Zhejiang University and
University of Illinois, Urbana-Champaign
Joint Research Center

2022–2023
Annual Report

Dynamic Research Enterprise for
Multidisciplinary Engineering Sciences (DREMES)
October 1, 2022 – August 15, 2023

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Welcome to the third annual report of the Dynamic Research Enterprise for Multidisciplinary Engineering Sciences (DREMES). This report presents a wide range of deeply impactful developments and innovations from our teams. DREMES is the joint research collaboration (JRC) between Zhejiang University and the University of Illinois at Urbana-Champaign. It operates on the International Campus of Zhejiang University (ZJU) in Haining, China, on other ZJU campuses in Hangzhou, China, and on the campus of the University of Illinois at Urbana-Champaign (Illinois) in the United States. DREMES is linked largely to the joint Zhejiang University-University of Illinois at Urbana-Champaign Institute (ZJUI), although it is a broader effort that includes research leaders from ZJU and from UIUC. This report covers activities from October 1, 2022 through August 15, 2023.

During this year, three major programs and two smaller seed projects were supported through DREMES. The three programs were the Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE), the Center for Adaptive and Resilient Cyber-Physical Manufacturing Networks (CyMaN), and the Center for Pathogen Diagnostics (CPD). Through the end of 2022, two smaller seed projects were supported to help broaden the impact of DREMES. These are a project on traffic-related air pollution and the Heterogeneous Integration for Neuromorphic Integrated Circuits center (HYBRID). Early in 2023, a proposal-based renewal process was carried out. Beginning on August 16, 2023, four major programs will be supported. These include continued funding for CPD and for CIRCLE. The HYBRID center was approved as a major program going forward. The new Center for Cancer Immunotherapy (CCIT) joins DREMES as a new program. We are delighted to share, in this report, the high-impact research progress from the initial five programs. We look forward to the four future endeavors.

The breadth of impact among the DREMES programs this past year has been remarkable. Just a few highlights:

- The CIRCLE team has continued its successful Distinguished Lecture Series, typically with hundreds of audience members for each event.
- The CPD team has leveraged DREMES support into more than US$10 million in current external grant; and is working on technology translation for it high-sensitivity pathogen detection approaches.
- For the second time, the CyMaN team organized a comprehensive special session on Adaptive and Resilient Cyber-Physical Manufacturing Networks at the IEEE Conference on Automation Science and Engineering (CASE) 2023.
- The traffic air pollution team confirmed that individual heavy trucks with improper emissions equipment are substantial contributors to local air pollutants and identified senor-fusion methods to detect these vehicles.
- The HYBRID team in developing a comprehensive "materials-to-systems" strategy to move toward their goal of brain-inspired hybrid circuits with 1000x performance improvements over conventional computing.

The total annual budget of DREMES is US$1 million. The project annual budget for the operating year in this report was US$900,000, supplemented with just over US$50,000 in unexpended travel funds. The remaining US$50,000 supported DREMES administration. These funds are expended at Illinois. During the reporting year, the funds were fully spent, with approximately US$300,000 per major project, US$25,000 per seed project, and US$50,000 for administration. Almost all project funding supports direct research personnel on the programs: graduate research assistants, post-doctoral associates, and undergraduate summer students. Remaining funding provides limited faculty support, laboratory costs, related research expenses, and program travel, only if they are direct expenses of the respective DREMES programs. Illinois-side principal investigators (PIs) submit comprehensive annual budget plans to the Illinois Grainger College of Engineering. Expenses are reviewed and tracked against each program's approved budget plans. On the ZJU side, project support takes the form of China-side research assistants, post-doctoral associates, and facilities. These additional funds are managed separately by ZJU. The large programs are supplementing DREMES support from a variety of sources. In the coming year, the renewed programs (CPD and CIRCLE) will supplement part of their funds directly. Other projects have also been adjusted to allow support for four major programs plus administration within the $1 million total budget.

DREMES programs involve more than 50 faculty members across UIUC, ZJU, ZJUI, and now ZJE. The budgets support about 11 post-doctoral students and at least 65 graduate students. More than 110 journal and conference publications were produced during this year.

The co-directors extend our thanks and congratulations to all DREMES faculty, students, and research contributors. Their diligence and commitment represent a spectacular start to our incredible potential for long-term impact. We are grateful for your interest in DREMES and hope you find this annual report informative and stimulating.

Li Erping, ZJU co-Director

Philip Krein, Illinois co-Director

CIRCLE: Center for Infrastructure Resilience in Cities as Livable Environments

2023 Annual Report

Center Overview

The Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE) is one of the joint research themes established between the University of Illinois Urbana-Champaign's (UIUC) Grainger College of Engineering and Zhejiang University (ZJU). Over 80% of the U.S. population and 60% of China's population live in urban environments and rely on their infrastructure systems for essential needs like energy, water, food, waste management, transportation, and telecommunications. Despite advances in engineering and design, cities remain vulnerable to extreme events such as floods, heat waves, droughts, earthquakes, and terrorist attacks. Researchers at CIRCLE have identified four thrust areas as critical to achieving their overarching goal of developing infrastructure-resilient cities as livable environments: energy, water and environment, transportation, and built infrastructure. Each of these thrust areas encompasses unique, essential components of modern cities, tightly coupled through physical, cyber, geographical, and societal connections. Through thrust integration, CIRCLE has adopted a holistic "infrastructure ecology" and "system of systems" approach to study and evaluate urban system stressors, risks, and overall resilience to provide more resilient infrastructure design and, ultimately, enhance the livability of cities.

The next section presents highlights of activities and achievements of CIRCLE in the 2022-2023 academic year. Subsequently, the annual summary of each of the thrust areas and thrust integration is provided.

Center Progress Highlights

- CIRCLE has recruited several young faculty members from ZJUI and UIUC to join the team.
- Dean Sue Welburn and Prof. Jenna Fyfe from ZJE have joined CIRCLE, lending their expertise in public health. Discussions with ZIB have also been initiated.
- CIRCLE has formed an International Advisory Board (IAB) of world-renowned experts from academia and industry, co-chaired by Prof. Der-Horng Lee (ZJUI) and Prof. Amr Elnashai (U Houston), to guide CIRCLE in scaling up research activities, as well as for outreach and technology transfer to industries and governmental agencies.
- CIRCLE has strong industry support.
- In addition to pursuing and securing funding from several external sources, we applied to the Zhejiang Province International Collaboration Center on Smart and Livable Cities in October. Ultimately, we aim to establish CIRCLE as a national laboratory. CIRCLE is committed to

improving the diversity of its funding sources, including both private and public, to reach full financial independence.

- We are committed to further strengthening the well-established partnership among UIUC and ZJUI researchers through collaboration and exchange.
- The CIRCLE Distinguished Lecture Series has been very successful (see https://circle.cee.illinois.edu/circle-distinguished-lecture-series/).

Project Annual Summaries

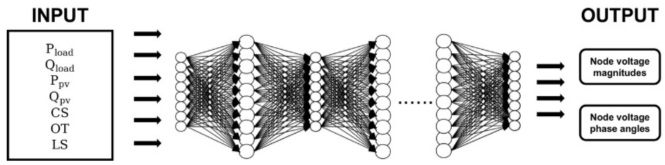
Project 1: Energy Thrust

Co-PIs: Ashlynn Stillwell (UIUC), Ruisheng Diao (ZJUI)

Thrust Highlights

The Energy Thrust is working on data-driven modeling and understanding of city-scale electricity consumption. The goal is to build a digital twin model of the electric power system for Chicago from observed 30-minute data, which can be used for electricity consumption prediction, abnormality detection, and demand response management programs. We have created various forecasting models, including a State-Space model, Artificial Neural Networks, and Random Forest, to predict electricity demand with different temporal horizons. Our results show that different models have varying performance, dependent on the forecasting window, with State-Space models best for forecasting 30 minutes ahead and Neural Networks best for 1 day ahead. This analysis improves the understanding of electricity demand predictive models as a critical component of electric power system operations and the further development of a digital twin model. These findings are described in a collaborative manuscript between UIUC and ZJUI researchers, currently in revision for publication in *Energy*.

To reach the goals of carbon peaking by 2030 and carbon neutrality by 2060 in China, a growing penetration of photovoltaic (PV) generation is integrated into the modern distribution power grid, causing challenges in operating the grid to meet security requirements due to the increased dynamics and stochastics. The team has developed a deep neural network (DNN)-based method for estimating load flow solutions in active power distribution networks that typically suffer from incomplete measurements. Adaptive DNN models are trained from massive historical observations obtained from actual measurements or high-fidelity simulations, whose hyperparameters are tuned automatically. Comprehensive case studies are conducted on the IEEE 123-node feeder model with renewable generation considering various levels of missing information as inputs, which validate the effectiveness and robustness of the proposed method. A technical paper titled “Deep Integration and Learning of Measurement Data in Active Distribution Power Networks for Load Flow Estimation Considering Incomplete Information” was presented at the 2023 IEEE 6th International Electrical and Energy Conference (CIEEC), Hefei, China.



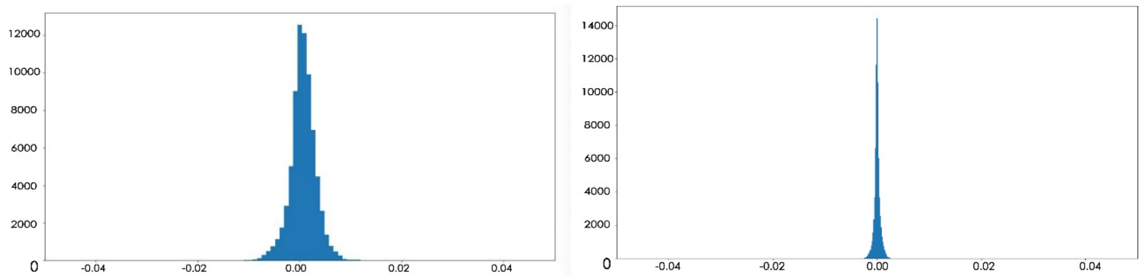
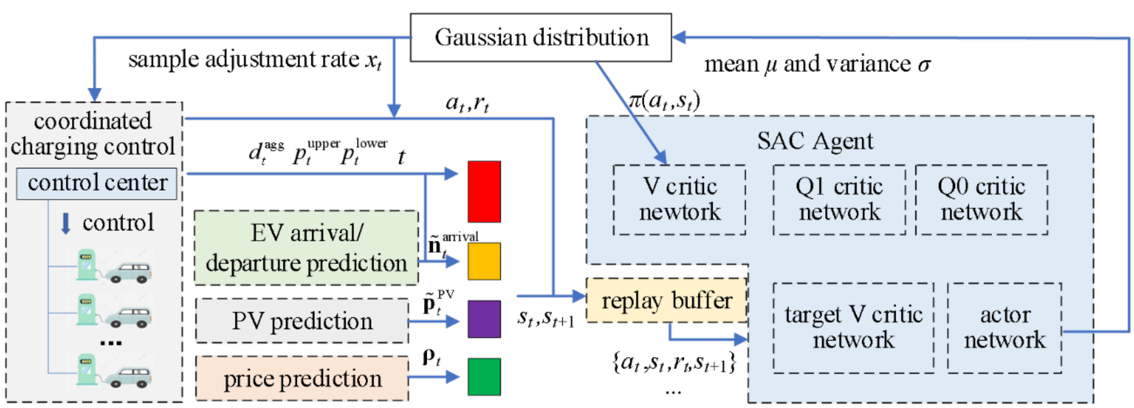


Figure 1. Histogram of estimation error, (a) voltage magnitude, in pu (b) voltage phase angle, in rad

In addition, the team developed a novel real-time electric vehicle (EV)-PV coordination strategy using deep reinforcement learning (RL) algorithm for providing real-time controls based on short-term prediction of PV outputs and EV arrivals. This strategy can deal effectively with uncertainties caused by PV power output and EV behaviors and avoid large deviations between actual and optimal conditions. The EV-PV coordination problem is first described by an EV station model and a Markov decision process (MDP). A charging control strategy inside the station is also proposed. Then, based on the soft actor-critic (SAC) algorithm, an RL training process for EV-PV coordination is proposed. Though only short-term prediction is used in real-time control, the proposed strategy can balance short-term and long-term profit and achieve optimal charging control for EV stations. Comprehensive case studies with realistic EV charging station data verify the feasibility and effectiveness of the proposed method.



Researchers supported through this project include Dr. Jorge Pesantez (former UIUC postdoctoral researcher), Christopher Lee (UIUC; graduate student jointly working with Thrust Integration), Zihan Liao (ZJUI, graduate student), Zichen Bao (ZJUI, undergraduate), Fangyuan Sun (ZJUI, graduate student), Tu Lan (ZJUI, research assistant).

Project 2: Water and the Environment Thrust

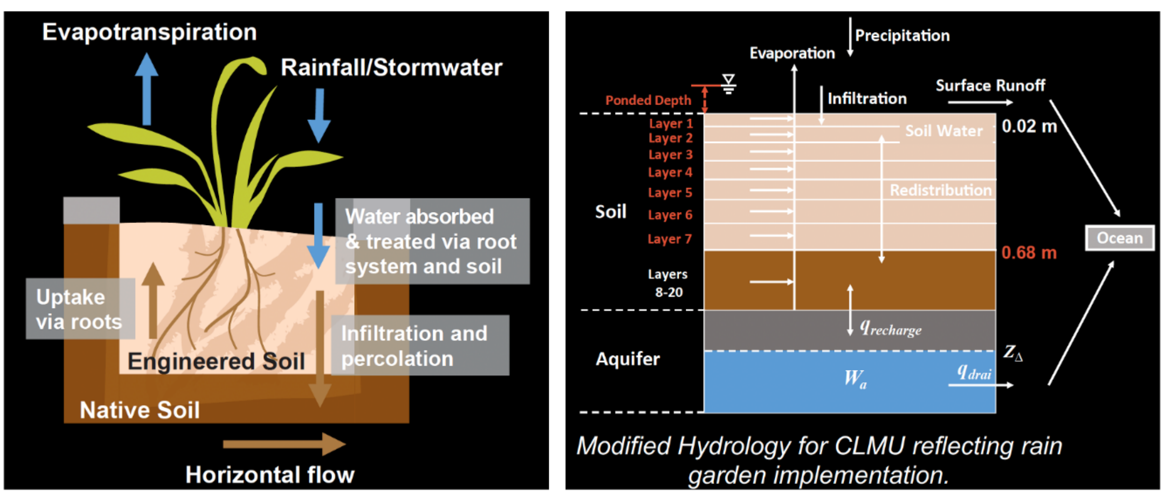
Co-PIs: Lei Zhao (UIUC), Tingju Zhu (ZJUI)

Thrust Highlights

This year, the water and environment thrust has made significant progress along several fronts, including model development, simulations, data products, and scientific reporting. First, we develop a new urban hydrology scheme in CESM/CTSM to represent urban green stormwater infrastructure (GSI), which is one significant CIRCLE product. Second, we evaluate the performance of GSI in improving urban hydroclimatic environments over U.S. cities. Third, the urban greenspace irrigation project has been completed. Last, we develop an urban water-energy-carbon nexus model. Out of these research activities this year, we have a manuscript published in the *Journal of Hydrology*. One manuscript was presented at the International Conference on Urban Climate and one additional manuscript has been accepted for presentation at the American Geophysical Union Fall Meeting (Dec. 2023).

