Zhejiang University and
University of Illinois, Urbana-Champaign

Joint Research Center

2021–2022 Annual Report

Dynamic Research Enterprise for
Multidisciplinary Engineering Sciences (DREMES)
October 1, 2021 – September 30, 2022

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Directors Note

This second annual report on the ZJU-UIUC Joint Research Center of Dynamic Research Enterprise for Multidisciplinary Engineering Sciences (DREMES) presents a wide range of exciting developments and innovations from our teams in 2022. 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, 2021 through September 30, 2022.

There are five major programs supported through DREMES. These include 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). In 2022, two smaller seed projects were supported to have broaden the impact of DREMES. These are a project on traffic-related air pollution and the Heterogeneous Integration for Neuromorphic Integrated Circuits center (HYBRID). We are delighted to share, in this report, the high-impact research progressing in all five of these programs. An open proposal car from late 2022 will lead to an updated set of programs for the 2023-24 academic year. We look forward to these future endeavors and hope to summarize some of the plans in the third annual report.

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

- The CIRCLE team is working with the Ningbo government to relocate and rebuild a nearly abandoned village, based on zero-carbon housing, bio-based building materials, renewable energy, and intensive digital infrastructure.
- The CPD team is working on technology translation for single-virus diagnostics they have invented. Just a few milliliters of whole blood support detection with lab time under an hour. The point-of-care tests they are developing are less sensitive, but can be performed in the field in about 30 minutes.
- 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) 2022. There were six associated CyMaN publications.
- The traffic air pollution team showed how sensors collocated with traffic cameras can identify individual vehicles in need of maintenance to their onboard catalytic converters and particulate filters.
- The HYBRID team is developing physics-based neural network approaches likely to lead to 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 is US$900,000, supplemented this year with just over US$50,000 in unexpended travel funds. The remaining US$50,000 supported DREMES administration. These funds are expended at Illinois. 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 these 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 three large programs are supplementing DREMES support from a variety of sources.

DREMES programs involve more than 50 faculty members across UIUC, ZJU, and ZJUI. The budgets support about eight post-doctoral students and at least 65 graduate students. More than 100 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

2022 Annual Report

Center Overview

The Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE) is one of three 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, yet the areas are 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 details a few highlights of the activities and achievements of CIRCLE in the second year. Subsequently, the annual summary of each of the thrust areas and thrust integration will be provided.

Center Progress Highlights

- ***Students Graduated:*** Three CIRCLE students graduated in the past year. Zhoutong Jiang received his PhD at UIUC in July 2021 and has started his new job as a research scientist at Facebook. Giacomo Listrani after received his MS at Politecnico di Milano in December 2021 after a visiting semester at UIUC and will be seeking a position in Italy. Christopher Lee received his MS at UIUC in August 2022 and will continue for his PhD at UIUC. Additionally, CIRCLE research assistant Sicheng Zhou left to pursue a Ph.D. at the University Politecnico di Milano.
- ***Undergrad supervision:*** Yueer Cai (undergraduate student of ZJUI) is taking CEE497 (independent study) remotely at UIUC under the supervision of Profs. Spencer and Demartino on topics related to digital twins. Yutao Lai, Jianye Chen, Qi Hong, Zhekai Li, Haitian Liu, Benhao Lu, Ruihao Ma, Chenxiao Yu, and Rongjia Sun are doing SRTP and SRPP projects under the supervision of Profs. Narazaki and Demartino on a project for developing a framework for long-term structural health monitoring by computer vision and vibration-based model updating. Yuxin Qu (undergraduate student at ZJUI) conducted undergraduate research at UIUC in summer 2022 on electricity demand changes from electric vehicle charging under the supervision of Prof. Stillwell. One of the students, Haojia Cheng, did an REU with Prof. Yan and co-authored one paper that is currently under review. He will enroll in the Ph.D. program at UIUC under the supervision of Prof. Yan in 2023 Fall.
- ***External Funding:*** (i) The CIRCLE team led by Prof. Demartino received funding for a project entitled "Traffic load monitoring and structural assessment of bridges using digital twins" from the Argo Innovation Lab for Autostrade per l'Italia. The project aims at developing a digital twin-based framework for bridge management and performance evaluation. The digital twin models in the framework are to be updated with data collected from its physical twin (i.e., the bridge) in real-time and provide feedback to the physical twin to support the decision-making process. The project has been awarded a grant of 35 thousand euros which will support the development of the solution and will enhance the Thrust Integration efforts in the next year. (ii) The CIRCLE team members Simon Hu, Binbin Li, Cristoforo Demartino were awarded funding from Zhejiang University on a project entitled "Sustainable Smart Livable Cities Alliance (SSLCA)." (iii) The CIRCLE team members Simon Hu, Cristoforo Demartino submitted a proposal to NSFC/MAECI Joint Research on Sustainable Urbanization and Smart Cities on a project of "Urban smart mobility management and life cycle transportation systems sustainability," which is currently under review. (iv) Finally, a team of CIRCLE researchers are applying for a joint NSF-NSFC project on Sustainable Regional Systems which reviewed well, but ultimately was not funded.
- ***CIRCLE Distinguished Lecture Series:*** CIRCLE established a distinguished lecture series to provide opportunities for faculty and students to meet and interact with internationally renowned researchers in the field, provide opportunities to showcase CIRCLE to national and international colleagues, increase our potential for national and international collaborations, enhance the research experience for our students. To

date, we have hosted four international scholars, with three more scheduled. All lectures, including the question-and-answer period, are recorded and made available at: https://circle.cee.illinois.edu/previous-events/.

- ***ZJU-Ninghai Joint Research Center:*** Zhejiang University has partnered with the local government to establish Joint Research Center on Bio-based Materials and Carbon Neutral Development. Launched in May 2021, the ultimate goal is to off-set the carbon footprint of buildings, helping China to achieve the carbon neutrality in 2060 using bio-based materials construction materials combined with renewable energy. The center, led by CIRCLE ZJU Co-Director Prof. Xiao, will be run in a close collaboration with CIRCLE. The Center receives 10 million RMB distributed over three years from the Ninghai prefecture, a suburb city near Ningbo, and one of the major industrial and trading hubs in China.
- ***Bamboo Building Design:*** CIRCLE is co-sponsoring an International Student Competition for Modern Bamboo Structure Building Design. The competition is aimed at encouraging architecture and civil engineering students to seek alternative materials and new technologies in modern building design. For more information, see: www.BambooDesign.net.
- ***Digital Village:*** The team has developed a working relationship with a local government in Ningbo, Zhejiang, for relocation and rebuilding an old village. Because the village is located uphill with poor agriculture conditions, the village has almost been discarded, with only a few elders still staying in near collapsing houses. CIRCLE faculty led a student team to survey the area around the village and developed a preliminary plan to relocate the village, building low-carbon or zero carbon houses using bio-based materials and renewable energy. This includes suggestions for business development for bringing younger villagers back. The entire mountainous region is planned to be turned into a forest park for locals and tourists. Research has also begun to create digital twins of two dams in the area that have lost their original function for irrigation due to the rapid urban development in the foothill areas. The flood control function of the dams has been identified for potential risk increase for the downhill new urban industrial facilities, which are densely located.
- ***Butala Delivered Keynote:*** Prof. Mark Butala (ZJUI) delivered a keynote lecture entitled "Construction of a living, integrated cybermodel of complex urban environments," at the 2nd ZHITU Symposium on Advances in Civil Engineering. The associate paper was co-authored by Prof. Zhizhen Zhao (UIUC).
- ***Spencer Elected to Chinese Academy of Engineering:*** CIRCLE Co-Director, Prof. Billie F. Spencer, Jr. (苏磐石), was elected as a Foreign Member of the Chinese Academy of Engineering (CAE) in recognition of his distinguished contributions to Civil Engineering and to the promotion of China-America exchanges and cooperation. Spencer is one of 20 foreign members elected to CAE in 2021, the highest academic title in engineering sciences and technology in China.

Project Annual Summaries

Project 1: Energy Thrust

Co-PIs: Ashlynn Stillwell (UIUC), Binbin Li (ZJUI)

Thrust Highlights

The Energy Thrust has made strong progress in analyzing electricity consumption. We published our assessment of residential electricity consumption as a function of socioeconomic conditions, and are finalizing analysis residential heating and air conditioning (see Figure 1) and forecasting of residential electricity consumption for publication. Members of the team will present work at the American Geophysical Union Fall Meeting in December 2022.

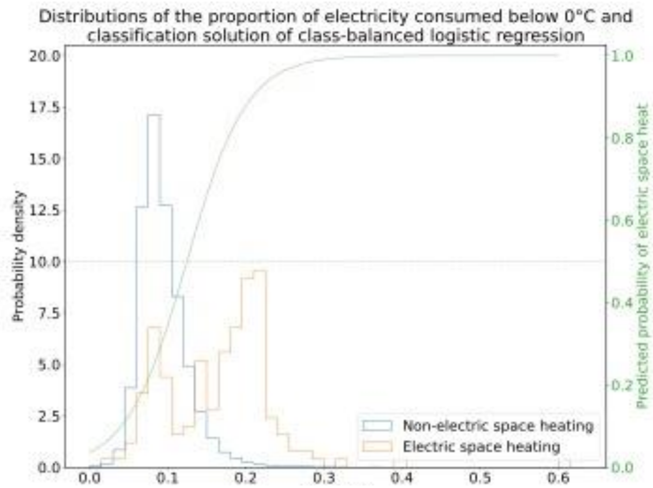


Figure 1. We created a feature (proportion of electricity consumed below 0°C) to classify residential electric space heating.

Forecasting residential electricity consumption

Using data from Commonwealth Edison (ComEd) representing the City of Chicago, we are developing forecasting models for predicting residential electricity consumption. These forecasting profiles will support further digital twin efforts and have including many CIRCLE team members from both the Energy Thrust (Stillwell, Li, Pesantez) and the Thrust Integration (Butala, Zhao) teams. Our results show high performance of state space regression, feed-forward neural network, and univariate nonlinear autoregressive neural network models, with the neural network models slightly outperforming the state space regression in a day-ahead capacity.

Classification of electric space heating

In work led by graduate student Christopher Lee, we have examined ComEd smart electricity meter data in the context of other published classification methods, finding that smart meter data approaches in other locations are not directly transferrable to Chicago's climate. We instead create a new feature, proportion of electricity consumed below 0°C, to classify residential electric space heating with logistic regression. These results were published in Lee's M.S. thesis and are under preparation for submission to a journal.

Researchers supported through this project include Dr. Jorge Pesantez (UIUC; postdoctoral researcher), Christopher Lee (UIUC; graduate student), Zihan Liao (ZJUI, graduate student), Zichen Bao (ZJUI, undergraduate).

Project 2: Water and the Environment Thrust

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

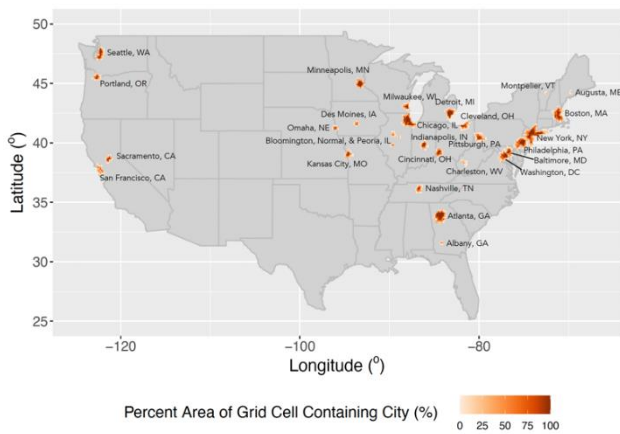
Thrust Highlights

The water and environment thrust has made strong progress in the following three areas: (i) publishing the work on projecting future urban runoff and flooding potential under climate change; (ii) CESM/CTSM development for urban green stormwater infrastructure (GSI) modeling; and (iii) Completing the urban greenspace irrigation project. One manuscript has been submitted to *Journal of Hydrology*, and is in moderate revision now. Two additional manuscripts have been accepted for presentation at the American Geophysical Union Fall Meetings (one in Dec. 2021 and one in Dec. 2022).

Projecting future total and urban runoff under climate change

This project uses the U.S. National Center for Atmospheric Research (NCAR)'s CESM to project future gridcell mean and urban-specific runoff under multiple climate change scenarios. This is a tightly integrated collaboration between Water & Environment Thrust and Energy Thrust in CIRCLE. This work is led by CIRCLE Ph.D. student Laura Gray. The manuscript of this work has been submitted to *Journal of Hydrology* – the top #1 journal in hydrology field, and is nearly accepted for publication by now.

Modeling Urban Green Stormwater Infrastructure (GSI)



In the past year, we have finished the development of CESM urban hydrology module to enable the model's representation of urban GSI. We are now conducting high-resolution (~10 km) simulations over CONUS cities to model the impacts of GSI on urban hydrology and heat mitigation. We selected 30 cities of interest which have issues with combined sewer overflows (CSOs) in the U.S. for detailed analysis. Faculty members from ZJU (Tingju Zhu and Yueping Xu) and their students will all be involved in this phase of the research collaboration.

