Zhejiang University and
University of Illinois, Urbana-Champaign

Joint Research Center

2020–2021 Annual Report

Dynamic Research Enterprise for
Multidisciplinary Engineering Sciences (DREMES)
October 1, 2020 – September 30, 2021

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Welcome to the first annual report of the Dynamic Research Enterprise for Multidisciplinary Engineering Sciences (DREMES). 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. Many activities are engaged with the joint Zhejiang University-University of Illinois at Urbana-Champaign Institute (ZJUI). This report covers activities from October 1, 2020 through September 30, 2021.

DREMES supports thematic thrust areas proposed by collaborative faculty teams. Proposals are vetted through a two-stage peer-review process, and selection is processed by the JRC leadership committee. The leadership committee for DREMES includes an Illinois co-director, a ZJU co-director, and principal investigator representatives from Illinois and from ZJU for each thrust area. Final thrust area selections are approved by the Joint Management Committee (JMC) of ZJUI. At the beginning of academic year 2020-2021, the JMC approved three thrust areas.

The combined thrust areas are provided with an annual budget of up to US$900,000 for an initial three-year period, plus an operating budget of US$100,000. These funds are to be used at Illinois, and typically support research assistants, post-doctoral associates, laboratory costs, related research expenses, and program administration. Illinois-side principal investigators (PIs) submit comprehensive annual budget plans to the Illinois College of Engineering, and expenses are reviewed against these approved budget plans. On the China side, additional project support takes the form of China-side research assistants, post-doctoral associates, and facilities. These additional funds are managed separately by ZJU.

By mutual agreement and JMC approval, DREMES has initiated research centers in three theme areas for 2020-2021. The work began by October 1, 2020. The thrust areas are:

- Engineering sciences for human health, organized as the Center for Pathogen Diagnostics (CPD).
- Engineering sciences for flexible manufacturing, organized as the Center for Adaptive Resilient Cyber-Physical Manufacturing Networks (CyMaN).
- Engineering sciences at the nexus of energy, environment, and sustainable development, organized as the Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE).

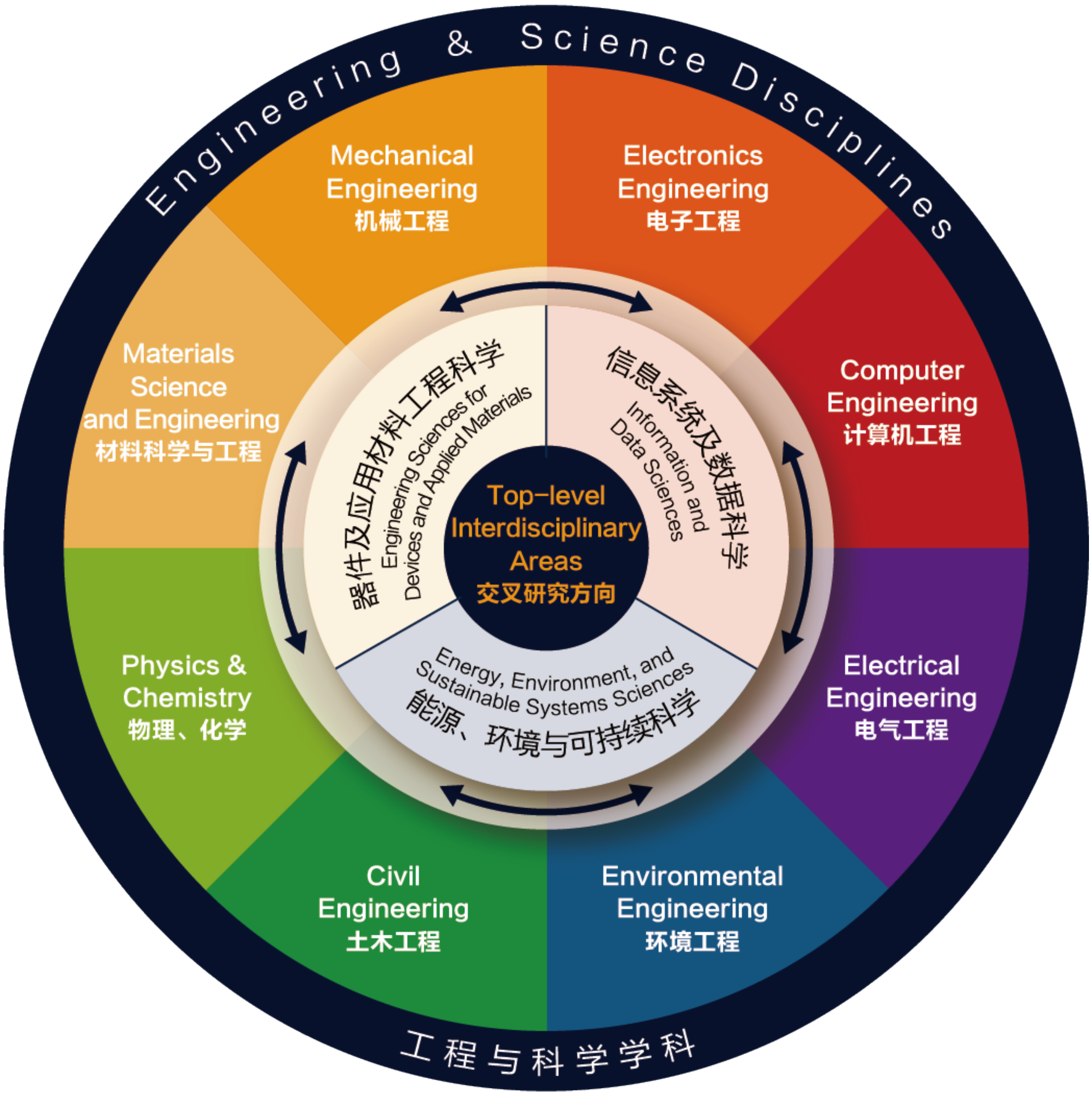
Each of these research centers manages smaller collaborative projects within its purview.

CPD activities involved 13 faculty members across ZJU, Illinois, and ZJUI. The center supported thirty research students and four post-doctoral associates. In addition, at least six undergraduate students were active in CPD laboratory projects. CPD research has been documented in more than 30 journal and conference publications. The faculty have presented at least 18 invited talks in a range of meetings and academic settings. CyMaN has involved 14 faculty members across ZJU, Illinois, and ZJUI. The center supported nine research assistants and one postdoctoral associate. The work has been documented in eight journal and conference publications. CIRCLE has involved 12 faculty members across ZJU, Illinois, and ZJUI, plus a new faculty member who joined ZJUI recently. The center supported 19 research students and two post-doctoral associates. At least ten undergraduate students have been active in CIRCLE research efforts. The work has been documented in at least 15 journal and conference publications, and already two students have finished their degrees through work on CIRCLE projects.

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


Engineering & Science Disciplines
Mechanical Engineering 机械工程
Electronics Engineering 电子工程
Computer Engineering 计算机工程
Electrical Engineering 电气工程
Environmental Engineering 环境工程
Civil Engineering 土木工程
Physics & Chemistry 物理、化学
Materials Science and Engineering 材料科学与工程
器件及应用材料工程科学
Engineering Sciences for Devices and Applied Materials
信息系统及数据科学
Information and Data Sciences
Energy, Environment, and Sustainable Systems Sciences
能源、环境与可持续科学
Top-level Interdisciplinary Areas
交叉研究方向
工程与科学学科

CIRCLE: Center for Infrastructure Resilience in Cities as Livable Environments

Center Overview

The Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE) is one of three joint research themes established in 2020 between the University of Illinois at 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 thrusts 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.

Here, we highlight a few of the activities and achievements of CIRCLE in the first year. An annual summary of each topic areas and of topic integration is also provided.

CIRCLE Progress Highlights

- ***Students Graduated***: Two 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 received his MS at Politecnico di Milano in December 2021 after a visiting semester at UIUC and will be seeking a position in Italy. In addition, CIRCLE research assistant Sicheng Zhou left to pursue a Ph.D. at the Universit Politecnico di Milano.

- ***Undergrad supervision***: Yueer Cai (undergraduate student at 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.

- ***External Funding***: (i) The CIRCLE team led by Prof. Demartino has submitted a proposal entitled "Traffic load monitoring and structural assessment of bridges using digital twins" to Argo Innovation Lab. The project has passed the screening process and is under final review. This project will enhance the Thrust Integration efforts in 2022. (ii) A team of CIRCLE researchers is applying for a joint NSF-NSFC project on Sustainable Regional Systems.

- ***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, and enhance the research experience for our students. The series runs approximately monthly, and the first lecture was in July 2021. 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 offset carbon footprints of buildings, helping China to achieve carbon neutrality in 2060 using bio-based construction materials combined with renewable energy. This center, led by CIRCLE ZJU Co-Director Prof. Xiao, will be run in close collaboration with CIRCLE. The new center receives 10 million RMB distributed over three years from 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 degrading 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 irrigation function due to rapid urban development in the foothill areas. The flood control function of the dams has been identified for potential risk for dense new downhill urban industrial facilities.

- ***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 associated 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.

CIRCLE Project Annual Summaries

CIRCLE 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 have completed an assessment of residential electricity consumption as a function of socioeconomic conditions, and we are continuing to analyze residential heating and air conditioning in institutional buildings on the ZJU International Campus. One journal manuscript has been submitted, and members of the team will present work at the American Geophysical Union Fall Meeting in December 2021.

Analysis of residential electricity consumption

This project explores building-scale electricity consumption across testbeds in Chicago and in Haining. In the Chicago testbed, we are focusing on residential electricity consumption based on smart meter data from Commonwealth Edison (ComEd), quantifying variation in load profiles in response to weather conditions and socioeconomic factors (Figure 1). To analyze residential electricity demand for heating and air conditioning, we have implemented various machine learning approaches that characterize load variation in response to outdoor temperature. We have made substantial progress in the Chicago testbed analyzing single- and multi-family residential electricity consumption as a function of various socioeconomic factors. The team showed that education attainment levels, in terms of percent with high school or higher education, and median age of occupants have the highest importance in explaining variation in single- and multi-family residential electricity consumption, respectively. This part of the effort has appeared in a conference abstract (2021 American Geophysical Union Fall Meeting) and a journal submission is pending approval by our data sharing partner. In the Haining testbed, we are analyzing ZJU International Campus building-level energy and water consumption profiles, with preliminary analysis showing various occupancy signatures and data anomalies in institutional buildings.

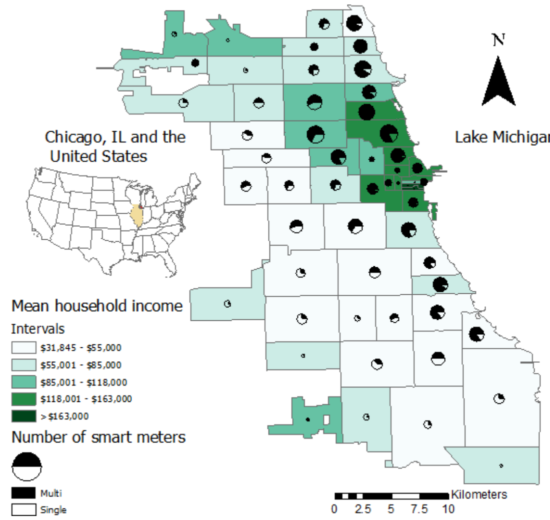


Figure 1. We quantify the variation in residential electricity consumption in our Chicago testbed with socioeconomic factors based on smart meters and census data.

At a micro level, the CIRCLE team at ZJU is working with an industrial partner in Zhejiang to assess the energy efficiency of a hybrid power generator combining solar and wind for a single house. The house was built by the team using bamboo and timber as structural and envelope materials. A prototype power generator has been manufactured and installed on site.

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).

Figure 2. Energy efficiency study of bio-material-based house equipped with small scale solar-wind power

CIRCLE 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) model validation and development; (ii) projections of future climate change-driven risks to cities; and (iii) data and model preparation and preprocessing for testbeds in Hangzhou and in Chicago. One paper has been published in *Nature Communications*, and a manuscript has been submitted to *Environmental Research Letters*. Four more manuscripts have been accepted for presentation at the American Geophysical Union Fall Meetings (one in Dec. 2020 and three in Dec. 2021).

Modeling Urban Green Stormwater Infrastructure (GSI)

This project emphasizes fundamental engineering principles of green infrastructure for urban climate adaptation and sustainable development. The team is a tightly integrated collaboration between the water and environment thrust and the energy thrust. In Year 1, we have finished Phase 1 of this project: validating the model and project future urban runoff on a global scale (Figure 3). The paper "Impacts of global climate change on urban total runoff" has been submitted to *Environmental Research Letters*. We are now working on Phase 2: conducting high-resolution city simulations to model the impacts of GSI on urban hydrology and heat mitigation. Faculty members from ZJU (Yueping Xu) and their students will all be involved in this phase of the research collaborations.