New urban GSI parameterization in CESM

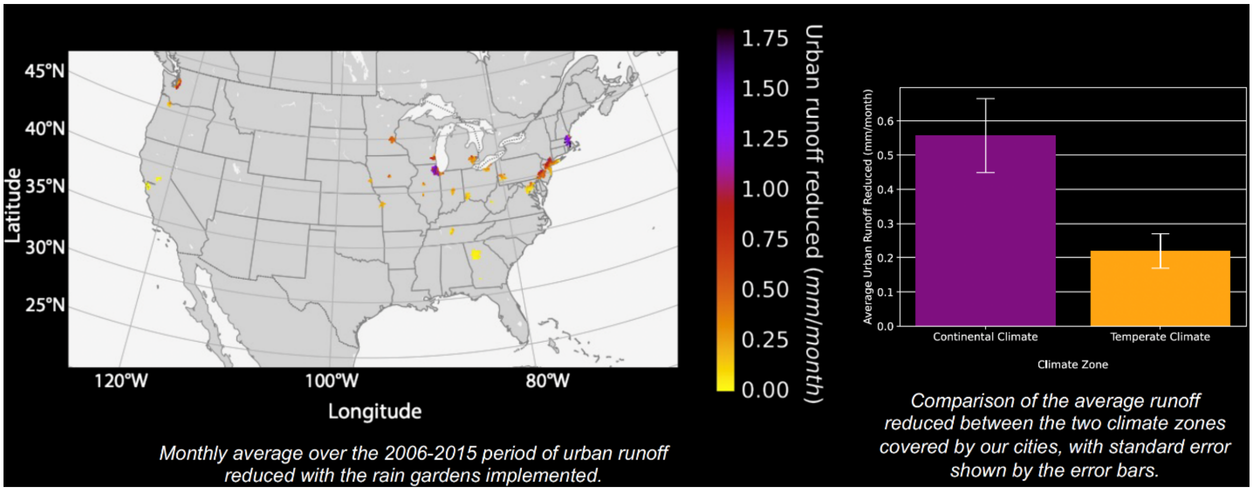
Over the past year, we successfully developed and implemented a new urban hydrology parameterization to enhance the model's capacity in simulating urban GSI. The new parameterization has been tested and incorporated into the whole Earth system model. This new development bridges global-scale climate modeling and local-scale urban infrastructure-based adaptation strategies, which is an important step forward for urban studies and allows for future work simulating present and future conditions.



Modified Hydrology for CLMU reflecting rain garden implementation.

Assessing the hydrologic performance of urban GSI

This year, we conducted a suite of high-resolution (~10 km) simulations over the continental U.S. to model the impacts of GSI on local urban hydroclimates. We selected 30 cities of interest which have issues with combined sewer overflows (CSOs) for detailed analysis. Our results show consistent urban runoff reduction by implementing rain gardens across all cities, and the climatic influence on rain garden performance.

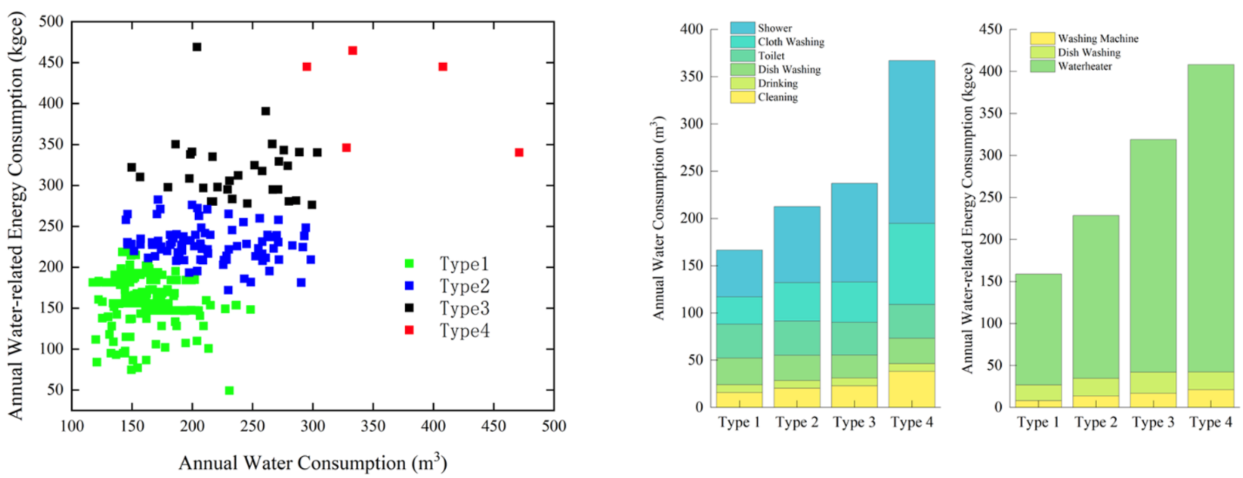


Monthly average over the 2006-2015 period of urban runoff reduced with the rain gardens implemented.

Comparison of the average runoff reduced between the two climate zones covered by our cities, with standard error shown by the error bars.

Urban water-energy-carbon nexus in China

During the past year, we built an urban water-energy-carbon nexus model and estimated water-related energy consumption across Chinese cities. We developed a novel strategy for optimized water and energy savings.



Researchers supported through this project include: Laura Gray (UIUC; graduate student), and Yuhan Yan and Lianlian Pan (ZJUI, graduate students).

Project 3: Transportation Thrust

Co-PIs: Yanfeng Ouyang (UIUC), Simon Hu (ZJUI)

Thrust Highlights

Between October 2022 and August 2023, the transportation thrust has made strong progress in the following two areas: (i) developing new models for emerging urban mobility services; and (ii) data collection, model verification, and testbed preparation. One new paper has been accepted for journal publication during this period. Two additional papers were submitted for publication in leading journals, and one of them was accepted for presentation at the 2023 Annual Meeting of the Transportation Research Board.

New Mobility Services for Livable Communities

This project focuses on leveraging emerging technologies to revolutionize urban mobility services, with specific focuses on (i) explore opportunities of using extra-long trains (i.e., trains longer than station platforms) in megacities to increase line capacity without additional infrastructure construction; (ii) optimize shared autonomous electric taxi operations with mobile charging services in a dynamic and stochastic environment; and (iii) developing models for a newly proposed freight-on-transit system. The work is conducted via tight collaboration between UIUC and ZJUI. Students involved in this project have joint supervisors from Illinois and Zhejiang.

Research efforts and results are summarized as follows.

(i) On the planning level, we developed two distinct modeling frameworks to optimize train operational protocols and passenger trip plans under general system settings. One approach integrates two coupled vehicle routing problems. The other is based on a 3-D space/station vs. train/block vs. time network (see Figure 2). Numerical experiments with real-world data (Beijing and Santiago) show 15-126% increase in capacity, from our new operational protocols, compared to systems with regular trains. This effort has been reported in two papers currently under review for publication (Shen et al., 2023; Osorio et al., 2023).

(ii) On the operational level, we focus on routing and charging scheduling of two fleets of EVs. A fleet of autonomous electric taxi vehicles provides real-time ride services to customers, while a fleet of mobile charging vans are deployed as a supplementary resource to fixed charging stations, offering on-demand charging services to taxis. This problem particularly emphasizes the dynamic and stochastic aspects of taxi energy consumption, charging price, and the availability and charging rates of fixed charging stations; as illustrated in Fig. 3. A dynamic program model is formulated with the aim of maximizing the expected profits of the system operator in the planning horizon. A customized solution algorithm based on approximate dynamic programming is under development. A working paper on this effort is in preparation.

(iii) In light of declining U.S. transit ridership linked to COVID-19, a freight-on-transit system is proposed to utilize available transit vehicle capacities for freight deliveries in cities. Transit vehicles, while providing regular transit service, are also used to conduct freight line-haul shipments across disjoint city zones, while dedicated local vehicles provide intra-zonal and last-mile deliveries. We combine a continuum approximation (CA) modeling method and an aspatial queuing network model to jointly optimize zone partition, bus loading plans, and last-mile service configurations. We have been conducting numerical experiments on both hypothetical and real-world cases (e.g., building upon Champaign-Urbana mass transit districts) to showcase the applicability of the proposed modeling framework.

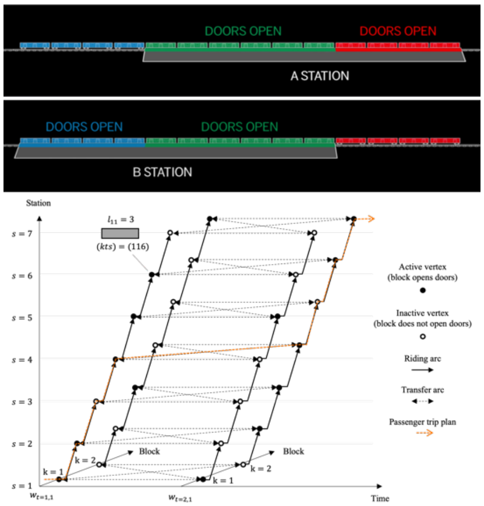


Figure 2. Illustration of extra-long train operations and the 3-D network model

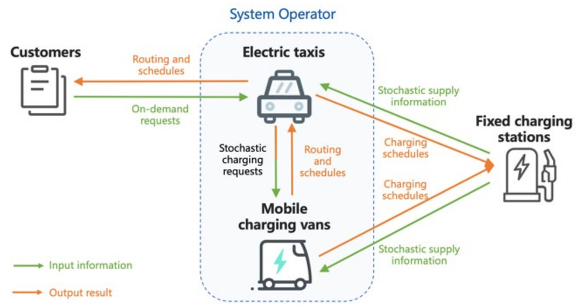


Figure 3. Operation of electric taxis with mobile charging services

Researchers supported through this project include Shiyu Shen (UIUC, graduate student) and Qinru Hu (ZJUI, graduate student).

Project 4: Built Infrastructure Thrust

Co-PIs: Jinhui Yan (UIUC), Cristoforo Demartino (ZJUI)

Thrust Highlights

The infrastructure thrust has made progress in developing enabling technologies and tools for digital twins of infrastructure systems. The research efforts include (i) data-physics machine learning models; and (ii) photogrammetry-based computational fluid dynamics. One paper is published and another one is under review in leading journals. Two invited presentations were given at major conferences. Former undergraduate researcher Haojia Cheng from ZJUI has joined Jinhui Yan's group as a Ph.D. student. A postdoc student, Dr. Xuguang Wang, now holds a tenure-track faculty position in the department of civil engineering at the University of Hong Kong.

Data-Physics Coupling Driven Simulation for Mechanical Behaviors in Frame-shear Wall Buildings

The present work seeks to provide an accurate and efficient data-physics coupling driven simulation method for mechanical behavior in frame-shear wall buildings. To obtain the stress, strain and crack maps of shear wall components, refined simulations based on finite element models (FEMs) are necessary. These are computationally expensive and cannot be adopted in large scale simulation tasks. In this study, a tree-branched neural network is developed to model the behavior of shear wall cases. The designed neural network is shown in Figure 4. The prediction accuracy (for strain, stress, and crack maps) is significantly enhanced through stepwise regression and multi-level backpropagation (Figure 5). This study formulates a solid foundation for data-physics coupling driven simulation of frame-shear wall buildings.

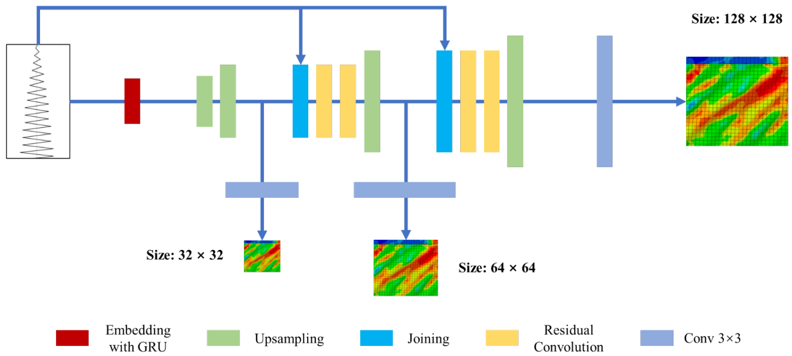


Figure 4. Branched neural network designed for shear wall component behavior prediction

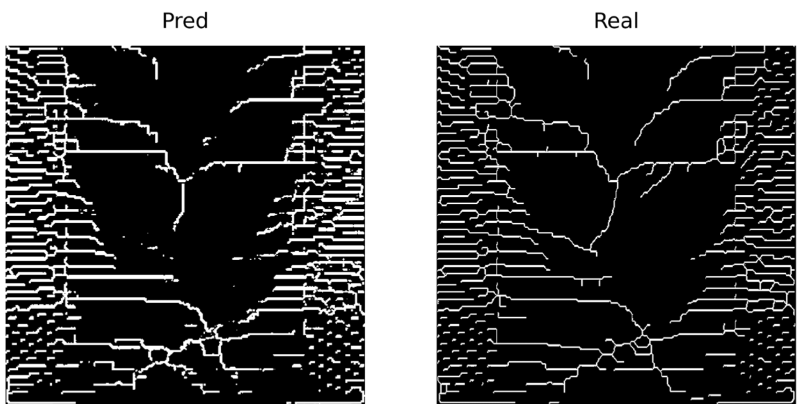


Figure 5. Typical prediction result of crack map

Sensitivity-Guided Neural Network for Parameter Calibration in Timber Structures and Joints

The study of timber structures is of great significance to sustainable development, but timber response behavior is complex, and the corresponding physical model parameters are numerous, making it difficult to calibrate a model effectively. A neural network-based method was developed to tackle this bottleneck. It uses response behavior as its input and predicts a group of reasonable parameters efficiently. Sensitivity analysis is embedded in the loss function to guide the training process. Case studies on timber trusses with steel-in-plate joints were carried out. The selected physics-based models for steel-in-plate joints with 80 flexible parameters, together with the simulated behavior based on calibrated parameters, are shown in Figure 6. Two journal papers from this project are under review in top journals (Earthquake Engineering & Structural Dynamics, and Engineering Structures).

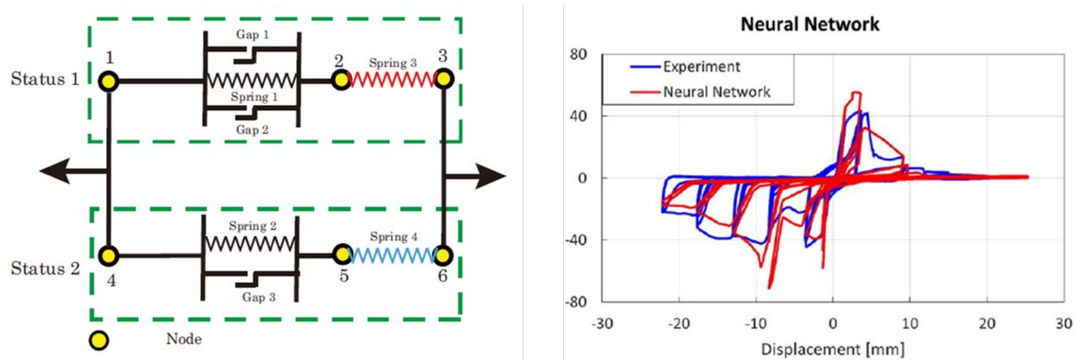


Figure 6: Selected physics-based model and the simulated behavior based on calibrated parameters

Researchers supported through this project include Dr. Jinhui Yan (UIUC, assistant professor), Dr. Yasutaka Narazaki (ZJU; assistant professor), Dr. Xuguang Wang (UIUC; postdoctoral researcher), Dr. Yongjia Xu (ZJUI; postdoctoral researcher), Ze Zhao (UIUC; graduate student), Qiming Zhu (UIUC, graduate student), and Chenyu Zhou (ZJUI, graduate student).