Modeling China's Urban Greenspace & Devising Sponge City Best Management Practices (BMPs)

This is a cross-campus collaborative project between ZJUI and UIUC. We have analyzed the spatiotemporal pattern of Hangzhou green space distribution, the underlying factors influencing the distributions, and its water consumption and impacts. We also assessed the environmental impacts of existing "sponge city" best management practices (BMPs) in Hangzhou, and more importantly, optimizes the BMPs (coupled natural and engineered systems; size, location, distribution) to maximize the resilience with respect to compounding climate extreme events. At the national scale, using daily meteorological data in 1986-2015 and the spatial distribution and areas of grassland, shrubs and trees in urban greenspace taken from the 30-meter resolution EULUC database and the 10-meter resolution GLC database, we estimated irrigation water demand of urban greenspace for 289 cities at prefecture level or above in China using a newly developed evapotranspiration and soil water budgeting model. Such water demand results were then compared with water uses of those cities in recent years to approximate the shares of urban greenspace irrigation in total urban water uses for each city, thus revealing water stress imposed by urban greenspace where this is concerned. The manuscript of this work is to be submitted.

In the past year, we also kickstarted another project which is to building an urban water-energy-carbon nexus model which we started earlier this year. Our other ongoing projects all have synergies with this modeling effort.

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

Project 3: Transportation Thrust

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

Thrust Highlights

In the past year, 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. Two papers were newly submitted for publication in leading journals, and one manuscript was newly accepted for presentation at the upcoming 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) propose a dynamic and pareto-improving vehicle allocation strategy to enhance shared mobility services; and (ii) optimize shared autonomous taxi operations with intermittent charging at capacitated parking facilities. The work is conducted via tight collaboration between UIUC and ZJUI. Both 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 propose a dynamic vehicle swap strategy (see Figure 2) to enhance efficiency of shared mobility services, by reducing unproductive deadheading time and needed fleet size. Approximate analytical formulas, derived from a series of differential equations and probability models, are used to predict the expected system performance against fleet sizes in the steady state. This system of nonlinear differential equations is solved numerically to yield the equilibrium points and the associated system performance metrics. Agent-based simulations are used to verify the accuracy of the derived formulas, and to demonstrate the effectiveness of the proposed strategy in a variety of application contexts. This effort is reported in a paper currently accepted for presentation and under review for journal publication (Shen and Ouyang, 2022). (ii) on the operational level, we focus on routing and scheduling of autonomous taxi vehicles to provide reservation-based shared ride services, while a set of capacitated parking facilities are used for vehicle intermittent charging. A mixed-integer linear program model is formulated in the form of a vehicle routing problem with satellite facilities. The number of vehicles inside each parking facility is tracked so as to ensure that the capacity is never exceeded during the entire service horizon. A customized solution method based on an adaptive large neighborhood search algorithm is developed to solve this problem. A series of numerical experiments, including both hypothetical examples and a real-world case study of Hangzhou, China (see Figure 3), are carried out to test the effectiveness and applicability of the proposed model and algorithm.

Figure 2. Dynamic vehicle swap strategy

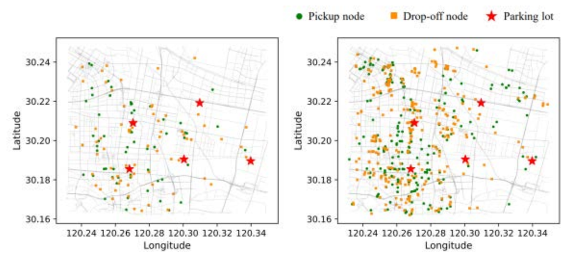


Figure 3. Case study for Hangzhou, China

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 strong progress in the following two areas: (i) formulating physics-based and data-driven CFD and FSI models; and (ii) enabling technologies and tools for digital twins of infrastructure system. Three papers are published or under review in leading journals, and four invited presentations were given at major conferences. The project also provides an opportunity for one ZJUI undergraduate student, Yueer Cai, to complete the course of independent study (CEE497). Weekly meetings are scheduled to ensure the student has sufficient exposure to the research project. Moreover, a master student, Giacomo Listrani, from the Polytechnic University of Milan and a Ph.D. student, Qiming Zhu, from UIUC have graduated with the topic related to this research project under the co-supervision of the PIs. Yutao Lai, Jianye Chen, Qi Hong, Zhekai Li, Haitian Liu, Benhao Lu, Ruihao Ma, Chenxiao Yu, and Rongjia Sun are doing SRTP and SRPP projects under the supervision of prof. Yasutaka Narazaki and Cristoforo Demartino on a project for developing a framework for long-term structural health monitoring by computer vision and vibration-based model updating. The two co-PIs have been co-teaching CEE 360 for three consecutive times. One of the students, Haojia Cheng, did an REU with Prof. Yan and co-authored one paper that is currently under review. He will enroll in the Ph.D. program at UIUC under the supervision of Prof. Yan in 2023 Fall.

Physics-informed machine learning for fluid-structure interaction and computer vision-based CFD analysis

This project explores physics-informed machine learning for computational fluid dynamics (CFD) and fluid-structure interaction (FSI) problems for wind engineering in sparse data regions. The goal is to develop fast CFD/FSI evaluation models that can be employed inside an optimization framework and enable real-time predictions to realize true digital twins for civil buildings and energy harvest structures, such as wind turbines. One journal paper from this project has been accepted in a top journal in mechanics and wind engineering and one manuscript is under revision. Moreover, research CFD analysis that utilizes the point cloud through computer vision-based UVA surveys is undergoing. A high-fidelity numerical analysis for wind pressure over the smart bridge at UIUC campus has been carried out as the benchmark. Figure 4 shows the analysis result of the analysis.

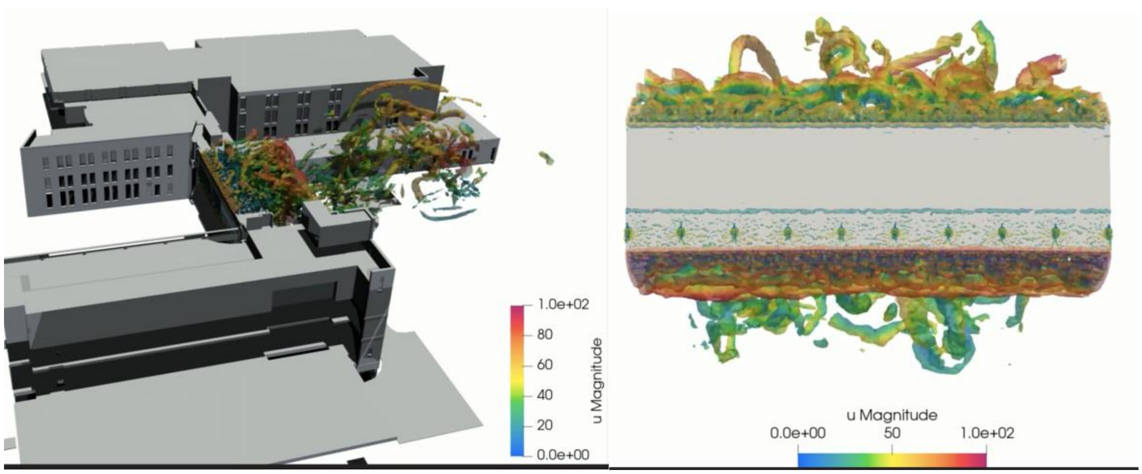


Figure 4. High-fidelity CDF analysis of the bridge.

Rapid seismic risk assessment of bridges using UAV aerial photogrammetry and machine learning-based fragility curve generation

This research aims to increase structural resilience by reducing the cost of risk assessment. A UAV-based rapid assessment framework for RC bridge piers subjected to seismic load is established. The framework employs UAV surveys to collect geometrical data on bridge piers and consider the epistemic uncertainties in material properties and pier details through Monte Carlo simulations. The safety of piers is assessed by the confident distribution of the capacity-to-demand ratios. The architecture is shown in Figure 5. The result of the study is submitted to a high-level journal in structural engineering and is currently under review. Furthermore, machine learning-based bridge fragility curve generation methods are proposed in this research. A database for bridge pier capacities is generated, which considers the epistemic and aleatoric uncertainties in the geometry and material properties. Machine learning models are then trained using the generated database. The trained models can calculate fragility curves accurately and efficiently with limited input information of a bridge pier. This work has been presented at *XIX ANIDIS Conference and XVII Assisi Conference, in September 2022, in Turin, Italy*. The manuscript on the topic is being prepared for a leading peer-review journal in the field. This research is made in cooperation with Dr. Giorgio Monti (ZJU).

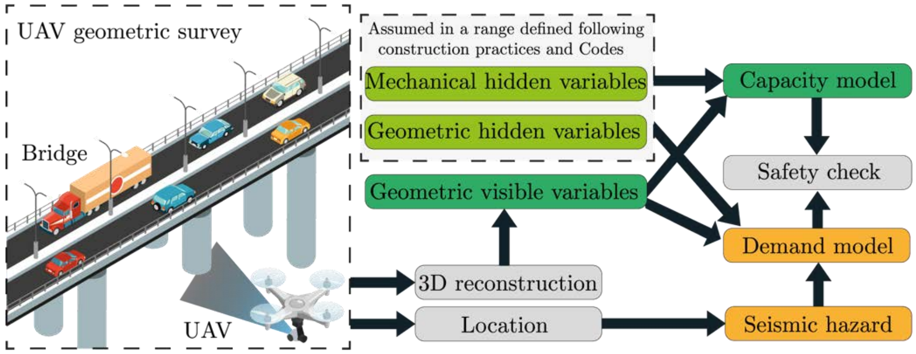


Figure 5. The overall architecture of the proposed rapid assessment framework

Iterative self-transfer learning methods for response time-history prediction

An iterative self-transfer learning method for training neural networks based on small datasets is proposed in this study (Figure 6). A new mapping-based transfer learning network, named as deep adaptation network with three branches for regression (DAN-TR), is proposed. A general iterative network training strategy is developed by coupling DAN-TR and the pseudo-label strategy, and the establishment of corresponding datasets is also discussed. The proposed method can improve the model performance by near an order of magnitude on small datasets without the need of external labeled samples, well behaved pre-trained models, additional artificial labeling, and complex physical/mathematical analysis. One journal paper from this project has been published in a high-level journal.

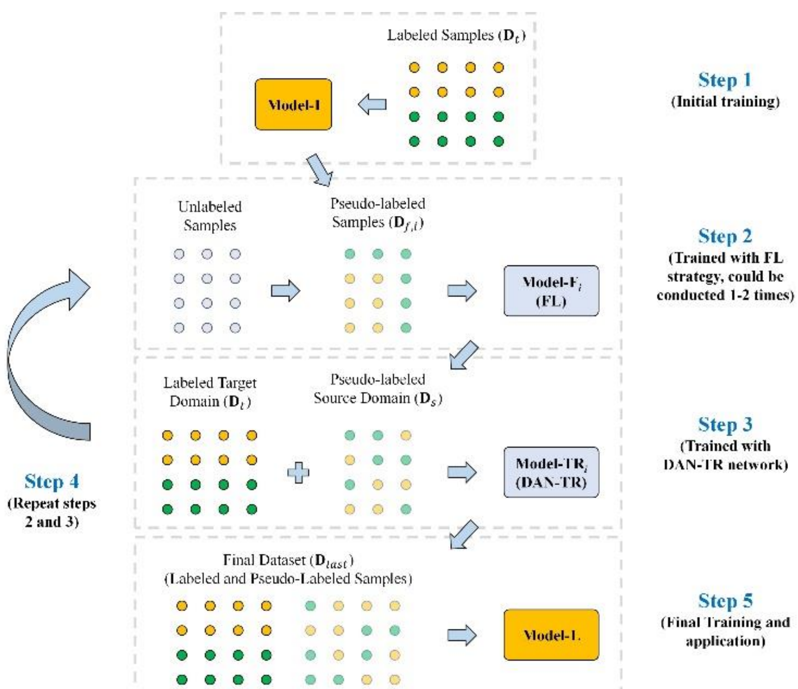


Figure 6. Proposed self-transfer training *framework.*

Framework for long-term structural health monitoring by computer vision and vibration-based model updating

This research aims at developing and demonstrating a framework for assessing structural conditions by combining computer vision-based three-dimensional (3D) reconstruction and vibration measurement (Figure 7). Starting from a finite element (FE) model with unknown geometric and material properties, the framework seeks to obtain the accurate representation of the structure by applying a sequence of two types of operations: (1) image collection, 3D reconstruction, and the extraction of localized geometric properties, and (2) vibration measurement, operational modal analysis, and extraction of global stiffness properties. The framework was validated using a laboratory-scale bamboo cantilever beam, and its field validation is ongoing.

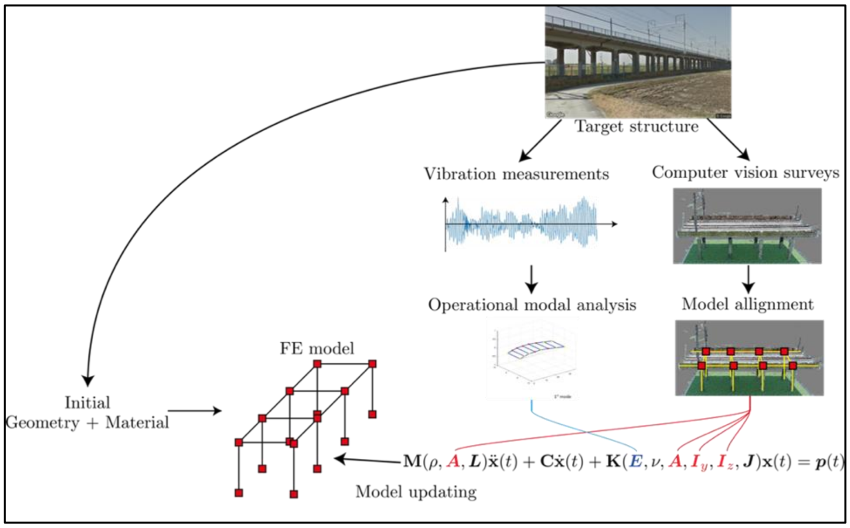


Figure 7. Framework for long-term structural health monitoring by computer vision and vibration-based model updating.