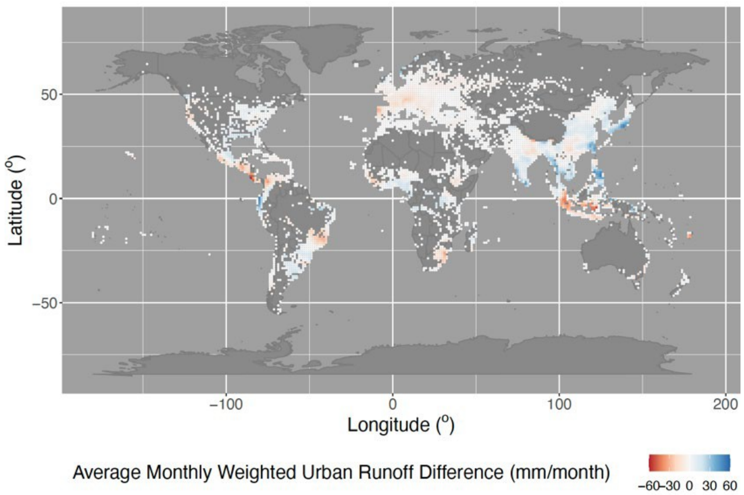


Figure 3 *Overall average difference of weighted urban monthly runoff between 2041-2050 and 2016-2020.*

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

This cross-campus collaborative project between ZJUI and UIUC will analyze spatiotemporal patterns of Hangzhou green space distribution, underlying factors influencing distributions, water consumption, and environmental impacts. This work assesses the environmental impacts of existing "sponge city" best management practices (BMPs) in Hangzhou, and optimizes BMPs (coupled natural and engineered systems; size, location, distribution) to maximize resilience with respect to extreme climate events. At the national scale, we examined daily meteorological data from 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. This information allowed us to estimate 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 coded in Python. The water demand results were then compared with recent water use of those cities to approximate the shares of urban greenspace irrigation in total urban water use, thus revealing water stress imposed by urban greenspace.

A preliminary digital model was developed for the Tongshan Late dam, a small agriculture dam in the Ningbo area. The dam was originally built for irrigation, but lost this function due to rapid industrial development. Potential risks are identified for possible flooding due to this functional change. The digital model will be worked further to assess other possibilities such as adding tourism and water thermal functions with the dam.

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

CIRCLE Project 3: Transportation Thrust

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

Thrust Highlights

The transportation thrust has made strong progress in the following two areas: (i) address sustainability and resilience challenges; and (ii) examine emerging technology-enabled opportunities. One Ph.D. student, Zhoutong Jiang, graduated in July 2021 and has started his new job as a research scientist at Facebook. Three papers have been published in leading journals, and two additional manuscripts were accepted for presentation at the upcoming 2022 Annual Meeting of the Transportation Research Board.

Planning of Surveillance, Evacuation and New Mobility Services for Livable Communities

This project focuses on planning reliable evacuation services under the threat of disasters and technology- enabled shared mobility services, aiming to enhance the sustainability and resilience of urban transportation systems. The team is a tightly integrated collaboration across UIUC and ZJUI. All of the students involved in this project have joint supervisors from Illinois and Zhejiang.

Research efforts and results are summarized as follows: (i) We developed a reliable multi-type joint-service facility location model (e.g., for surveillance or first responders), which considers the need for cooperative service from multiple types of responder stations, as well as the risk of facility disruptions (Jiang and Ouyang, 2021); (ii) We developed a probabilistic location-routing model that plans reliable services for targeted evacuation against the threat of disasters, so as to minimize the total expected cost for setting up a set of rendezvous points, assigning evacuees to rendezvous points, and routing rescue vehicles to pick up evacuees, as illustrated in Figure 4. The efforts are reported in a paper currently accepted for presentation and under review for publication (Jiang and Ouyang 2022). (iii) We tackled the shared autonomous vehicle (SAV) routing problem in a network with parking facilities. An integer linear programming model was proposed to jointly optimize vehicle-trip assignments and vehicle route choices to maximize SAV company profits considering passenger benefits. The efforts were reported in a paper currently accepted for presentation and under review for publication (Hu et al., 2022). (iv) To examine new technology-enabled opportunities for urban mobility and logistics, we built upon our efforts on UAV based last-mile deliveries (She and Ouyang, 2021) and further strengthen our collaboration on planning and operation of shared autonomous transportation systems. In the coming year, the thrust will conduct further research on joint design of parking locations and vehicle routing for SAV systems, as illustrated in Figure 5, and on the planning and operations of shared modular chassis for autonomous vehicles.

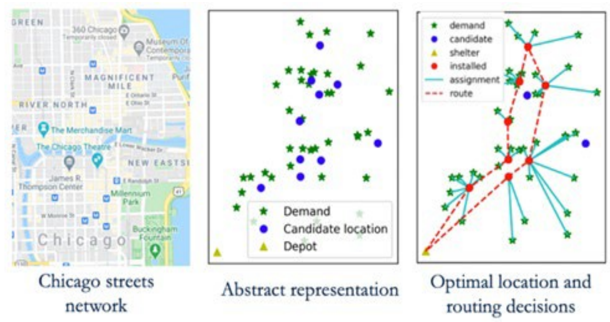


Figure 4: Case study on targeted evacuation in downtown Chicago.

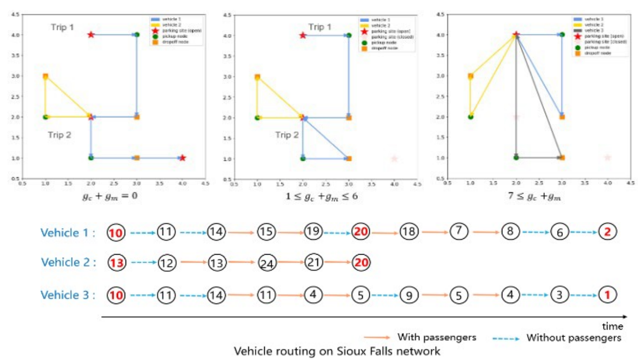


Figure 5: Case studies on parking location choice and vehicle routing.

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

CIRCLE Project 4: Built Infrastructure Thrust

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

Thrust Highlights

The infrastructure thrust has made strong progress in two areas: (i) formulate physics-based and data-driven computational fluid dynamics (CFD) and fluid-structure interaction (FSI) models; and (ii) enabling technologies and tools for digital twins of infrastructure system. Two papers have been published or are under review in leading journals, and two invited presentations were given at major conferences. The project provided an opportunity for one ZJUI undergraduate student, Yueer Cai, to complete an independent study course. Weekly meetings are scheduled to ensure that students have sufficient exposure to the research project. A master's student, Giacomo Listrani from the Polytechnic University of Milan, graduated with a 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 Profs. Yasutaka Narazaki and Cristoforo Demartino on a framework for long-term structural health monitoring by computer vision and vibration-based model updating.

Physics-informed machine learning for fluid-structure interaction

This project explores physics-informed machine learning for CFD and 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 buildings and energy harvest structures such as wind turbines. Figure 6 shows the concept of the FSI model and its

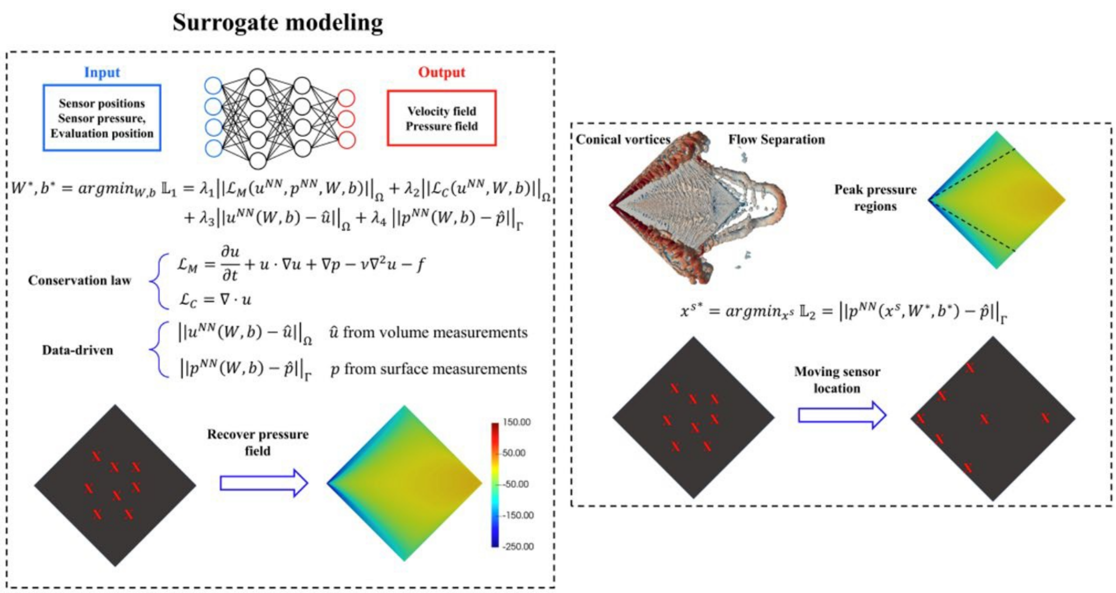


Figure 6. Physics-informed machine learning for wind engineering.

application to structures. Two journal papers from this project are under review. Prof. Yan was invited to give talks about the project at ISC 2021: International Supercomputing Conference (virtual) and 2021 Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering & Technology (San Diego).

Energy Harvesting from Pedestrian-Induced Footbridge Vibrations for Smart Monitoring Applications

The present work is meant to contribute to innovation of current methodologies for pedestrian bridge monitoring. Vibrational energy harvesters for self-powered wireless structural monitoring of footbridges is explored for the first time, and a novel sensorless strategy is also proposed to survey serviceability conditions (see Figure 7).

Comprehensive numerical investigations were conducted to obtain statistical estimates of electrical energy generated from a composite piezoelectric cantilever beam subjected to vertical footbridge response as pedestrians pass. Randomness related to pedestrian dynamics and various footbridges was taken into account. An investigation based on experimental data was presented. One case study is concerned with a footbridge susceptible to large vibrations due to resonant conditions. A second case study deals with a stiffer footbridge. Ultimately, this work indicates that energy harvesting from vertical pedestrian-induced vibrations can be promising for footbridge monitoring, and provides useful design guidelines.

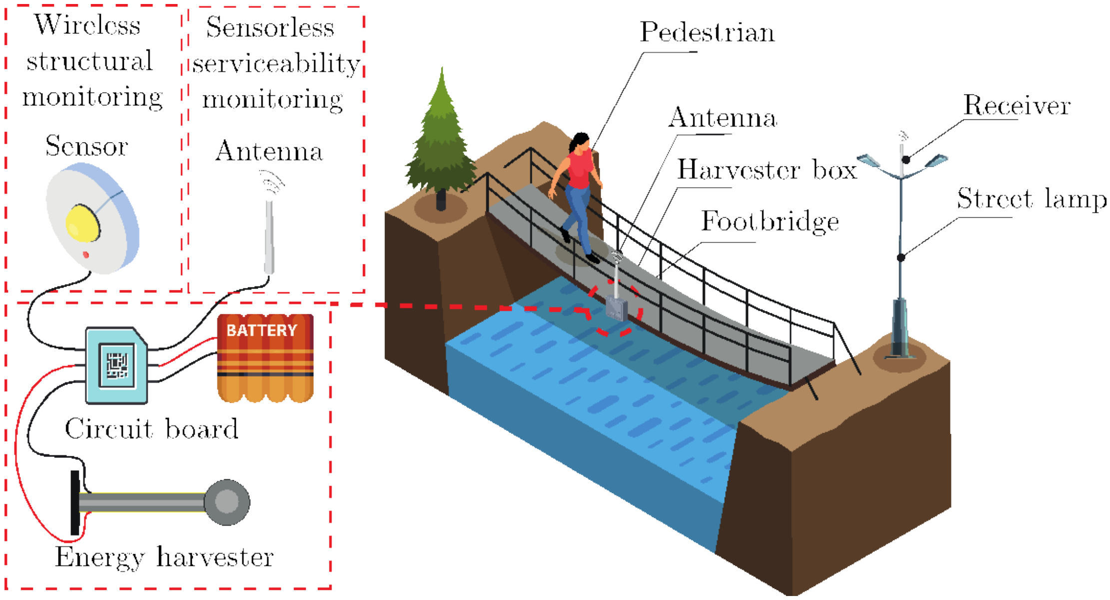


Figure 7: Proposed framework.

