Accessible Remote Testbeds: Opportunities, Challenges, and Lessons Learned

Workshop Report

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This report summarizes the outcomes from an NSF funded workshop on Accessible Remote Testbeds (ART) held in Arlington, VA, November 12-13, 2015. ART focused particularly on remotely accessible testbeds that can broadly be characterized as having non-trivial mechanical, electrical, computing, and communications components, i.e., on cyber-physical systems (CPS).

Why ART?

Experimental work on CPS is done largely in isolation and there is a significant gap between the theoretical foundations that are being broadly pursued, and a focused, application-driven transition from small-scale experiments to robust and impactful deployments. This gap is both scientific and practical. By having researchers from different institutions, disciplines, and backgrounds come together around a common testbed, there is potential to accelerate innovation and to build on past findings in a more effective manner than what is currently done. Moreover, the development and maintenance of meaningful, large-scale CPS testbeds is a resource-intense undertaking, which is why this application domain is particularly well-suited to the remote-access format.

The ART workshop explored the use of remote access testbeds as a way of getting researchers to come together around a shared platform, lowering the barrier-to-entry in cyber-physical systems research, and ensuring that practical relevance is an achievable goal to a larger group of CPS researchers. The establishment of such remote access testbeds would moreover provide researchers and would-be-researchers—including under-served groups and researchers at under-served institutions—access to state-of-the-art experimental platforms.

Additionally, the utilization rate at existing experimental facilities is usually quite low, which in essence means that valuable resources that could be deployed to advance the field, are sitting idle the majority of the time. By developing shared, remote access testbeds advances in the field are expected to accelerate greatly.

Workshop Objectives

Were the ART vision to be fully realized, the outcome would be a collection of research testbeds (supported by committed researchers), that could be used by researchers, educators, and students all over the country, without incurring prohibitive costs associated with setting up and maintaining the actual research facilities.

The ART workshop focused on how to realize this vision, with the particular objectives:

1. Articulate an over-arching vision for how remote access CPS testbeds should be structured and organized;
2. Identify existing efforts across different disciplines;
3. Gather stakeholders together to form a critical mass of people committed to the idea of remote access testbeds; and
4. Identify challenges that need to be overcome for remote access testbeds to reach their full potential.

Technical Areas Covered by the Workshop

In order to meet the objectives, the workshop program was assembled across a number of CPS-centric application domains and we here, briefly, discuss the rationale for selecting this particular set of topics.

Robotics

One CPS-related research area in which remote access testbeds would be highly useful is robotics. A functional robotics laboratory requires expensive hardware, such as robotic platforms, motion-capture systems, a large amount of physical space, and specialized knowledge to build, maintain, and run a laboratory system. Further, it is unlikely that individual robotics laboratories are used continually. Remote access robotics testbeds lower the barrier to entry to robotics research, reduce overall operational costs by allowing continuous operation, and provide a standardized setting for comparing different technology solutions.

Energy and Power

One of the greatest challenges in evaluating proposed features of the smart grid is limited access to power grid infrastructure. Energy providers are also constrained as to what data they can provide to researchers due to confidentiality and competition concerns. Smart grid research is therefore typically restricted to mathematical analysis or high-fidelity simulators. While these techniques are useful, they cannot provide the same realism as implementation on physical, networked hardware and software. Remote access to smart-grid testbed facilities present several security and safety challenges, which is especially true for cyber security experimentations. These issues are arguably even more important than for remote access robotics facilities, as running unverified software without proper guarantees could lead to significant damage to the testbed infrastructure or hazards to the human operators.

Transportation Systems

Another prime example of a cyber-physical systems domain where remote access testbeds are expected to have an impact is in intelligent transportation systems. Novel vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems afford coordination and cooperation among autonomous and semi-autonomous vehicles. Use of these systems can potentially enhance traffic throughput and significantly reduce the number and severity of vehicular collisions.

Proper evaluation of intelligent transportation systems technologies requires a large amount of physical space, e.g. sufficiently long roadways, distributed infrastructure, e.g. a mock traffic light system, and distributed instrumentation, e.g. a network of cameras positioned along roadways. Building a testbed that meets these requirements is prohibitively expensive for many research and development groups, making remotely accessible testbeds particularly appealing

Smart Buildings

The advent of low-cost wireless sensor networks has enabled so-called ``smart'' building technologies. A smart building would be able to, for instance, automatically modulate a building's HVAC and lighting system based on the number of occupants throughout the building, the time of day, and external conditions. Although the cost of sensors used in smart building research may be relatively low, implementing and maintaining a testbed facility still requires time and engineering expertise.