Photogrammetry-based computational fluid dynamics

Computational fluid dynamics (CFD) is the cornerstone of the design and analysis process in many engineering applications. However, creating a 3D mesh-based model of in-use structures that can be used by conventional boundary-fitted CFD methods is labor-intensive, time-consuming, and sometimes impossible. Due to the challenges introduced by geometry complexity and lack of design information, it is often difficult to perform an accurate and efficient CFD analysis of these objects. This project overcomes these challenges by proposing a novel photogrammetry-based CFD framework for simulating in-use structures whose design models and analysis meshes are hard to obtain. The proposed framework integrates machine learning-based 3D point cloud reconstruction of structures from 2D images obtained from portable devices (e.g., cell phones and drones), as shown in Figure, and an immersogeometric approach that can carry out flow analysis directly on reconstructed point clouds. The technical details of point cloud reconstruction techniques and the immersogeometric analysis method were studied in the project. A simulation of flow past a standard 12 oz soda can that was reconstructed using photogrammetry was conducted and compared with the reference solutions to assess the accuracy of the approach. The proposed photogrammetry-based CFD was also applied to simulations of a bell tower at the Zhejiang University International Campus (Figure 7) and the Kavita and Lalit Bahl Smart Bridge on the University of Illinois Urbana-Champaign (UIUC) campus (Figure 7) to demonstrate the robustness of the framework and its applicability to real-world in-use civil structures.

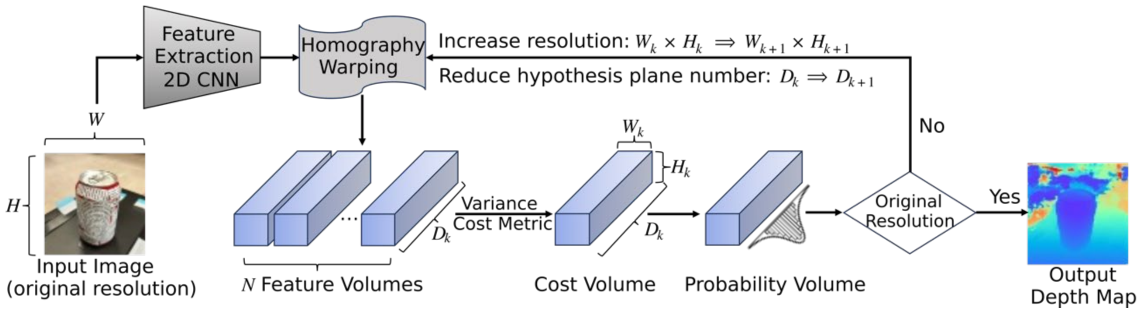


Figure 7: The overall architecture of the machine learning-based point cloud reconstruction method

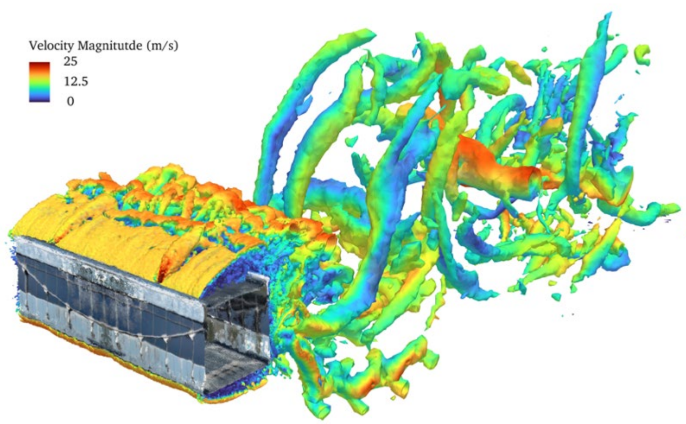


Figure 8: The CFD analysis result on the point cloud representation of the Bell Tower and Smart Bridge

Thrust 5: Thrust Integration

Ann Sychterz (UIUC), Zhizhen Zhao (UIUC), Mark D. Butala (ZJUI), Binbin Li (ZJUI)

Thrust Highlights

The thrust integration (TI) team continues in its role to explore and solidify interaction pathways between the other thrusts and to act as a nexus for collaboration between CIRCLE team members. A significant team effort involved the transition and evolution of TI personnel between the initial and second project phases. Momentum is building and guidance and suggestions from the CIRCLE International Advisory Board have provided renewed focus. Close collaboration with the Energy Thrust team has yielded a forthcoming journal publication on urban electricity demand forecasting based on residential smart meter data.

Energy Grid Life Cycle Assessment for Adaptive Structures as Transport Stations

The TI team has been embarking on new science to develop life cycle assessment (LCA) of adaptive structures at vehicle charging stations. This work links the thrusts of built environment, energy, and transportation from this initiative. Adaptive shelters are proposed for charging stations as they can be transported in a compact state and deployed on site through actuation, which is much faster than traditional construction. A digital twin has been created of a scale model of the shelter (Figure 9) that mimics the rolling of an armadillo. Origami as a form of structural design is novel and provides new architectural pathways. The model is built using a form-finding method, called dynamic relaxation, which calculates nodal displacements and element forces through large deformations without inversion of the stiffness matrix, which is the basis for conventional FEMs. Energy grid consumption from the City of Chicago, in collaboration with the Energy Thrust, will be used in the life cycle assessment to determine impacts of adaptive structure actuation in a community. Regions in Chicago that would be candidates for installations, for example, where EV charging stations already exist, provide the closest basis of comparison. Distribution of adaptive transportation stations is currently under investigation with the Transportation Thrust.

Figure 9. Mid-scale adaptive origami transportation station [left] and digital model of structure [right].

Real-Time Monitoring and Modeling of the Zhejiang University International Campus

Efforts are underway to construct a digital twin of the ZJU International Campus. The effort includes contributions from ZJUI faculty and students, both under- and postgraduates. The overall digital twin infrastructure comprises three modules: modeling of the physical infrastructure, structural health monitoring, and event detection based on multiple video streams. The campus digital twin will utilize data routinely measured on campus from 1) water and power utility monitoring sensors, 2) CCTV video sources deployed throughout campus, and 3) structural health sensors, e.g., accelerometers, deployed in key structures. The goal is to first provide a real-time "nowcast" of the campus system state as in Figure 10. Work is underway to construct additional modules and to develop predictive and forecasting capabilities. These developments can translate into general digital twin infrastructure to support similar efforts in other thrust areas.

Figure 10. The user interface to the ZJU International Campus digital twin system under development by members of the Thrust Integration team.

Center Personnel

Faculty PIs and Co-PIs

- Mark Butala (ZJUI), Assistant Professor
- Ann Sychterz (UIUC), Assistant Professor
- Simon Hu (ZJUI), Assistant Professor
- Binbin Li (ZJUI), Assistant Professor
- Yanfeng Ouyang (UIUC), Professor
- Billie Spencer (UIUC), Newmark Endowed Chair
- Ashlynn Stillwell (UIUC), Associate Professor
- Yan Xiao (ZJUI), Distinguished Professor
- Yueping Xu (ZJUI), Professor
- Lei Zhao (UIUC), Assistant Professor
- Zhizhen Zhao (UIUC), Assistant Professor
- Tingju Zhu (ZJUI), Associate Professor

Other Faculty

- Yasutaka Narazaki (ZJUI), Assistant Professor

Postdocs

- Yongjia Xu (ZJUI)
- Xuguang Wang (UIUC)

Graduate Students

- Laura Gray (UIUC)
- Yifan He (UIUC)
- Qinru Hu (ZJUI)
- Zhoutong Jiang (UIUC)
- Christopher Lee (UIUC)
- Zhan Liao (ZJU)
- Xinfeng Liu (ZJU)
- Zihan Liao (ZJUI)
- Lianlian Pan (ZJUI)
- Sun Young Park (UIUC)
- Ruifeng She (UIUC)
- Peixiang Wang (ZJU)
- Yuhan Yan (ZJUI)
- Hongjie Yu (ZJU)
- Ze Zhao (UIUC)
- Ronghui Zheng (ZJUI)
- Chenyu Zhou (ZJUI)
- Qiming Zhu (UIUC)

Undergraduate Students

Undergraduate students Yueer Cai, Yutao Lai, Jianye Chen, Qi Hong, Zhekai Li, Haitian Liu, Benhao Lu, Ruihao Ma, Chenxiao Yu, Rongjia Sun, Yuxin Qu, and Haojia Cheng were actively engaged in laboratory/research work for CIRCLE.

Publications

Peer-reviewed journals

1. Shen, S. and Ouyang, Y. "Dynamic and Pareto-improving swapping of vehicles to enhance integrated and modular mobility services." To appear in *Transportation Research Part C*, 2023.
2. Jiang, Z., Shen, S., Ouyang, Y. "Planning of reliable targeted evacuation under the threat of disasters." *Transportation Research Part C*, 153: 104197.
3. Jiang, Z. and Ouyang, Y. "Reliable location of first responder stations for cooperative response to disasters." *Transportation Research Part B*, 149: 20-32, 2021.
4. She, R. and Ouyang, Y. "Efficiency of UAV-based last-mile delivery under congestion in low-altitude air." *Transportation Research Part C*, 122: 102878, 2021.
5. Liu, Q., Hu, S., Angeloudis, P., Wang, Y., Zhang, L., Yang, Q., and Li, Y. "Dynamic wireless power transfer system for electric-powered connected and autonomous vehicle on urban road network." *IET Intelligent Transport Systems*, May, 1–14, 2021.
6. Demartino C., Quaranta G., Maruccio C., Pakrashi V. (2021). "Feasibility of energy harvesting from vertical pedestrian-induced vibrations of footbridges for smart monitoring applications.", *Computer-Aided Civil and Infrastructure Engineering*.
7. Liu, J., Li, J., Chen, Y., Lian, S., Zeng, J., Geng, M., Zheng, S., Dong, Y., He, Y., Huang, P., Zhao, Z., Yan, X., Hu, Q., Wang, L., Yang, D., Zhu, Z., Sun, Y., Shang, W., Wang, D., Zhang, L., Hu, S., Chen, X.M. "Multi-scale urban passenger transportation CO_2 emission calculation platform for smart mobility management." *Applied Energy*, 331: 120407, 2023.
8. Hu, S., Zhou, Q., Li, J., Wang, Y., Roncoli, C., Zhang, L., Lehe, L. "High time-resolution queue profile estimation at signalized intersections based on extended Kalman filtering." *IEEE Trans Intelligent Transportation Systems*, vol. 23, no. 11, pp. 21274-21290, November 2022.
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2. Pesantez, J.E., Stillwell, A.S., and Li, B. (2022). "Smart Metered Data to Forecast Electricity Demand from Single- and Multi-family Residential Users." Conference presentation at American Geophysical Union Fall Meeting, December 12-16, 2022; Chicago, IL, USA.
3. Pan, L., T. Zhu, and C. Li (2021). Estimating Urban Greenspace Irrigation for 400 Cities in China: Implications for Urban Land Use and Water Management. AGU Fall Meeting, 13-17 December 2021, New Orleans, LA.
4. Gray, L.C., Zhao, L., and Stillwell, A.S. (2022). "Urban Climate Modeling to Quantify Runoff Reduction from Rain Gardens in 30 U.S. Cities." Conference presentation at American Geophysical Union Fall Meeting, December 12-16, 2022; Chicago, IL, USA.
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7. Shen, S. and Ouyang, Y. "Dynamic Swapping of Modular Vehicles to Enhance Shared Mobility Services." Presented at the 102nd Annual Meeting of Transportation Research Board, Washington DC, January 8–12, 2023.
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4. Qiming, Z. (2022). "A Hybrid Physical-based/Data-driven Computational Framework for Multi-physics Modeling of Metal Additive Manufacturing." Ph.D. Thesis, University of Illinois.

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BS ME Univ of Missouri-Rolla (1981), MS & PhD TAM UIUC (1983, 1985)

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Yongjia Xu

Postdoctoral Researcher, ZJUI

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Lecturer in Global Health, University of Edinburgh
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PhD Molecular Epidemiology, The Univ of Edinburgh (2007)

PgCert Digital Education, The Univ of Edinburgh (2014)

DREMES: Center for Pathogen Diagnostics

Annual report for the academic year 2022-2023

Center Overview

An essential component of an effective strategy for minimizing the impact of infectious diseases and defending against emerging pathogens and new epidemics or pandemics is pervasive and early diagnosis. Impactful diagnostic technologies must be rapid, cost effective, highly specific, and highly sensitive, regardless of whether they are used in a laboratory environment or at the point of care. The economic and human health impacts of the COVID-19 pandemic and antibiotic resistant microorganisms highlight the shortcomings in existing technologies for viral and bacterial detection and serological testing. Lack of access to effective tests, long waits to obtain results, and unacceptable false positive/negative rates contribute to quarantine failure, confusion among health authorities, and anxiety of the public. A fundamental limitation of current gold-standard pathogen diagnostics stems from their reliance upon detection of specific nucleic acid sequences, in RNA or DNA form, within the pathogen genomes using PCR. As a result, these tests require labor-intensive, laboratory-based protocols for pathogen isolation and lysis with multiple steps that require genome extraction and purification to remove inhibiting materials, enzymatic amplification of nucleic acids, thermal cycling, and interpretation of complex results by professionals. Likewise, animal-borne viral pathogens such as African swine fever virus have been responsible for enormous economic losses in the swine and poultry industries, having recently caused at least a quarter of the world's pigs to die in a year. Animal pathogens remain an economic threat to Chinese, American, and global agriculture. Similarly, food-borne bacterial pathogens such as *E. coli* O157:H7, *S. Typhimurium,* and *L. monocytogenes* in food samples can be very hazardous, representing an important cause of illness.