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 (see Figure 8). 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 computer vision techniques. The acceleration response time histories at various locations are measured using accelerometers located on the deck. The FE model is used together with traffic flow information to describe dynamic behaviors of the bridge. The digital twin platform allows for the real-time estimation of vehicular loads and health monitoring of the bridge. The system can be trained to automatically detect anomalous events and provides warnings. The potential implementation of artificial intelligence techniques can make the system capable of autonomous decisions such as traffic interruption.

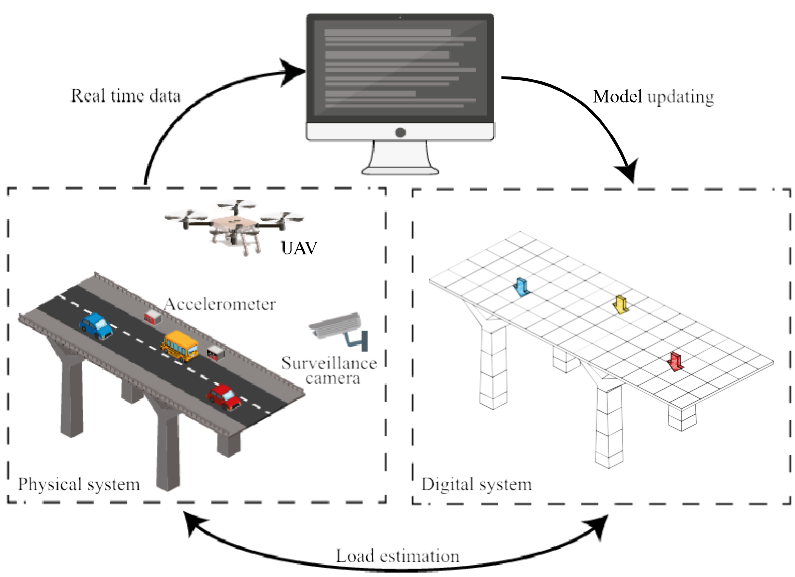


Figure 8. Proposed digital twin framework.

This preliminary study focuses on real-time estimation of vehicular load. The team has worked to plan experiments on a real bridge to obtain a dataset to validate the proposed concept in collaboration with the transportation thrust and the integration thrust. The digital twin concept developed in this project can also be applied to wind turbine monitoring and control. This potential application is under discussion. Prof. Demartino and Prof. Narazaki from ZJUI and Prof. Spenser and Prof. Sychterz from the UIUC are meeting each week to define more collaborative projects between the two campuses. One conference paper was published in EUROSTRUCT 2021: Conference of the European Association on Quality Control of Bridges and Structures, and an invited presentation was given during TRC2021: The Transportation Research Congress. A funding application entitled "Traffic load monitoring and structural assessment of bridges using digital twins" was submitted to Argo Innovation Lab. That proposal passed the screening process and is under final review.

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

CIRCLE Project 5: Thrust Integration

Co-PIs: Marcelo Garcia (UIUC), Zhizhen Zhao (UIUC), Mark Butala (ZJUI), Yueping Xu (ZJU)

Thrust Highlights

The thrust integration team focuses on the interface, interoperation, and interaction between the different model and data assets available across CIRCLE thrust areas. The efforts of the thrust integration team were highlighted in a keynote presentation at the 2nd ZHITU Symposium on Advances in Civil Engineering. Progress has been made on several fronts.

Chicago Hydrologic Modeling

First, we have begun implementing a hydrologic and hydraulic Storm Water Management Model (SWWM) coupled with the Illinois Urban Hydrology Model (IUHM) for the Racine Avenue Pumping Station (RAPS) watershed in Chicago, Illinois. Specific tasks include the coupling of the RAPS SWWM/IUHM model to the Deep Tunnel System (TARP), linking, and integrating connections to Bubbly Creek to assess combined sewer overflows (CSOs) as well as discharge towards the Stickney Water Reclamation Plant during extreme flow events. A summary of the various models involved and their interconnections is provided in Figure 9. Efforts are underway to integrate the models with the water, energy, and environmental thrust to assess the impact of extreme weather events on flooding risk, energy consumption and public transportation.

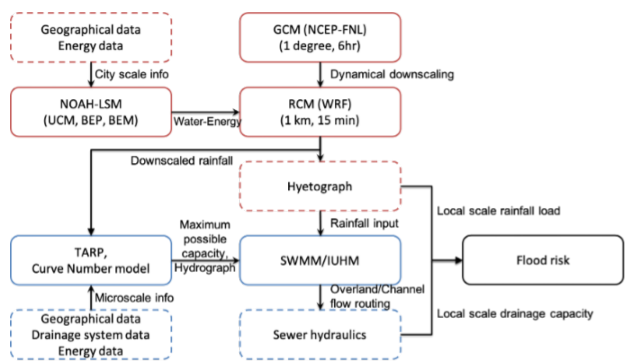


Figure 9: Overview of the models connecting WRF with SWMM/IUHM to assess flooding risk during extreme storm events in Chicago, Illinois.

Edge Computation and Computer Vision System

We have developed a low-cost embedded system for continuous measurement of structural bridge parameters (vibration via acceleration), computer vision for vehicle location and tracking, and other relevant physical parameters (acoustic signatures). The system has been field tested and has been designed for expandability to incorporate additional sensors in the coming months, e.g., for structural strain measurement. The efforts will culminate into the construction of a testbed digital twin of the Juanhu Bridge south of the International Campus in Haining with the support and collaboration of faculty across the transportation and built infrastructure thrusts.

Machine Learning and Statistical Analysis of Chicago-Area Electrification Data

Thrust integration and energy thrust area members have collaborated on the classification of Chicago-area households with respect to electric space heating from meter data using neural networks for classification in addition to feature engineering and logistic regression. The primary challenge is the imbalance between positive and negative samples.

Hangzhou Hydroclimatic Modeling
This is another tightly integrated collaborative project between ZJUI and UIUC. This project leverages our expertise in regional climate modeling and experience in modeling Chicago's hydroclimatic change to model urban climate change and variability in the Hangzhou region. Climate extremes are a focus of this project. Results from this project will inform Hangzhou's urban planning, risk management, and sustainable development under climate change. In Year 1, we have finished data collection and preprocessing work for the Hangzhou testbed including meteorological data, climate model data, flood data, hydrologic and hydraulic data, and river channel geometry. We are now setting up a coupled urban climate-hydrology model for Hangzhou and analyzing climate change data.
Students supported through this project include: Yifan He (UIUC), Sun Young Park (UIUC), Zhan Liao (ZJUI), Peixiang Wang (ZJUI), Xinfeng Liu (ZJUI), Ronghui Zheng (ZJUI), and Yu Hongjie (ZJU).

CIRCLE Personnel

Faculty PIs and Co-PIs
- Mark Butala (ZJUI), Assistant Professor
- Marcelo Garcia (UIUC), Yeh Endowed Chair Professor
- Simon Hu (ZJUI), Assistant Professor
- Binbin Li (ZJUI), Assistant Professor
- Yanfeng Ouyang (UIUC), Professor
- Billie Spencer (UIUC), Newmark Endowed Chair Professor
- 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)
- Xuguang Wang (ZJUI)

Graduate Students
- Laura Gray (UIUC)
- Yifan He (UIUC)
- Qinru Hu (ZJUI)
- Zhoutong Jiang (UIUC)
- Christopher Lee (UIUC)
- Zhan Liao (ZJU)
- Giacomo Listrani (UIUC, on leave from Politecnico di Milano)
- 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, and Rongjia Sun were actively engaged in laboratory 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.
4. Demartino C., Quaranta G., Maruccio C., Pakrashi V. (2021). “Feasibility of energy harvesting from vertical pedestrian-induced vibrations of footbridges for smart monitoring applications.” *Computer-Aided Civil and Infrastructure Engineering*, submitted.
5. Gray, L., Zhao, L., and Stillwell, A. “Impacts of global climate change on urban total runoff,” *Environmental Research Letters*, 2021 (under review).

Conference proceedings

1. Mark D. Butala and Zhizhen Zhao, “Construction of a living, integrated cybermodel of complex urban environments,” (Keynote) in *Proc. 2nd ZHITU Symposium on Advances in CivilEngineering*, pp. 3-4, 2021.
2. Pesantez, Jorge E., Grace E. Wackerman, and Ashlynn S. Stillwell. (2021). “Smart Meter Data to Analyze Electricity Demand from Single- and Multi-Family Consumers in a Diverse Urban Environment.” Conference presentation at American Geophysical Union Fall Meeting, December13-17, 2021; New Orleans, LA, USA.
3. Pan, L., T. Zhu, and C. Li (2021). Estimating Urban Greenspace Irrigation for 400 Cities in China:
4. Implications for Urban Land Use and Water Management. AGU Fall Meeting, 13-17 December 2021, New Orleans, LA.
5. Gray, L., Zhao, L., and Stillwell, A. (2021). Urban Climate Modeling to Quantify Runoff Reductionfrom Ground-Based Green Stormwater Infrastructure Implementation. AGU Fall Meeting, 13-17 December 2021, New Orleans, LA.
6. Hu, Q., Chen, X., and Hu, S. "An optimization model for network routing and parking of shared autonomous taxis." Accepted for presentation at the 101st Annual Meeting of Transportation Research Board, Washington DC, United States, January 9–13, 2022.
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.
8. Qiming Zhu, Jinhui Yan, Physics-informed machine learning for fluid-structure interaction problems.

ISC 2021: International Supercomputing Conference (ISC), CFDML2021 (to appear).
9. Zhou, C.Y., Xiao, D.H., Hu, J.H., Yang, Y.T., Li, B.B., Hu, S., Demartino, C., and Butala, M. (2021). "An example of digital twins for bridge monitoring and maintenance: preliminary results." *EUROSTRUCT 2021: Conf. European Association on Quality Control of Bridges and Structures.*
10. Zhou, C.Y., Xiao, D.H., Hu, J.H., Yang, Y.T., Li, B.B., Hu, S., Demartino, C., and Butala, M. (2021). "Preliminary Results of Vehicle Load and Noise Estimation Using Digital Twins." *TRC2021: The Transportation Research Congress.*

Theses and dissertations

1. Listrani, G. (2021). "Computer Vision for Damage Initiation and Recovery Assessment of Self-healing Concrete Structures." Master Thesis, Politecnico di Milano & University of Illinois.
2. Jiang, Z. (2021). "Resource Allocation and Pricing under Competition in Shared MobilityMarkets." Ph.D. Thesis, University of Illinois.

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CPD: Center for Pathogen Diagnostics

Center Overview

As highlighted by the ongoing COVID-19 pandemic, technologies and commercial products for disease diagnosis and immunity determination have important limitations that drive cost, detection limits, fast turnaround, sensitivity and selectivity against false results, and availability at the point of care. The shortcomings of COVID-19 diagnostics are representative of those used in the contexts of bacterial pathogens, fungal pathogens, vector-borne illness, food safety, and monitoring of environmental resources. The vision of 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 an innovation pipeline 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 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.

CPD Founding Team. Prof. Rashid Bashir (BioE, UIUC) has joined CPD in October 2021. Profs. Xiuling Li and Yi Lu left UIUC for UT-Austin in August 2021.

CPD Progress Highlights

Research achievements: Centered on the development of novel pathogen diagnostic technologies that are rapid, inexpensive, ultrasensitive, user friendly, point-of-care (POC) capable, and manageable by AI and big data, major CPD accomplishments this year include:

(1) 24 peer-reviewed journal articles (including papers in *Nature Materials*, *Nature Communications*, *PNAS*, *JACS*, and *Advanced Functional Materials*) and 9 conference papers.

(2) We have developed a label-free SARS-CoV-2 detection method with single-virus resolution and sensitivity commensurate to PCR techniques. Our virus detection platform is the first label-free biosensing method that can detect single viral particles in human saliva. The single-step process workflow can be performed at room temperature. The test sample is mixed with an aptamer-

immobilized biosensor. By leveraging the versatility of DNA aptamers and the SELEX process for aptamer screening, we envision that this technique can be extended quickly to other viruses to prepare for future epidemics and pandemics.

(3) We have created multiple wearable and portable devices that can be used to provide real time pathogen infection monitoring. Such devices can be adapted for monitoring infection status of individuals to help curb future epidemics and pandemics.

(4) We have been pursuing AI and data science questions that arise from novel pathogen diagnostics methods. These speak to broader testing protocols and to public health system-level implications of testing.

(5) We have developed a novel method for selecting better aptamers with higher pathogen biomarker binding affinity and selectivity.