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

Thrust 5: Thrust Integration

Marcelo Garcia (UIUC), Zhizhen Zhao (UIUC), Mark D. Butala (ZJUI), Yueping Xu (ZJU)

The CIRCLE Thrust Integration (TI) team focuses on multiplying the strengths and expertise of CIRCLE thrust areas by exploring and developing pathways of interaction and collaboration. Several activities deserve highlighting given the interactions they fostered between collaborators at UIUC and ZJUI.

Digital Twins for Bridge Monitoring and Maintenance

This project explores a digital twin-based framework for real-time monitoring of bridges using heterogenous information: (*i*) an image-based measurement scheme of traffic flow and (*ii*) an accelerometric system. Unmanned Aerial Vehicles (UAV) and surveillance cameras on the bridge are used to monitor traffic and to extract trajectory and geometry information of vehicles using compute vision techniques. The acceleration response time histories at different locations are measured using accelerometers located on the deck. The FE model is used in conjuncture with the traffic flow information to describe the dynamic behaviors of the bridge. The so-obtained digital twin platform allows for the real-time estimation of the vehicular load and the health monitoring of the bridge. Moreover, the system can be trained to automatically detect anomalous events and provides warnings. Finally, the potential implementation of artificial intelligence techniques can make the system capable of autonomous decisions such as traffic interruption. This preliminary study focuses on the real-time estimation of the vehicular load.

The efforts led to funding awarded by Argo Innovation Lab. A collaboration between the team and ARGO Innovation Lab was established to create a suitable and accurate structural monitoring system on the bridge Settefonti Viaduct, located in Italy and designed in the 1960s. Current progress includes a preliminary system for a data process, bridge dynamics identification, and OpenSees model updating with a report introducing the system. The test using the FE simulation response has shown the strong feasibility of the proposed framework. The collaboration will end in mid-December with a completed system, mathematics and theoretical explanation, and instructions for operators.

Integrated Infrastructure Modeling Framework

The TI team has also been working to build a digital twin to provide a high-resolution flood risk early warning system in Chicago and to control optimal pump operation minimizing the flood risk in the RAPS service area. The team focused on the physics-based model used for analytics in the digital twin in this period. The team simulated the SWMM model by injecting extreme rainfall events from the WRF model's output, calibrated the model using the actual pumping operational records, and found the optimal spatial scale for the digital twin. To make this digital model a living entity representing the Chicago drainage system, the team is working on data assimilation by linking the dynamic model (WRF-SWMM) and wireless sensor networks (installed by Array of Things (AoT) project) using an open sensor platform (Waggle) for edge computing (developed by Argon National Laboratory). Due to some practical issues connecting different data types in diverse spatial representations, the team is working on extra processes in various perspectives for the data assimilation loop.

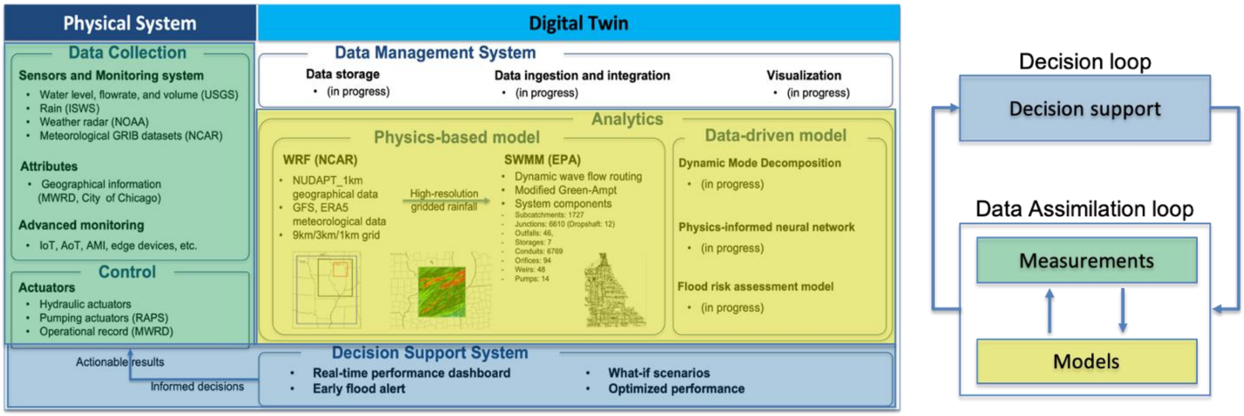


Figure 8. The digital twin architecture and the hierarchy of the cycles

Center Personnel

Faculty PIs and Co-PIs

- Mark Butala (ZJUI), Assistant Professor
- Marcelo Garcia (UIUC), Yeh Endowed Chair
- 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

- Jorge Pesantez (UIUC)
- 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. Jiang, Z. and Ouyang, Y. "Reliable location of first responder stations for cooperative response to disasters." Transportation Research Part B, 149: 20-32, 2021.
2. 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.
3. 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.
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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.

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4. Implications for Urban Land Use and Water Management. AGU Fall Meeting, 13-17 December 2021, New Orleans, LA.
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7. Jiang, Z. and Ouyang, Y. "Planning of reliable targeted evacuation under the threat of disasters." Accepted for presentation at the 101st Annual Meeting of Transportation Research Board, Washington DC, United States, January 9–13, 2022.
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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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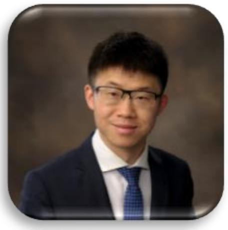

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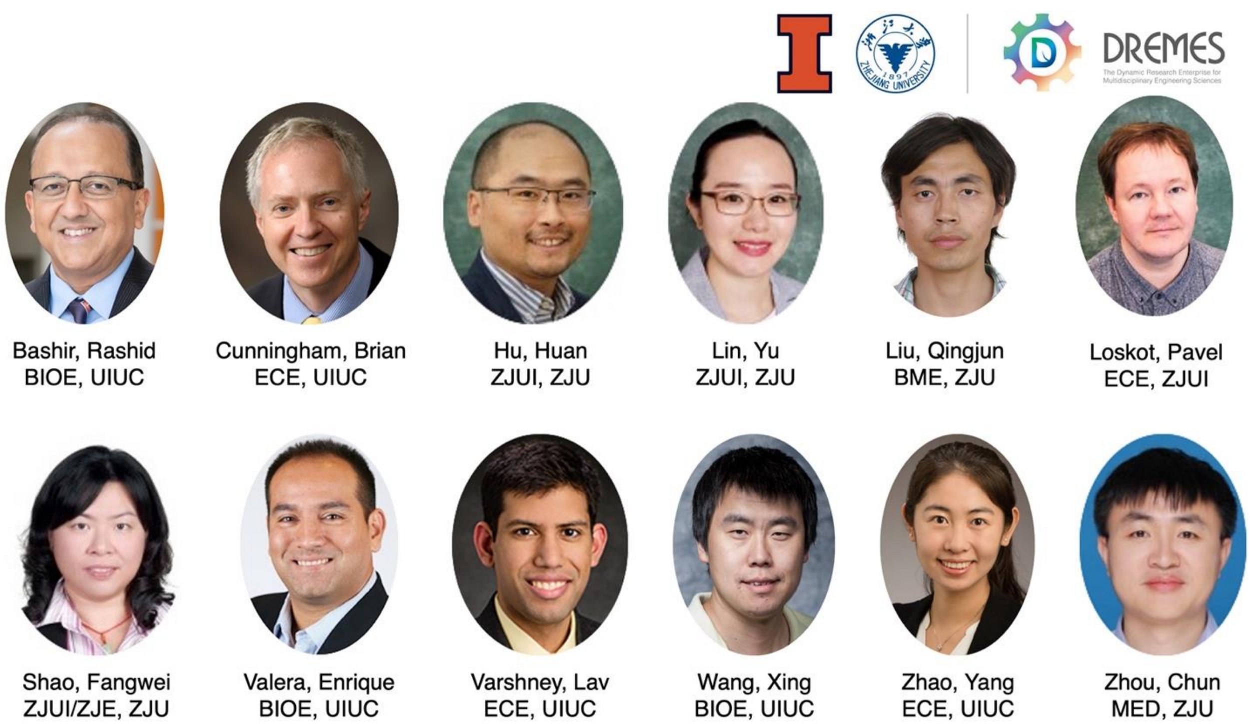
DREMES: Center for Pathogen Diagnostics

Center Overview

The vision for the Center for Pathogen Diagnostics (**CPD**) is to establish a multi-disciplinary and multi-institutional research and development team to address significant technological and scientific gaps in the field of pathogen detection. The CPD goal is to establish a pipeline of innovation that includes identification of biological and structural characteristics of pathogens that can serve as a basis for next-generation detection techniques, sample preparation technologies that effectively separate target materials from complex media, ultra-selective molecular biology methods, ultra-sensitive biosensor signal transduction, mobile detection instruments, and machine learning tools that convert detection data into clinically relevant knowledge. The CPD aims to deliver technologies and commercial products available for disease diagnosis and immunity determination, and environment monitoring that target bacterial pathogens, fungal pathogens, vector-borne illness, food safety, and monitoring of environmental resources.

CPD Faculty



Center Highlights

1. *The CPD is a mechanism for seven ZJUI undergraduates to engage in leading-edge research with UIUC faculty*.
2. *The CPD faculty are highly productive researchers in the field of pathogen diagnostics with >30 published papers in highly selective journals and conferences during the funding period.*
3. *The excellence of CPD students and faculty has been recognized with several honors and awards during the funding period*. Ibtihal FERWANA (Surge Fellowship), Nantao LI (Robert T. Chien Memorial Award), Jongwon LIM (Baxter Young Investigators Award, Hong Scully Fellowship), Brian CUNNINGHAM (Intel Alumni Endowed Chair), Lav VARSHNEY (White House Fellowship), Hanwei WANG (Illinois International Graduate Achievement Award)
4. *The CPD is contributing to the development of ZJUI-UIUC joint courses.* Biosensors (ECE 416, Cunningham and Hu) and Advanced Biosensors (ECE 516, Cunningham and Hu)
5. *The CPD research activities are leveraged into $8.5M of current grants and $40.8M 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. *The CPD faculty are actively involved in technology translation through the NIH-RADx project to develop novel diagnostic approaches to COVID-19, in addition to Industry-supported projects sponsored by large companies (Foxconn, CSL Behring).* Translation activities include characterization of technologies with clinical samples, human factors/usability testing, manufacturability, and pre-EUA inquiries.

Summary of Selected Projects

Project 1: APINet: A new machine learning method for predicting aptamer-protein interactions (<u>ZJUI undergraduate driven projects</u>)

Aptamers are short single-stranded oligonucleotides with a defined three-dimensional structure. They have drawn significant attention and emerging as an alternative for diagnostics due to 'high degree of selectivity, affinity, and specificity. The traditional way to generate aptamers is the systematic evolution of ligands by exponential enrichment (SELEX). Though SELEX is still the gold standard for generating aptamers, it is time-consuming. Thus, developing a computational/in silico way to design aptamers is pertinent for rapid generation of aptamers for multiple or rapidly mutating target proteins for existing and emerging pathogen diagnostics. Predicting possible aptamer sequences by computational mean can significantly reduce the selection time, cost, and allow us to exclude unlikely sequences and preparation of screening ingredients, thus resulting in a quicker synthesis of the desired aptamer than traditional SELEX. Very few computational models for predicting aptamer–protein interaction have been reported (**Fig. 1**).

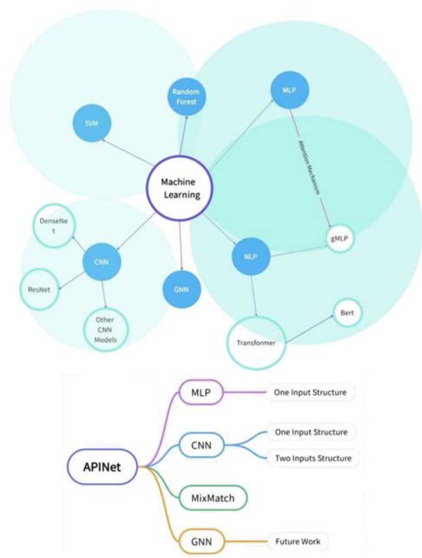


Fig. 1. Computational models for predicting aptamer-protein interaction.