Leveraging the scientific and technological depth of a group of faculty members affiliated with the UIUC Grainger College of Engineering, ZJUI, ZJU main campus and medical school, we have a unique opportunity to continue the ZJU-UIUC Center-scale effort that integrates the entire *science-engineering-translation* pipeline for establishing a new paradigm of pathogen diagnostics. The Center for Pathogen Diagnostics (CPD) advances broad themes of fundamental engineering and scientific research, while developing innovative technologies to address the spectrum of challenges in pathogen diagnostics. Research themes include advanced sample processing, ultrasensitive detection, ultra-selective recognition of pathogen targets, and prediction of molecular interactions and future epidemics/pandemics. Our objectives will be achieved through exploration of molecular mechanisms, invention of novel sensor fabrication approaches, development of instrumentation for wearable, point of use, and laboratory-based usage scenarios. Importantly, CPD encompasses the exploration of artificial intelligence (AI) and machine learning (ML) methods to study molecular interactions to rapidly develop selective biomolecular probes, while using sensor data to inform epidemiological studies that can assist in prediction of future outbreaks. CPD investigators have complementary world-leading expertise in electrical and computer engineering, bioengineering, computer science, AI/ML/big data, and biochemistry. Through a multidisciplinary team-science approach, we integrate synergistic expertise in microfluidic sample handling, nanoparticle contrast agents, super-resolution imaging and analysis, diagnostic instrumentation, micro/nanofluidic devices, novel sensor fabrication, functional nucleic acids engineering, protein structure analysis and engineering, genome sequence analysis, AI/ML based data analyses and predictions.

CPD Faculty

Bashir, Rashid BIOE, UIUC | Cunningham, Brian ECE, UIUC | Hu, Huan ZJUI, ZJU | Lin, Yu ZJUI, ZJU | Liu, Qingjun BME, ZJU | Loskot, Pavel ECE, ZJUI

Shao, Fangwei ZJUI/ZJE, ZJU | Valera, Enrique BIOE, UIUC | Varshney, Lav ECE, UIUC | Wang, Xing BIOE, UIUC | Zhao, Yang ECE, UIUC | Zhou, Chun MED, ZJU

Center Highlights

1. *CPD is a mechanism for ZJUI undergraduate students to engage in leading-edge research with UIUC faculty*. Many of these students have been accepted by the graduate programs at prestigious universities, including: Ziyu Xiao (Georgia Tech), Yichi Zhang (Northwestern), Zhongqi Wu (UCSD), Zheng Fan (NUS), Shixin Chen (UIUC), Ruike Yan (EPFL), Kai Zhang (ETH Zyrich).
2. *CPD faculty are highly productive researchers in the field of pathogen diagnostics and sensing with >30 published papers in highly selective journals and conferences.*
3. *CPD is contributing to offering ZJUI-UIUC joint courses.* Biosensors (ECE 416, Cunningham and Hu) and Advanced Biosensors (ECE 516, Cunningham and Hu).
4. *The excellence of CPD students has been recognized with honors and awards during the funding period*. Hanwei WANG (Hong Fellowship).
5. *CPD research activities are leveraged into ~$11M of current grants and ~$40M of pending grants (including large research centers supported by NIH, NSF, CDC, EPA) directly related to pathogen diagnostics*. ZJU undergraduate and graduate students participating in the CPD take part in efforts to solve real-world problems through development of state-of-the-art engineering solutions.
6. *CPD faculty are actively involved in technology translation through the NIH-RADx Program to develop novel diagnostic platforms for the detection of SARS-CoV-2, influenza A, etc., in addition to Industry-supported projects sponsored by large companies (CSL Behring).* Translation activities include characterization of technologies with clinical samples, human factors/usability testing, manufacturability, and FDA inquiries.

Summary of Selected Projects

Project 1: APIPred: An XGBoost-based methods for predicting aptamer-protein interactions (<u>ZJUI undergraduate students driven projects</u>)

The widespread dissemination of the COVID-19 virus has increased the urgency in drug development and vaccine research. The traditional antibody-based drug discovery process has some limitations compared to aptamers, thus failing to recognize some regions of the antigen. Antibody production is also more time-consuming and expensive compared to in vitro selection process of specific aptamers. Aptamers are short single-stranded oligonucleotides with a defined three-dimensional structure. In recent times, aptamers have drawn significant attention and emerged as an alternative for diagnostics and therapeutics due to their high degree of selectivity, affinity, and specificity. Unlike antibody sequences, which comprise about 20 amino acids, aptamers contain only four nucleobases. This limits the diversity of functional side-chain groups, secondary and tertiary structures of aptamers, reducing the repertoire of target molecules that they can bind to. This poses a major challenge for generating the aptamer through the selection process called the "systematic evolution of ligands by exponential enrichment" (SELEX), which is a time-consuming process. Thus, developing a computational/in silico way to design aptamers is pertinent for the rapid generation of aptamers for multiple or rapidly mutating protein targets. Predicting possible aptamer sequences by computational mean can significantly reduce the selection time and cost, leading to quickly generating aptamers for epidemic management. A computational platform further allows us to exclude unlikely sequences and preparation of screening ingredients, thus resulting in a quicker synthesis of the desired aptamer than conventional SELEX.

To improve the accuracy of aptamer-protein interaction and to address the challenges faced by previously reported models and algorithm, we proposed "APIPred" – a novel model with multiple feature extraction of protein and aptamer (**Fig. 1**). Since using various distinctive feature extraction methods can derive a wide variety of useful information from protein-aptamer pairs, it is a logical strategy to integrate different feature types to enhance the performance of our model. For aptamers, we employed a combination of Kmer frequency and Reverse complement kmer frequency representation. For protein feature extraction, we used the primary structure as well as the three-dimensional information by taking multiple protein sequence representation methods: AAC, PAAC, and the Python package Pepfeature. Based on the multiple feature extraction strategies, key sequence features of proteins and aptamers are extracted efficiently. We compared the performance of multiple advanced deep-learning models, by using the reported training datasets. After analyzing the performance of each model, XGBoost showed the highest accuracy (96%) in predicting aptamer-protein interaction on the development dataset than previously reported models. We used molecular docking, MD simulation and SPR binding assays to validate the prediction algorithm.

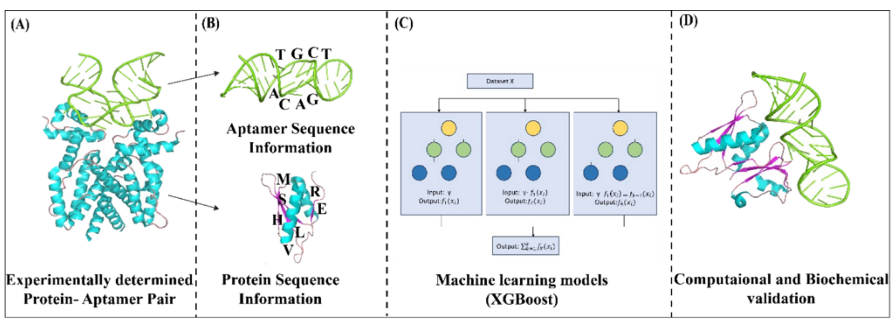


Fig. 1. Schematic of APIPred pipeline that involves machine learning models (XGBoost) for predicting aptamer-protein interactions.

Student and faculty participants: Zheng Fang (ZJUI), Shixin Chen (ZJUI), Zhongqi Wu (ZJUI), Addison Adrian (UIUC), Xinbo Wu (UIUC), Pavel Loskot (ZJUI), Fangwei Shao (ZJUI), Lav Varshney (UIUC), Xing Wang (UIUC), Saurabh Umrao (UIUC), Abhisek Dwivedy (UIUC)

Project 2: Direct direction of pathogens from whole blood samples

To address the challenges in pathogen identification in blood stream infections, we coupled our *bi-phasic* blood processing and reaction module with conventional bead-based mechanical pathogen lysis[83,84]. We developed a protocol (**Fig. 2a**) where 0.8 mL of whole blood with pathogens is loaded into a 2 mL tube containing a hypotonic red blood cell (RBC) lysis buffer and 100 µm glass beads. The blood is mixed with the RBC lysis buffer to lyse the majority of the cells and then centrifuged to pellet the intact cells. After discarding the supernatant from the RBC lysis, TE buffer is added, and mechanical bead lysis is performed. Any cell free DNA will be discarded with the supernatant in the above step and only intact cells will be retained. The blood lysate post-mechanical lysis from a single sample is aliquoted into eight 0.2 mL-PCR tubes (30 µL/tube) and dried for the *bi-phasic* amplification. A sample is considered positive for the target if any of these eight tubes show amplification. The drying is performed by heating (95°C, 10 min.), followed by the LAMP reaction protocol for *bi-phasic* format. The threshold time bar graphs for *MRSA* (**Fig. 2b**), *MSSA* (**Fig. 2c**), *E. coli* (**Fig. 2d**), and *C. Albicans* (**Fig. 2e**) spiked in 0.8 mL of blood is shown. The concentration range of the assay (1.2 x 10^4 to 1.2 CFU/mL) was chosen to overlap with the reported pathogen concentration in patients with blood stream infections[85-88]. In this case, MRSA, MSSA, *E. coli*, and *C. Albicans* serve as good targets to demonstrate our platform, not only because MRSA and MSSA are gram positive (thicker cell wall) whereas *E. coli* is gram negative, thus covering a range of bacterial infectious pathogens, but also because they have among the highest disease burden of all BSI pathogens[89]. *C. Albicans* (a fungal pathogen) was also detected using the mechanical lysis coupled with *bi-phasic* blood processing. In comparison to bacteria, fungus cells are larger (10-12 µm) and their cell wall composition includes layers of complex polysaccharides with proteins covalently bonded to this network, instead of peptidoglycan and lipid layers[90,91]. This makes the fungal cell wall mechanically strong and difficult to break. To disrupt the fungal cell wall, we included larger 0.5 mm diameter glass beads[92] for mechanical bead lysis. We reliably detected 1 CFU/0.8 mL of *Candida Albicans*. Overall**,** the detection of these pathogens was performed in 134 spiked samples (62 samples were at 10 or 1 CFU/0.8 mL of blood and 39 were negative control samples, **Fig. 4**). The LOD of our MRSA, MSSA and *E. coli* assays was 1.2 CFU/mL. These results show one order of magnitude improvement over the current state of the art *E. coli* LOD = 11 CFU/mL in the only FDA approved blood culture-free diagnostic platform[93]. *Assay validation for pathogen identification from clinical whole blood samples:* We also demonstrated the efficacy of our *bi-phasic* reaction to identify circulating pathogens in blood from clinical samples, using

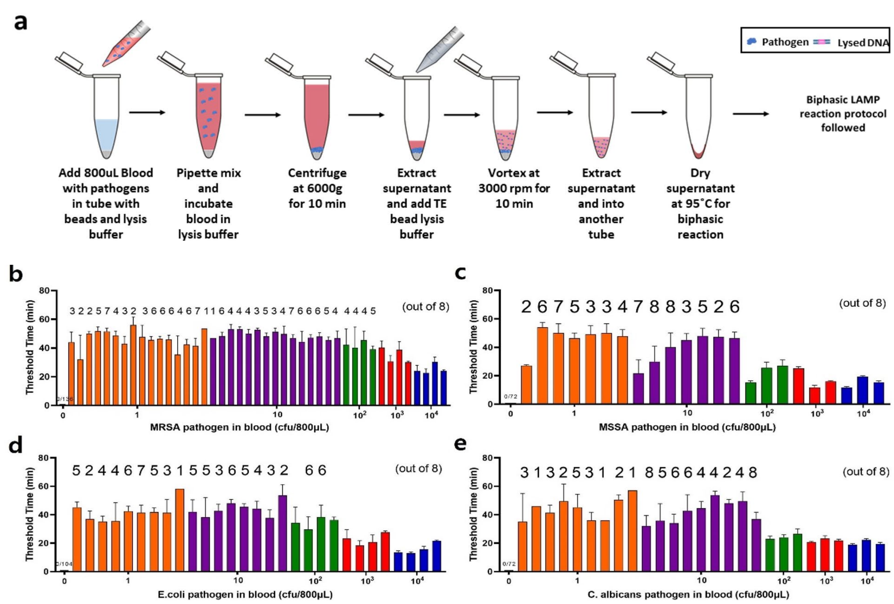
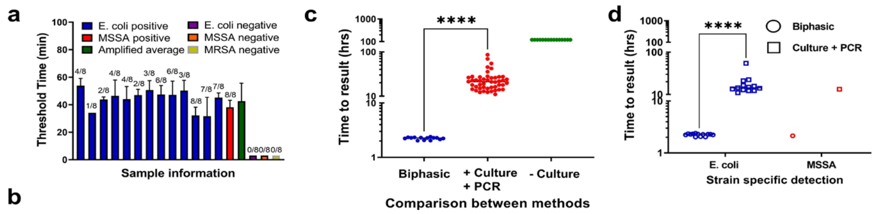


Fig. 2. Bi-phasic reaction coupled with mechanical lysis (bead beating) for LOD ~1 CFU/mL for MRSA, MSSA, E. coli and C. Albicans. **a)** Process flow schematic consisting of RBC lysis, mechanical lysis, drying, and bi-phasic reaction; **b-e)** amplification threshold data for **b)** MRSA**, c)** MSSA, **d)** E. coli and **e)** C. albicans in 0.8 mL of whole blood. If not all 8 tubes amplified for a sample, the number of tubes that amplified is indicated above. 1 bar = 1

the process currently followed in clinical practice as a control. We tested 63 clinical samples (15 negative, 48 positive) using our *bi-phasic* approach. The samples were first analyzed by Carle Hospital using the current clinical practice (blood culture and PCR) and then the results were compared with our results (*bi-phasic* approach). To analyze the samples, primer sets (specific to *E. coli*, MRSA, and MSSA) were used. Of the clinical samples tested, 14/63 samples (13 *E. coli* and 1 MSSA) were specific to targets that our primer sets can detect. **Fig. 3a** demonstrates the threshold times for 14 amplified samples (average threshold time = 42.5±10.1 min.). On the other hand, no amplification was observed in the analysis of negative samples (15) nor during the analysis of positive samples (40) for organisms other than *E. coli,* MSSA, and MRSA. **Fig. 3b** summarizes the sensitivity and specificity of our assay. Our assay correctly identified all samples that were positive for *E. coli* and MSSA and identified all samples that were negative or positive for other organisms as negative for *E. coli,* MSSA, and MRSA, resulting in a sensitivity and specificity of 100%. The overall and species-specific time to results are far lower with the new approach (**Fig. 3c-d**). On average, the *bi-phasic* reaction required 2.2 h to achieve pathogen identification but the clinical laboratory required 23.2 h. The t-test showed a statistically significant difference between the *bi-phasic* assay and clinical practices (p-value < 0.0001, **Fig. 3c**). This same behavior can be observed when analyzing the *E. coli* results (**Fig. 3d**). The results in **Figs. 2** and **3** have been published by our group.



	Our result	Blood culture + Identification result					
Species	Biphasic result	BC+ ID+	BC+ ID -	BC-	Metric	Value, % (n/N)	95% CI
E. coli	POS	12	0	0	Sensitivity	(12/12)	-
	NEG	0	9	2	Specificity	(11/11)	-
MRSA	POS	0	0	0	Sensitivity	-	-
	NEG	0	11	13	Specificity	(24/24)	-
MSSA	POS	1	0	0	Sensitivity	(1/1)	-
	NEG	0	11	0	Specificity	(9/9)	-
Overall	POS	13	0	0	Sensitivity	100%, (13/13)	75.29% to 100%
	NEG	0	31	15	Specificity	100%, (46/46)	92.29% to 100%

Fig. 3. Evaluation of the bi-phasic approach using clinical samples. **a)** Threshold times for 14 positive samples (13 E. coli and 1 MSSA), average time (42.5 min., green bar) and negative samples; **b)** table summarizing sensitivity and specificity of the bi-phasic approach against blood culture and PCR identification; **c-d)** time-to-result comparison between bi-phasic and

Student and faculty participants: Jongwon Lim (UIUC), Huan Hu (ZJUI), Min Jiang (ZJUI), Rashid Bashir (UIUC), Enrique Valera (UIUC).