(6) We have integrated an optical force nanoscopy system with an optical fluorescence imaging system to measure and differentiate various induced optical forces, and have measured chiral molecular signals enhanced by plasmonic nanoantennas.

Awards:

(1) Fangwei Zhao received a 2021 Research Fund for International Excellent Young Scientists in China.
(2) Xing Wang and Brian Cunningham were awarded a grant by the U.S. National Institutes of Health.
(3) Xing Wang won the Mikashi Award.
(4) Lav Varshney secured an NSF grant as a co-PI.
(5) The faculty team secured multiple NSFC project grants.
(6) Nantao Li (PhD student) was nominated by Illinois to compete for the NIH F99/K00 award and for a Schmidt Science Fellowship.

Activities:

(1) Organized internal and external seminar series and hosted a sequence of three international scholars to present their research.
(2) Presented CPD research activities to ZJUI juniors for undergraduate student involvement in CPD research. We have recruited three students to date.
(3) Sam Spencer completed his Ph.D. and has joined MITRE.
(4) Lav Varshney gave a plenary talk at the India Science Festival in January 2021, which was attended by more than 14000 students.
(5) Lav Varshney is serving as a mentor to the Data Informatics Center of Epidemiology, a branch of the PathCheck Foundation.
(6) Xing Wang and Brian Cunningham are working with the US FDA to get emergency use approval of our COVID-19 diagnostics in POC settings.
(7) The team is planning a workshop in Summer of 2022 that will involve ZJU, ZJUI, ZJE, and Illinois students and faculty.

CPD Project Annual Summaries

CPD Project 1: PRISM digital counting of intact SARS-CoV-2 virus

Achievements: In response to limitations of current diagnostic techniques for viral load measurement, we present a label-free sensing method for intact viral particles with single-virus resolution. As shown in Fig. 1a, we prepare a photonic crystal (PC) biosensor with nucleic acid aptamer molecules that can bind selectively with a SARS-CoV-2 virus outer surface protein. When an intact virus is captured, it is detected and counted using “photonic resonator interferometric scatting microscopy” (PRISM), recently invented by the Cunningham group (Fig. 1). PRISM uses the PC surface to amplify light scattering from captured viruses to provide a high-contrast image.

We performed PRISM detection of SARS-CoV-2 virus in human saliva with a detection limit of 1000 copies/mL at room temperature in a single-step assay. The approach is an alternative to enzymatic amplification diagnostic assays, with sensitivity equivalent to PCR tests, but with results in minutes (see

Fig. 2a-b). Our approach is selective against detection of other viruses, including SARS- CoV-1 (Fig. 2c-d).

The team is improving and perfecting pathogen detection technologies. Huan Hu's group is developing one- time use microfluidic devices that can process clinical specimens (e.g., breath aerosol droplets) based on PRISM. Xing Wang's group is optimizing designer DNA nanostructures (DDN) that will be immobilized on the PC biosensor surface for faster and more sensitive pathogen detection. Qingjun Liu's group is developing portable and wearable devices (described below as Project 2). Lav Varshney's group has developed AI algorithms (described below as Project 3) to process detection data and guide public health teams to prepare for future epidemics or pandemics. Steven Blanke's group has developed pathogen-related resources (bacterial toxins, anthrax toxin, diphtheria toxin, and cytolethal distending toxins) that will help verify the detection technology.

Teams under Xing Wang, Fangwei Shao, and Yi Lu are developing a novel aptamer selection method (described below as Project 4) to obtain aptamers that can target specific pathogens with high selectivity.

Students involved in these projects include Yat-Yin Chan (UIUC), Neha Chauhan (UIUC), Henry Chen (UIUC), Min Jiang (ZJUI), Nantao Li (UIUC), Feng Tian (ZJU), Xiaojing Wang (UIUC), Shaoxiong Wu (ZJU), Xihang Wu (ZJU), Yeyao Wu (ZJU).

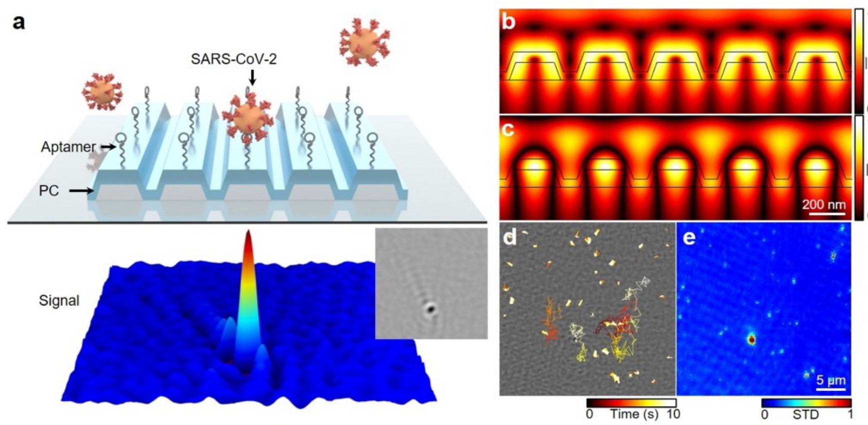


Fig. 1. Working principle of label-free optical detection for intact SARS-CoV-2. a, Schematics of the label-free optical biosensor design, in which DNA aptamers are immobilized on a photonic crystal (PC) surface by epoxysilane-based covalent chemistry. The scattered light from viral particles near the surface will be enhanced and detected by the PC via interferometric scattering imaging. Inset: Sample image of a single SARS-CoV-2 virion. b-c, Magnetic and electric fields of the PC at resonance. d, Lateral trajectories of viral particles on the aptamer-decorated PC surface. e, Image of temporal standard deviation for the visualization of captured virions

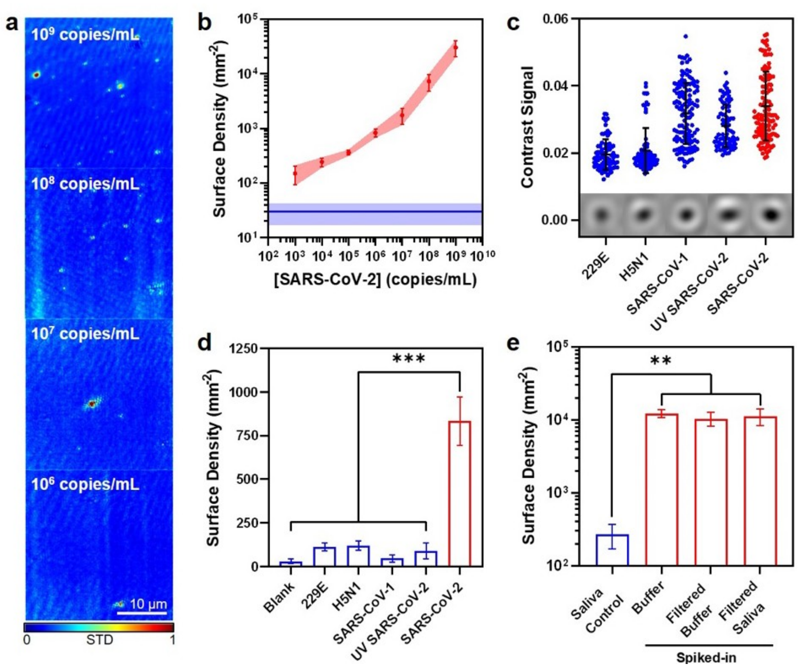


Fig. 2. Performance analysis of SARS2-AR10 based single-virus detection. a, Representative temporal standard deviation images of captured p-SARS-CoV-2 at various concentrations with 2-hour incubation. b, Surface density quantification of captured virions as the dose response curve. Negative control (blue baseline) contains only buffer solution. c, Contrast distribution of each type of virus for size characterization. Each dot represents the interferometric contrast signal from one viral particle. d, Specificity test for viral detection based on SARS2-AR10. All viruses used were at a concentration of 1×10^6 copies/mL. e, Sensor performance in human saliva. For spiked-in sample, SARS-CoV-2 concentration was adjusted to 1×10^9 copies/mL with crude human saliva pooled from healthy subjects. Error bars represent the standard deviations of at least three independent measurements.

CPD Project 2: Translate diagnostic protocols to devices and instrumentation

Topic 1: Wearable VOC device for real-time breath monitoring

Achievements: This topic aims to enable wearable breath analysis with MXene sensors. The team first developed a humidity sensor in the form of Ti3C2Tx/chitosan/quercetin multilayers. The sensor takes advantages of MXene's hydrophilicity, enhanced by a chitosan intercalation layer and stabilized by quercetin that resists oxidation. By depositing this multilayer on a flexible polyurethane amide (PI) membrane, the humidity sensor is flexible and wearable. This humidity sensor provides superior response to humidity change compared to other methods, with fast response and recovery. Integrated with a flexible tag, the MXene based humidity sensor enables noninvasive respiration monitoring and wireless communication with smartphones. To create MXene nanosheets with high affinity for volatile organic compounds (VOCs), hydrophilic terminations were replaced by esterification of trimethylacetic anhydride. This improved room-temperature ethanol detection sensitivity by a factor of five. To demonstrate real-time monitoring of exhaled VOCs, we developed a smart face mask with an MXene based sensor and a wearable VOC detection tag (Fig. 3). With this face mask, we were able to distinguish alcoholic breath from normal breath. The effort has appeared in three peer-reviewed papers. Two more manuscripts are in preparation. Students involved in this topic include Zijian An (ZJU), Xin Li (ZJU), Guang Liu (ZJU), Zhenghan Shi (ZJU).

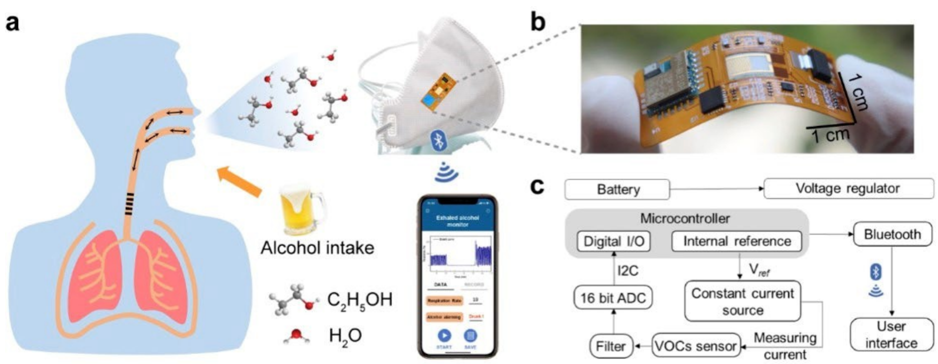


Fig. 3. Wearable VOCs detection tag for exhaled breath ethanol monitoring. a, schematic illustration of the breath ethanol detection with a wearable VOC device. b, The flexible VOCdetection tag. c, Circuit design of the VOC detection tag.

Topic 2: Ingestible capsule system for health condition monitoring

Achievements: This topic aims at developing an ingestible system for health monitoring. For demonstration, a wireless ingestible capsule for monitoring gastrointestinal (GI) pH was developed. Iridium oxide was deposited on a screen-printed electrode (SPE) to form the pH sensor. It has high sensitivity and a wide detection range for hydrogen ions. The rigid-flexible composite printed circuit board (RFPCB) technique was used to design the detection circuit (Fig. 4a). The sensor and circuit were encapsulated in a 3D-printed structure. With biocompatibility treatment, the entire capsule is 14.5 mm in diameter and 26 mm long (Fig. 4b). The ingested capsule performs real-time pH detection of biofluids in the GI tract. The signal is transmitted to an external receiver, which could be a smartphone, personal computer, or

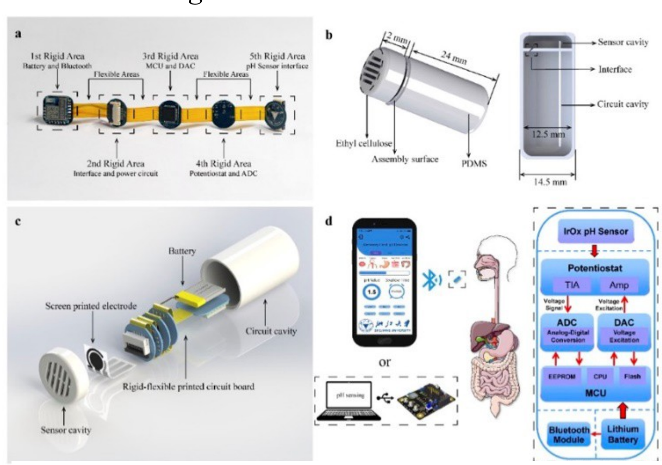


Fig. 4. Integrated ingestible, wireless, iridium oxide(IrOx)-based capsule for the detection of GI pH. a, The capsule detection circuit uses rigid-flexible composite printed circuit board (RFPCB) technology. b, Structure and cross-sectional view of the capsule structure designed with 3D-printed technology. c, Combined assembly drawing of the capsule system. d, Block diagram of the capsule system

an auxiliary circuit (Fig. 4c). Large-animal in vivo evaluation was performed, and the capsule system could detect pH in real time. The system has potential applications in the clinical diagnosis of GI diseases (Fig. 4d). The team made substantial progress and the effort has appeared in two peer-reviewed papers.
Students involved in this topic include Zijian An (ZJU), Chen Cheng (ZJU), Xinru Li (ZJU), Yue Wu (ZJU), Jie Xu (ZJU).