To improve the accuracy of aptamer-protein interaction, we propose a novel model with multiple feature extraction of protein and aptamer. 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: Amino acid composition (AAC) and Pseudoamino acid composition (PAAC) Pepfeature. Based on the multiple feature extraction strategies, key sequence features of proteins and aptamers are extracted efficiently. Moreover, we compared the performance of three advanced deep-learning models, CNN (convolutional neural network), MLP (multiple layer perceptron), and semi-supervised model using the same training datasets as Li's. After analyzing the performance of each model, MLP showed the highest accuracy in predicting aptamer-protein interaction, with an 99% accuracy on the development dataset, which is higher than all the previously reported models (91.38%). Therefore, an MLP model with integrated feature extraction methods of aptamers and proteins was created to predict aptamer-protein interactions and was subsequently named APINet.

Student and faculty participants: Zheng Fang (<u>ZJUI</u>), Shixin Chen (<u>ZJUI</u>), Zhongqi Wu (<u>ZJUI</u>), 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

Infections, such as Hepatitis B and Hepatitis C, cause symptoms 1-4 months after infection. These liver infections brought on by Hepatitis B virus (HBV) and Hepatitis C virus (HCV), respectively, can be spread through contaminated blood that enters the bloodstream of an uninfected person. Chronic Hepatitis C is a long-term infection which is usually "silent" for many years, until the virus damages the liver enough to cause the signs and symptoms of liver disease. Unfortunately, as viruses are not grown in clinical labs, the viral limit of detection is much higher and technologies for detecting low numbers of viruses from milliliters of whole blood are not available. Other important case is HIV, which continues to be a major global public health issue. However, lack of availability of the appropriate diagnostic technologies essential to informing treatment in routine HIV care still prevents access to the standard of care for millions of HIV-positive individuals worldwide, particularly in resource-limited settings. As a solution to the rapid and sensitive detection of viruses, we propose to develop a Non-Culture Based Testing (NCT) platform which uses isothermal amplification methods directly from crude biological matrices such as blood to detect low pathogen concentrations within milliliter-scale volume samples. Although virus detection assays are commercially available (e.g., cobas® HIV, HBV, HCV tests from Roche), they use a 500 mL sample size and cannot process whole blood (serum or plasma is required, which again necessitates the use of a centrifuge or other devices). Therefore, a current game-changing approach would be to offer the option of testing multiple pathogens from the same whole blood sample (large volume) within a few hours. To work towards this goal, we will build on a new approach

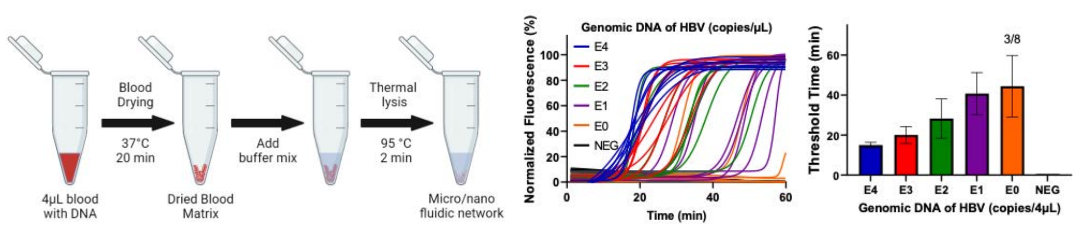


Fig. 2. Detection of HBV DNA in whole blood using the bi-phasic approach. a) Bi-phasic protocol followed. b) Isothermal amplification results. LOD = 1 copy/4µL.

developed in our group and recently reported in PNAS, based on the detection of pathogens from blood. As we have shown in previous reports, the approach has demonstrated the culture-free detection of bacterium using thermal heating/drying of blood which results in a bi-phasic reaction mix. Our bi-phasic reaction, which has been validated with clinical samples, has demonstrated the possibility of performing LAMP reactions directly on 1mL of blood to detect low bacteria counts.Our current efforts in this area are focused on demonstrating the applicability of the bi-phasic approach for virus detection in whole blood. Preliminary results can be seen in **Fig. 2**, where HBV DNA was spiked to whole blood (4 mL) and detected using our bi-phasic approach. The limit of detection (LOD) achieved is 1 copy/4 mL.

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

Project 3: Smartphone clip-on instrument and microfluidic processor for rapid sample-to-answer detection of Zika virus in whole blood using spatial RT-LAMP

Rapid, simple, inexpensive, accurate and sensitive point-of-care (POC) detection of viral pathogens in bodily fluids is a vital component of controlling the spread of infectious diseases. The predominant laboratory-based methods for sample processing and nucleic acid detection face limitations that prevent them from gaining wide adoption for POC applications in low resource settings and self-testing scenarios. Here, we report the design and characterization of an integrated system for rapid sample-to-answer detection of a viral pathogen in a droplet of whole blood comprised of a 2-stage microfluidic cartridge for sample processing and nucleic acid amplification, and a clip-on detection instrument that interfaces with the image sensor of a smartphone (**Fig. 3**). The cartridge is designed to release viral RNA from Zika virus in whole blood using chemical lysis, followed by mixing with the assay buffer for performing reverse-transcriptase loop mediated isothermal amplification (RT-LAMP) reactions in six parallel microfluidic compartments. The battery-powered handheld detection instrument uniformly heats the compartments from below, and an array of LEDs illuminates from above, while the generation of fluorescent reporters in the compartments is kinetically monitored by collecting a series of smartphone images. We characterize the assay time and detection limits for detecting Zika RNA and gamma ray deactivated Zika virus spiked into buffer and whole blood and compare the performance of the same assay when conducted in conventional PCR tubes. Our approach for kinetic monitoring of the fluorescence-generating process in the microfluidic compartments enables spatial analysis of early fluorescent “bloom” events for positive samples, in an approach called “Spatial LAMP” (S-LAMP). We show that S-LAMP image analysis reduces the time required to designate an assay as a positive test, compared to conventional analysis of the average fluorescent intensity of the entire compartment. S-LAMP enables the RT-LAMP process to be as short as 22 minutes, resulting in a total sample-to-answer time in the range 17-32 minutes to distinguish positive from negative samples, while demonstrating a viral RNA detection as low as 2.70×10^2 copies/ml, and a gamma-irradiated virus of 10^3 virus particles in a single 12.5 ml droplet blood sample.

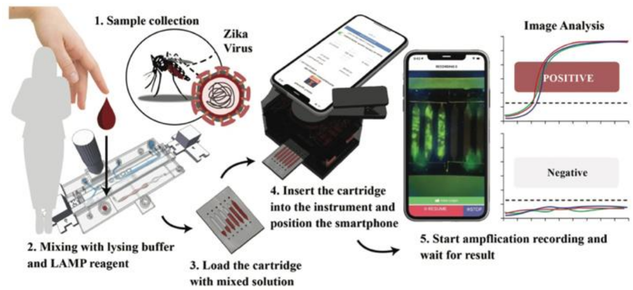


Fig. 3. Point-of-care testing workflow of the smartphone-based Spatial RT-LAMP ZIKV detection system. (1) The patient blood droplet is collected and loaded into the inlet port of Module A; (2) the blood is thoroughly mixed with lysing buffer and RT-LAMP reagents using the mixing channel and threaded syringe of Module A; (3) the final assay mixture is extracted from Module A and loaded into Module B, followed by sealing of inlet and outlet holes; (4) the prepared Module B is inserted into the detection instrument where the amplification reaction occurs, and a smartphone is locked in position using a clip to align the rear-facing camera with the instrument; (5) using an audio cable connection between the smartphone and the instrument (not shown in the figure), the app is initiated to take consecutive images of the reaction compartments at 10-seconds intervals, producing a collection of images that are subsequently analyzed by software.

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Project 4: Interrogating the biophysical interactions between host cells and pathogens

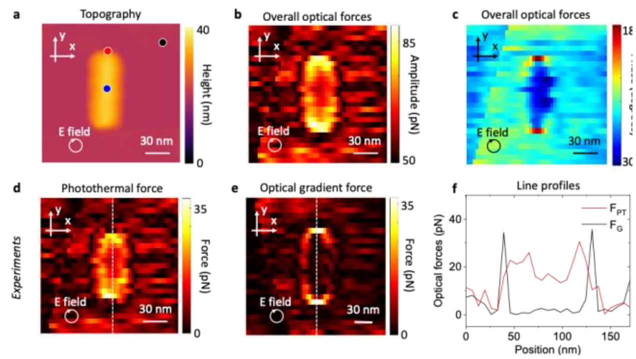

Fig. 4. Experimental measurement of the decoupled optical forces with different origins using the Dofn system. a, AFM topography of a nanorod. b, Overall force map of the nanorod. The excitation is left-hand circularly polarized. c, Phase response of the optical force map with the background phase removed. d, Decoupled photothermal force map of the nanorod. The force map is close to uniform around the body of the nanorod. e, Decoupled optical gradient force map. The force dominates at the two ends of the

Building upon our recent customized decoupled optical force nanoscopy (Dofn), we extend Dofn's applications in measuring decoupled photothermal force, optical radiation pressure, and photoacoustic force separately. Prior works focus on measuring light-induced (or photon-induced) forces as one entity, which is not precise. However, because light-induced photothermal expansion and photoacoustic signals accompany with the optical radiation pressure, it is extremely challenging to decouple all the force component triggered simultaneously by light. We employ a unique temporal modulation of the excitation laser, which encode the optical forces that come from the different physical mechanism with different phase responses. **Fig. 4** shows the decoupled optical forces and their phase distributions, demonstrating the feasibility of separating the photothermal forces from the other two. Along the direction of the chiral metasurface sensor, we continue our effort on large-scale device nanofabrication. We also started to explore the option of ebeam lithography, although it is limited in the total footprint of the device.

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Project 5: Hierarchical micro/nanostructures for breath analysis

This project aims to capture virus from human breath and then proceed to nucleic acid test. We employed a scalable nanofabrication method to add metal nanowires on silicon micropillars. These hierarchical micro/nanostructures lead to superhydrophobic and anti-ice properties. This is a scalable approach of producing hierarchical micro/nanostructures potentially applicable for capture exosomes, virus from human breath (**Fig. 5**).

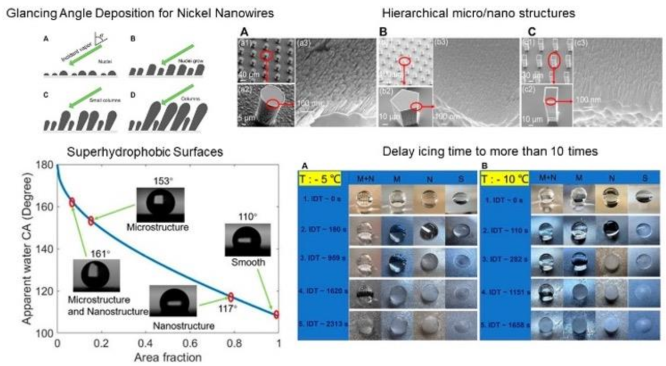

Fig. 5. Nanofabrication process for creating breath analyzer to detect viruses from human breath.

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Project 6: MXene-based wireless facemask enabled wearable breath acetone detection for lipid metabolic monitoring

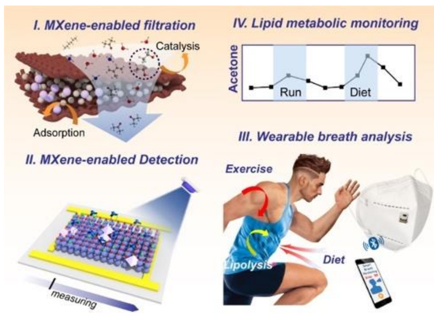

Fig. 6. Schematic of the MXene-based facemask platform for wearable breath acetone detection and lipid metabolic

This project has reported a $Ti_3C_2T_x$ MXene-based wireless facemask for on-body BrAC detection and real-time tracking of lipid metabolism (**Fig. 6**), where $Ti_3C_2T_x$ MXene serves as a versatile nanoplatform for not only acetone detection but also breath interference filtration. The incorporation of in situ grown TiO_2 and short peptides with $Ti_3C_2T_x$ MXene further improves the acetone sensitivity and selectivity, while TiO_2-MXene interfaces facilitate light-assisted response calibration. To further realize wearable breath monitoring, a miniaturized flexible detection tag has been integrated with a commercially available facemask, which enables facile BrAC detection and wireless data transmission. Through the hierarchically designed filtration-detection-calibration-transmission system, we realize BrAC detection down to 0.31 ppm (part per million) in breath. On-body breath tests validate the facemask in dynamically monitoring of lipid metabolism, which could guide dieter, athletes, and fitness enthusiasts to arrange diets and exercise activities. The proposed wearable platform opens new possibility toward the practice of breath analysis as well as daily lipid metabolic management.

