CPS Medium: Autonomous Control of Self-Powered Critical Infrastructures

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Project motivation

Development of novel sensing, actuation, and embedded computing technologies that allow civil **infrastructures** to be **responsive**, **resilient** and **adaptive**

- Traditional technologies require **delivery of electrical power**, typically either via an external power grid, or through the use of battery storage
- However, grid power **may be unreliable** during extreme loading events, and batteries must be **periodically recharged or replaced**
- The technologies developed in this project is that they **power themselves**, by **storing and reusing energy** injected into infrastructures by external loads
- **Energy-autonomy** enhances system reliability, and **lowers adoption barriers** for advanced control technologies

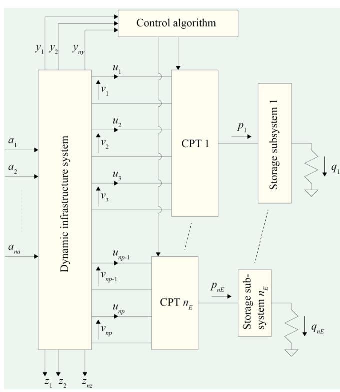
Technical challenge

Project will develop a **generic framework** for controlling self-powered systems

- Infrastructure system may be viewed as an **exogenously-excited plant**
- Embedded in the plant are n_p **transducers** that convert energy
- Transducer inputs u controlled via **controllable power trains** (CPTs) that interface with localized energy storage
- **Energy** in storage system j obeys

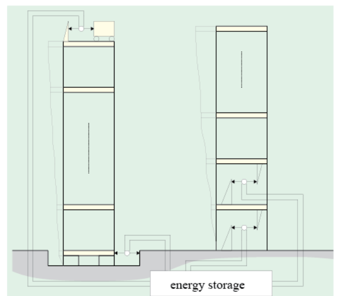
$$\frac{d}{dt}E_j = -\frac{1}{T_j}E_j - u_j^T v_j - \mu(u_j, v_j)$$

Central challenge: Optimize control algorithm to maximize favorability of performance outputs z, subject to the constraint that $E_j(t) \geqslant 0, \quad \forall t, j$

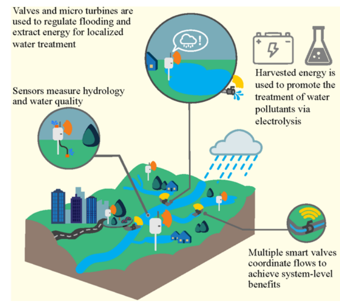


Three target applications

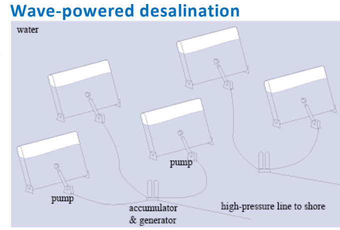
Seismic control of structures



Control of urban watersheds



Wave-powered desalination



Broader applications

Self-powered technologies have strong relevance in many **control applications** where **energy & power availability** are **constrained, unreliable, or unavailable**:

- Self-powered robotic prosthetics that operate in energy-autonomy by harvesting energy from the host
- Reliable response control of offshore wind turbines in extreme storms, for enhanced system reliability
- Control of hybrid energy storage systems to maximize efficiency of hybrid & electric vehicles

Experimental campaign

Self-powered control technologies will be demonstrated experimentally for each of the three **target applications**

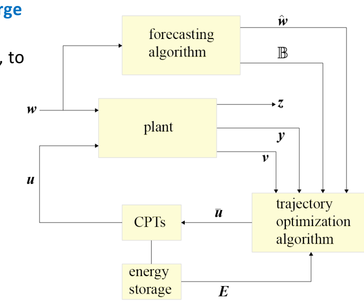
- *Structural control application*: HiL testbed will simulate interaction of self-powered transducers with virtual structure
- *Desalination application*: HiL testbed will dry-test a self-powered desalination system with a virtual wave environment
- *Urban watershed application:* Self-powered control deployed using microturbines to generate energy for controllable valves & gates

Self-powered control design techniques **validated on all testbeds** and data used to **develop accurate loss models**

Technical approach, contributions, & novelty

No theory exists for optimal control of self-powered systems that is **scalable to large and complex systems** such as the ones under consideration. The research to be conducted here will augment recent advances in **Model Predictive Control** theory, to result in a new body of knowledge in this area. Challenges include:

1. Innovation of optimization algorithms that can contend with the **inherent nonconvexity** of optimal self-powered control problems
2. Development of effective techniques for handling the **stochastic** nature of the dynamics for the target applications
3. Synthesis of controllers that are computationally tractable, but which also optimally compensate for **complex losses and constraints** in the power trains
4. Derivation of systematic techniques for ensuring the **robustness** of the controllers, to uncertainties in the system model and disturbances.



Impact on society

The innovation of energy-efficient and resilient infrastructure constitutes one of the **grand challenges of our times**

- **CPS technology** has a central role to play, but its **reliance on energy** presents technology adoption barrier
- All three target applications focus on technologies that enhance the **safety and health** of urban populations
- Target applications also have potential to **improve equity** in urban society
- Energy-autonomous control technology enhances the energy efficiency of **smart cities**

Education and outreach

- Undergraduate education innovation through a **freshman-level course** in Smart Water Systems, in which students get hands-on experience instrumenting and collecting data from smart watersheds
- Building on this class, **a three-day workshop to be held at a high school**, in which students build, test, and analyze data from oxidation reduction potential (ORP) sensors, deployed at locations in Ann Arbor's watershed
- Graduate-level curricular innovation in **Systems Engineering courses**
- Collaboration with municipal partners to **transition smart watershed technologies into practice**, through the creation of a publicly-accessible "virtual watershed tour" featured on the project's web portal
- **Interface with stakeholders** in the wave-powered desalination industry, to ensure that the control techniques being developed are transferrable
- Black-box multi-physics simulation modules for self-powered structural control transducers incorporated into Open/sEES **simulation environment**

Quantifying impact

- Undergraduate and graduate educational initiatives will be **evaluated** through the Center for Research in Learning & Teaching (CRLT) at the University of Michigan
- Educational outputs and resources for the high school workshop will be made publicly available, to **foster adoption** by other programs
- Research results will be **documented** in peer-reviewed publications, such that they may be reproduced
- All data & code are **open-source** to foster adoption by other researchers

Project duration: 10/1/22-9/31/25 Award ID#:2206018