Topic 3: Smart dressing for wound infection monitoring

Achievements: This topic aims to establish a closed-loop monitoring and treatment system: a fully integrated, battery-free, wireless smart dressing for wound infection detection and on-demand drug delivery. This smart wound dressing, integrated with a near-field communication module, supports wireless power harvesting and data transmission, on-site signal processing, and drug delivery control through an external smartphone. Temperature, uric acid levels, and pH of the wound can be detected simultaneously to assess wound conditions. A drug delivery electrode in the dressing was designed to provide on-demand infection treatment by controlled delivery of antibiotics. Through in vitro antibacterial experiments and in situ animal studies, it was demonstrated that the dressing can inhibit bacterial growth and accelerate healing.

This smart wound dressing requires no power supply, is comfortable to wear and easy to operate, and shows great potential for improving wound management. The device can support development of a closed-loop medical system, integrating monitoring, diagnosis, and therapy (Fig. 5). The team made substantial progress and the effort has appeared in one peer-reviewed paper. Two more manuscripts are in preparation.

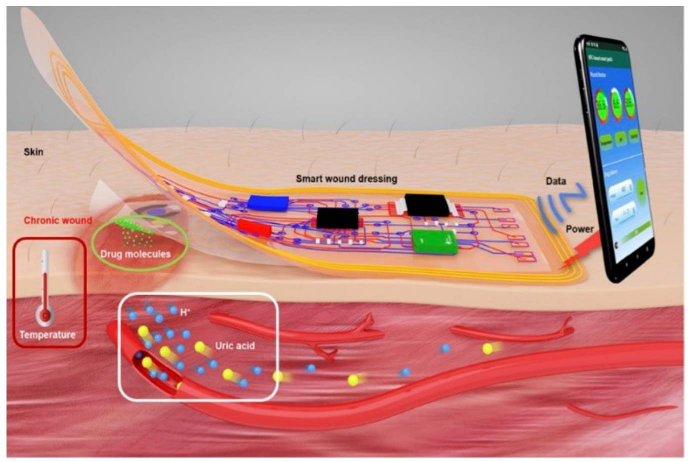


Fig. 5. A battery-free wireless wound dressing for wound infection monitoring and controlled on-demand drug delivery.

Students involved in this topic include Zetao Chen (ZJU), Chen Cheng (ZJU), Xin Li (ZJU), Guang Liu (ZJU), Jinglong Liu (ZJU), Zhaoyang Liu (ZJU), Zhenghan Shi (ZJU), Gang Xu (ZJU), Jie Xu (ZJU).

CPD Project 3: AI and Data Science in Pathogen Diagnostics

Achievement: We have been pursuing several data science questions that arise due to novel pathogen diagnostics methods, which speak to broader testing protocols and to public health implications.

Previous work has shown that there is a simple, accurate, closed-form approximation to find the most likely infection source for contagious diseases based on extended star networks (trees with exactly one node of degree greater than two). Here, we generalize that result to a class of hypertrees which provides a much richer representation space. This approach can be used to estimate "patient zero" initial sources, even after an infection has been propagated via large group gatherings rather than person-to-person spread, and when it is spreading through social bubbles with varying degrees of overlap. For contact tracing, this estimator can help identify the source of a local outbreak. The information can then be used for forward tracing or for further backward tracing.

We model an epidemic in which per-person infectiousness across geographic locations changes with the total number of active cases. This would happen as people adopt more stringent precautions with a growing number of active cases. We show that there is a sharp threshold. When the cure rate is above this threshold, the mean time for the epidemic to die out is logarithmic with the initial infection size. When the cure rate is below this threshold, the epidemic never disappears. When the per-person infectiousness goes to zero asymptotically as a function of the number of active cases, the mean extinction times all have the same asymptote independent of network structure. Simulations bear out these results. They also demonstrate that if the infectiousness is high when the epidemic is small (i.e., precautions are lax when the epidemic is small and only get stringent after the epidemic has become large), it might take a long time for the epidemic to die out.

In the U.S., social distancing policies were enacted during March 2020 to limit the spread of COVID-19. Lockdowns and movement restrictions increased the potential negative impact on mental health. Depression and anxiety were reported by various population groups during COVID-19 lockdowns. However, causal data linking mitigation policies and national mental health treatment is lacking. This study investigates the effect of COVID-19 mitigation measures on mental health across the United States, down to county and state levels. It examines effects on the number of mental health patients, impacts among various age and gender groups, and patients with selected mental health diagnoses. We used large-scale medical claims data from September 1, 2019 to December 31, 2020, with publicly available state- and county-specific COVID-19 cases from January through December 31, 2020, and used lockdown dates for states and counties. We designed a difference-in-differences (DID) model, which infers causal effects of a policy intervention by comparing pre-policy and post-policy periods in different regions. We focused primarily on stay-at-home orders and school closures. Based on common pre-treatment trend assumptions, we found that lockdowns have significantly and causally increased the number of people seeking treatment for mental health across counties and states. Mental health patients in regions with lockdown orders have increased by 18%, compared to a 1% decline in regions without a lockdown. Females show a larger lockdown effect, with a 24% increase in regions with lockdowns compared to 3% increase in regions without. Male mental health patients decreased by 5% in regions without lockdowns. Patients diagnosed with panic disorders and reaction to severe stress both showed large effects to lockdowns. Patients with life management difficulties doubled in regions with stay-at-home orders but declined with school closures. Patients with attention-deficit hyperactivity actually declined in regions without stay-at-home orders. The number of mental health patients older than 80 decreased in regions with lockdowns. Adults between 21 - 40 years old were exposed to the greatest lockdown effects with patient numbers increasing 20% to 30% in regions with lockdowns. All of these results met tests for statistical significance. Although these social intervention policies were effective in containing the spread of COVID-19, our results show that mitigation policies led to population-wide increase in mental health patients. Our results suggest the need for greater mental health treatment resources in the face of lockdown policies.

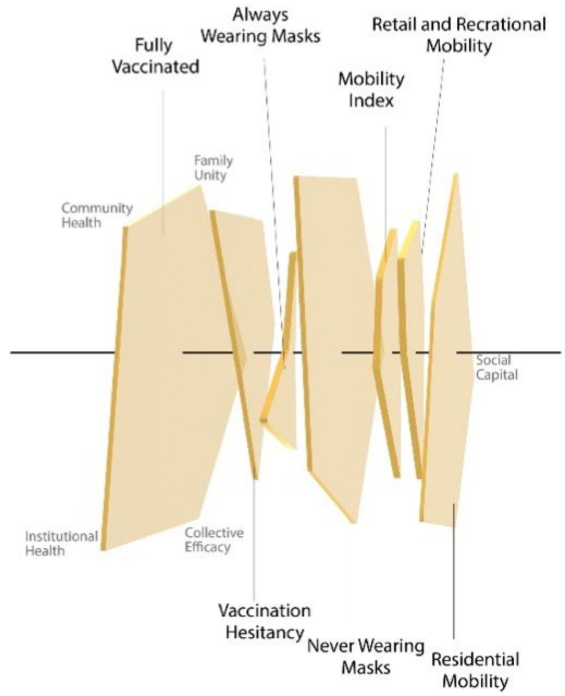


Fig. 6. A Swiss cheese model for social capital, with pentagons representing social capital indices' impact on social behaviors for COVID-19 public health.

Social capital has been associated with health outcomes in communities and can explain variations in different geographic locations. Social capital has also been associated with behaviors that promote better health and reduce the impacts of disease. During the COVID-19 pandemic, social distancing, masking, and vaccination have all been essential in controlling contagion. These behaviors have not been uniformly adopted by communities in the United States. Analysis is lacking of various facets of social capital to explain the differences in public behaviors among communities during pandemics. This study examine relationships among public health behavior—vaccination, masking, and physical distancing— during the COVID-19 pandemic and social capital indices in counties in the United States. We used publicly available vaccination data as of June 2021, masking data from July 2020, and mobility data from mobile phones movements starting at the end of March 2020. Correlation analysis was conducted with county-level social capital indices and subindices (family unity, community health, institutional health, and collective efficacy) obtained from the U.S. Senate Social Capital Project. We found that the social capital index and subindices correlate with various public health behaviors. Vaccination is associated with institutional health: positively with fully vaccinated population and negatively with vaccination hesitancy. Wearing masks negatively associates with community health, whereases reduced mobility associates with better community health. Residential mobility positively associates with family unity. By comparing correlation coefficients, we find that social capital and subindices show largest effect sizes on vaccination and residential mobility. Our results show that various facets of social capital are significantly associated with adoption of protective behaviors, e.g., social distancing, masking, and vaccination. The results can be represented with a Swiss cheese model of pandemic control planning in which institutional health and community health, provide partially overlapping behavioral benefits (Fig. 6).

We are currently exploring new research directions that focus on optimal testing protocols in the face of arrival processes, queuing, and arbitrary correlations among infection states, with the possibility of pooling. Signal processing questions arise for physical sensors of pathogen diagnostics, and these issues are being explored. We seek to draw on ideas from information theory for universal vaccine design. We are expanding ZJUI faculty collaborations to include Hao (Howard) Yang, Zuozhu Liu, and Thomas Honold. We are also involving ZJUI undergraduate students who are currently visiting UIUC in our research, Tianyu Liu (ZJUI), Zilinghan Li (ZJUI), and Rongjia Sun (ZJUI).
Graduate students involved in these projects include Akhil Bhimaraju (UIUC), Ibtihal Ferwana (UIUC), Sam Spencer (UIUC).

CPD Project 4: Development of a novel aptamer selection strategy built on a tetrahedron-shaped DNA nanostructure

Achievement: This project aims to evolve DNA aptamers as novel targeting subjects for pathogen biomarkers. DNA aptamers are generated from a large DNA library of 1015 sequences via a process called systematic evolution of ligands by exponential enrichment (SELEX). To improve the affinity and selectivity of aptamers targeting a pathogen surface antigen, we integrate these libraries into a designer DNA nanostructure, a *DNA tetrahedron* (DNA-TH). A DNA-TH is assembled from four DNA oligonucleotides with programmed sequences, one of which contains three segments of 15-nt long degenerated libraries (Fig. 7a). Non-denaturing agarose gel electrophoresis (AGE) has been used to demonstrate successful formation of a DNA-TH complex for ongoing experiments. The complex forms a predominant DNA species on the gel (Fig. 7b). Degenerated DNA segments are embedded in the DNA-TH edges and facing inward to form a space-refined cavity.

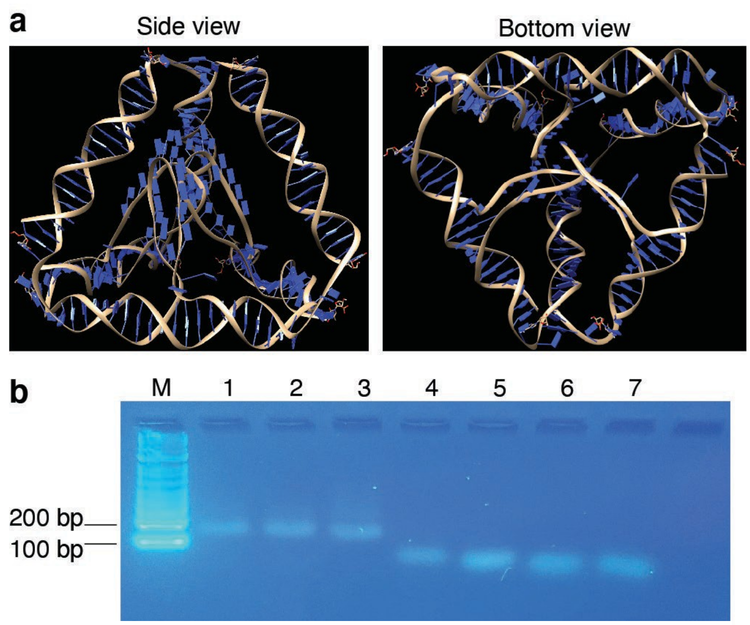


Fig. 7: Design of the DNA-TH complex containing SELEX library. a, Side and bottom views of the DNA-TH design. b, 3% Non-denaturing AGE of DNA-TH complexes and the four individual component strands. Lane-M: 1kb+ DNA ladder; Lane-1: DNA-TH complex library -1; Lane-2: DNA-TH complex library -2; Lane-3: DNA-TH complex library -3; Lane-4: TH DNA- 1; Lane-5: TH DNA-2; Lane-6: TH DNA-3; Lane-7: TH DNA-7.