Project 3: Towards Multiplex Detection of Zika, Dengue, and Chikungunya through Smartphone-Based Detection and Microfluidic Sample Processing

Detecting pathogens is needed quickly, accurately, and inexpensively to control the spread of infectious diseases. We developed the Pathtracker detector and detection module to provide detection for viruses for use outside of the laboratory without training, showing in previous work that sample processing required minimal pipettes. A detector that only requires a smart phone was able to detect Zika viruses down to only 1000 viral copies in whole blood. As Zika has similar symptoms to other insect carried viruses that require a blood test to diagnose, we are now going forward to create a multiplex version of our Pathtracker detector and detection module. Using the same RT-LAMP method as in the original platform, assays for Dengue-1 and Dengue-3, as well as Chikungunya have been developed (**Fig. 4**).

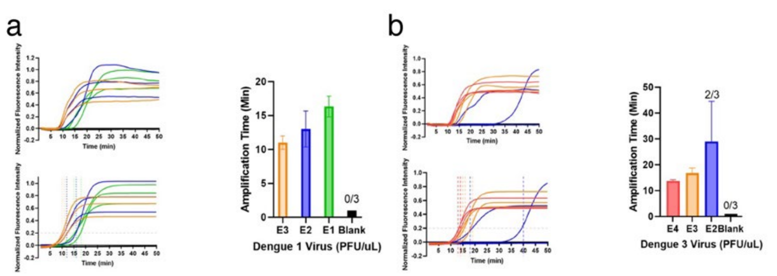


Fig. 4. RT-LAMP primer assay using (a) Dengue 1 or (b) Dengue 2 spiked into whole blood.

The Pathtracker Detector has been improved with a new design to decrease the size and to upgrade the heating components for more regular heating. The new heater feedback loop provides users the ability to know the temperature used in the test. The more compact size decreases costs and decreases humidity/outside air variability. The new design is outlined in **Fig. 5**. Primer drying was also achieved and found to be successful. This paves the way forward for multiplexing since the detector module can be prepared to detect multiple viruses from just one sample. It was tested within PCR tubes and has been found that primers remain active after 1 month of storage at room temperature.

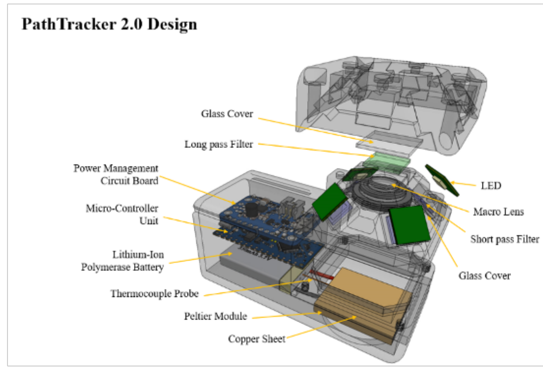


Fig. 5. Schematic of Pathtracker V2 that consists of a thermocouple probe with the full assembled instrument in the left-hand corner.

Student and faculty participants Amanda Bacon (UIUC), Katie Kaprowski (UIUC), Hankeun Lee (UIUC), Trung-Hieu Hoang (UIUC), Weijing Wang (UIUC), Aaron Jankelow (UIUC), Ninawa Odicho (UIUC), Minh N. Do (UIUC), Enrique Valera (UIUC), Rashid Bashir (UIUC), Brian Cunningham (UIUC)

Project 4: Hierarchical micro/nanostructures for breath analysis

We developed a scalable and low-cost fabrication process of producing bio-inspired silicon nanospikes that can kill bacteria physically as shown in **Fig. 6**. The next step is to replicate silicon nanospikes with plastic or polymer materials that can be used for bio-implants or antibacterial surfaces such as tubes for drinking water. We wrote a review paper on the use of silicon nanostructures and nanocomposites for antibacterial and theranostic applications. In addition, we developed a high aspect ratio atomic force microscopic (AFM) probe that is advantageous in obtaining accurate topography images of deep micro/nano trenches and can be used to measure surface tension of liquid droplets.

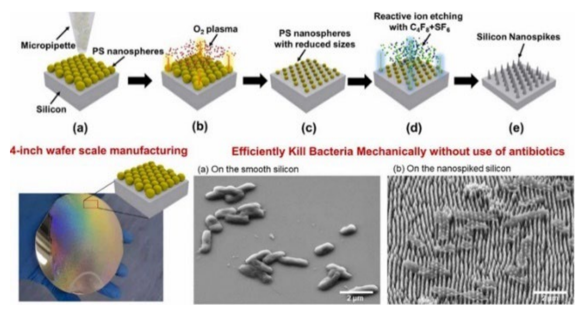


Fig. 6. Antibacterial surface made of silicon nanospikes.

To increase molecular sensing sensitivity, we have employed wafer-scale low-cost complementary vertically coupled plasmonic structures for surface-enhanced infrared absorption, as shown in **Fig. 7**. This fabrication approach consists of nanosphere lithography, reactive ion etching, and metal deposition and can be implemented on a four-inch wafer scale with low cost and high uniformity. The CVCP structure contains dense plasmonic nanoparticles inside a three-dimensional cavity nanoantenna array. The localized surface plasmon resonance between the top-bottom metallic nanoantenna couple generates a solid localized electric field inside the cavity. High simulated and experimental SEIRA electric-field enhancement was achieved by optimizing the height of the silicon nanopedestals. This study demonstrates a feasible fabrication approach for producing three-dimensional nanoantenna structures with high enhancement factors in a scalable fashion, empowering the practical application of SEIRA substrates structure for surface-enhanced infrared absorption. We combined silicon plasmonics with Au/silicon Schottky junctions to

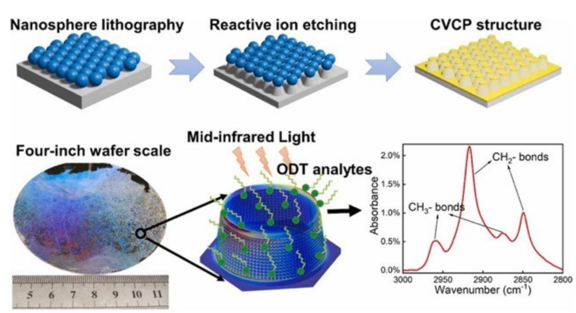


Fig. 7. Wafer-scale plasmonic structures for surface-enhanced infrared absorption.

achieve a photodetector with customized spectral response. Base on dozens or hundreds of individual photodetectors with different spectral responses, and using computational algorithms incorporating artificial intelligences, we constructed a miniaturized spectrometer for recognizing molecules.

Student and faculty participants: Feng Tian (ZJUI), Shaoxiong Wu (ZJUI), Xiaolei Ding (ZJUI), Brian Cunningham (UIUC), Huan Hu (ZJUI).

Project 5: Molecular Precision Mechanisms: Chiral Metamaterial Sensor

Our team advanced TIRF microscopy capabilities to introduce chiral super-resolution imaging. By incorporating a continuous wave (CW) laser and polarizing optics, we first investigated the localization of Cy5 molecules in a flow chamber, utilizing a specialized imaging buffer to observe and analyze molecular blinking (**Fig. 8**). Our ongoing work is now centered on refining localization algorithms for these molecules. Previously, we encountered a notable technical challenge from the disparity between co-registered microscopy and AFM images. Although microfabricated substrates provided an interim solution, we recognize their limited scalability and are turning our focus to digital image processing algorithms for a more sustainable resolution.

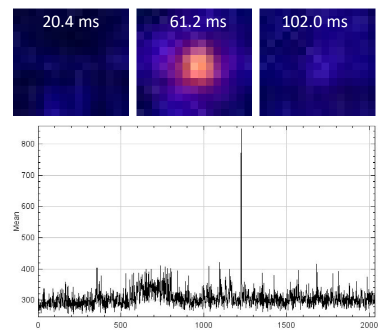


Fig. 8. Blinking of a Cy5 molecule in the imaging buffer, imaged using our TIRF setup.

Following the successful synthesis of enantiomeric nanoparticles (Wang Lab) that exhibited distinct circular dichroism (CD) spectra confirmed by CD spectroscopy in bulk solutions, we extended to tag these nanoparticles with fluorescent dyes for super-resolution imaging. Notwithstanding, we identified a challenge regarding nanoparticle sensitivity during ligand exchange. Addressing this will be a priority as we progress.

Student and faculty participants: Ziyu Xiao (ZJUI), Ruike Yan (ZJUI), Kai Zhang (ZJUI), Yichi Zhang (ZJUI), Yuemin Ma (ZJU), Hanwei Wang (UIUC), Ning Zang (ZJU), Yang Zhao (UIUC), Chun Zhou (ZJU), Yu Lin (ZJUI), Xing Wang (UIUC), Huan Hu (ZJUI).

Project 6: Point-of-care design and test of a portable, pocket-sized V-Pod SARS-CoV-2 detection system using a designer DNA nanostructure assay.

Rapid, sensitive, and inexpensive point-of-care (POC) diagnosis is a vital element for controlling and monitoring highly infectious diseases, including COVID-19. Nucleic acid-based molecular testing methods have inherent complexity that prevents translation to self-testing applications, while the predominant self-testing methods lack sufficient sensitivity to prevent viral transmission from asymptomatic carriers. Here, we report the design and characterization of a compact fluorimeter called a "Virus Pod" (V-Pod) that enables sensitive self-testing of SARS-CoV-2 viral load in saliva. The rechargeable battery-operated device is designed to read the fluorescence generated by Designer DNA Nanostructures (DDN) when they specifically interact with the outer spike proteins on intact SARS-CoV-2 virions (**Fig. 9**). DDNs are net-shaped self-assembling nucleic acid constructs that provide an array of highly specific aptamer-fluorescent quencher duplexes located at precise positions that match the pattern of spike proteins on the virion. The room-temperature assay is performed by simply mixing the test sample with the DNA Net sensor in a conventional PCR tube, placing the tube into the V-Pod, and closing the instrument's door. Fluorescent signals are generated when multivalent aptamer-spike binding releases fluorescent quenchers, resulting in rapid (5 minute) generation of dose-dependent output. The V-Pod instrument is a smartphone-linked palm-sized fluorimeter that performs laser excitation, photodiode fluorescence intensity quantitation, secure transmission of data to a software app through a Bluetooth connection, and result display to the user. We characterized the fluorescence sensing capability of the V-Pod through direct comparison with two commercially available laboratory-based fluorimeters. The detection limits for SARS-CoV-2 testing using a V-Pod were characterized using pseudo-typed wild-type (WT) SARS-CoV-2, and its real pathogenic variants (Delta, Omicron, and D614G) spiked into synthetic saliva. We show that the V-Pod and DNA Net assay achieves a clinically relevant detection limit of 3.92×10^3 viral genome copies/mL for pseudo-typed SARS-CoV-2 WT and 1.84×10^4, 9.69×10^4, 6.99×10^4 viral genome copies/mL for pathogenic Delta, Omicron, and D614G variants produced in cell cultures, representing sensitivity that is like laboratory-based PCR. The pocket-sized, instrument (costing less than US$300), inexpensive reagent cost/test ($1.26), single step, rapid sample-to-answer, and quantitative output represent a capability that is compatible with the needs of frequent self-testing in a consumer-friendly format that can link with medical service systems such as health providers, contact tracing, and infectious disease reporting.

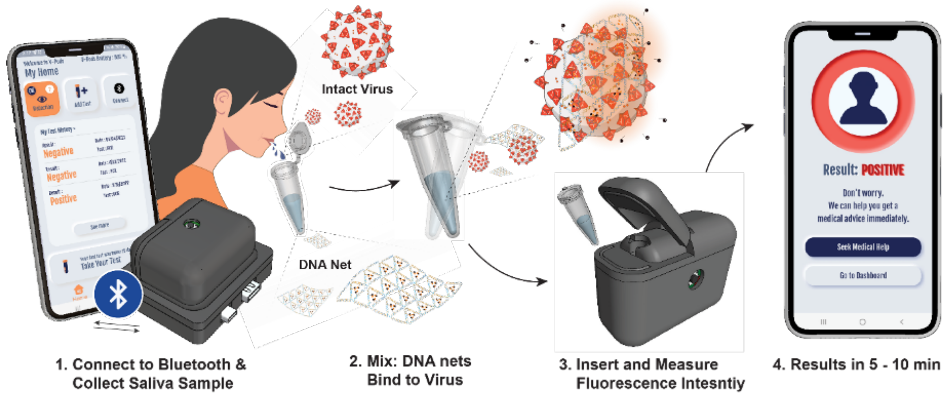


Fig. 9. Point-of-care testing workflow of the portable, pocket-sized V-Pod SARS-CoV-2 detection system using the DDN assay. 1. A Bluetooth™ connection is established between the V-Pod and a linked mobile device, followed by saliva sample collection into a PCR tube, pre-loaded with DDN reagents. 2. The PCR tube is gently shaken for 10 seconds. 3. The tube is inserted into the shape-matched slot for fluorescence measurements at 1-min intervals. 4. The app interprets the collected data giving diagnostic results in 5 – 10 minutes.

Student and faculty participants: Hankeun Lee (UIUC), Weijing Wang (UIUC), Neha Chauhan (UIUC), Fangwei Shao (ZJUI), Xing Wang (UIUC), Brian Cunningham (UIUC)

Project 7: Plasmon-Enhanced Multiplexed Lateral Flow Assay for SARS-CoV-2 RNA and Antigens

The need for fast, accurate, and affordable COVID-19 diagnostics has led us to develop a next-generation diagnostic platform that connects self-examination and point-of-care (POC) scenarios with patients' mobile devices. Lateral flow (immuno)assay (LFA) is a powerful diagnostic platform technology for home and point-of-care (POC) settings. It utilizes the ultra-brightness of plasmonic fluorescence as biomarkers. Using multiplex amplification-free detection of RNA and antigen, we plan to design a personal handheld fluorometer named "Test-Pod" (T-Pod). The device will communicate wirelessly with a linked mobile device to measure the fluorescent signal from the LFA test strip, as shown in **Fig. 10a**. However, traditional colorimetric LFA is approximately 1,000 times less sensitive than standard laboratory tests such as RT-PCR and enzyme-linked immunosorbent assay (ELISA). Plasmon fluorescence, as an ultra-bright fluorescent nanolabel in LFA, as shown in **Fig. 10b**, can greatly improve the sensitivity. The LOD of AuNPs-based LFA was approximately 100 pg/mL, while the LOD of p-LFA was 93 fg/mL, a 1,075-fold improvement. The structure of the T-pod has also been improved. Instead of scanning and detecting fluorescence signals with laser illumination, we gather images with an inexpensive CMOS camera with LED illumination. To improve image contrast, we reduced the wavelength of the excitation LED, which substantially reduced background fluorescence. As a result, we can get a very clear signal image of the lines from the test strip, as shown in **Fig. 10c**. We also changed the image transfer method. In view of the slow speed of Bluetooth image transmission, we changed the image transmission mode to first upload to Google Cloud via Wifi, and then download to our smartphone app by Wifi, which will greatly improve the transmission speed and user experience.