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- Wang, Weijing (UIUC)
- Wu, Shaoxiong (ZJU)
- Wu, Xihang (ZJU), co-advised by Huan Hu and Brian Cunningham
- Wu, Yeyao (ZJU)
- Wu, Yue (ZJU)
- Xu, Gang (ZJU)
- Xu, Jie (ZJU)

- Zang, Ning (ZJU)
- Zhao, Jing (ZJU)
- Zhao, Shensheng (UIUC)

Postdocs

- Dwivedy, Abhisek (UIUC)
- Ma, Yuemin (ZJU)
- Umrao, Saurabh (UIUC)
- Wu, Xinbo (UIUC)

Undergraduates

- Chen, Shixin (ZJUI), co-advised by Xing Wang, Lav Varshney, Pavel Loskot
- Fang, Zheng (ZJUI), co-advised by Xing Wang, Lav Varshney, Pavel Loskot
- Lee, Eunji (UIUC/POSTECH)
- Liu, Jinpeng (UIUC)
- Schwartz, Ella (UIUC)
- Wu, Zhongqi (ZJUI), co-advised by Xing Wang, Lav Varshney, Pvael Loskot
- Xiao, Ziyu (ZJUI), co-advised by Yang Zhao, Huan Hu
- Yan, Ruike (ZJUI), co-advised by Yang Zhao, Huan Hu
- Yilmaz, Berke (UIUC)
- Zhang, Kai (ZJUI), co-advised by Yang Zhao, Huan Hu
- Zhang, Yichi (ZJUI), co-advised by Yang Zhao, Huan Hu

Publications

Peer-reviewed journals

1. Low, S. S., Chen, Z., Li, Y., Lu, Y. & Liu, Q. Design principle in biosensing: Critical analysis based on graphitic carbon nitride (G-C3N4) photoelectrochemical biosensor. *TrAC Trends in Analytical Chemistry* **145**, doi:10.1016/j.trac.2021.116454 (2021).
2. Park, I. *et al.* Detection of SARS-CoV-2 Virus Amplification Using a Crumpled Graphene Field-Effect Transistor Biosensor. *ACS Sensors* **6**, 4461-4470, doi:10.1021/acssensors.1c01937 (2021).
3. Mostafa, A. *et al.* Culture-free biphasic approach for sensitive detection of Escherichia coli O157:H7 from beef samples. *Biotechnology and Bioengineering* **118**, 4516-4529, doi:10.1002/bit.27920 (2021).
4. Cheng, C. *et al.* Battery-free, wireless, and flexible electrochemical patch for in situ analysis of sweat cortisol via near field communication. *Biosensors and Bioelectronics* **172**, doi:10.1016/j.bios.2020.112782 (2021).

5. Li, X. *et al.* Room Temperature VOCs Sensing with Termination-Modified Ti3C2Tx MXene for Wearable Exhaled Breath Monitoring. *Advanced Materials Technologies*, doi:10.1002/admt.202100872 (2021).
6. Patel, S. K. S., Ferwana, I. & Varshney, L. R. Social capital dimensions are differentially associated with COVID-19 vaccinations, masks, and physical distancing. *Plos One* **16**, doi:10.1371/journal.pone.0260818 (2021).
7. Li, N. *et al.* Label-Free Digital Detection of Intact Virions by Enhanced Scattering Microscopy. *Journal of the American Chemical Society* **144**, 1498-1502, doi:10.1021/jacs.1c09579 (2022).
8. Li, N. *et al.* Overcoming the limitations of COVID-19 diagnostics with nanostructures, nucleic acid engineering, and additive manufacturing. *Current Opinion in Solid State and Materials Science* **26**, 100966, doi:10.1016/j.cossms.2021.100966 (2022).
9. Ren, S. *et al.* Designer DNA nanostructures for viral inhibition. *Nature Protocols* **17**, 282-326, doi:10.1038/s41596-021-00641-y (2022).
10. Chakraborty, B. *et al.* Aptamers for Viral Detection and Inhibition. *ACS infectious diseases* **8**, 667-692, doi:10.1021/acsinfecdis.1c00546 (2022).
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13. Oh, C. *et al.* Design of SARS-CoV-2 Variant-Specific PCR Assays Considering Regional and Temporal Characteristics. *Applied and Environmental Microbiology* **88**, doi:10.1128/aem.02289-21 (2022).
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18. Jankelow, A. M. *et al.* Smartphone clip-on instrument and microfluidic processor for rapid sample-to-answer detection of Zika virus in whole blood using spatial RT-LAMP. *The Analyst* **147**, 3838-3853, doi:10.1039/d2an00438k (2022).
19. Ganguli, A. *et al.* A culture-free biphasic approach for sensitive and rapid detection of pathogens in dried whole-blood matrix. *Proceedings of the National Academy of Sciences* **119**, doi:10.1073/pnas.2209607119 (2022).

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23. Zhang, L., Chu, X., Tian, F., Xu, Y. & Hu, H. Bio-Inspired Hierarchical Micro-/Nanostructures for Anti-Icing Solely Fabricated by Metal-Assisted Chemical Etching. *Micromachines* **13**, doi:10.3390/mi13071077 (2022).
24. Ranoa, D. R. E. *et al.* Mitigation of SARS-CoV-2 transmission at a large public university. *Nature Communications* **13**, doi:10.1038/s41467-022-30833-3 (2022).

Conference proceedings

1. “Photonic resonator-outcoupled magnetic-plasmonic nanoTags (PROMPT) for ultrafast and ultrasensitive detection of microRNA”, C. Che, R. Due, N. Li, X. Wang, and B.T. Cunningham, in *Proc. IEEE BMES Annual Meeting*, Orlando, FL, October 2021.
2. “Point-of-care detection of nucleic acid using a portable photonic resonator absorption microscope”, S. Ghosh, N. Li, Y. Xiong, Y.-G. Ju, M.P. Rathslag, E.G. Onal, E. Falkiewicz, M. Kohli, and B.T. Cunningham, in *Proc. IEEE BMES Annual Meeting*, Orlando, FL, October 2021.
3. “Digital-resolution and highly sensitive detection of exosomal small RNA by DNA toehold probe-based photonic resonator absorption microscopy”, B. Zhao, W. Wang, N. Li, T. Garcia-Lezana, X. Wang, C. Che, A. Villanueva, and B.T. Cunningham, in *Proc. IEEE BMES Annual Meeting*, Orlando, FL, October 2021.
4. “Rapid Isothermal Detection of SARS-CoV-2 in Saliva Using Point-Of-Care System”, Jongwon Lim, Robert Stavins, Enrique Valera, Willian Paul King, Rashid Bashir, in *Biomedical Engineering Society Annual Meeting (BMES 2021)*, Oct 2021, Florida, USA.
5. “On Chip Detection of Zika Virus in whole blood using RT-LAMP”, Aaron Jankelow, Han-Keun Lee, Fu Sun, Victoria Kindratenko, Katherine Koprowski, Enrique Valera, Brian Cunningham, Rashid Bashir, in *Biomedical Engineering Society Annual Meeting (BMES 2021)*, Oct 2021, Florida, USA.
6. “V-Pods: Rapid, sensitive detection of intact SARS-CoV-2 using DNA nets and a smartphone-linked fluorimeter”, N. Chauhan, W. Wang, H.K. Lee, Y. Xiong, T. Zhang, N. Magazine, Lu Peng, L. Zhou, W. Huang, X. Wang, B.T. Cunningham, in *SPIE Defense+Commercial Sensing Conference*, Orlando, FL, April 2022.
7. “Photonic crystal enhanced emission and blinking suppression for single quantum dot digital resolution biosensing of cancer-associated miRNA biomarkers”, Y. Xiong, Q. Huang, T.D. Canady, P. Barya, S. Liu, O.H. Arogundade, C.M. Race, X. Wang, L. Zhou, X. Wang, M. Kohli, A.M. Smith, and B.T. Cunningham, in *Conference on Lasers and Electro-Optics (CLEO)*, San Jose, CA, May 2022.

8. “Point-of-care Multiplex Diagnostic Platform for the Detection of Various Viruses and Differentiation of Early Strains and B.1.1.7 Variants of SARS-CoV-2”, Jongwon Lim, Robert Stavins, Victoria Kindratenko, Janice Baek, Leyi Wang, Karen White, James Kumar, Enrique Valera, William P. King and Rashid Bashir, in *Biomedical Engineering Society Annual Meeting (BMES 2022)*, Oct 2022, San Antonio, TX.
9. “On Chip Point-of-Care Detection of Zika Virus in whole blood using Spatial RT-LAMP”, Aaron Jankelow, Hankeun Lee, Weijing Wang, Trung-Hieu Hoang, Fu Sun, Victoria Kindratenko, Katherine Koprowski, Enrique Valera, Mihn N. Do, Brian Cunningham, Rashid Bashir, in *Biomedical Engineering Society Annual Meeting (BMES 2022)*, Oct 2022, San Antonio, TX.

Thesis and dissertation

1. “Photonic resonator interferometric scattering microscopy”, ***Ph.D. Dissertation*** by Dr. Nantao Li. Abstract: The capability to image the species of interest without exogenous labeling with visible light has been one of the central mission for modern optical microscopy. Among the huge variety of photophysical processes in light-matter interaction, elastic scattering is one of the most universal and fundamental phenomena, and thus is an ideal means for optical contrast generation. Recent development in interferometric scattering microscopy has enabled the detection of individual nanoscopic objects as small as single proteins by their elastically scattered light. To push the limit of the smallest detectable features in interferometric imaging system, in this dissertation, we try to address this challenge from the nanophotonic perspective. Specifically, dielectric photonic crystal slabs are designed and utilized as the imaging substrates to improve the imaging sensitivity. First, the delocalized photonic crystal guided resonance can confine light to generate an elevated optical field for the enhanced excitation of elastic scattering light. Additionally, the photonic band edge effect greatly reduces the transmissivity of the incident field, thus resulting in the suppressed background noise and significantly enhanced signal-to-noise ratios. Finally, the far-field angular distribution of the elastic scattered light can be reshaped by the photonic crystal towards smaller numerical aperture, thus allowing for the efficient signal collection by a non-contacting objective. The nanophotonically enhanced imaging platform, named photonic resonator interferometric scattering microscopy, offers a simple and low-cost solution for label-free biosensing for single SARS-CoV-2 viruses and quantitative mass measurement for individual protein molecules.

CyMaN: Center for Adaptive and Resilient Cyber-Physical Manufacturing Networks

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.

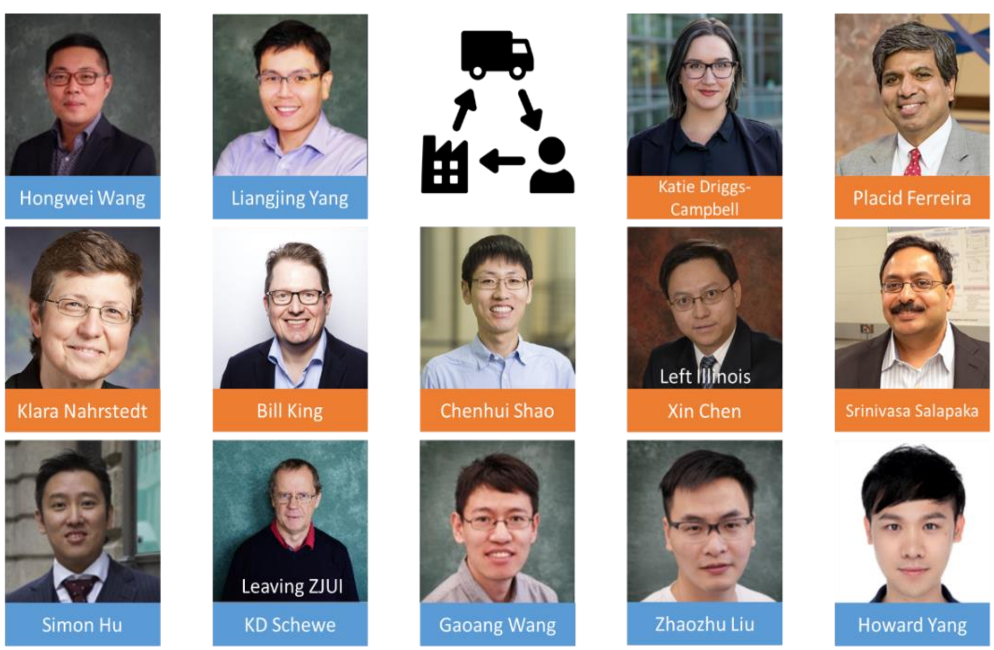

Figure 1: Faculty in CyMaN

Collaborations are all organized under a five topical umbrellas over smart manufacturing areas. In the last year, the center hired a post-doctoral researcher, organized a joint course in robotics for the two campuses, and organized a symposium on CyMaN topics at the IEEE/ASME Conference on Automation Science and Engineering (CASE). In addition, research over its existence, CyMaN researchers have published 67 journal and conference papers.

CyMaN Collaboration Highlights

Joint Research Highlights

Our team (see Figure 1) 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 special session on Adaptive and Resilient Cyber-Physical Manufacturing Networks at the IEEE Conference on Automation Science and Engineering (CASE) 2022, which is one of the flagship conferences for the IEEE Robotics and Automation Society. This session led to six peer-reviewed publications from the center alone. We are continuing to publicize our efforts at the upcoming IEEE CSCWD2023 conference.

Our research efforts have focused in five areas (cyber infrastructure, metrology, collaborative shop floors & assembly lines, anomaly detection, and planning &

Figure 2: Special Session on ARCyMaN organized at IEEE CASE 2022

optimization), with equal representation from both ZJUI and UIUC faculty in each topic. Our list of publications is provided in the publications section.

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 institutions that create a small network. The vision and metrology team (Gang Wang, Bill King, and Chenhui Shao) have also begun discussing how to integrate their research challenges into the ECE470 labs as a final project showing the real-world applications in smart manufacturing of the course content. Further, the robotics course development and the AR-CyMaN center have enriched the ZJUI undergraduate research experience by providing new opportunities. Last summer, we engaged three ZJUI undergraduates in research projects. The students worked with PhD students who are ZJUI alumni, and mentored them on the research project and gave insights about the path to graduate school.