The three DNA segments can restrict target protein movement and promote interaction with the same protein target at various interfaces in the cavity. This setup improves selectivity and affinity of the aptamer. We are finishing this DNA TH selection process to get aptamer candidates that target SARS-CoV-2 spike protein and influenza-A H1N1 HA protein. We will characterize these candidates to determine the best candidates for downstream detection applications. In addition to CPD meetings that involve all teams, our team meets once per month to troubleshoot experiments and brainstorm ideas. We have published three peer-reviewed journal papers.

Students and postdocs involved in these projects include Addison Adrian (UIUC), Min Jiang (ZJUI), Tingjie Song (UIUC), Jing Zhao (ZJU).

CPD Project 5: Interrogating biophysical interactions between host cells and pathogens

Achievements: This project focuses on fundamental mechanisms of biophysical interactions between host cells and pathogens. Results will illuminate effective and novel designs for pathogen detection approaches and devices. The team involves close collaborations across ZJUI and Illinois. Students and faculty in Prof. Huan Hu's group and Prof. Yang Zhao's group have conducted Zoom meetings and exchanged samples to contribute to a nanostructured probe. This probe has been designed and fabricated by Dr. Hu's lab and will be imaged in Dr. Zhao's lab to study optically-induced forces. Near-field optical forces promise precise tools that can be integrated into optical force microscopy to study biophysical interactions. During the first year, we have set up an optical force microscope and successfully made several angle-corrected probes (Fig. 8). We are developing new probes that can enhance optical forces to eliminate background noise, which will contribute to a higher signal to noise ratio for optical forces. Our team has also worked on designs and simulations of metamaterials. These designs will be translated to an AFM probe to create focused electromagnetic fields for enhancing optical forces and interactions. Some of our metamaterial designs have been published in *VIEW* and in the *New Journal of Physics* by Hanwei Wang (an Illinois graduate student).

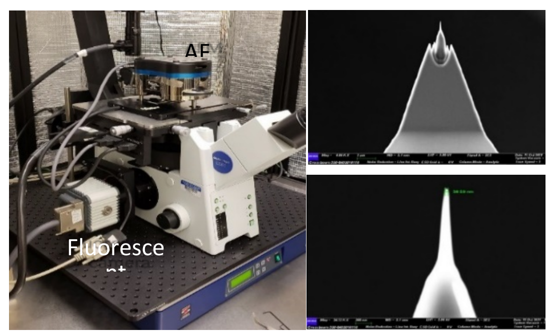


Fig. 8. Optical force microscopy by Hanwei Wang (Dr. Yang Zhao's graduate student) and probe fabricated by Xiaolei Ding (Dr. Huan Hu's graduate student).

Drawing upon these concepts, we will continue to study how metamaterials can integrate with our probes and enhance pathogen detection, for example, by detecting chiral molecules on a viral envelope when chiral optical forces are enhanced.

During the first year, in addition to center meetings that involve all teams, our team have met as frequently as needed to exchange ideas and experimental results. We have published three peer-reviewed journal papers, including two research papers and one invited review paper.

Students and postdocs involved in these projects include Xiaolei Ding (ZJUI), Thomas Kmieciak (UIUC), Yen- Ting Liu (UIUC), Yuemin Ma (ZJU), Jason Pan (UIUC), Hanwei Wang (UIUC), Ning Zang (ZJU), Shensheng Zhao (UIUC).

CPD Personnel

Faculty

- Brian Cunningham (UIUC), PI, co-director, 2020-
- Xing Wang (UIUC), co-PI, co-director, 2020-
- Huan Hu (ZJUI), co-PI, co-director, 2020-
- Rashid Bashir (UIUC), 2021-

- Steven Blanke (UIUC), 2020-
- Xiuling Li (UIUC), 2020-2021
- Yu Lin (ZJUI), 2020-
- Qingjun Liu (ZJU), 2020-
- Yi Lu (UIUC), 2020-2021
- Fangwei Shao (ZJUI), 2020-
- Lav Varshney (UIUC), 2020-
- Yang Zhao (UIUC), 2020-
- Chun Zhou (ZJU), 2020-

Students
- Adrian, Addison (UIUC), 50% research assistant, co-advised by Xing Wang, Fangwei Shao, Yi Lu
- An, Zijian (ZJU)
- Bhimaraju, Akhil (UIUC)
- Chan, Yat-Yin (UIUC), 50% research assistant appointment
- Chen, Henry (UIUC), 50% research assistant appointment
- Chen, Zetao (ZJU)
- Cheng, Chen (ZJU)
- Ding, Xiaolei (ZJUI)
- Ferwana, Ibtihal (UIUC), 50% research assistant appointment
- Jiang, Min (ZJUI), co-advised by Huan Hu, Fangwei Shao, Xiuling Li
- Li, Nantao (UIUC), 50% research assistant appointment
- Li, Xin (ZJU)
- Li, Xinru (ZJU)
- Liu, Guang (ZJU)
- Liu, Jinglong (ZJU)
- Liu, Zhaoyang (ZJU)
- Liu, Yen-Ting (UIUC), 50% research assistant appointment
- Shi, Zhenghan (ZJU)
- Spencer, Sam (UIUC)
- Tian, Feng (ZJU)
- Wang, Hanwei (UIUC)
- Wu, Shaoxiong (ZJU)
- Wu, Xihang (ZJU), co-advised by Huan Hu and Xiuling Li
- Wu, Yeyao (ZJU)
- Wu, Yue (ZJU)
- Xu, Gang (ZJU)
- Xu, Jie (ZJU)
- Zang, Ning (ZJU)
- Zhao, Jing (ZJU), 30% research assistant appointment
- Zhao, Shensheng (UIUC)

Postdocs
- Chauhan, Neha
- Ma, Yuemin (ZJU)
- Song, Tingjie (UIUC), 50% appointment
- Wang, Xiaojing (UIUC)

Undergraduate students: Tommy Kmeciak (UIUC), Zilinghan Li (ZJUI), Tianyu Liu (ZJUI), Jason Pan (UIUC), Rongjia Sun (ZJUI), Matthew Wildenradt (UIUC) were engaged in laboratory work for the center.

Publications

Peer-reviewed journals

1. Li, N. *et al.* Photonic resonator interferometric scattering microscopy. *Nat Commun* **12**, 1744, doi:10.1038/s41467-021-21999-3 (2021).
2. 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).
3. Chauhan, N. & Wang, X. Nanocages for virus inhibition. *Nature Materials* **20**, 1176-1177, doi:10.1038/s41563-021-01088-y (2021).
4. Ganguli, A. *et al.* Rapid isothermal amplification and portable detection system for SARS-CoV-2. *Proc Natl Acad Sci U S A* **117**, 22727-22735, doi:10.1073/pnas.2014739117 (2020).
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. Chen, Z. *et al.* Bioelectronic modulation of single-wavelength localized surface plasmon resonance (LSPR) for the detection of electroactive biomolecules. *Chinese Chemical Letters*, doi:10.1016/j.cclet.2021.10.027 (2021).
7. Cheng, C. *et al.* A wireless, ingestible pH sensing capsule system based on iridium oxide for monitoring gastrointestinal health. *Sensors and Actuators B: Chemical* **349**, doi:10.1016/j.snb.2021.130781 (2021).
8. Li, X., Lu, Y. & Liu, Q. Electrochemical and optical biosensors based on multifunctional MXene nanoplatforms: Progress and prospects. *Talanta* **235**, doi:10.1016/j.talanta.2021.122726 (2021).
9. Xu, J. *et al.* Implantable platinum nanotree microelectrode with a battery-free electrochemical patch for peritoneal carcinomatosis monitoring. *Biosensors and Bioelectronics* **185**, doi:10.1016/j.bios.2021.113265 (2021).
10. Xu, G. *et al.* Battery-Free and Wireless Smart Wound Dressing for Wound Infection Monitoring and Electrically Controlled On-Demand Drug Delivery. *Advanced Functional Materials* **31**, doi:10.1002/adfm.202100852 (2021).
11. Li, X. *et al.* Onion-inspired MXene/chitosan-quercetin multilayers: Enhanced response to H2O molecules for wearable human physiological monitoring. *Sensors and Actuators B: Chemical* **329**, doi:10.1016/j.snb.2020.129209 (2021).
12. Shi, Z. *et al.* Electrochemical non-enzymatic sensing of glycoside toxins by boronic acid functionalized nano-composites on screen-printed electrode. *Sensors and Actuators B: Chemical* **329**, doi:10.1016/j.snb.2020.129197 (2021).
13. 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).
14. 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).
15. Wang, H., Huang, H. K., Chen, Y. S. & Zhao, Y. On-demand field shaping for enhanced magnetic resonance imaging using an ultrathin reconfigurable metasurface. *View* **2**, doi:10.1002/viw.20200099 (2021).
16. Pan, J. *et al.* Quantifying molecular- to cellular-level forces in living cells. *Journal of Physics D: Applied Physics* **54**, doi:10.1088/1361-6463/ac2170 (2021).
17. Wang, H., Chen, Y.-S. & Zhao, Y. A Wearable Metasurface for High Efficiency, Free-Positioning Omnidirectional Wireless Power Transfer. *New J Phys*, doi:10.1088/1367-2630/ac304a (2021).
18. Jing, R. *et al.* Cas9-Cleavage Sequences in Size-Reduced Plasmids Enhance Nonviral Genome Targeting of CARs in Primary Human T Cells. *Small Methods* **5**, doi:10.1002/smtd.202100071 (2021).
19. Wu, J. *et al.* Self-Assembly of Dendritic DNA into a Hydrogel: Application in Three-Dimensional Cell

Culture. *ACS Applied Materials & Interfaces* **13**, 49705-49712, doi:10.1021/acsami.1c14445 (2021).
20. Huang, G. *et al.* The Active Subunit of the Cytolethal Distending Toxin, CdtB, Derived From Both Haemophilus ducreyi and Campylobacter jejuni Exhibits Potent Phosphatidylinositol-3,4,5-Triphosphate Phosphatase Activity. *Frontiers in Cellular and Infection Microbiology* **11**, doi:10.3389/fcimb.2021.664221 (2021).
21. Holland, R. L. *et al.* Chronic in vivo exposure to Helicobacter pylori VacA: Assessing the efficacy of automated and long-term intragastric toxin infusion. *Scientific Reports* **10**, doi:10.1038/s41598- 020-65787-3 (2020).
22. Seeger, A., Ringling, M., Zohair, H. & Blanke, S. Risk factors associated with gastric malignancy during chronic Helicobacter pylori infection. *Medical Research Archives* **8**, doi:10.18103/mra.v8i3.2068 (2020).

Conference proceedings

1. "On chip detection of Zika virus in whole blood using RT-LAMP." A. Jankelow, H.-K. Lee, F. Sun, V. Kindratenko, K. Koprowski, E. Valera, B.T. Cunningham, and R. Bashir, IEEE BMES Annual Meeting, Orlando, FL, October 2021.
2. "Photonic resonator interferometric scattering microscopy." N. Li, T.D. Canady, Q. Huang, X. Wang, and B.T. Cunningham, IEEE BMES Annual Meeting, Orlando, FL, October 2021.
3. "Wireless and battery-free sensing system for in vivo and in vitro biomedical detections." X. Gang, X. Lin, C. Cheng, Y. Jia, and Q. Liu, 31st Anniversary World Congress on Biosensors.
4. "Wearable breath analysis with MXene sensors." X. Li, Z. An, Y. Lu, and Q. Liu, 31st Anniversary World Congress on Biosensors.
5. "A battery-free and wireless flexible dental patch for in situ oral pH monitoring and electrically controlled on-demand drug delivery." Z. Shi, Y. Lu, and Q. Liu, 31st Anniversary World Congress on Biosensors.
6. "Implantable platinum nanotree microelectrode with a battery-free electrochemical patch for peritoneal carcinomatosis monitoring." J. Xu, C. Cheng, Y. Lu, and Q. Liu, 31st Anniversary World Congress on Biosensors.
7. "An ingestible capsule system based on rigid-flexible composite printed circuit board for detecting gastrointestinal conditions." Y. Wu, C. Cheng, Z. An, X. Li, Y. Lu, Z. Chen, and Q. Liu, 3rd International Conference on Flexible Electronics (ICFE 2021).
8. "Wearable and flexible dental patch system for intraoral electrochemical sensing and actively controlled drug delivery." Z. Shi, Y. Lu, S. Shen, Y. Xu, Y. Wu, J. Lv, Z. Yan, X. Li, F. Zhang, C. Shu, L. Su, and Q. Liu, 3rd International Conference on Flexible Electronics (ICFE 2021).
9. "Social Bubbles and Superspreaders: Source Identification for Contagion Processes on Hypertrees." S. Spencer and L. R. Varshney, in Proceedings of the 2021 IEEE Statistical Signal Processing Workshop (SSP), Rio de Janeiro, Brazil, July 2021.