Main Challenges Discussed at the Workshop

Based on the previous discussion, one of the key issues covered during the workshop was the identification of challenges that must be overcome for remote access CPS testbeds to become shared and effective research platforms. The challenges identified fell under the following categories:

- *Access:* For the remote access testbeds to become truly useful, it is important that a sufficiently large community is served. How do we go about ensuring that the reach is large enough and that a community of committed users is established and maintained? One recurring theme was that just building a testbed was not enough, the recruitment of committed users is a key activity associated with successful remote-access testbeds.
- *Safety and security:* Since a key feature is to allow users to interact with experimental equipment remotely, there is a real issue associated with the safe and secure operations. This goes all the way from ensuring that the experiments are not harmful to the equipment (and to people) due to poorly constructed code, all the way to protection from malicious cyber attacks.
- *User experiences*: How should the testbeds be structured so that remote users can easily define, debug, deploy, and evaluate their experiments? Effective APIs—defined largely by the user communities—must be developed and the scientific data must be conveyed back to the user in a manner that supports the intended experiments.
- *Maintenance*: The testbeds will indeed reside physically somewhere. They will have to be maintained and experiments will have to be scheduled. How should one structure the testbeds from an organizational and maintenance vantage-point?
- *Ownership and funding mechanisms*: How are the testbeds established, funded, and who owns them? It is vitally important that the user communities become stakeholders yet, at the same time, well-defined ownership and funding mechanisms must be defined for the testbeds to have sufficient longevity.

Workshop Logistics and Attendees

Based on the aforementioned challenges and technical areas, a program was assembled—by participation by invitation (or recommendation) only—with the explicit objective of having sufficient topical breadth and thematic focus. Moreover, two keynote presentations were allocated to existing remotely accessible testbeds with a proven track record of recruiting users, enabling research, and sustaining operations.

The following participants attended the ART workshop.

V. Ajjarapu (Iowa State)	David Gao (University of Denver)	Daniel Pickem (Georgia Tech)
Aaron Ames (Georgia Tech)	Manimaran Govindarasu (Iowa State)	Dipankar Raychaudhuri (Rutgers)
Dhananjay Anand (NIST)	Santiago Grijalva (Georgia Tech)	Wei Ren (UC Riverside)
Todd Atkins (MathWorks)	Adam Hahn (Washington State)	Robert Ricci (University of Utah)
Abul Azad (Northern Illinois)	Marija Illic (CMU)	Mark Rice (PNNL)
David Balenson (SRI)	Michael Ingram (NREL)	Dezhen Song (Texas A&M)
Terry Benzel (USC)	Chad Jenkins (Michigan)	Jonathan Sprinkle (Arizona)
Giampiero Campa (MathWorks)	Austin Jones (Georgia Tech)	Aaron St. Clair (Georgia Tech)
Aranya Charkabortty (NC State)	Amy LaViers (UIUC)	Aaron Striegel (Notre Dame)
Mariesa Crow (Missouri S&T)	Chen-Ching Liu (Washington State)	Tim Tkacz (DAPRA)
Geir Dullerud (UIUC)	Rahul Mangharam (UPenn)	Ersal Tulga (Michigan)
Walton Fehr (US DOT)	Zhixin Miao (USF)	Yufeng Xin (North Carolina)
Magnus Egerstedt (Georgia Tech)	Osama Mohammed (FIU)	Tim Yardley (UIUC)
John Everett (DARPA)	Nader Motee (Lehigh University)	Saman Zanouz (Rutgers)
Rose Gamble (Tulsa)	Todd Murphey (Northwestern)	Michael Zavlanos (Duke)

Technical Program

The program was as follows:

Day 1: November 12, 2015

8:00-8:30	**Registration, breakfast, and networking**	
8:30-8:40	Welcome	**Kishan Baheti**, NSF
8:40-8:50	Welcome	**David Corman**, NSF
8:50-9:00	DHS Perspectives on ART	**Dan Massey**, DHS
9:00-9:30	Accessible Remote Testbeds and the NSF	**Pramod Khargonekar**, NSF
9:30-9:45	Workshop Objectives	**Magnus Egerstedt**, Georgia Tech
9:45-10:15	**Coffee Break**	
	Session 1 (Chair: Manimaran Govindarasu)	
10:15-10:55	The DETER Project – Cybersecurity Experimentation	**Terry Benzel**, Information Sciences Institute
10:55-11:35	Remote Testbeds: Experimenting in the Cyber Physical Space	**Tim Yardley**, University of Illinois at Urbana-Champaign
11:35-12:05	The Robotarium: An Open, Remote-Access Swarm-Robotics Testbed	**Magnus Egerstedt**, Georgia Tech
12:05-1:10	**Lunch**	
	Session 2 (Chair: Todd Murphey)	
1:10-1:30	Remote Research Testbed for Robot Manipulation	**Sonia Chernova**, Georgia Tech
1:30-1:50	Developing a Remote Test Bed for Heavy Vehicle Cyber Security Research	**Rose Gamble**, University of Tulsa, **Indrakshi Ray**, Colorado State
1:50-2:10	The Flux Group at the University of Utah	**Rob Ricci**, University of Utah

2:10-2:30	Cloud Robotics and the HoTDeC Testbed	**Geir Dullerud**, UIUC
2:30-2:50	**Coffee Break**	
	Session 3 (Chair: Geir Dullerud)	
3:00-3:20	The FIU Smart Grid Testbed—Platform and Remote Access	**Osama A. Mohammed**, Florida International University
3:20-3:40	Open Operating Systems in Low-Infrastructure Testbeds	**Todd Murphey**, Northwestern University
3:40-4:00	Enabling High-Fidelity Closed-Loop Integration of Remotely Accessible Testbeds	**Tulga Ersal**, University of Michigan
4:00-4:20	Smart Grid in a Room Simulator at CMU	**Maria Ilic**, CMU
4:20-5:20	**Breakout Session**: Technical/Scientific Remote-Access Challenges	
5:20-6:00	Report back from Breakout Session	

Day 2: November 13, 2015

8:00-8:30	**Registration, breakfast, and networking**	
	Session 4 (Chair: Magnus Egerstedt)	
8:30-9:00	CPS Security Testbed for Smart Grid: Fidelity, Federation, and Remote Access	**Manimaran Govindarasu**, Iowa State University
9:00-9:20	Humanoid Robots as ART: Challenges and Opportunities in Dynamic Walking	**Aaron Ames**, Georgia Tech
9:20-9:40	A Remote Testbed in the Wilderness: Collaborative Observation of Natural Environments	**Dezhen Song**, Texas A&M University
9:40-10:00	Lessons Learned through the NetSense and NetHealth Studies Exploring Security and Networking Instrumentation	**Aaron Striegel**, University of Notre Dame
10:00-10:20	The Experimental Research Testbed at the University of Arizona	**Jonathan Sprinkle**, University of Arizona
10:20-11:20	**Breakout Session**: Creating and Sustaining Active User Communities	
11:20-12:00	Report back from Breakout Session	
12:00-1:00	**Lunch**	
	Session 5 (Chair: Jonathan Sprinkle)	
1:00-1:40	The ORBIT Open Access Testbed for Research on Next-Generation Wireless Networks	**Dipankar Raychaudhuri**, Rutgers University
1:40-2:00	A Testbed for PV and Energy Storage Management and Control	**Mariesa Crow**, Missouri University of Science and Technology
2:00-2:20	Cyber-Physical Testbeds and Security Experimentation at Washington State University	**Adam Hahn**, Washington State University
2:20-2:40	Experiment as a Service: Providing Remote Access to Equipment for Cyber Security Research	**David Manz**, Pacific Norwest National Laboratory
2:40-3:00	ExoGENI-WAMS: A Testbed for Wide-Area Monitoring of Power Systems using Distributed Cloud Computing	**Aranya Chakrabortty**, North Carolina State University**, Yufeng Xin**, Renaissance Computing Institute
3:00-3:20	Experimental Research Testbeds at USF SPS Lab	**Zhixin Miao**, USF
3:20-4:00	**Posters, demos, networking, and coffee**	
4:00-4:30	Workshop Wrap-up	

Successful, Sustained Examples

Two particularly successful remote-access testbeds were presented at the workshop, namely the DETER testbed (presenter: Terry Benzel, Information Sciences Institute, USC) on cyber security and the ORBIT testbed (presenter: Dipankar Raychaudhuri, Rugters University) on Wireless Networking. Both of these testbeds have been in existence for over a decade and they have had thousands of users during that time period.

