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RETTL: Year Two of Sizing Up Physical Computing to Explore Threshold Concepts in Cyber-Physical Systems

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Context of the Project

This paper reports on Year 2 of a Research in Emerging Technologies for Teaching and Learning (RETTL) project focused on exploring threshold concepts in cyber-physical systems (CPSs). Threshold concepts, when mastered, are said to lead to a transformed understanding of the subject – in this case, CPS design – and a shift in the students' identities within the field's context [1-3]. Given the cruciality of these concepts to a field, not just CPS, the threshold concept framework has been used to unpack student misconceptions and to design formative learning experiences that help students master a subject's core ideas. In this project, we are developing a tabletop testbed to learn core CPS design concepts, mirroring a smart grid application called the CYber-PHysical systems Education & Research platform (CYPHER). We plan to identify which of these concepts constitute threshold concepts within the field, involving both students and engineers in experimenting with the testbed.

Research Aims

This project aims to develop a new approach for teaching undergraduate students about cyber-physical systems (CPSs) by leveraging physical computing to foster collaborative CPS design experiences and identify threshold concepts—key ideas whose mastery transforms understanding. The work seeks to engage students with CPS concepts, educational pathways into CPS, and career opportunities while generating design principles that support systematic, collaborative CPS education and research.

The project is structured around two complementary thrusts. The Technology Thrust (TT) focuses on the design, implementation, and evaluation of CYPHER. This physical computing testbed enables collaborative, problem-based learning in both formal and informal settings and captures student design strategies. The Learning Thrust (LT) uses CYPHER to explore threshold concepts in CPS design, beginning with a Delphi study to identify core and potential threshold concepts, followed by the development of model-eliciting activities and the refinement of a preliminary CPS concept inventory.

Anticipated outcomes include a user-friendly interface and a taxonomy of CPS design principles from the TT, and from the LT, a threshold-concept–based concept inventory to guide teaching, curriculum design, and assessment in CPS education. Together, these thrusts aim to advance both practical and theoretical understanding of how students learn and engage with CPS design.

Year One Activities

Technology Thrust: The first year of the project was development-heavy on the TT thrust, which included defining system objectives, identifying necessary electrical components, and designing printed circuit boards (PCBs) for the physical, cyber, and network layers. Building on this foundation, the team successfully coded the initial device drivers for microprocessors and other microchips on the PCBs, laying the groundwork for future functionalities.

Learning Thrust: For the LT thrust, we began with a literature review to identify threshold concepts that had already been proposed. Through our search, we found that no previous work had proposed any threshold concepts specifically for CPS, which is understandable given its relative youth as a field. Still, other fields related to CPS did provide some leads, such as abstraction (i.e., procedural and pattern), modularization, specific machine learning techniques (e.g., support vector machines, neural networks) [4]. To expand on these findings, we began a Delphi study that culminated in a set of core concepts for CPS and potential threshold concepts to explore using the testbed [5].

A Delphi study is a structured research approach used to gather and refine expert judgment on complex or uncertain topics [6-8]. Delphi studies are characterized by the following qualities: anonymity, iteration, controlled feedback, statistical group response, and expert consensus [9]. A typical Delphi study involves recruiting a panel of experts who provide input individually and anonymously (*anonymity*), typically through questionnaires or rating tasks. After each round, researchers summarize the group's responses (*statistical group response*) and feed this information back to participants (*controlled feedback*), allowing them to reconsider or refine their views in subsequent rounds (*iteration*). Through this iterative process, the group moves toward areas of consensus while documenting persisting disagreements (*expert consensus*). The Delphi study persisted into Year 2.