Invited lectures

1. "Novel microscopies and digital resolution biosensor diagnostics using photonic metamaterial surfaces." National Institutes of Standards and Technology, Biophysical and Biomedical Measurement Seminar, (delivered virtually by Brian Cunningham), October 2021.
2. "Biosensor diagnostics: Transitioning from personalized medicine to personalized nutrition." Frontiers in Nutritional Science Lecture Series, Center for Personalized Nutrition, University of Illinois at Urbana-Champaign (delivered virtually by Brian Cunningham), March 2021.
3. "Photonic metamaterial surfaces for digital resolution biosensor microscopies using enhanced absorption, scattering, and emission." SPIE Photonics West (delivered virtually by Brian Cunningham), March 2021.
4. "Digital resolution biosensing: New Technology and Applications in Cancer and COVID-19." Nazarbayev University, Kazakhstan (delivered virtually by Brian Cunningham), March 2021.

5. “Novel approaches for breaking the COVID testing bottleneck.” Zhejiang University-UIUC Center for Pathogen Diagnostics Symposium (delivered virtually by Brian Cunningham), January 2021.
6. “Designer DNA nanostructures for virus sensing and inhibition.” Seminar at LSU School of Veterinary Medicine, (delivered virtually by Xing Wang), October 2021.
7. “Programming designer DNA nanostructures for sensing and inhibition of virus infection.” Joint seminar at Institute of Bioengineering, Materials Research Institute, School of Biological and Chemical Sciences, Queen Mary University of London, (delivered virtually by Xing Wang), October 2021.
8. “Nucleic acids engineering for the detection of small molecules and biomarkers.” Personalized Nutrition Initiative, UIUC, (delivered virtually by Xing Wang), September 2021.
9. “Designer DNA nanostructures for virus sensing and inhibition.” Bioengineering Department seminar, UIUC, (delivered virtually by Xing Wang), August 2021.
10. “Viral sensing and inhibition with DNA star strategy.” European Materials Research Society Spring Meeting, (delivered virtually by Xing Wang), June 2021.
11. “Viral inhibition with DNA star strategy.” Materials Research Society Spring Meeting and Exhibit, (delivered virtually by Xing Wang), April 2021.
12. “On-demand field shaping for enhanced magnetic resonance imaging using an ultrathin reconfigurable metasurface.” 2021 Metamaterials Congress, New York, USA, (delivered virtually by Yang Zhao), September 2021.
13. “Few molecular nanoscopic circular dichroism imaging, SPIE Conference on Optics and Photonics.” San Diego, CA, USA, (delivered virtually by Yang Zhao), August 2021.
14. “Sensing and imaging with chiral nanophotonics, Department seminar, Electrical & Systems Engineering.” Washington University in St Louis, MO, USA, (delivered virtually by Yang Zhao), May 2021.
15. “On-demand field shaping for enhanced magnetic resonance imaging using an ultrathin reconfigurable metasurface.” 2021 Materials Research Society MRS Spring Meeting, Seattle (Virtual), WA, USA, (delivered virtually by Yang Zhao), April 2021.
16. “Chiral optical sensing and imaging, Department seminar, Photonics Research Centre.” Macquarie University, Sydney, Australia, (delivered virtually by Yang Zhao), April 2021.
17. “Self-assembly of dendritic DNA into a hydrogel: application in three-dimensional cell culture”. Chinese materials conference 2021, Xiamen, China, (delivered by Fangwei Shao), July 2021.
18. “Platinum complexes as G-quadruplex targeting theranostics.” The 12th Chinese national conference on chemical biology, Taiyuan, China, (delivered by Fangwei Shao), October 2021.

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

Center Overview

The fourth industrial revolution, also known as Industry 4.0, seeks to evoke new capabilities in manufacturing by exploiting recent advances in computing. Connectivity, data access and analysis, and computer-driven automation -- all made possible by modern cyber-infrastructure -- will enable us to make timely, perceptive, and data-supported manufacturing decisions. 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.

ZJUI Project Lead

Hongwei Wang
Professor, ZJUI

ZJUI Project Co-Lead

Liangjing Yang
Assistant Professor, ZJUI

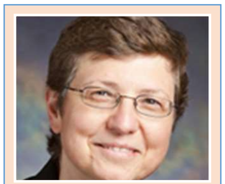
UIUC Project Lead

Katherine Driggs-Campbell
Assistant Professor, UIUC

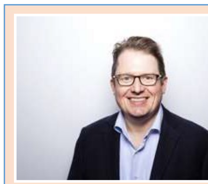
UIUC Project Co-Lead

Placid Ferreira
Professor, UIUC

KD Schewe
Professor, ZJUI



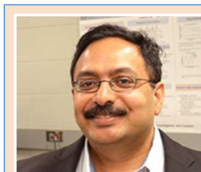
Klara Nahrstedt
Professor, UIUC



Wiliam King
Professor, UIUC

Chenhui Shao
Assistant Professor, UIUC

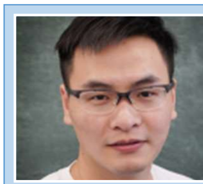
Xin Chen
Professor, UIUC



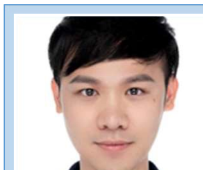
Srinivasa Salapaka
Professor, UIUC

Simon Hu
Assistant Professor, ZJUI

Gaoang Wang
Assistant Professor, ZJUI



Zhaozhu Liu
Assistant Professor, ZJUI



Howard Yang
Assistant Professor, ZJUI

CyMaN Progress Highlights

The primary focus for CyMaN this year has been on building collaborations across institutions and forming a foundation for our research endeavors. We led a working group to brainstorm open challenges in resilience and adaptivity across disciplines relevant to the manufacturing domain. These brainstorming sessions have outlined key opportunities for research impact. A white paper assembled by the team captures collaborative efforts across the center. To further grow collaborations, we have created a Slack channel to improve team organization and collaboration for faculty and students to discuss research in a less structured fashion. We have also hosted student-only events that include lightning talks and social meet-and-greet sessions to encourage engagement and networking. These events are led and run by students.

In addition, we have focused our efforts on data collection and curation as well as benchmarking. Towards this end, we have two internal datasets to enable algorithm development for anomaly detection and metrology. Results will eventually be released to the research community. We are currently setting up infrastructure for easier data collection during experiments to build up a repository for advancing capabilities in manufacturing. This builds on a new networked lab facility that we have created: the Operating System for Cyber-physical Manufacturing (OCSM). This cloud platform allows us to interface across campuses, as has been demonstrated by connecting the ZJUI Intelligent Robotics Lab with Prof. Ferreira's lab, connecting manufacturing machines, mock shop floors, and assembly testbeds. The cloud platform is also the interface to algorithmic aspects of the project, unifying how we curate data, close loops with adaptive feedback, and optimize processes across the network. We have adopted a modified version of the US National Institute of Standards and Technology (NIST) assembly benchmark as a baseline manufacturing process that we can use to demonstrate the potential impact and utility of our research.

During the first year, we graduated three students and one postdoc, all of whom contributed to CyMaN efforts. Qinan Zhou earned his MS under Prof. Ferreira working on models for metal processes, and is now studying for a PhD at the University of Michigan. Amber Srivastava, who earned his PhD under Prof. Salapaka, working on planning and optimization, is now a postdoctoral researcher at ETH Zurich. Tianyuan Liu, who worked with Prof. Nahrstedt on gathering cleanroom data, graduated in Summer 2021 and is now with Facebook.

CyMaN Project Annual Summaries

CyMaN Project 1: Cyber Infrastructure for Manufacturing Networks

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

This project emphasizes fundamental cyber infrastructure for manufacturing, enabling networked and connected manufacturing capabilities (even across campuses). The team is a tightly integrated collaboration across ZJUI and Illinois, connecting lab components from both institutions. All students involved in this project have joint supervisors from Illinois and from Zhejiang. The full project team meets bi- weekly over zoom, with additional subteam meetings as needed. This part of the effort has produced one peer-reviewed paper. Two journal manuscripts are being prepared, with joint authorship and collaboration between Illinois and Zhejiang.

This year, we created a networked facility on the Operating System for Cyber-physical Manufacturing (OSCM) cloud platform to interface groups with manufacturing machines, mock shop floors, and assembly testbeds (Figure 1). This effort created a

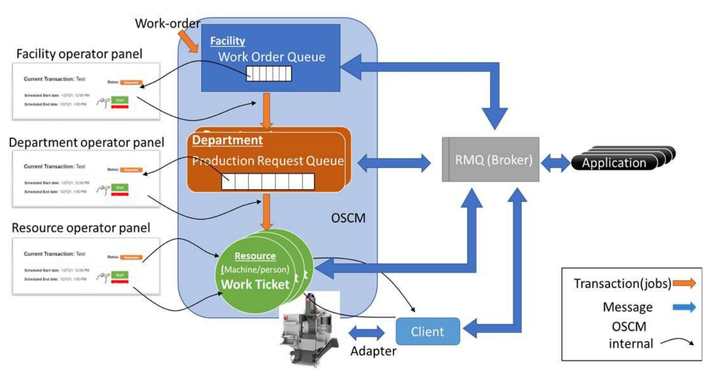


Figure 1: OSCM architecture for a hierarchically organized factory.

shared lab and computational resource that connects the two campuses. Building on this infrastructure, we are developing models and simulations of real-world processes, using knowledge graphs that represent domain knowledge and observations of manufacturing processes. Knowledge graphs can help adapt a process efficiently from one particular product to another with minimal real-world testing. A graph database can also be used for storing and querying data in databases (e.g., mongoDB, mySQL) to improve access performance. OSCM is being used to optimize physical processes, by developing a nano-precision ruling engine for surfaces that will test infrastructure ability to couple to and monitor events on advanced manufacturing machine tools.
Students supported through this project include Ricardo Toro (UIUC) and Zhenyu Zong (ZJUI).

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

Comprehensive measurements and metrics are needed in any manufacturing process, especially additive manufacturing due to accumulated errors. The team is a tightly integrated collaboration across ZJUI and UIUC. The two Illinois students working on this effort are co-supervised by Zhejiang faculty. The full project team meets biweekly over zoom, with additional subteam meetings as needed. This part of the effort has one manuscript currently being prepared for the peer-reviewed literature, with joint authorship and collaboration between Illinois and Zhejiang.

Automated data collection, data processing, and meaningful metrics present open challenges from a computational and manufacturing process perspective. Our team has been working closely on image analysis software for manufacturing systems. We designed, fabricated, and measured 100 parts using additive manufacturing. The parts have complex internal three-dimensional features whose dimension and fidelity are critically important to performance (see Figure 2). We have scanned parts using X-ray computed tomography (CT) and analyzed image data. We trained a learning model to recognize various defects, and our preliminary results show test accuracy of about 90%. We aim to expand current efforts to operate in real time (many current approaches function on offline analysis of previously observations). This extension will require advances in adaptive and unsupervised learning and in causal inferencing techniques to understand defect root cause. This effort will be integrated with Project 4.
Students supported through this project include Hyeongkeun Kim and Kuan-Chieh Lu (Illinois).

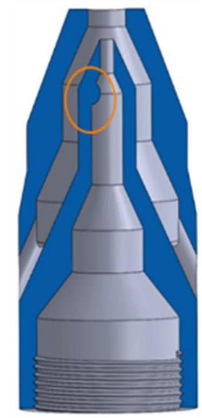


Figure 2: Example of a faulty part

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

This project focuses on the need to develop tools that enable scale-neutral (e.g., high or low volume) assembly for arbitrary processes that can be adapted and modified as needed. The team is a tightly integrated collaboration across ZJUI and UIUC. All students involved in this project have joint supervisors from Illinois and from Zhejiang. One student (Haonan Chen) spent two semesters working from ZJUI with Prof. Wang before coming over to UIUC to work with Prof. Driggs-Campbell. The full project team meets bi-weekly over Zoom, with additional subteam meetings as needed. This part of the effort has produced two conference publications, one of which won a paper award. One manuscript is currently being prepared, with joint authorship and collaboration between Illinois and Zhejiang.