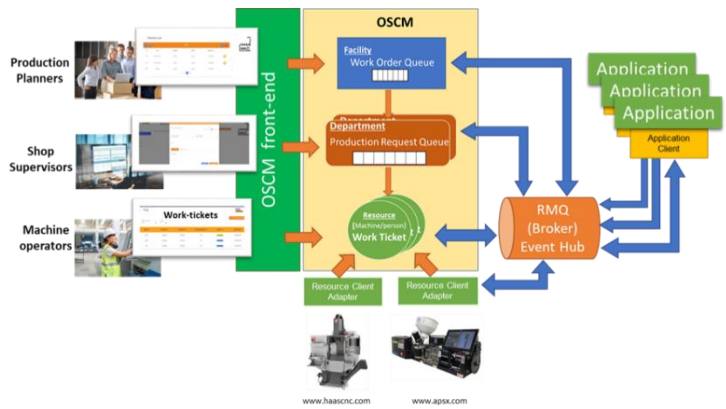

Figure 3: OSCM Architecture

CyMaN Research

Research in CyMaN is organized into five umbrella projects or themes. Short descriptions of research status in each of these projects are given below.

Project 1: Cyber Infrastructure for Manufacturing Networks

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

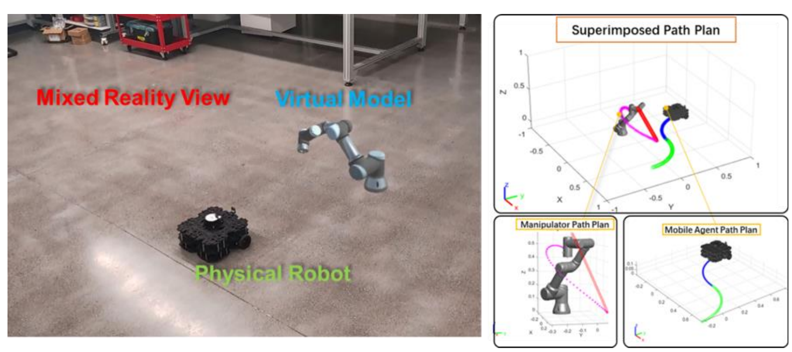

Figure 4: Mixed reality system for collaborative resource sharing

The emphasis of this project is cyber infrastructure to enable flexible, data-enabled manufacturing decision-making. With a great deal of progress in computer-driven shopfloor automation (CNC machines, robots, etc.), often in manufacturing systems, the information infrastructure emerges as the most inflexible and limiting component. Therefore, we have architected and implement the Operating System for Cyber-physical Manufacturing (OSCM), a configurable and extendible cloud platform for managing manufacturing resources (machines, robots, etc.) and transactions (work orders, production requests, etc.); data-streams and events generated in the system; and manufacturing apps and users that access these resources, transactions and data. Figure 3 shows the components of OSCM and the integration of the aforementioned machines, jobs, applications and users. Much of the recent and on-going work in this project has been on integrating manufacturing components into the OSCM framework to build our cross-institution manufacturing network. For example, to facilitate data collection in Project 4, we are integrating an ultrasonic metal welder into OSCM. The data includes signals from an online monitoring system and environmental measurements that are routed to machine-learning applications to build neural-network based surrogate models of the process. In Project 5, OSCM is used to capture and route event information to an MEP (Max. Entropy Principle) based scheduler and return schedule back to the machines. In project 3, OSCM is being used to make virtual models with physical robots to make them accessible to students. Yang and Ferreira have developed a mixed reality framework that uses OSCM to integrate remote (virtual) and local (physical) systems (see Figure 4) for plan visualization and verification. This work has led to a joint paper in the CyMaN special session at IEEE CASE (see Center Efforts and Publications sections).

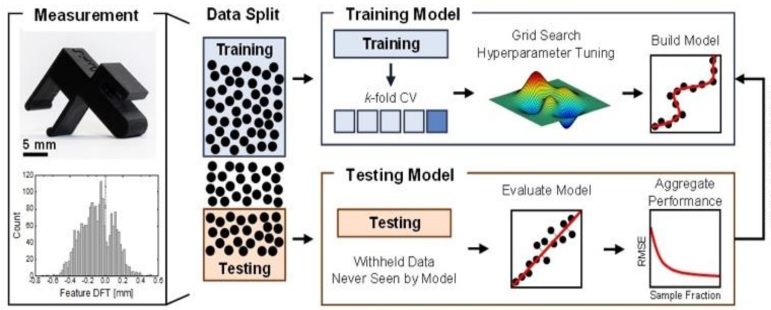

Figure 5: Training and testing in machine learning approaches to manufactured part metrology

Project 2: Automated Metrology for Resilient Manufacturing Processes
Zuozhu Liu (ZJUI), Bill King (UIUC), Chenhui Shao (UIUC)

Comprehensive metrics and measurements are needed in any manufacturing process, especially additive manufacturing due to accumulated errors. Automated data collection, data processing, and meaningful metrics present open challenges. In addition to the collaborative effort described in the Project 1 section, we are building a new data set from 2500 additively manufactured parts that we designed and fabricated for this purpose. The fabricated parts have been scanned to create high-resolution optical images, and we are conducting a preliminary investigation of the data quality. The team is working with X-ray CT scan images of metal additive parts and AI techniques to detect and analyze part defects. The team is also working on machine learning approaches to detecting dimensional and other quality related errors (see Figure 5). Additionally, the ongoing effort to integrate vision insights into the part analysis (a collaboration with King, Shao, and Liu) has led to a joint paper in the CyMaN special session at IEEE CASE (see Center Efforts and Publications sections).

Project 3: Adaptive and Collaborative Shopfloors and Assembly Lines

Hongwei Wang (ZJUI), 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. As a practical example and use-case, we aim to improve virtual educational labs for the undergraduate Introduction to Robotics class offered at UIUC and ZJUI, which was recently co-taught by Driggs-Campbell and Yang. The lab syllabus innovation received an

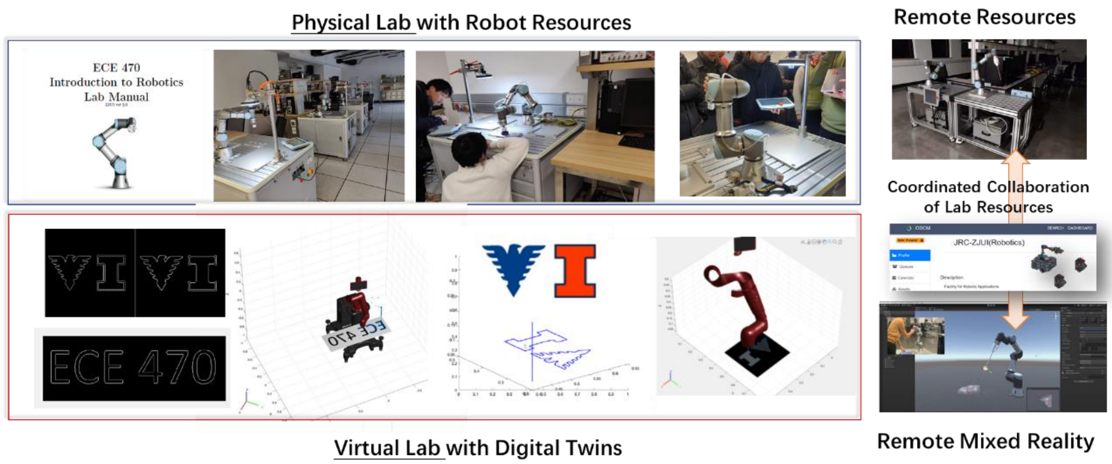

Figure 6: Use-case study: coordinated lab resource collaboration using the cloud platform for ZJU-UIUC collaborative teaching

industrial sponsorship under the University-Industry Collaboration Grant support for curriculum development in ZJU-UIUC Institute endorsed by Ministry of Education, China. We have currently begun testing collaborative manufacturing mechanisms using the NIST assembly benchmark. We have developed methods to optimizing the assembly process in an online fashion, which will eventually provide data and services to the OSCM framework (Figure 6). More recently, we have begun expanding the robot capabilities to use 3D printed parts from Project 2 to provide active assessment and continual feedback on the manufacturing process using active perception. Our ongoing efforts in knowledge driven digital twins has led to a joint paper in the CyMaN special session at IEEE CASE (see Center Efforts and Publications sections).

Project 4: Understanding Anomaly and Heavy-tailed Events in Manufacturing Processes

Gaoang Wang (ZJUI), Klara Nahrstedt (UIUC), Katie Driggs-Campbell (UIUC)

Heavy-tailed distributions are prevalent in nearly all manufacturing processes, meaning that infrequent failures and anomalies present a fundamental challenge. At scale, these faults may introduce significant inefficiencies across facilities. Nahrstedt and Shao have been collaborating on collecting sensor data and integrating both the machines and data collection process into OSCM (as described above in Project 1). This effort builds off prior efforts in the SENSELET system, which is a sensor network-edge system that connects hardware, sensors, and computation in a SENSELET server (Figure 7). We have begun integrating this SENSELET platform with OSCM to detect anomalous events on an ultrasonic welding machine in Shao's lab. We have outfitted this machine with many sensors (temperature, acoustic, vibration, power, etc.) to build a dataset of environmental factors during operation. This dataset is to be shared among the center and eventually the smart manufacturing community. This effort will be extended to create a digital twin of the sensing environment around manufacturing machines, develop fault models for sensors and networks and learn thresholds for anomaly detectors in the cyber-infrastructure.

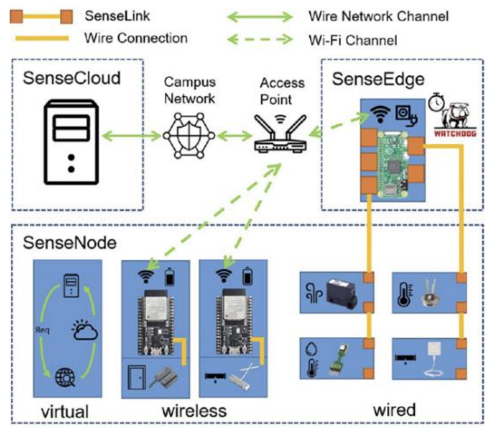

Figure 7: Schematic of SENSELET sensor edge network

Project 5: Planning and Optimization for Flexible Manufacturing Networks

KD Schewe (ZJUI), Xin Chen (UIUC), Srinivasa Salapaka (UIUC)

In this topic, we have been exploring modeling and planning methods that underlie a flexible manufacturing network. Specifically, we consider parametric sequential decision-making (Para-SDM) framework for optimizing resource allocation problems in manufacturing. Figure 8 shows the rich set of problems that can be addressed by this framework. Recently, we have been exploring how to integrate anomaly detection (for example, the outputs of Project 4) into the planning and optimization framework. Salapaka has developed clustering method to extract outliers from mainstream data. The primary technical challenge is determining the number of clusters or groupings for effective performance, and how this can connect to domain knowledge from the manufacturing and logistic problems of interest. We aim to connect this to the manufacturing-job organization problem, where we design/organize/analyze a set of jobs given historical data of jobs in a manufacturing setup. This work has led to a joint paper in the CyMaN special session at IEEE CASE (see Center Efforts and Publications sections).

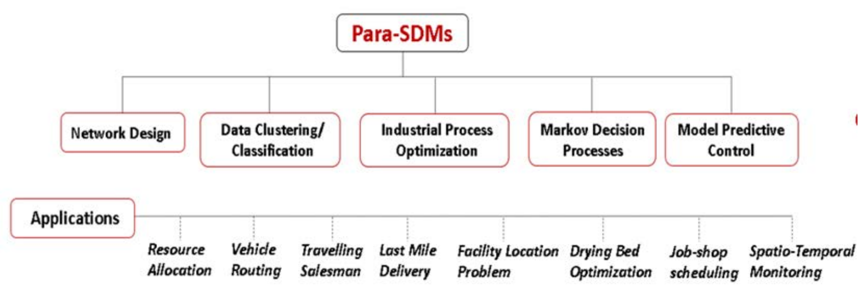

Figure 8: Taxonomy of problems solvable in the Para-SDM framework

Funding Leveraged/Related

The team has leveraged research work in CyMaN in with a number of other research grants and contracts, including:

a) C-NICE (Center for networked intelligent components and Environments):
    a. Smart Factory Framework: K. Nahrstedt and P. Ferreira, USD1.2M over 3 years
    b. Smart Metrology: W. King: USD500K over 3 years
    c. Assembly Cobotics: K. Driggs-Campbell: USD1M over 3 years

d. Simultaneous Facility Location and Routing Optimization in Wireless Networks - A Maximum Entropy Principle Based Framework: Salapaka USD584K over 2 years

b) NASA: Robust and Resilient Autonomy for Advanced Air Mobility: Salapaka: Total award USD6M over 3 years.
c) NSF CAREER Grant: K. Driggs-Campbell, $500K over 5 years
d) Intel: Experimentation Management for Highly Complex Manufacturing Operations- End-To-End DOE Lifecycle Management Methodologies: P. Ferreira, USD390K over 3 years
e) MGI: Leadless Gage Microfabrication Process Development: P Ferreira, USD124K over 1 year
f) National Natural Science Foundation of China: Data-Driven Wafer Manufacturing Process Anomaly Detection and Fault Diagnosis Method: H. Wang.
g) Zhejiang Provincial Natural Science Foundation of China: Combined computing and collaborative learning method for abstract cross-modal knowledge: H. Wang.