Year Two Activities

Technology Thrust: In Year 2, we focused on designing and fabricating an enhanced testbed prototype, successfully developing version 2.0 with significant improvements over its predecessor. This new iteration achieved substantial component miniaturization compared to version 1 while incorporating more sophisticated, realistic functionality. The enhanced design features bidirectional electrical and data flow, representing a significant advancement in system flexibility. We also implemented an expandable, interconnected network architecture that replaces the limited, sequential chain-link design in version 1, enabling more complex and realistic testing scenarios. Complementing these hardware improvements, we upgraded the software infrastructure and developed a dedicated control application that enables wireless remote access for real-time system monitoring and data collection.

Learning Thrust: The Delphi study initiated in Year 1 was completed in Year 2, yielding a refined, synthesized set of candidate threshold concepts for CPS design. Across three rounds, an expert panel of 11 CPS experts iteratively evaluated and refined proposed concepts using threshold concept qualities [1] as a guiding lens.

The process began with a broad set of 66 candidate concepts generated in Round 1. Through structured ratings and expert feedback in round 2, this list was reduced to six high-consensus concepts, which the panel regarded as ways of thinking and practicing that students must adopt to engage meaningfully in CPS work. This final synthesis resulted in six potential threshold concepts, each representing an integrated form of reasoning rather than a discrete content topic.

Table 1 summarizes the six potential threshold concepts and their alignment with the National Academies of Sciences, Engineering, and Medicine (NASEM) CPS education report [10]. This alignment highlights how expert-identified threshold concepts map onto established CPS foundations while also extending existing frameworks by focusing on cognitive transformation and ways of thinking and practicing required for mastery.

Table 1: Threshold Concepts as Ways of Thinking and Practicing

Theme	Synthesized Potential Threshold Concepts	Connection to NASEM CPS Report
Optimization	Designing CPS requires balancing competing constraints (e.g., performance, safety, cost, energy), leading to trade-offs rather than single optimal solutions.	Principle: Control, stability, and optimization (p. 26); Foundation 4: Optimization and optimal control (p. 29)
Abstraction	CPS modeling relies on abstraction to represent complex cyber–physical interactions at a system level.	Principles: Bridging physical and cyber worlds (p. 25); Foundation 5: Modeling with abstraction and heterogeneity (p. 29)
Complexity Management and System Thinking	CPS designers must reason under uncertainty, accounting for emergent behavior, nonlinearity, and interconnected components.	Foundation 5: Modeling heterogeneous, dynamic systems (p. 29); System characteristic: Operating under uncertainty (p. 31)
Cybersecurity	CPS security requires accounting for cyber threats that can produce physical consequences.	Foundations 4 & 6: Security, safety, and resilience (pp. 29–30); System characteristic: Security and privacy (p. 31)
Mathematical & Algorithmic	CPS design requires integrating multiple mathematical and algorithmic approaches (e.g., formal methods and machine learning).	Principle: Physical-world constraints on computation (p. 26); Foundation 3: Discrete and continuous mathematics (p. 28)
Critical Realist Perspectives	CPS designers adopt a cybernetic view of systems as open, evolving, and continuously changing.	System characteristic: Operating with acceptable risk under uncertainty (p. 31); Complementary skills (p. 33)

While the Delphi study establishes expert consensus on potential threshold concepts in CPS, these concepts alone do not guarantee meaningful learning experiences. Accordingly, the Year 2 focus of the project shifted toward translating these expert-identified potential threshold concepts into concrete learning activities supported by the CYPHER physical computing testbed.

In anticipation of the testbed's completion, we developed a set of draft model-eliciting activities (MEAs) based on the potential threshold concepts identified in the Delphi study. These activities engage students in developing a model (broadly defined) in response to a real-world scenario that is flexible in the face of changing constraints, and are characterized by six principles [11]. The *model-construction principle* requires students to build their own explicit descriptions, explanations, or procedures for a mathematically significant situation rather than rely on predetermined formulas. The *reality principle* situates the task in a realistic, potentially client-driven, engineering context that students can interpret meaningfully based on their backgrounds. The *self-assessment principle* ensures students have criteria and data to test, revise, and refine their models as they uncover new information. The *model-documentation principle* requires students to document their thinking naturally - often via a memo - so that instructors can assess conceptual understanding. The *construct share-ability and re-usability principle* emphasizes that solutions must be communicable to others and modifiable for related situations rather than tailored to a single dataset. Finally, the *effective prototype principle* pushes students to produce models that are as simple as possible while remaining mathematically significant and grounded in sound reasoning.