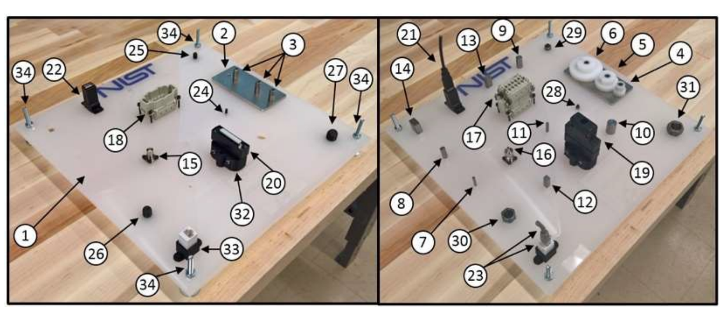


Figure 3: NIST assembly benchmark

The foundation of this project is in integrating laboratory platforms with the

framework in Project 1. As a practical example and use-case, we aim to improve virtual educational labs for the undergraduate Introduction to Robotics class offered at Illinois and ZJUI (taught by Prof. Driggs-Campbell and Yang, respectively). This enables the students to gain broad exposure to manufacturing challenges both remotely and in person. Using this basis, we aim to develop perception, planning, and control frameworks to handle high-mix, low-volume assembly lines. As a motivating task, we are expanding upon US National Institute of Standards and Technology (NIST) assembly benchmarks as a baseline to compare our methods with state-of-the-art approaches (see Figure 3). Specifically, we aim to develop new methods for detecting, grasping, and assembling components that we have never seen before and that may be defective. Wang and Driggs-Campbell are exploring the optimization of assembly and insertion processes from model-based computations (e.g., digital twins) and real-world testing. Yang has developed methods for robust adaptive control in dynamic physical interaction between human and machines using variable admittance control, with visual and haptic information. This project directly interfaces with Projects 2 and 4 to assess the success (or failure) of attempts to improve the overall assembly process.
Students supported through this project include Haonan Chen (Illinois) and Mengxuan Li (ZJUI).

CyMan Project 4: Understanding Anomaly and Heavy-tailed Events in Manufacturing Processes
Gaoang Wang (ZJUI), Klara Nahrstedt (UIUC), Katie Driggs-Campbell (UIUC)

This project focuses on the need to understand data curation, heavy-tailed distributions, and anomalous events, and their effect on resilient manufacturing. The team is a tightly integrated collaboration across ZJUI and UIUC. Both postdocs and students involved in this project have joint supervisors from Illinois and from Zhejiang. The full project team meets bi-weekly over Zoom, with additional subteam meetings as needed. Currently, two manuscripts are being prepared, with joint authorship and collaboration between Illinois and Zhejiang.

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. We have collected and curated process data from academic cleanrooms on the Illinois campus as a shared resource to facilitate collaboration. As we integrate more labs and machines into our manufacturing network (Project 1), we will continue to collect exemplar data for testing and comparing our proposed methods. These datasets will be curated and made publicly available to computing and manufacturing communities.

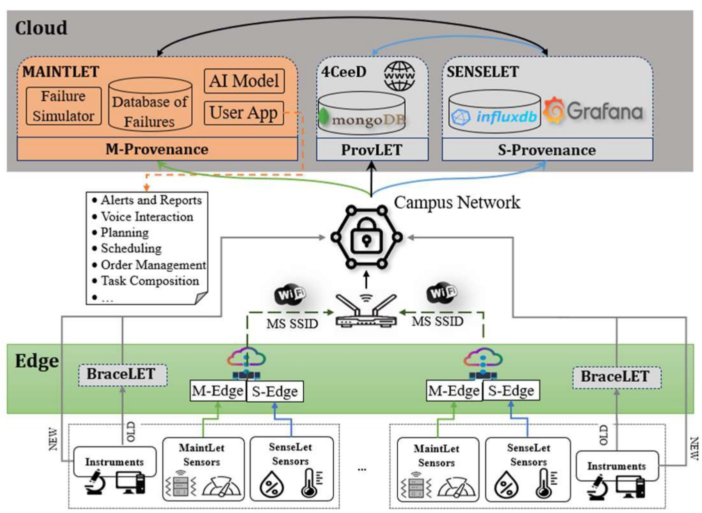


Figure 4: Cyber infrastructure and data curation system.

This data curation effort has led to a collaboration between Wang and Nahrstedt, which proposes methods for semi-supervised anomaly detection that relies on cluster representation learning. To help us understand and process large-scale datasets, we have developed a provenance graph that provides insights into sensor-based events. These graphs can be used to enhance anomaly detection algorithms and can eventually provide predictive insights. This effort aims to connect to other projects, including interfacing with the manufacturing network (Project 1), examining the role of various sensors for enabling reliable detection of faulty components (Project 2), and to improve our dynamic and kinematic models for assembly processes (Project 3).
Postdocs supported through this project include Hessam Moeini (UIUC).

CyMaN Project 5: Planning and Optimization for Flexible Manufacturing Networks

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

This project explores modeling and planning techniques that underlie the development of a flexible manufacturing network. The team is a tightly integrated collaboration across ZJUI and UIUC. All students involved in this project have joint supervisors from Illinois and from Zhejiang. The full project team meets bi-weekly over Zoom, with additional subteam meetings as needed. This has resulted in one peer-reviewed journal article, with more joint publications in preparation.

Figure 5: Network optimization visualization

We consider planning at various levels, ranging from operational planning (e.g., process control) to strategic planning (e.g., revenue management and facility placement) (see Figure 5). On the lowest level, we have developed novel methods for resource allocation and scheduling of a single plant or process, in which a group of machines $\{Mj\}$ shares resources (or tools) $\{Ri\}$. Each machine has a pre-specified sequence for resource use. Our goal is to minimize operation time while correctly allocating resources. To address revenue management of manufacturing networks, we have developed stochastic gradient descent methods. This is a non-convex minimization problem but admits an equivalent convex reformulation. We derived the sampling complexity to obtain a near-optimal solution. We aim to integrate this effort into OSCM to derive optimal plans across the full network, from a low-level manufacturing process to high-level operation of factories across the supply chain. We also aim to understand network resilience deeply through sensitivity analysis, which will give us insight into how reasonable our planned optimal output is, given the uncertainty in our model. Results can be observed in real-time with feedback in accordance with Project 4. We will consider constraints like capacity on each resource and commodity flow between nodes (e.g., factories, workstations).

Students supported through this project include Alisina Bayati and Zikun Ye (UIUC).

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- Wang Hongwei (ZJUI), PI, Associate Professor
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- Xin Chen (UIUC), Professor
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- Simon Hu (ZJUI), Assistant Professor
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- Bill King (UIUC), Professor
- Klara Nahrstedt (UIUC), Professor
- Srinivasa Salapaka (UIUC), Professor
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- Chenhui Shao (UIUC), Assistant Professor
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- Zixuan Wang (ZJUI)
- Zikun Ye (UIUC)
- Zhenyu Zong (ZJUI)

Postdocs

- Hessam Moeini (UIUC)

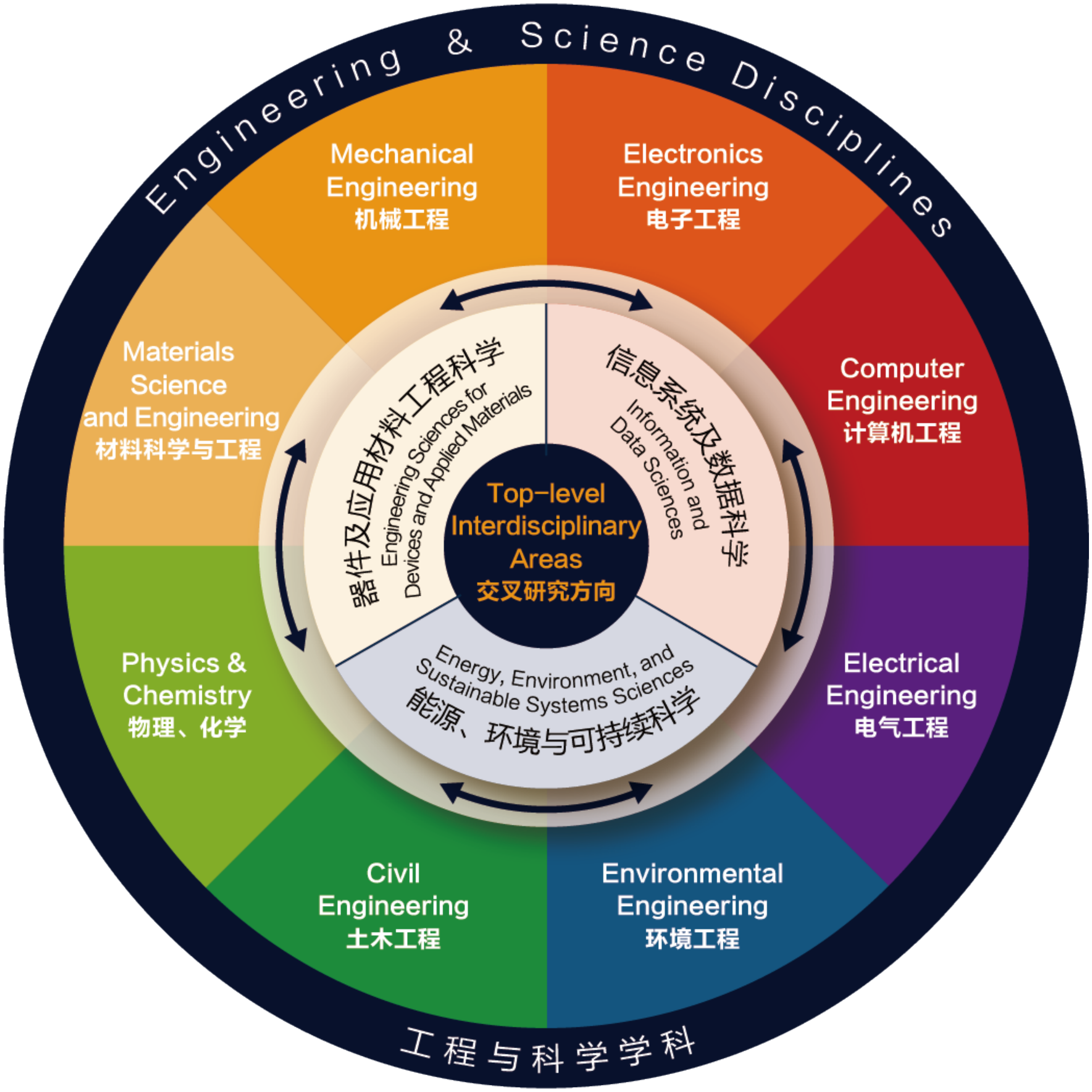
Publications

Peer-reviewed journals

1. A. Srivastava and S.M. Salapaka. "Parameterized MDPs and Reinforcement Learning Problems – A Maximum Entropy Principle-Based Framework." *IEEE Transactions on Cybernetics* (2021).
2. 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].
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. 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].
5. 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].

Conference proceedings

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. 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.
3. 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 17^{th} Intl. Conf. Automation Science & Engineering, IEEE CASE 2021, Lyon, France, 2021.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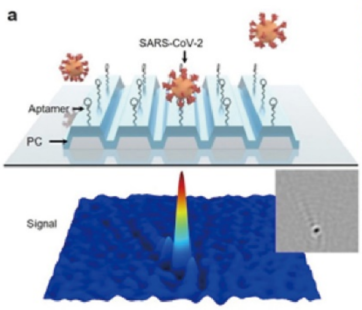

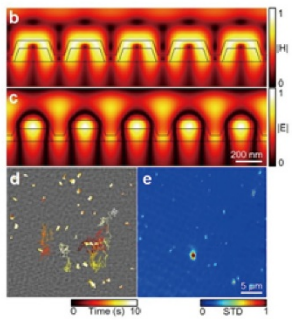

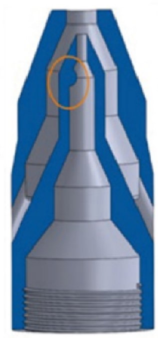

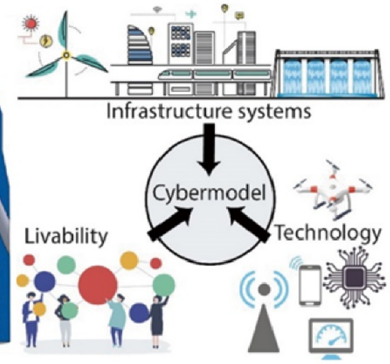

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