Center for Adaptive and Resilient
Cyber-Physical Manufacturing Networks
Personnel List

UIUC Personnel List

Faculty

- [Co-Lead] Katie Driggs-Campbell, Assistant Professor – 0.7 summer months
- [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)
- Yuquan Meng – 25% appointment. Supervised by Shao (UIUC), Collaborating with Liu (ZJUI)
- Zikun Ye – 25% appointment. Supervised by Chen (UIUC)
- Alisina Bayati – 25% appointment. Supervised by Salapaka (UIUC)
- Ricardo Toro (other support). Supervised by Ferreira (UIUC), Collaborating with Yang (L) (ZJUI)
- Ahmadreza Eslaminia – 50% appointment. Supervised by Nahrstedt and Shao (UIUC), Collaborating Wang and Liu (ZJUI)

ZJUI Personnel List

Faculty

- [Co-Lead] Wang Hongwei, Associate Professor (ZJUI Institute)
- [Co-Lead] Yang Liangjing, Assistant Professor (ZJUI Institute)
- Hu Simon, Assistant Professor (ZJUI Institute)
- Yang Hao, Assistant Professor (ZJUI Institute)
- Wang Gaoang, Assistant Professor (ZJUI Institute)
- Liu Zuozhu, Assistant Professor (ZJUI Institute)
- Schewe Klaus-Dieter, Professor (ZJUI Institute)

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)

Center for Adaptive and Resilient Cyber-Physical Manufacturing Networks

Publication List

1. S Xiao, C Wang, Y Shi, J Yu, L Xiong, C Peng, L Yang, "Visual Optimization of Ultrasound-Guided Robot-Assisted Procedures Using Variable Impedance Control" in 2021 World Robotics Conference, WRC SARA 2021, Beijing, China, 2021. (Best Student Paper Award)
2. H-Y. Li, I. Paranawithana, L. Yang, U-X. Tan, "Variable Admittance Control with Robust Adaptive Velocity Control for Dynamic Physical Interaction between Robot, Human and Environment" in 17th Intl. Conf. Automation Science & Engineering, IEEE CASE 2021, Lyon, France, 2021.
3. C. Xu, Y. Xie, X. Wang, H. H. Yang, D. Niyato, and T. Q. S. Quek, "Optimal Status Update for Caching Enabled IoT Networks: A Dueling Deep R-Network based Approach," IEEE Trans. Wireless Commun., 2021 [Early Access].
4. H. H. Yang, A. Arafa, T. Q. S. Quek, and H. V. Poor, "Spatiotemporal Analysis for Age of Information in Random Access Networks under Last-Come First-Serve with Replacement Protocol," IEEE Trans. Wireless Commun., 2021 [Early Access].
5. Z. Song, H. Sun, H. H. Yang, X. Wang, Y. Zhang, and T. Q. S. Quek, "Reputation-based Federated Learning for Secure Wireless Networks," IEEE Internet of Things J., 2021 [Early Access].
6. Y. Fu, T. Q. S. Quek, Z. Yang, and H. H. Yang, "Towards cost minimization for wireless caching networks with recommendation and uncharted users ' feature information," IEEE Trans. Wireless Commun., 2021 Early Access.'
7. Nicholas Toombs and Placid M. Ferreira, "Hydrostatic Fast Tool Servo for Micro Freeform Surfaces," ASPE (American Society of Precision Engineers) Spring Topical Meeting - Freeform and Structured Surfaces, April 28-29, 2021.
8. Srivastava and S.M. Salapaka. "Parameterized MDPs and Reinforcement Learning Problems – A Maximum Entropy Principle-Based Framework." IEEE Transactions on Cybernetics (2021).
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MS Thesis: Design and Implementation of Nuclear Power Equipment Health Management System Based on Knowledge Graph

Student: Xiaoying Liu

Supervised by Wang (H) (ZJUI)

Abstract: In recent years, nuclear power enterprises at home and abroad have successively promoted the application of innovative technologies in the nuclear power industry, such as artificial intelligence and big data mining in nuclear power. In nuclear power enterprises, large scale equipment has complex structure and high cost, which requires a lot of manpower and material resources in operation and maintenance. Therefore, equipment health management is the most concerned field of nuclear power enterprises. The nuclear power base has been accumulating massive various technical documents for many years. These documents contain equipment related knowledge and maintenance data such as defects, causes and corrective action, which constitute a multi value chain space in the field of nuclear power equipment. However, they have not been fully integrated, and there are data islands between various documents. In order to better integrate data spaces of various documents, this thesis studies the knowledge extraction technology for equipment text, extracts equipment related knowledge from various documents, and constructs an integrated knowledge graph of Equipment Document Maintenance. Based on this graph, a web application system is designed to help nuclear power personnel conduct comprehensive intelligent retrieval and knowledge management towards various documents of equipment that were originally cross system and isolated in data, which has practical engineering application value.

Firstly, this thesis researches the technologies of preprocessing and vectorization representation for text of nuclear power equipment. In the preprocessing phase, the maximum forward and backward algorithm is constructed to realize word segmentation, and then the stop words are removed. On the above basis, three word vectorization models, separately based on Bag of Words, TF IDF and Word2Vec, are constructed to represent the knowledge of text. The comparative experimental results show that the vectorization model based on Word2Vec has the highest F1 Score of 92.23%, which provides high quality word vector representation for subsequent knowledge extraction.

Secondly, this thesis researches the knowledge extraction technology for text of equipment. According to the common entities and relationships in various text, three models for entity extraction, respectively based on CRF, Bi LSTM and Bi LSTM CRF, are constructed, while two models for relationship extraction, respectively based on CNN and ATT CNN, are constructed subsequently. The experimental results show that the F1 Score of the Bi LSTM CRF model for entity extraction trained in this thesis is the highest that reaches 91.38%, while the F1 Score of the ATT CNN model for relationship extraction is the highest that reaches 89.70%. Thirdly, based on rule based method, this thesis extracts the remaining structured data of various documents, and merges these data into the results of

entities and relationships extracted above, to construct a whole equipment knowledge graph of Equipment Document Maintenance, which is stored in the Neo4j graph database.

Finally, combined with the above two research results, a system of equipment health management is designed and developed, which is integrated many functions, such as knowledge query visualization, semantic search, expansion of knowledge graph, query of knowledge graph, maintenance for various documents and system management. This system provides services for nuclear maintenance workers and experts of equipment, and realizes the construction of knowledge graph and knowledge application services towards various documents of equipment maintenance in nuclear power. Through system testing, the functional performance and compatibility of this system can meet the engineering requirements of nuclear power enterprises.

PhD Dissertation : Machine Learning-Based Measurement, Modeling, and Control of Spatial Variability in Advanced Manufacturing

Student: Yuhang Yang

Advisor: Chenhui Shao

Abstract: Spatial and spatiotemporal variabilities commonly exist in many advanced manufacturing processes and systems. High-performance characterization, modeling, and control of such variabilities are crucial for enabling next-generation smart decision-making in quality inspection, process control, machine health monitoring and prognostics, etc. However, fundamental challenges exist in these decision-making tasks. Although the recent development in measurement technologies has made it possible to acquire spatial and spatiotemporal data at different scales, it is generally expensive and time-consuming to use such technologies in real-world production settings. Additionally, there is a lack of effective and data-efficient methods for analyzing high-dimensional, heterogeneous spatial and spatiotemporal data in manufacturing. This dissertation presents novel machine-learning-based approaches for the measurement, modeling, and control of spatial and spatiotemporal variabilities. The effectiveness of these approaches is demonstrated using real-world data collected from different manufacturing processes and systems at different length scales including ultrasonic metal welding, additive manufacturing, and two-photon lithography. A hierarchical measurement strategy is developed to cost-effectively acquire spatiotemporal data by optimally allocating the measurement efforts in both spatial and temporal domains. Determining the observation times and measurement locations is formulated as a two-level decision-making problem. To expedite the solution search process, hierarchical genetic algorithm is adopted and implemented using high-performance computing. A hybrid multi-task-learning approach is created for accurate and cost-effective response surface modeling. This approach recognizes the differences and similarities between multiple manufacturing processes and accordingly constructs physics-informed self-learning and multi-task-learning models. Data efficiency and learning performance are thus improved through the transfer of information across processes. A

hybrid hierarchical modeling method is developed to data-efficiently predict the feature-level geometric accuracy of parts produced by multiple identical additive manufacturing machines. The modeling method decomposes the geometric variability into a large-scale part-level trend and a small-scale feature-level term, which are characterized by a hierarchical Bayesian linear model and a Gaussian process model, respectively. A geometric compliance improvement framework for two-photon lithography is established to quantify the spatial variation in the geometric accuracy of 3D structures and generate compensation designs to improve geometric compliance. It is revealed for the first time that both systematic and random geometric errors exist in 3D structures fabricated by two-photon lithography.

PhD Dissertation: Parameterized Sequential Decision Making Problems

Student: Amber Srivasatava

Advisor: S. Salapaka

Abstract: This thesis addresses a class of optimization problems that deals with the twofold objective of making sequential decisions, and simultaneously determining the unknown problem parameters such that the associated cost function gets minimized. We refer to these problems as parameterized Sequential Decision Making (para-SDM) problems. The application areas are plenty; for instance, network design problems, job-shop scheduling, industrial process optimization, last mile delivery, vehicle routing, sensor networks, clustering and classification.

In this work, we develop a combinatorial optimization viewpoint for these problems where the viewpoint is facilitated by the combinatorically large number of possible decision sequences, and use a Maximum Entropy Principle (MEP) framework to address them. The optimization problems considered in this thesis have been shown to be NP-hard, accompanied by a non-convex cost function whose surface is riddled by multiple poor local minima. The combinatorically large number of possible sequences of decisions on top of the above challenges render para-SDM as a difficult class of optimization problems. Our proposed MEP-based framework is designed to overcome the aforesaid challenges in para-SDM. For instance, we employ annealing from a suitable convex function to the non-convex cost function to avoid getting stuck in a poor local minima. Additionally, we utilize the problem structures (such as the law of optimality of the paths) to represent the combinatorial number of possibilities using a much smaller decision variable space. The proposed framework can incorporate application-specific capacity, inclusion-exclusion, and dynamic constraints. Our framework also extends to the class of problems where information about the underlying model is lacking, and we develop suitable stochastic iterative updates that interact with the underlying system to simultaneously learn sequences and parameter values. A peculiar characteristic of the annealing process in our MEP-based frameworks is the phase transition phenomenon. These are specific instances in the annealing procedure at which the solution undergoes significant changes. We demonstrate the utility of these phase transitions in determining certain design hyperparameters in para-SDMs, and in general, in combinatorial optimization problems; for instance, estimating the

true number of clusters in a data set, or determining the appropriate choice of the sparsity level in sparse linear regression problems.

PhD Dissertation: METROLOGY AUTOMATION AND GEOMETRIC ANALYSIS FOR ADDITIVE MANUFACTURING

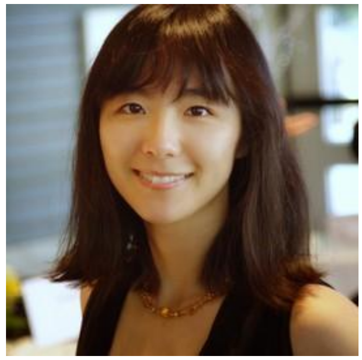
Student: Davis McGregor

Advisor: W. P. King

Abstract: Additive manufacturing (AM) enables flexible, scalable production of parts that can have complex geometries; however, inspection of these parts is challenging with traditional measurement methods and technologies, which often have low sampling density and, in some cases, high labor intensity. This research introduces a machine vision measurement system and analysis methods capable of automatically extracting high density measurements from optical scan data. The system utilizes Canny edge detection and Hough transforms to detect and measure geometric features of interest. We employ the measurement system to extract strut geometries from lattice parts, and accurately predict their compression properties, which largely depend upon strut geometry. In a second study, we measure over 21,000 individual features from lattice parts fabricated using multiple, identical AM machines. We apply variance decomposition on part-level geometric features, and quantify the effects that using different machines, tools, and locations within the print area have on the geometric variance of strut length, thickness, and part height. We extend these methods to analyze the internal geometry of a batch of AM nozzle parts inspected using three-dimensional X-ray computed tomography (CT). The parts were made using 11 polymer materials and 3 AM processes. We demonstrate scalable CT metrology and extract over 100,000 measurements from 69 CT scans. We find that AM can have very high part-to-part repeatability, while feature accuracy can be poor. The manufacturing accuracy of internal and external features can differ substantially and highlights the need for analysis methods capable of automatic batch processing of CT and other types of scan data. The research concludes by investigating how automatic geometry measurements can be combined with machine learning (ML) to predict AM quality in the production of parts of different designs. We collect measurement data from 405 parts having three different designs with common features. Using recorded manufacturing conditions and feature descriptors, ML models predict feature geometries to within 55 μm, which is close to the limit of random manufacturing variation and measurement uncertainty. In addition to predicting geometry, tunable thresholds convert the regression predictions into classification models and enable more accurate acceptance or rejection of features and parts than traditional ML classification strategies. This research demonstrates opportunities for metrology automation in AM applications, and the methods are extensible to numerous processes, materials, part designs, and types of scan data. Flexible AM currently exhibits large variability and low accuracy, and detailed measurement data can help address and control these issues.

