Position Paper for the
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Philip Brisk
Department of Computer Science and Engineering
University of California, Riverside

1. The Limitations of Modeling, Simulation, and Synthetic Test Data

My interest in cyber-physical systems (CPS) research from an academic perspective is to learn how to build and program computer systems that can interact with and control the physical world. I believe that CPS projects should strive to build working prototypes, which can positively validate fundamental contributions to the field of CPS obtained through modeling and simulation. Modeling and simulation are important when used properly; however, they cannot account for all possible physical artifact effects, which necessitates validation on realistic testbeds.

I am also concerned about the prevailing usage of synthetic test data in CPS research. In its favor, synthetic test data lowers the barrier to entry to many research topics, as well as the barrier to publication; however, excessive reliance on synthetic test data can create a chasm between academic research and industrial practice which can be very difficult to overcome.

In my view, CPS research and education should emphasize construction and interaction with physical systems; anything less is false advertising, and at best incrementally advances scientific knowledge and understanding, industrial innovation, and economic competiveness.

2. The Goal: Common, Low-cost Infrastructure for Smart Grid Research

Within the specific area of energy CPS, I believe that these concerns can be addressed through the establishment of common research infrastructure: in particular, a low cost smart grid testbed platform that can be controlled by a distributed collection of embedded processors. A basic power generation and distribution system can be constructed for approximately $1000 to $2000 using standard COTS parts, which is well within the typical budget for NSF-funded research and education projects. Additional components can be added at a reasonable cost (e.g., approximately $500 for a 400 Watt Marine-grade wind turbine[1]).

Upon completion and validation of a working prototype, the design specifications can be disseminated openly to other researchers who can then replicate the system in their own laboratories. Other researchers can then perform follow-up studies that alter the configuration, control policies, etc. Likewise, it should be possible to develop undergraduate and graduate-level coursework, including design projects, based on the testbed.

The report from the 2009 NSF Workshop “Research Recommendations for Future Energy Cyber-Physical Systems” outlined several challenges for smart grid research, all of which can be addressed through experimental evaluation using a low-cost configurable testbed[2]:

- Temporal complexities at time scales ranging from microseconds to hours (load behavior and intermittency of renewable sources due to environmental conditions);
- Topological complexities resulting from system changes due to micro-grid operations; and
- Operational complexities, including multiple (and often conflicting) objectives (economic, environmental etc.), optimization subject to new constraints for loads, hybrid communication technologies with new protocol stack definitions to support the functions listed above, etc.

The report also suggested an urgent and pressing need for dynamic estimation/control of the smart grid, advancements in sensor technology, and integrated intelligence to perform fault detection and restoration.

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[1] http://www.amazon.com/NPower-Wind-Turbine-Marine-Grade/dp/B005BPWN7W

[2] The list of complexities is quoted directly from the workshop report.

A well-designed testbed would enable solid empirical evaluation of any advancement in the aforementioned areas. Moreover, it would offer the following benefits to stakeholders:

- Students who work with the platform can obtain experience designing, programming, and controlling both the cyber and the physical portions of the platform.
- Stronger experimental methodology compared to current practice, leading to peer-reviewed publications having higher impact.
- Improved experimental reproducibility across the wider research community.
- Greater relevance to industry.
- Improved return on investment for funding agencies that support projects to develop and that commit to replicating and using the proposed testbed.

3. Testbed Design

A testbed prototype is under development as part of a senior design project by a group of motivated undergraduate students in the Electrical Engineering Department of the University of California, Riverside. The testbed is a distributed collection of smart-grid elements that can scale up or down as needed, and can be compatible with either centralized or distributed control.

Fig. 1 illustrates the power distribution system: the distribution system itself can be a set of PCB-mounted integrated circuits, or can be implemented using an FPGA. In this particular configuration, power is supplied by a 400 Watt Marine-grade wind turbine, priced at $500, and an $80 monocrystalline solar panel; a bank of absorbed glass mat (AGM) marine batteries, each priced at $120-$300, provides temporary storage; different components can be assembled to vary the dynamic load for a relatively cheap cost. Although the amount of power generated and consumed by the testbed is miniscule compared to a national-scale smart grid, the platform provides a variety of configuration options that can be used to test different power generation and transmission scenarios of interest.

Fig. 2 extends Fig. 1 with a feedback controller. The integration of computation and control into the smart grid testbed is of paramount importance. Depending on the computational and timing requirements of a control application, different layers of distributed computation may be necessary. A distributed microcontroller network may suffice for normal operation, but under adverse circumstances, more powerful processing elements (e.g., processor with floating-point capabilities) or accelerators (e.g., FPGAs) may be necessary.