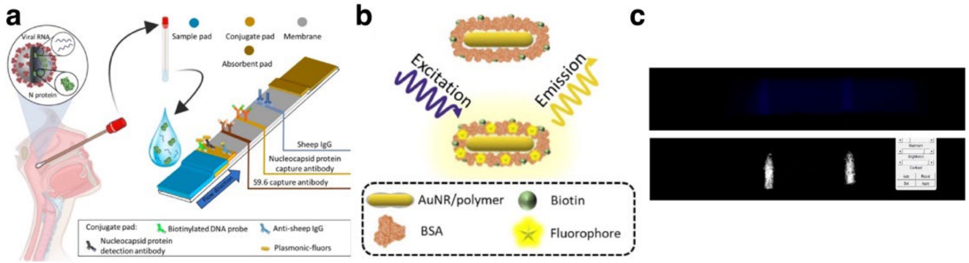


Fig. 10. Plasmon-enhanced multiplexed LFA. (a) Schematic illustration of the design of plasmon-enhanced multiplexed lateral flow assay for multiplexed detection of SARS-CoV-2 RNA and antigens in point-of-care settings. (b) Schematic illustration of plasmonic-fluor, employed as a bimodal (colorimetric+fluorescent) reporter element in LFAs, comprising of gold nanorod as plasmonic core, silane polymer as spacer layer, fluorophores and universal recognition element, biotin. (c) LFA images obtained before and after processing to extract the position and intensity of the lines in the test strip, comprised of accumulated plasmonic fluor tags.

Student and faculty participants: Anqi Tan (UIUC), Hankeun Lee (UIUC), Yuxiong liu (UIUC), Leyang Liu (UIUC), Srikanth Singamaneni (WUSTL), Brian T Cunningham (UIUC)

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- Ke, Xuanyu (ZJUI)
- Lee, Eunji (UIUC/POSTECH)
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- Li, Zhenfu (ZJUI)
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- Tang, Yufei (ZJUI)
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- Zheng, Kaijun (ZJUI)
- Zhu, Yuele (ZJUI)
- Zhu, Yutao (ZJUI)

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21. P. Loskot, “On Machine Integers and Arithmetic,” *Proc. 8th International Conference on Advances in Signal, Image and Video Processing (SIGNAL)*, Barcelona, Spain, 13-17 March 2023.
22. X. Wang, S. Shepherd, N. Li, C. Che, T. Song, Y. Xiong, I.R. Palm, B. Zhao, M. Kohli, U. Demirci, Y. Lu, B.T. Cunningham, "Ultrasensitive Detection of microRNA Using Photonic Resonator Absorption Microscopy," *Pittcon*, Philadelphia, PA, March 2023.
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24. “Plasmonic-Photonic Hybrid System for Enhanced Fluorescent-based Digital Resolution Biosensing”. Y. Xiong*, P. Barya*, S. Shepherd*, R. Gupta, L. D. Akin, J. Tibbs, H. K. Lee, S. Liu, S. Singamaneni, and B. T. Cunningham, *International Conference on Surface Plasmon Photonics (SPP10)*, Houston, Texas, May 2023.

Thesis and dissertation

1. “Metal-silicon nano-plasmons based spectral detection”, *Ph.D. Dissertation* by Dr. Shaoxiong Wu (ZJUI).
   Abstract: To build a miniaturized spectrometer, we propose a metal-silicon plasmonic structure and investigate its application in light enhancement and spectral recognition. Furthermore, we enhance the responsivity of the detectors by combining the charge injection mechanism with this plasmonic structure, and extend the application in refractive index sensor. Combining both nano-plasmonics with computational spectrometer technology, we demonstrated a feasible route for a super compact spectral detection chip by using metal/silicon plasmonic structure as well as Schottky junctions.
2. “Study of Mechanical and Acoustic Detection for Adjunctive Digital Treatment of Frozen Shoulder”, *M.S. Dissertation* by Cong Wang (ZJUI).
   Abstract: Due to the lack of digital monitoring equipment, intraoperative injury may occur if the surgeon does not control the manipulation force properly. To monitor the surgeon's force and the patient's shoulder status in real time, the mechanical detection system and acoustic detection technology were investigated in this paper. This thesis verifies the feasibility and reliability of the mechanical detection system, proves the feasibility of acoustic detection technology in practical applications, and provides a new digital aid solution for manipulation under anesthesia.

3. “Fabrication of hybrid low-dimensional material heterojunction photodetectors based on atomic force microscopy”, *M.S. Dissertation* by Xin Pan (ZJUI).
   Abstract: To address the challenges of fabricating hybrid low-dimensional material devices, this study proposes a method for preparing hybrid low-dimensional material photodetectors based on AFM nanomanipulation technology. This approach allows for device assembly and fabrication at room temperature and atmospheric pressure, with a simple process and minimal material damage. Utilizing AFM nanomanipulation as the technical means, the research investigates the motion behavior of nanowires under AFM manipulation, directly manipulating one-dimensional nanowires to form contacts with other materials, thus fabricating mixed-dimensional heterojunction optoelectronic devices and exploring the potential applications of AFM in heterogeneous integration.

Center for Adaptive and Resilient
Cyber-Physical Manufacturing Networks (CyMaN)

Annual Report, academic year 2022-2023

Center Overview

The fourth industrial revolution, also known as Industry 4.0, is an information-centric overhaul of manufacturing systems, technology, and practice. It seeks to evoke new capabilities in manufacturing by exploiting recent advances in computing, connectivity and data access, and computer-driven automation to enable near real-time, perceptive, and data-enabled manufacturing decision-making. We view this next generation manufacturing infrastructure as a cyber-physical system (CPS) that integrates manufacturing resources (mechanical and electrical equipment, and processes) with high-bandwidth communications and high- performance edge and endpoint computing. The Center for Adaptive, Resilient Cyber-physical Manufacturing Networks (CyMaN) aims to develop foundations for understanding how ubiquitous computing can achieve new levels of efficiency, flexibility, and reliability in manufacturing at all scales. We explore organizational frameworks that make advanced manufacturing more accessible and democratic, to spur innovation and enterprise. Specifically, we consider: (1) Interactions between autonomous hardware and software to produce verifiable and safe manufacturing processes; (2) The curation and use of networks and data to optimize performance; (3) Continuous analysis and learning for both low- and high-level decision-making and control; and (4) On-the-fly adaptation to changing needs and detected errors or risks to ensure resilience.

Comprised of faculty, students, and postdocs on both campuses, the personnel of CyMaN are involved in collaborative research and education. They meet on a regular (biweekly) basis for research presentations, center planning, and brainstorming discussions. Collaborations are all organized under a topical umbrella over smart manufacturing areas. This past year, the center worked with a post-doctoral researcher who has spent one year at ZJUI and will spend this next year at UIUC; organized a joint course in robotics for the two campuses; and organized the second symposium on CyMaN topics at the IEEE/ASME Conference on Automation Science and Engineering (CASE).

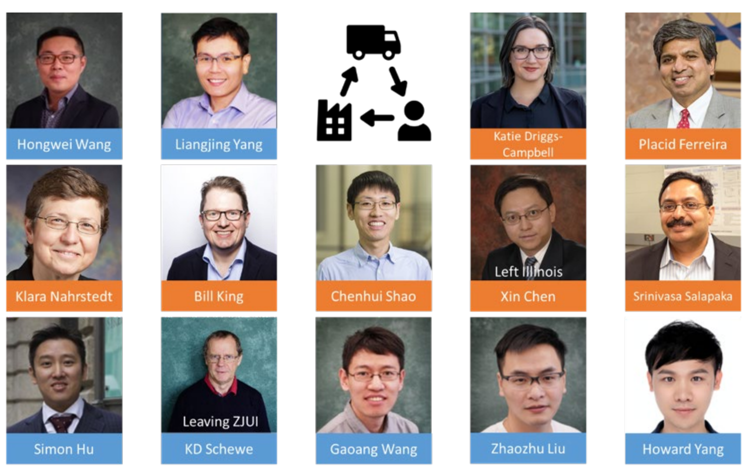


Figure 1: CyMaN Faculty

CyMaN Collaboration Highlights

Joint Research Highlights

Our team has established joint mentoring across the institutions for all students involved in AR-CyMaN projects. This has led to fruitful discussions, on-going research efforts, and joint publications. Our collaboration has also gained international attention through our second annual special session on Adaptive and Resilient Cyber-Physical Manufacturing Networks at the IEEE Conference on Automation Science and Engineering (CASE) 2023, which is one of the flagship conferences for the IEEE Robotics and Automation Society. Our research efforts have focused in five areas (cyber infrastructure, metrology, collaborative shop floors & assembly lines, anomaly detection, and planning & optimization), with equal representation from both ZJUI and UIUC faculty in each topic. Our list of publications is provided below.

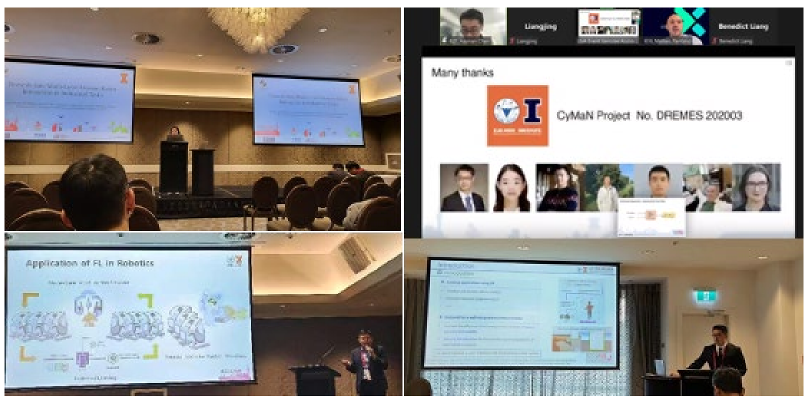


Figure 2: Photos from CASE2023 highlighting the CyMaN team

Joint Teaching Highlights

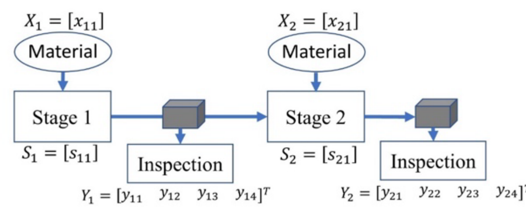
Professors Katie Driggs-Campbell and Liangjing Yang have co-taught ECE470/ME445 Introduction to Robotics and have updated the course content by developing new material. The course nominally focuses on the kinematics of robot manipulators (both in theory and with practical labs). We have developed new modules that use pick and place applications to motivate open challenges for robots in manufacturing settings. The joint course is going to have its second consecutive offering this spring. This course has acted as a proving ground for much of the research conducted in manufacturing networks, by having distributed labs at each institution that create a small network. Further, the robotics course development and the AR-CyMaN center have enriched the ZJUI undergraduate research experience by providing research opportunities. ZJUI students worked with Illinois PhD students who are ZJUI alumni, and mentored them on the research project and gave insights about the path to graduate school.

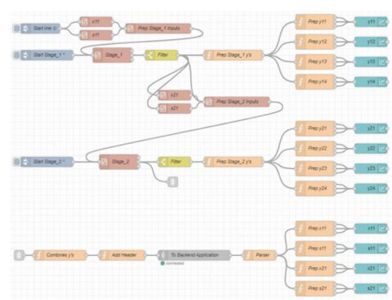
Project 1: Cyber Infrastructure for Manufacturing Networks

Liangjing Yang (ZJUI), Placid Ferreira (UIUC), Katie Driggs-Campbell (UIUC)

This project emphasizes fundamental cyber infrastructure for manufacturing. This effort has enabled new mechanisms for connecting processes and stakeholders to create flexible manufacturing networks. We have also designed novel ways to interface with low-level manufacturing processes, like assembly robots. Finally, we have developed simulation and modeling infrastructure through digital twins to help optimize manufacturing processes.

Manufacturing Networks: We have set up a networked facility using Operating System for Cyber-physical Manufacturing (OSCM) and several other components developed by the group, for both education and research. The OSCM team completed developed a MES (Manufacturing Execution System) application called Orchestrator for the operating system. This system routes jobs to work centers based on routes specified for them in a work order. It also monitors events emanating from work centers to identify the completion of the completion of work-tickets, to coordinate the progress of multiple jobs. An example job sequence is show to the right. Using Bayesian networks for root cause analysis and dispatch scheduling algorithms, the Orchestrator ensures that jobs meet their due-date constraints. This effort connects to the planning thrust, acting as a unifying framework for the research efforts. Using a low-code framework, Node-Red, a completely configurable simulator was developed for multi-station production lines (shown to the right). The simulator simulates the progress of jobs through the system along with feature characterization at the end of processing step to create features vectors for each part exiting the production line for the RCA decision process. This low-code interface is an example of how our work has lowered the barrier to entry for developing modules for manufacturing networks.

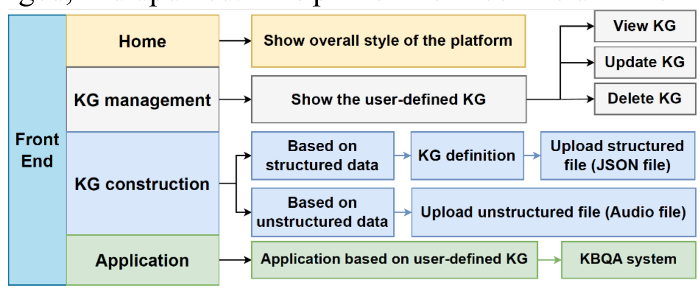




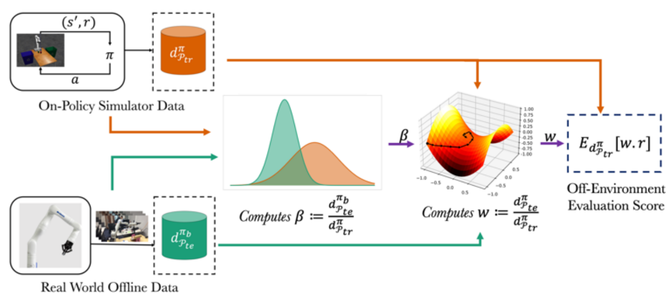
Immersive and Intuitive Interfaces: OSCM also acts as a cloud platform for an exemplar networked facility to interface groups with manufacturing machines, shopfloors, and testbeds. Yang and Ferreira have developed a mixed reality framework that uses OSCM to integrate remote (virtual) and local (physical) systems. We incorporated immersive technology for the development of human-robot collaborative control and man-machine interface, demonstrating our mixed reality-based interface for teleoperation of a robot micromanipulator (visualized above, right). Usability tests conducted on user subjects show significantly better learning curves using our immersive mixed reality-based

interface compared to conventional input devices including keyboard and mouse cursor for the operation of the micromanipulator.