The key findings from these successful examples were:

- *Flexibility*: In order to be a truly useful remote-access *research* testbed, it is vitally important that the testbed is structured in such a manner that it allows for a number of different research questions and experiments to be pursued. Moreover, the testbed itself must evolve over time to remain relevant to the changing research trends and directions.
- *Funding*: It is not cheap to maintain an effective, remote-access research testbed and proper funding mechanisms are required to ensure that the testbeds exist over sustained periods of time.
- *Scheduling*: As the testbeds grow in popularity, effective methods for scheduling the users become increasingly important. Particularly during high-peak periods (around conference and proposal deadlines), scheduling truly becomes an issue.
- *Experiment Description Languages*: In order to setup many different types of experiments, it must be easy for the users to define up their desired experimental scenarios, which calls for some form of domain-specific experimental description languages to be developed.

Key Findings:

The following are some of the key findings of the workshop from the presentations and breakout group discussions.

- *Technical challenge:* Building, maintaining, and providing remote access to CPS testbeds are a lot more technically challenging than just cyber testbeds.
- *Programability:* Configurability and programmability of hardware-in-the-loop CPS testbeds are somewhat limited compared to cyber-only testbeds.
- *Need-driven:* Testbeds architecture and design must be driven by the experimental needs and based on sound scientific principles.
- *Principles:* Both scientific and engineering principles of testbeds are very important for successful realization.
- *Remote-to-Open access:* Remote access is a step towards building open-access testbed environments with open-source models, libraries, and data sets.
- *Diversity of Users and Use-cases:* Testbeds must strive to accommodate a variety of experimental needs fulfilling experimental needs of a diverse R&D community – academia, industry, and government labs.
- *Education and Workforce Development:* Testbed can also serve as a platform for advancing and sharing practical education with hands-on learning experience (both in undergraduate and graduate education) and also imparting competition-based learning, such as CPS CDC (Cyber Defense

Competition) and robotic competitions, for students and industry professionals.

- *Target domains & Funding:* Targeted CPS domains need to be identified and seed funding needs to be provided to build testbed user community in those domains. Example CPS domains include: robotics, smart grid, and intelligent transportation.
- *Testbed Federation Model:* To sustain and grow testbed and its user-community, a "hub-and-spoke" model could be explored, such as key testbed facility with a set of small satellite testbeds (for a given domain) connected to it on need-basis via testbed federation for large-scale experimental needs.
- *Community Building:* Forums that brings together "testbed providers" and "testbed users" need to be created. Such forums needs to be held periodically to understand the needs, share the capabilities and best practices.

It was clear from the workshop that these two remote-access testbeds had managed to play a major role in the evolution of their fields and they can serve as clear role models for future remote-access testbeds in the CPS domain.

Lessons Learned

The workshop served its purpose of identifying areas (e.g., robotics and smart grid) where the existence of remote-access testbeds would enable innovation. There also is a significant user community that would welcome such testbeds for their research.

The additional lessons learned from the workshop all pointed to issues that must be resolved in order for remote-access testbeds to become highly effective and widely used research instruments, namely:

- *User recruitment:* A recurring theme was "*If you build it, they will not come!*" In other words, efforts toward building remote-access testbeds must be coupled around sustained community building.
- *Flexibility:* The testbeds must be flexible enough to support different types of research experiments in order for them to become truly useful.
- Security: Giving users access to physical assets through remote means has serious security implications that must be resolved in order for remote-access testbeds to flourish.
- *Funding*: To maintain world-class research facilities requires funding, and appropriate mechanisms to this end must be identified.

Looking Ahead

It is clear from the workshop that remote-access testbeds hold great promise in the cyber-physical domain. Such testbeds would be able to harness the power of multiple researchers and even research-communities coming together to accelerate innovation. As such, the organizers and participants at the ART Workshop uniformly were highly supportive of pursuing remote-access testbeds – either as developers or users – and, as discussed in previous sections, a number of important scientific questions remain to be solved in order for such testbeds to become ubiquitous.