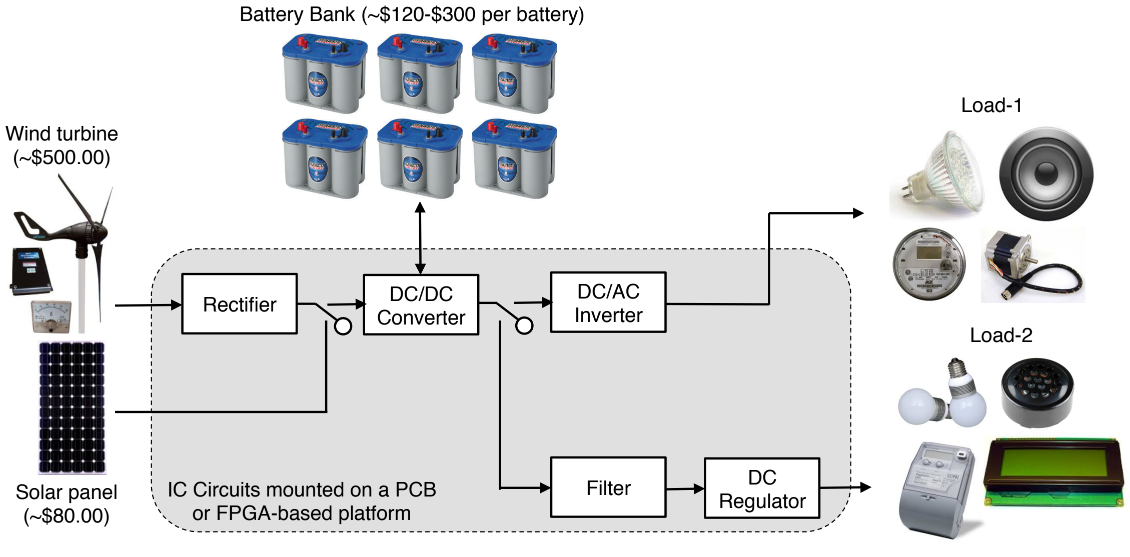

Fig. 1. Preliminary design of the smart grid testbed; price estimates are shown for the more expensive components.

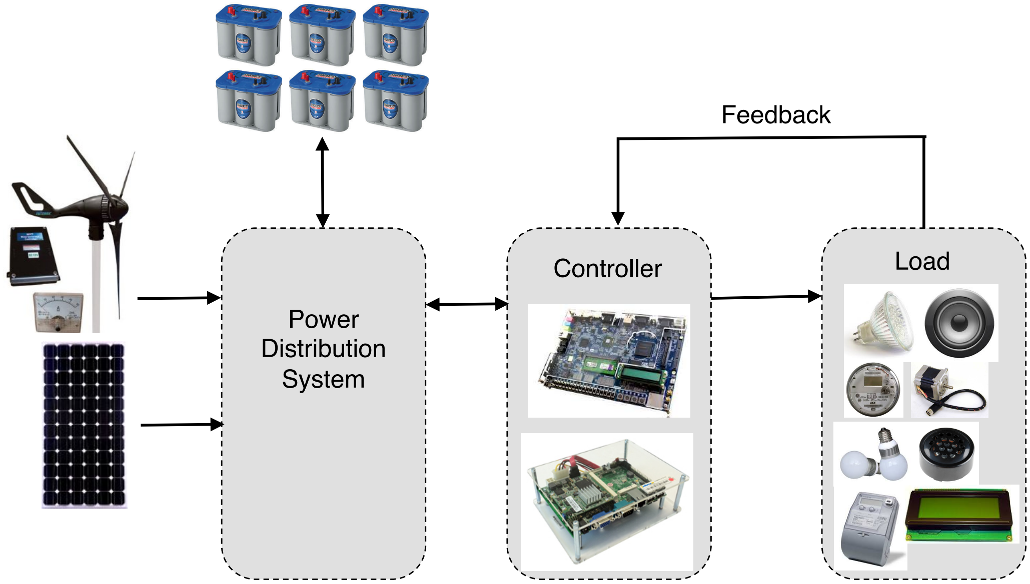

Fig. 1. The feedback-control loop, which represents the cyber aspect of the smart grid testbed.

Intel™ has donated several development boards that provide different capabilities: an Inforce™SYS940X-01 development board, featuring an Intel Atom E6xx processor, which provides floating-point capabilities and a Terasic™ DE2i-150 development board, which includes an Intel Atom N2600 processor and an Altera™ Cyclone IV FPGA. Different configurations of these computational elements will enable evaluation and comparison of a variety of centralized and distributed control policies that can respond to a multitude of normal and anomalous operating scenarios as reported by sensors integrated into the testbed.

In principle, the testbed is amenable to centralized or distributed control; multiple testbeds can be composed to form larger smart grids to test the scalability of distributed control policies; geographically distributed composition of testbeds, with distributed control provided through the Internet is also within reach. The most ambitious long-term goal is to demonstrate interoperability with other CPS testbeds. For example, an interconnected testbed could demonstrate how a mobile communication system directly connects first responders to a smart grid, to provide information regarding power losses due to natural disasters such as earthquakes and hurricanes. This way, the first responders could concentrate their efforts on the most vulnerable members of the population in an affected area, such as schools, hospitals, and assisted living facilities.

4. Dissemination and Tutorial

Once an initial testbed prototype is complete, dissemination of the parts list, assembly instructions, and testing scenarios can help spur widespread adoption so that other researchers can assemble a working design with minimal overhead. To further lower the barrier to entry, tutorial videos can be distributed through websites such as YouTube or social media sites to promote widespread adoption of the testbed. Design projects for undergraduate students to use or extend the testbed should developed and disseminated as well.

The wider research community must be made aware of the testbed, so that proper scrutiny can be applied to papers submitted for publication; modeling and simulation papers that could be made stronger through testbed evaluation should be encouraged to do so, as to maximize their potential scientific impact. Graduate students pursuing advanced degrees on topics relating to smart grids should be encouraged to use and develop their own testbeds to provide them with useful practical experience and stronger publications and thesis. Altogether, the proposed testbed has the potential to vertically advance the field of smart grid research beyond present capabilities using modeling, simulation, and synthetic test data alone.