Modeling Infrastructure: A key part of cyber infrastructure is how to incorporate domain knowledge into structured models. To this end, we have leveraged knowledge graphs (KG) to store and represent domain specific knowledge, specifically focusing on usability to lower barriers of entry. We developed Semi-Automated KG Construction and Application (SAKA, right), an easy-to-use platform for constructing knowledge graphs from various datatypes, where multiple versions of KGs can be stored, viewed, managed, and updated. This platform can collate data from multiple sources (e.g., audio) and is equipped with question answering modules.



We also explored how to leverage offline data to estimate how a simulated process will behave in the real-world, using an off-environment evaluation method. We developed a new approach to evaluate the real-world performance of simulated processes without deploying them in the real world, saving engineering effort and deployment time. The proposed approach incorporates a simulator along with real-world offline data to evaluate the performance of any policy using the framework of Marginalized Importance Sampling (MIS), learning the relationship between the simulated and the real-world data. The resulting ratio allows us to modify simulated data and evaluate performance (e.g., safety, efficiency, accuracy) without testing in hardware, thus improving the simulator's (digital twin's) ability to capture real-world phenomenon.

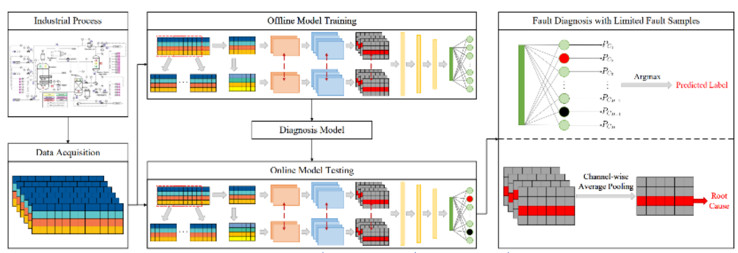


Project 2: Automated Metrology for Resilient Manufacturing Processes

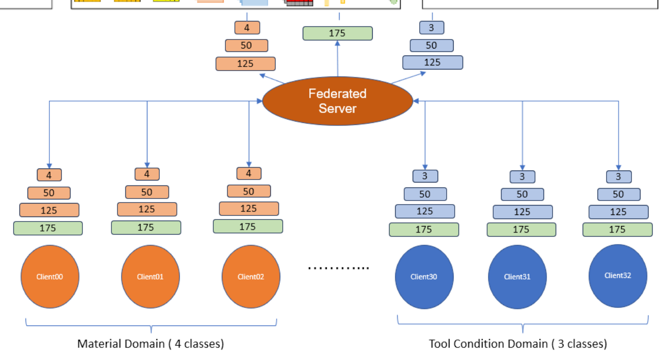
Zuozhu Liu (ZJUI), Hongwei Wang (ZJUI), Bill King (UIUC), Chenhui Shao (UIUC)

A crucial part of additive manufacturing (AM) quality control is the decision to accept or reject parts based on part geometry and the presence of defects. Traditional methods for part qualification in manufacturing are based on extensive geometry measurements collected from consistent manufacturing processes and machine configurations. This project looks at novel computer vision techniques for automating quality control and new frameworks for collating and parsing datasets collected across manufacturing networks.

Automating Quality Control: We have developed computer vision methods for additive manufacturing defect detection. We train a Vision Transformer (ViT) to automatically detect internal hidden defects in parts from X-ray Computed tomography (CT) scans. We consider a nozzle part that has millimeter-scale 3D fluid channels, like those used in modern combustion systems and medical equipment. We used general knowledge of internal defects, design automation, and computer vision to create synthetic CT data with realistic defects. The ViT model was trained using a large set of synthetic data and tested using CT data from real nozzles parts. We produced and scanned over 250 nozzle parts using SLA resin printers including nozzles that were defect free, and others having realistic defects. After training on synthetic data, the models could detect and classify several types of real defects with an accuracy greater than 90%. This work shows the potential for scalable automatic defect detection in AM parts using CT scanning and synthetic data.Additionally, we have conducted extensive work on fault diagnosis with limited samples, identifying root cause features in process faults, and improving fault diagnosis through novel sampling techniques (right).



Networked Learning for Manufacturing Processes: A unique architecture has been devised to address collaborative learning challenges arising from two distinct Ultrasonic Metal Welding (UMW) datasets with identical features (visualized below). Assessing all data collected to extract features as well as from each dataset individually. This design ensures that the initial features capture shared elements common to both datasets, while subsequent features specialize in the unique classification requirements of each dataset. A significant contribution of this project is enhancing domain generalization and accuracy across various dataset combinations and domains. This project is conducted on Raspberry Pis, which serve as representative devices within a manufacturing setting. This highlights the feasibility of implementing such collaborative learning approaches on resource-constrained edge devices, especially in real-world manufacturing environments. Furthermore, RabbitMQ is employed as the message broker, facilitating efficient communication between the distributed Raspberry Pi nodes.

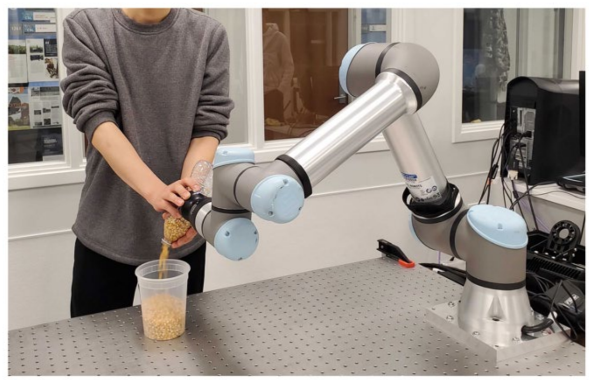


This project underscores the potential of Federated Learning in addressing complex real-world scenarios, where data heterogeneity and diverse classification requirements demand sophisticated solutions for enhanced collaboration and overall performance.

Project 3: Adaptive and Collaborative Shopfloors and Assembly Lines
Liangjing Yang (ZJUI), Gaoang Wang (ZJUI), Katie Driggs-Campbell (UIUC)

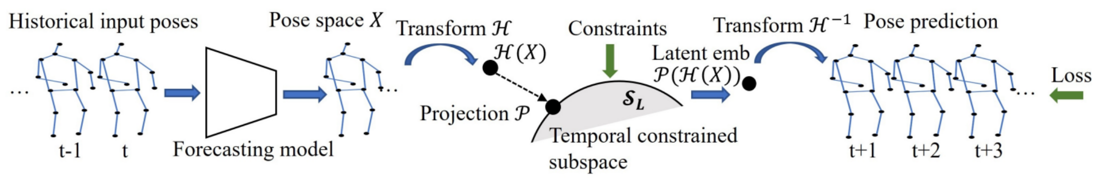
The foundation of this project is in integrating laboratory platforms with the framework in Project 1 and optimizing assembly processes to assist the assessments in Project 2. This project focuses on enabling intelligent, collaborative manufacturing processes and detecting and tracking human workers.

Automation for Assembly Lines: We developed a potential field-based interactive collaborative control and an immersive mixed-reality based interface for teleoperation based on a form of kinesthetic guidance that embeds task-specific motion plans and user-centric assistive control as show. This work unifies robot planning and HRC control using a virtual potential field generated from pre-acquired data. We further explore immersive mixed reality-based interface for teleoperation to facilitate interactive robot teleoperation. We have extended this planning to consider common warehouse tasks with multiple steps (e.g., stowing objects, pouring and filling bins) by combining behavior primitive with learning-based planning. First, we have developed a method to learn a generalizable robot stowing policy from predictive model of object interactions and a single demonstration with behavior primitives (prototypical human motions). Our framework enables robots to proficiently execute long-horizon stowing tasks from a single demonstration obtained from a human co-worker. Second, we have developed a framework for understanding human worker objectives through physical interaction. We simultaneously infer the human's goal (e.g., part to be assembled) as well as optimal actions (e.g., behavior primitives).



Human Worker Detection and Tracking: To enable collaborative environments, we need techniques to detect and track the humans operating with the automation. First we investigate robust human pose detection. When applying a pre-trained 2D-to-3D human pose lifting model to a target unseen dataset, large performance degradation is commonly encountered due to domain shift issues. We observe that the degradation is caused by two factors: 1) the large distribution gap over global positions of poses between the source and target datasets due to variant camera parameters and settings, and 2) the deficient diversity of local structures of poses in training. To this end, we combine global adaptation and local generalization in PoseDA, a simple yet effective framework of unsupervised domain adaptation for 3D human pose estimation. We also propose local pose augmentation (LPA) to enhance the diversity of 3D poses following an adversarial training scheme consisting of 1) a augmentation generator that generates the parameters of pre-defined pose transformations and 2) an anchor discriminator to ensure the reality and quality of the augmented data. Our approach improves upon the previous state-of-the-art method by 10.2%.

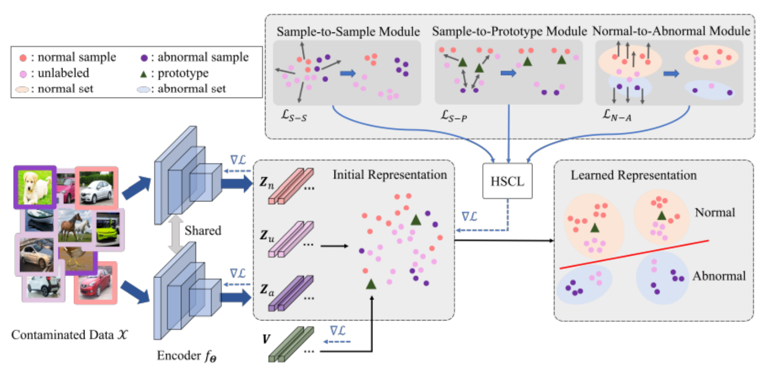
Further, we explore human pose forecasting is a sequential modeling task that aims to predict future poses from historical motions. We consider the temporal constrained feasible solutions for human pose forecasting, where the predicted poses of input historical poses are guaranteed to obey the temporal constraints strictly in the inference stage. Rather than direct supervision of the prediction in the original pose space, a temporal constrained subspace is explicitly learned and then followed by an inverse transformation to obtain the final predictions.



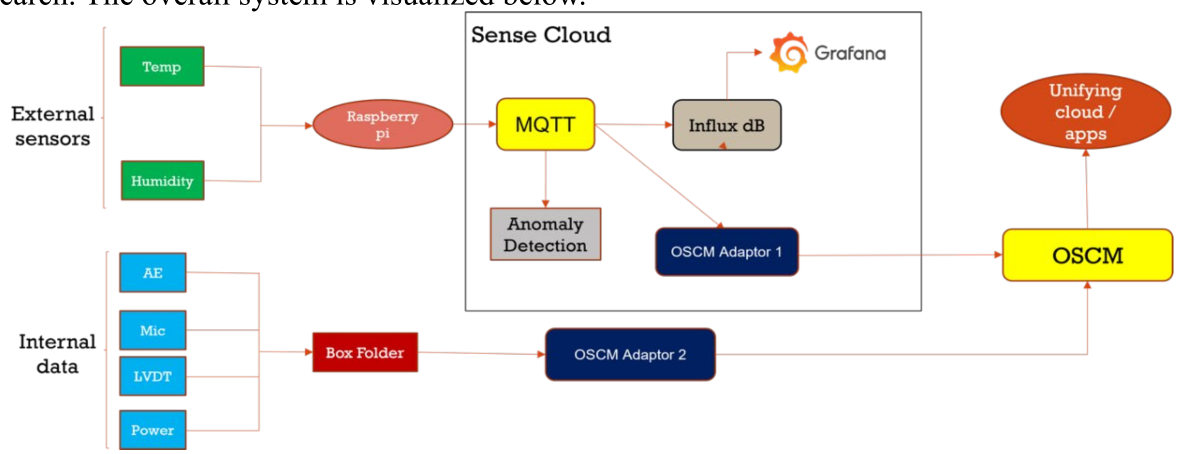
Project 4: Understanding Anomaly and Rare Events in Manufacturing Processes
Gaoang Wang (ZJUI), Klara Nahrstedt (UIUC), Chenhui Shao (UIUC), Placid Ferreira (UIUC)

Understanding rare events is a crucial part of creating large scale manufacturing systems that are resilient to errors and anomalous events. This project focuses on new techniques for detecting anomalies and the integration of comprehensive sensing technology into the cyber infrastructure.

Detecting Rare Events: Anomaly detection aims at identifying deviant samples from the normal data distribution. Contrastive learning has provided a successful way to sample representation that enables effective discrimination on anomalies. However, when contaminated with unlabeled abnormal samples in training set under semi-supervised settings, current contrastive-based methods generally 1) ignore the comprehensive relation between training data, leading to suboptimal performance, and 2) require fine-tuning, resulting in low efficiency. To address the above two issues, in this paper, we propose a novel hierarchical semi-supervised contrastive learning (HSCL) framework, for contamination-resistant anomaly detection. Specifically, HSCL hierarchically regulates three complementary relations: sample-to-sample, sample-to-prototype, and normal-to-abnormal relations, enlarging the discrimination between normal and abnormal samples with a comprehensive exploration of the contaminated data. HSCL achieves state-of-the-art performance in multiple scenarios, such as one-class classification and cross-dataset detection.



Sensor Integration into Cyber Infrastructure: This project aims to integrate data from environmental sensors (captured through SENSELET system) with internal cyber data into the OSCM infrastructure, a platform for manufacturing environments. By combining these data sources, we can benefit from it for anomaly detection and have a comprehensive dataset for cyber-physical manufacturing networks. One of the interesting design choices was that SENSELET became connected to an OSCM client/adaptor, so SENSELET was modeled as sensors that are feeding data to the OSCM client and then client streams the data to OSCM server where through RabbitMQ the data are available to different applications. The SENSELET system is a group of external sensors (temperature and humidity) streaming their data via MQTT to a SENSELET server, where the data are (a) stored temporarily in INFLUX DB, and (b) streamed to OSCM Client. The SENSELET server servers as an "adaptor" to the external sensors. This architecture is scalable because we can then attach also other external sensory acquisition systems to OSCM. We focused on integrating data from an ultrasonic metal welding (UMW) machine, including acoustic emission, microphone, LVDT, and power signals, alongside temperature and humidity sensors. The integration scheme involves data collection, publishing, and storage in OSCM. We have used a Raspberry Pi for capturing environmental data, MQTT brokers, and OSCM adapters for data flow. Additionally, the project addresses the challenges of handling high-frequency internal data. We've tackled challenges like data synchronization and handling high-frequency data. By implementing the efficient scenario for data collection and storage, we are now employing a feature extraction method based on Discrete Wavelet Transform (DWT) for more accurate predictions. This approach allows us to get close to real-time data streams, significantly enhancing our ability to analyze and apply the data in UMW research. The overall system is visualized below.