For example, our potential threshold concept for optimization has inspired an MEA built on CYPHER's natural functionality. CYPHER is designed as a set of nodes that can accommodate several types of units (e.g., single-family homes, power plants, stadiums, hospitals) that connect via branches, mirroring a power grid (see Figure 1).

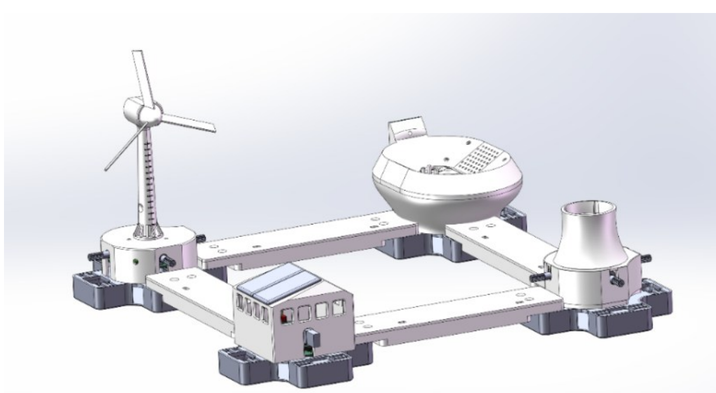

Figure 1: 3D model of the current prototype for one configuration of CYPHER

Each unit type can supply a certain amount of power and has its own power requirements to function. The basis of the *model construction* principle here is to design a system of *n* of these units that fulfills *m* constraints, which, as complexity increases, will go beyond technical feasibility (e.g., efficiency targets) and include other constraints such as economic, political, and social factors (*re-usability*). Sections of existing towns and cities will be used to ground the optimization problem in real communities (*reality)*. The model here can take many forms, such as a schematic of the connections or a computational solution (*documentation*), which the students can test (*self-assessment*) using CYPHER and use as their *prototype.* Although we have our preliminary MEA drafts, the specifics of these activities require finalizing the testbed. As the testbed's precise technical capabilities take shape, the MEAs will be further defined.

Future Work

Technology Thrust: The next reporting period focuses on delivering a fully functional prototype of the CYPHER testbed. Our technical development begins with finalizing the connector redesign and completing all PCB layouts, then sending the designs for fabrication. Once we receive the manufactured PCBs, we will conduct testing to validate proper connections and verify that all functionality meets our specifications. This work directly addresses the durability concerns identified in our current version 2.0 prototype. Following successful PCB validation, we will focus on driver development and integration, uploading and testing the necessary software drivers for all microprocessors and microchips embedded within the PCB architecture.

The culmination of our technical work involves the complete assembly of the system and comprehensive testing of the integrated CYPHER platform. This systems-of-systems evaluation will incorporate power producers, consumers, and prosumers to verify seamless interaction and proper coupling between the physical, cyber, and network layers. We have assembled a testing team with relevant expertise to conduct rigorous stress testing of the complete prototype, ensuring robustness under realistic operating conditions.

Learning Thrust: The LT component of the project is dependent on the advancement of the TT thrust. Once the testbed is ready for deployment, we will complete the MEAs to ensure the final technical specifications align with the feasibility of the activities in general educational settings. We plan to test the MEAs with undergraduate students and working engineers in Year 3. During these sessions, we plan to employ a think-aloud interview approach to gain insight into how each group approaches CPS design in response to the MEA prompts. As a result, we expect to extract design principles underlying the development of CPSs and gather evidence of the threshold nature of the core concepts advanced by the Delphi panel.

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