovation: Online programming paradigms are developed to handle data collected in CPS systems, where storage resources are constrained and computational power is limited. We propose a complete framework of approximate data processing. The key novelty is that we develop compact data structures that are probabilistic by nature, to form the foundation of a data-centric language design of DataSQL on resource constrained platforms, such as embedded devices and processors used in the grid.

Challenges: Although accurate data measurement and storage are crucial for many applications, keeping an individual counter or memory space for each data is too slow, costly, and non-scalable – a limitation of the classical bloom filter. Many applications can benefit from approximate identification and measurement.

Year 1,2 Findings: Developed Probabilistic Bloom Filter (PBF) and Key-value based Bloom Filter (kBF) as well as their hardware acceleration for effective item frequency identification, storage and queries, and speeded-up operations on basic insert/queries.

Year 3 Achievements: Developed open source python package for PBF (https://pypi.python.org/pypi/pypbf/0.0.0) with 229 downloads in August 2015 alone. Validated the GPU implementation of PBF (around 10 times faster than CPU). Developed a distributed version of kBF to support large-scale data storage/queries.



Evaluation results obtained by comparing across different software (LEFT) and hardware (RIGHT) implementations.