Project 5: Planning and Optimization for Flexible Manufacturing Networks

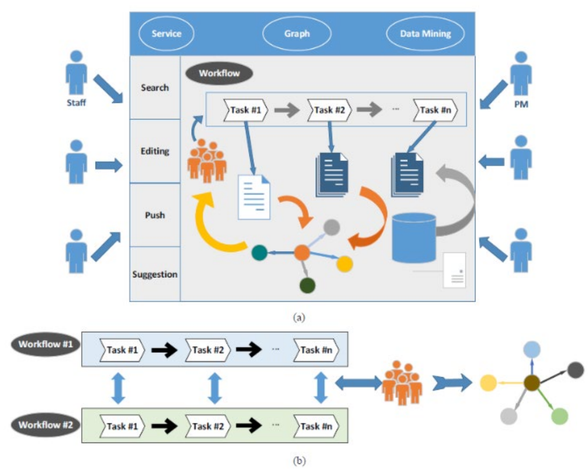
Hongwei Wang (ZJUI), Placid Ferreira (UIUC), Srinivasa Salapaka (UIUC)

This project has been exploring modeling and planning techniques that underlie the development of a flexible manufacturing network. We developed frameworks for scheduling jobs across a manufacturing network of shop floors and constructed graph representations of manufacturing tasks and workflows.

Planning for resource allocation: We have introduced an innovative conceptual framework devised to address the complex job-shop scheduling problem. This problem entails the allocation of a predetermined set of jobs onto a specified array of machines, while adhering to three pivotal constraints: (1) Precedence Order Constraint: Jobs are characterized by predefined sequences on machines, ensuring the satisfaction of a well-defined manufacturing process; (2) Machine Capacity Constraint: Machines are subject to capacity limitations, dictating the maximum number of jobs they can concurrently undertake; and (3) Processing Time Constraint: Each job assigned to a machine necessitates a minimum processing time to be completed. The efficacy of our proposed framework has been evaluated through a series of comprehensive simulations, encompassing diverse synthetic manufacturing scenarios. Our findings reveal that the framework consistently exhibits exceptional performance across various manufacturing scenarios. In particular, it outperforms Google OR tools in terms of minimizing total manufacturing time in small-scale manufacturing setups. Additionally, in the context of large-scale manufacturing environments, our framework provides an optimal solution which perfectly matches with the mentioned tools.

Connecting this work with Projects 2 and 4, we have developed a framework to discern "outlier" samples that exhibit significant deviations from the "mainstream" data. To address uncertainties in applications of interest, we incorporate a stochastic state-transition model. Additionally, we consider a stochastic policy for the optimization problem at hand. To encourage effective exploration during policy optimization, we leverage the Maximum Entropy Principle (MEP). Our proposed approach facilitates model-fitting optimization through two distinct methodologies: Dynamic programming, specifically value iteration, and online reinforcement learning, specifically Q-learning. By leveraging the recursive Bellman equations derived under the MEP, our approach enables iterative value computation and policy optimization, thus enhancing the accuracy and efficiency of anomaly detection within time-series data.

Manufacturing Workflows: Knowledge graphs can represent complex infrastructure and production models which can then be used for optimizing manufacturing workflows. Industrial knowledge graph construction includes named entity extraction and relationship extraction techniques. Graphs constructed based on the collaborative data space of the manufacturing industry’s value chain often take the form of open knowledge graphs. Link prediction in open knowledge graphs is crucial for applications such as question answering and text comprehension. We demonstrate knowledge graph construction and storage techniques using manufacturing industry data.



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Center for Adaptive and Resilient
Cyber-Physical Manufacturing Networks

Personnel List

UIUC Personnel List

Faculty

- [Co-Lead] Katie Driggs-Campbell, Assistant Professor
- [Co-Lead] Placid Ferreira, Professor
- Bill King, Professor
- Chenhui Shao, Assistant Professor
- Klara Nahrstedt, Professor
- Srinivasa Salapaka, Professor

Students

- Haonan Chen – 25% appointment, supervised by Driggs-Campbell (UIUC), Collaborating with Wang (H) (ZJUI)
- Tianyu Yang – 25% appointment, supervised by King (UIUC), Collaborating with Liu (ZJUI)
- Alisina Bayati – 25% appointment, supervised by Salapaka (UIUC)
- Ahmadreza Eslaminia – 50% appointment, supervised by Shao and Nahrstedt (UIUC), Collaborating with Wang (G) (ZJUI)
- Ricardo Toro, supervised by Ferreira (UIUC), Collaborating with Yang (L) (ZJUI)
  Graduated May 2023

ZJUI Personnel List

Faculty

- [Co-Lead] Wang Hongwei, Professor (ZJUI Institute)
- [Co-Lead] Yang Liangjing, Assistant Professor (ZJUI Institute)
- Yang Hao, Assistant Professor (ZJUI Institute)
- Wang Gaoang, Assistant Professor (ZJUI Institute)
- Liu Zuozhu, Assistant Professor (ZJUI Institute)

Postdoc

- Peng Peng (ZJUI), advised by Wang (H), Driggs-Campbell, and Ferreira

Students

- Mengxuan Li, Supervised by Wang (H) (ZJUI), Collaborating with Driggs-Campbell (UIUC)
- Zixuan Wang, Supervised by Wang (H) (ZJUI)
- Yufei Zhang, Supervised by Wang (H) (ZJUI)
- Zhenyu Zong, Supervised by Yang (L) (ZJUI), Collaborating with Ferreira (UIUC)

Heterogeneous Integration for Neuromorphic Integrated Circuits

Annual Report – For the 2022 through 2023 academic year

Project 1: Heterogeneous Integration for Neuromorphic Integrated Circuits

Jose Schutt-Aine, (UIUC)

The human brain is widely regarded as the ultimate computing engine with extremely high energy efficiency, reliability, and learning and cognitive capabilities. Although the field of brain-inspired or neuromorphic computing has made tremendous strides in the last decade, current neuromorphic systems have yet to demonstrate the cognitive functionality of mainstream artificial intelligence (AI) methods (e.g., deep nets) or the energy efficiency approaching that of the brain. The key reasons for this are (1) mismatch between the properties of the mainstream devices and architectures and those of the brain and (2) lack of heterogeneous integration strategies to deliver neuromorphic systems at scale. This report addresses efforts from the seed funding which has led to the creation of a proposed Center for HeterogeneouslY integrated BRain InspireD computing (HYBRID), whose goals will be to develop a unified "materials-to-systems" program with a strong emphasis on hardware-software co-design to realize neuromorphic systems with 1000x improvements in speed, energy, and cognitive abilities compared to state-of-the-art approaches with an emphasis on radically improving the speed and energy efficiency of neuromorphic systems and to make a sustained and meaningful impact on the next-generation computing infrastructure. HYBRID will be a funded major program within DREMES, starting with the 2023-2024 academic year.

During this year, our efforts focused on the creation of the HYBRID Center and the identification of various themes that will be essential for its operation. The team was assembled and a proposal for research was defined with the following themes (Figure 1): (1) Exploring neurobiology-driven algorithms and hardware software co-design methodologies; (2) Modeling intelligent materials and devices; (3) Designing scalable circuit macros and architectures; (4) Integrating heterogeneous components and chiplets at the system level.

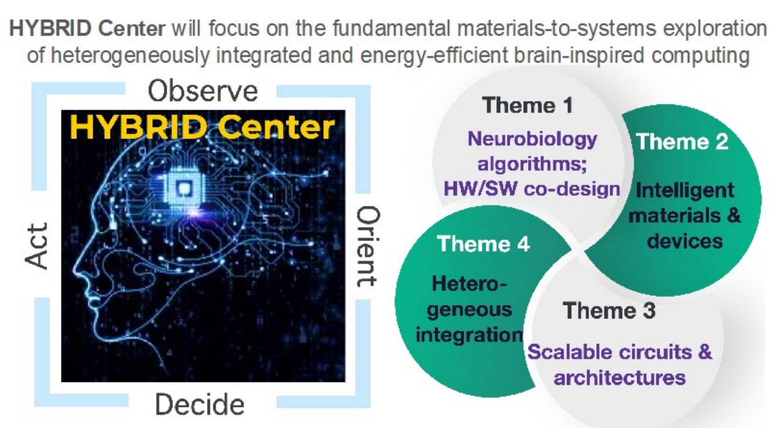


Figure 1. HYRBID Center Vision and Research Themes.

Our team plans to leverage our combined expertise to establish leadership in "Engineering sciences for data sciences and flexible manufacturing" and "Engineering sciences at the nexus of energy, environment, and sustainable development." HYBRID's convergent research is ambitious as it leverages neural design principles with rigorous information-theoretic foundations and materials-to-systems approaches toward overcoming the longstanding speed and energy limitations of today's AI hardware.

Since the inception of the center from January through August 2023, our focus has been on virtual meetings between the UIUC and ZJU sites. Meetings were held bi-weekly during which the PI and their graduate students presented preliminary work on the four center themes. Some of the topics covered and discussed included:

- Co-design challenges for heterogeneous integration (Schutt-Aine)
- Novel materials for brain-inspired computing (Rakheja)
- New computing architectures optimizing memory access (Ghose)
- Fast simulation of nanometer-scale devices (Schutt-Aine)
- PEEC method for electromagnetic extraction (Tan, Li)

These discussions set the stage for comprehensive research in which all the teams are fully engaged at the start of the coming 2023-2024 academic year.

Personnel List

<u>**Personnel List**</u>

Faculty

- Jose Schutt-Aine, Professor, ECE (UIUC)
- Wenchao Chen (ZJUI)
- Li Da (ZJUI)
- Hanzhi Ma (ZJUI)
- Shurun Tan (ZJUI)
- Said Mikki (ZJUI)
- Weiwei Qiu (ZJUI)
- Shaloo Rakheja, Assistant Professor, ECE (UIUC)
- Saughata Ghose, Assistant Professor, ECE (UIUC)
- Lav Varshney, Professor, ECE (UIUC)
- Aili Wang (ZJUI)
- Liang Zhao (ZJUI)

Postdocs

- Thong Nguyen (UIUC)

Students

- Yi Zhou (UIUC)
- Quankun Chen (ZJUI)

Traffic Related Air Pollution Prediction Using Video Footage and Deep Learning

Final Report – Period through December 2022

Christopher Tessum (UIUC), Mei Tessum (UIUC), Dantong Liu (ZJU)

In this project we are creating a system that uses traffic video footage and deep learning to predict traffic-related pollution concentrations in Hangzhou. This quarter, we have trained a model to detect and classify different vehicle types in videos, and then investigated the correlation between air pollutant concentrations and the identified vehicle. Currently, we can successfully identify vehicles from most video frames where we also see strong air pollution concentration peaks (Figure 1). And we have found some positive correlations between NO, Pm2.5, CO, and BC and the count of the truck that identified by our computer vision model (Figure 2).

Figure 1. Vehicles identified by our machine learning model (upper traces), consistent with photos. The first peak aligns well with our measured pollution peaks (bottom traces).

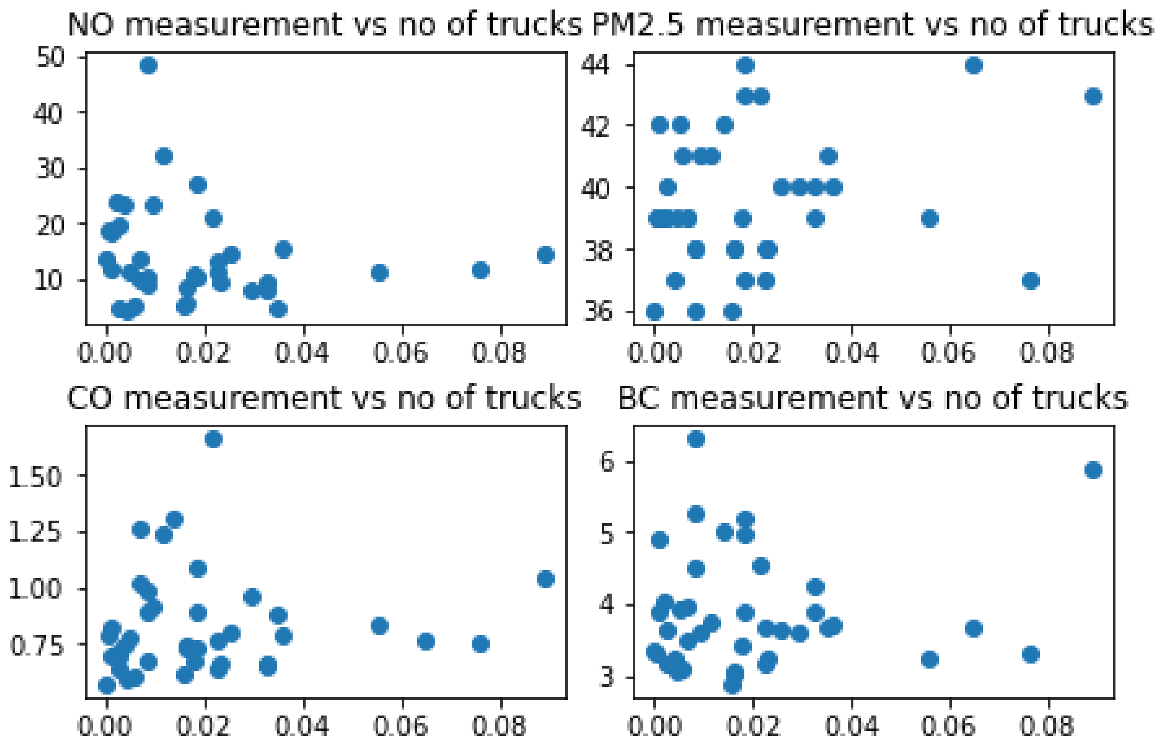


Figure 2. Relationships between NO, PM2.5, CO and BC concentration and single-unit heavy truck detections.

Personnel List

Faculty

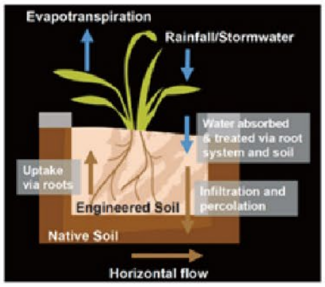
- Dantong Liu (ZJU), Professor
- Christopher Tessum (UIUC), Assistant Professor
- Mei Tessum (UIUC), Research Assistant Professor

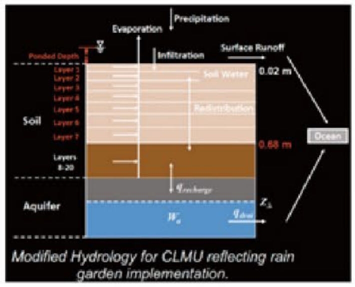
Students

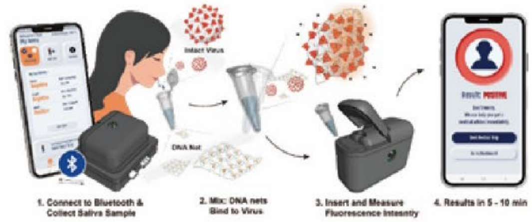
- Xiao Ran (UIUC) – 25% appointment (January-August 2022); Supervised by Mei Tessum and Christopher Tessum
- Qian Li (ZJU); Supervised by Dantong Liu
- Qurat ul ain Fatima (UIUC) – 25% appointment (August-December 2022); Supervised by Christopher Tessum

Publication List

Fatima, Q. u. A., Kim, Y. M., Ramesh, S. K., Kazemi, A., Liu, D., Tessum, M. W., Kindratenko, V., & Tessum, C. (2023). Hyperlocal air pollution prediction using traffic camera footage and computer vision techniques. Abstract submitted to the American Geophysical Union 2023 Annual Meeting.







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