Traffic Related Air Pollution Prediction Using Video Footage and Deep Learning

Annual Report – Period from October 2021 to September 2022


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

Traffic is a major source of air pollutants, causing approximately 20% of exposure to fine particulate matter ($PM_{2.5}$) in the United States (US), which is a major health risk factor in the US and in China, responsible for 63% of deaths from environmental causes and 3% of deaths from all causes in the US.

"Hyperlocal" information on how air pollutant concentrations vary in space and time is increasingly recognized as important for driving action to reduce air pollution and greenhouse gas emissions. Existing efforts to provide this information mainly focus on direct concentration measurement with high spatial and temporal density. However, the equipment required to collect these measurements is expensive and labor-intensive to acquire, maintain, and operate, which limits scaling of the direct measurement approach.

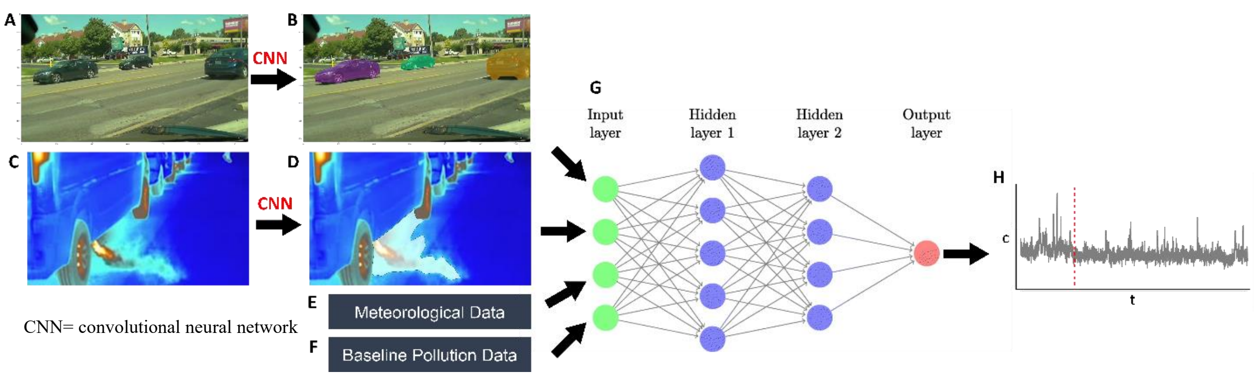


Figure 1. **Approach.** We use video sensing (A) with deep learning to represent the relevant aspects of the visual scene (B) and use infrared video sensing (C) with deep learning to represent the features of the exhaust (D) in Steps 1 and 2, then use the resulting information along with meteorological data (E) and air pollution baseline data (F) in a deep learning system (G) to predict elevated pollutant concentrations (H) caused by roadway sources in Step 3. Images shown above are from preliminary data collection. CNN= convolutional neural network.

Figure 2: A large truck identified by our machine learning model (in the green bounding box in the video frame) aligns well with our measured air pollution peaks (black vertical line shows the time of truck presence, and blue and red peaks are NO and black carbon concentration peaks in the bottom line plot).

As an alternative, we are building a system to leverage heterogeneous data sources in a machine learning system to make hyperlocal pollution and greenhouse gas concentration estimates. The general approach is shown in Fig. 1.

This project is creating a system that uses traffic video footage and deep learning to predict measured traffic-related pollution concentrations in Hangzhou. This year, the ZJU team has continually collected air pollution measurements and collocated traffic video in Hangzhou. Meanwhile, the UIUC team has trained a model to detect and classify different vehicle types in videos. In this project, we have successfully identified large trucks from most video frames where we also see strong correlations of air pollution concentration peaks (Figure 2). We have also found a relationship between nitrogen oxide concentration and single-unit heavy truck detections, corresponding to the time series in Figure 2 (as shown in Figure 3). Overall, we are able to predict ~17% of the variance that we observe in the air pollution concentrations using only the visual information available in the video.

Together, these results comprise a strong proof-of-concept, which we are continuing to refine while we scale up our workflow to leverage larger amounts of data, which will allow us to build more powerful and accurate models. We have successfully leveraged the DREMES seed funding to obtain a grant from the Discovery Partners Institute to work with researchers at Argonne National Lab to deploy this system in Chicago. We have also submitted a white paper for a DREMES center grant with a larger group of collaborators and are preparing a grant to the NSF Smart and Connected Cities program for submission early next year.

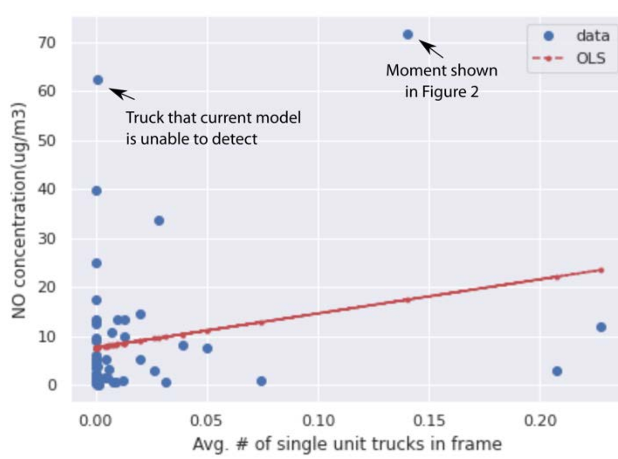


Figure 3. Relationship between nitrogen oxide concentration and single-unit heavy truck detections. p=0.10 for single-unit trucks only; all vehicle types together account for 17% of pollution variance.

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Publication List

None yet

Heterogeneous Integration for Neuromorphic Integrated Circuits Annual Report – 2021-2022

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DREMES Seed Project;
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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 the efforts from the DREMES seed funding which has led to the creation of a proposed Center for **H**eterogeneousl**Y** integrated **BR**ain **I**nspire**D** computing (HYBRID), whose goals will be to develop a unified "materials-to-systems" program. It is to have a strong emphasis on hardware-software co-design in order 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.

During the seed period, our group addressed the challenges related to the modeling and analysis of neuromorphic integrated systems from an electromagnetics standpoint. We assumed a chiplet approach to the design of the system. The packaging and wiring of circuit components have serious impact on the reliability and stability of signal transmission in heterogeneous integrated systems. For instance, a good power distribution strategy must be devised to provide accurate and reliable methods for estimating power-bus/ground plane impedance and its variation with frequency. The approach should also provide methods for determining the location and value of bypass capacitors.

In particular, we decided to focus our efforts in the design of the interposer. An interposer is a silicon chip that hosts a complex interconnection scheme that serves to bridge several different blocks that may consist of other functional smaller chips. Modeling, simulating and optimizing the performance of the interposer would constitute a major task. We have established that PEEC as one of the methods for carrying an efficient and accurate electromagnetic extraction. Examples are interconnections between digital circuits or integrated microwave circuits. Equivalent circuit models can be derived here from an integral equation to establish an electrical description of the physical geometry. These models, are referred to as partial element equivalent circuits (PEEC). Models of different complexity can be constructed, using the PEEC approach.

We investigated in parallel, methods for performing the electromagnetic extraction. One method is a physics-based neural network method (PINN). The other is the more traditional partial element equivalent circuit (PEEC) method. This could contribute a major component to the framework for developing a platform for this type of heterogeneous integration. The framework to be used in the circuits/electromagnetics portion of our effort is shown in Figure 1 and uses the latency insertion method (LIM) as its core simulation engine.

During this reporting period, we also focused on enhancements of LIM for frequency-domain simulations. The approach consisted of performing a transient simulation with a Gaussian excitation and extracting the frequency-domain response using Fourier transforms. Explicit, semi-implicit, and VinC LIMs with different time steps were tested and compared with ADS. Results showed good agreement with ADS for a power distribution network.

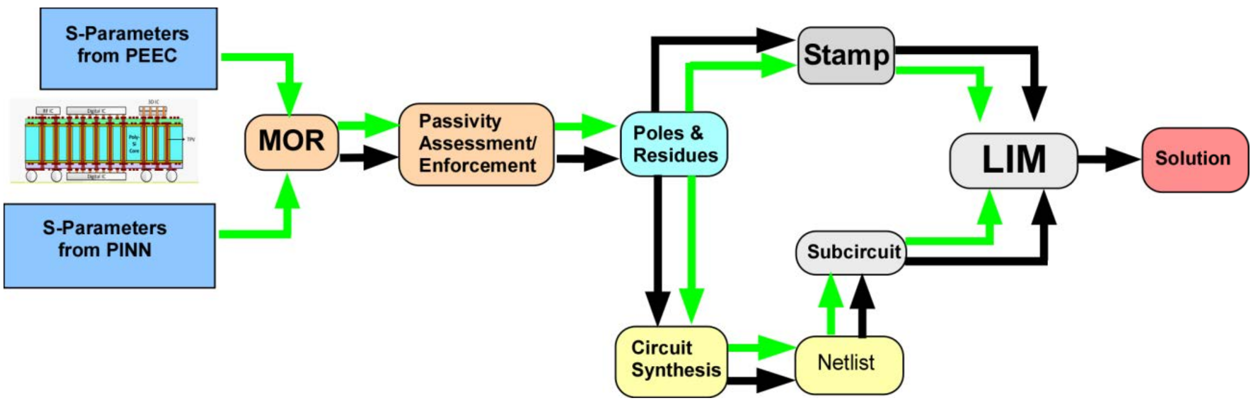

Figure 1. Flow diagram for simulation of heterogeneous neuromorphic system.

We plan to investigate strategies to tackle the multi-physics nature of our modeling task. Abstraction methods are possible by using model-order reduction techniques (MOR), known to be useful in electromagnetics, mechanical, and thermal analysis. Reduced models are computationally more efficient by an order of magnitude and are more easily connected with other types of macro-models. By creating reduced models for mechanical, thermal, electrical, and power analysis, one can achieve several orders of magnitude speedup and more module interconnectivity. Behavioral models are another approach for abstraction and simplification of complex models. Such techniques have been used in the electrical domain in the form of network parameters (S- parameters). We plan to investigate these avenues for handling multiphysics challenges.

Finally, we decided to broaden our team to include architecture, neuroscience and materials experts. This will place us in a better position to tackle the challenges of neuromorphic system design and prepare us for the next stage of the project.

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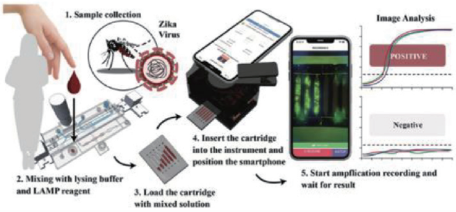
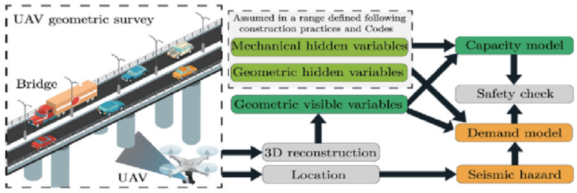
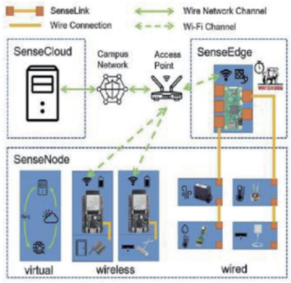
Publications

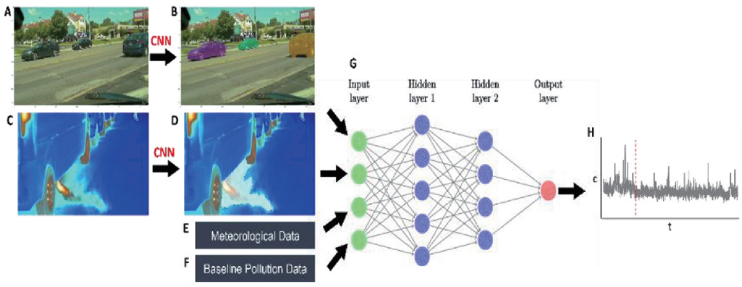
1. Yi Zhou, Bobi Shi, Yixuan Zhao, and Jose E. Schutt-Aine, "Fast Eye Diagram Simulation based on Latency Insertion Method", to be presented at the 2022 IEEE Electrical Design of Advanced Packaging and Systems Conference, Virtual, December 12-14, 2022.
2. Yi Zhou and Jose E. Schutt-Aine, "Latency Insertion Method for FinFET DC Operating Point Simulation Based on BSIM-CMG" to be presented at the 2022 IEEE Electrical Design of Advanced Packaging and Systems Conference, Virtual, December 12-14, 2022.
3. H. Ma， Da Li, Tuomin Tao, E.-X,Liu, J. Schutt-Aine, A.C. Cangellaris, E.-P. Li et al., "Uncertainty Quantification of Signal Integrity Analysis for Neuromorphic Chips," in IEEE Transactions on Signal and Power Integrity, vol. 1, pp. 160-169, 2022, doi: 10.1109/TSIPI.2022.3222122.

4. Hanzhi Ma, Da Li, E.-P. Li, A. C. Cangellaris, and Xu Chen. A Fast Optimization Method for High-Speed Link Inverse Design with SVR-AS Algorithm, in IEEE Transactions on Signal and Power Integrity, vol. 1, pp. 22-31, May 2022.









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