Cyber-Physical Systems and Wildland Fire or Contaminant Identification and Tracking Dynamic Data-Driven Application Systems

Craig C. Douglas, Robert Lodder, Jan Mandel, and Anthony Vodacek

Cyber-Physical Systems (CPS) is an emerging area related to Dynamic Data-Driven Applications Systems (DDDAS), a thrust at the National Science Foundation since 2001. In this note, we describe some DDDAS projects that appear to also be CPS in nature. DDDAS started in recent years and has received recognition in the United States and Europe. We conclude this note with three key questions concerning distinguishing CPS from DDDAS.

We quote from the 2005 DDDAS NSF solicitation, “DDDAS is a paradigm whereby application (or simulations) and measurements become a symbiotic feedback control system. DDDAS entails the ability to dynamically incorporate additional data into an executing application, and in reverse, the ability of an application to dynamically steer the measurement process. Such capabilities promise more accurate analysis and prediction, more precise controls, and more reliable outcomes. The ability of an application to control and guide the measurement process and determine when, where, and how it is best to gather additional data has itself the potential of enabling more effective measurement methodologies. Furthermore, the incorporation of dynamic inputs into an executing application invokes new system modalities and helps create application software systems that can more accurately describe real world, complex systems. This enables the development of applications that intelligently adapt to evolving conditions and that infer new knowledge in ways that are not predetermined by the initialization parameters and initial static data. The need for such dynamic applications is already emerging in business, engineering and scientific processes, analysis, and design. Manufacturing process controls, resource management, weather and climate prediction, traffic management, systems engineering, civil engineering, geological exploration, social and behavioral modeling, cognitive measurement, and bio-sensing are examples of areas likely to benefit from DDDAS.”

We are working on three kinds of DDDAS critical infrastructure projects funded by the NSF:

- **ITR/NGS: Collaborative Research: DDDAS: Data Dynamic Simulation for Disaster Management.** The emphasis is on wildland fire modeling, simulation, prediction, and a major milestone is to provide real-time information to people fighting actual fires. The final test of the project will be to do a full-scale test with a prescribed burn of a mountainside in 2008-2009.

- **ITR: Collaborative Research: Predictive Contaminant Tracking Using Dynamic Data Driven Application Simulation (DDDAS) Techniques.** Multiscale data-driven algorithms and software to easily move data from sensors to computers potentially far away has been developed.

- **DDDAS-TMRF: Collaborative Research: Adaptive Data-Driven Sensor Configuration, Modeling, and Deployment for Oil, Chemical, and Biological Contamination near Coastal Facilities.** Consider a networked drone operating off a coast that recognizes oil in water. Upon detection and alerting the simulation, by dynamically loading into the drone sensor a chemical library specific to hydrocarbon pollution, the sensor can search for chemicals that will identify the source of the hydrocarbons. For example, a diesel-driven ship may have sunk nearby, or a fishing boat may simply be leaking fuel. 100LL would indicate a small downed aircraft. Depending on the sensor result, very different computations can be done: trace where the ship or aircraft sank and alert rescue, or trace where the boat sailed and what its travel route was to identify the boat and mitigate the problem.

DDDAS environments require new software capabilities for application modeling and composition, dynamic runtime, resource management, data management, and measurement control aspects, as well software architecture drilling across all layers and end-to-end software infrastructure. The DDDAS program solicitation includes a comprehensive list of challenges and has inspired the scientific community, as exemplified by DDDAS projects that have started to address these and other related challenges. In our own DDDAS projects, we have identified several relatively diverse areas that have common issues that must be addressed by DDDAS: computer science, informational, and computational sciences, that lead to significant impact for addressing important problems. These include:
1. Effectively **assimilating** continuous streams of data into running simulations. These data streams most often will be…
   a. Noisy but with known statistics, and must be incorporated into the model using stochastic methods, such as filters and smoothers.
   b. Received from a large number of scattered remote locations and must therefore be assimilated to a usable computational grid.
   c. Missing bits or transmission packets, as for example is the case in wireless transmissions.
   d. Injecting dynamic and unexpected data input into the model.
   e. Limited to providing information only at specific scales, specific to each sensor type.

2. *Warm restarting* simulations by incorporation of the new data into parallel or distributed computations, which require the data but are sensitive to communication speeds and data quality.

3. *Tracking and steering* (control of measurements, models, reporting results, and visualization) of remote distributed simulations to efficiently interact with the computations and to collaborate with other researchers.

4. *Translation components* to rectify when simulation output parameters do not directly match observational data.

5. *Interpretation and analysis components* to assist researchers with collections of simulations.

6. *Application program interface and middleware components* for designing and creating a DDDAS or DDDAS problem solving environment.

7. Better *scheduling of computational and network resources* so that multiple models, possibly running at different locations, can be coordinated and data can be exchanged in a timely manner.

DDDAS assumes that application components, resource requirements, application mapping, interfaces and control of the measurement system can be modified during the course of the application simulation. The diagram in Figure 1 shows how a number of elements might dynamically interact with each other: Any of the components may change without resorting to a new simulation as the computation progresses. Many DDDAS applications are multiscale in nature. As the scale changes, models change, which in turn, changes which numerical algorithms must be used and possibly the discretization methods. DDDAS applications involve a complicated time dependent, nonlinear set of coupled partial differential equations, stochastic or agent-based simulation methods, which add to the complexity of dynamically changing models and numeric algorithms. It also causes computational requirements to change, particularly if dynamic adaptive grid refinement or coarsening methods are used, in response to the dynamically streamed data into the executing model.

![Diagram](image)

**Figure 1: DDDAS processing**

To support data management needs in our DDDAS projects, data acquisition, data accessing, and data dissemination tools are typically used. Data acquisition tools are responsible for retrieving of the real-time or near real-time data, processing, and storing them into a common internal data store. Data accessing tools provide common data manipulation support, e.g., querying, storing, and searching, to upper level models. Data dissemination tools read data from the data store, format them based on requests from data consumers and deliver the formatted data to the data consumers. Figure 2 illustrates a simplified view of the software framework of the DDAS system we are developing. In our implementation, the data used to drive a DDDAS system are retrieved periodically by a data retrieval service, extracted, converted, quality controlled, and then staged as dynamic inputs to our simulation models. The extraction process reads the retrieved data based on the meta data associated with them and feeds the extracted values to the conversion model whose major purpose is unit conversion, e.g., from inches to millimeters. The converted data are then analyzed for potential errors and missing values by the quality control model. This control process will ensure the correctness of the data, which is of great importance for the model simulation accuracy. The quality controlled data are then fed to the data storage model, which either saves the data to a central file.
system or loads them to a central database (this depends on project requirements). The data store model may also need to register the data in a metadata database so that other models can query it later.

Figure 2: Data acquisition, accessing, and dissemination software layout in a typical DDDAS project (e.g., a wildland fire DDDAS project)

DDDAS research projects have brought together multidisciplinary expertise, involving researchers from a number of fields to synergistically pursue research on creating DDDAS capabilities and environments. There is a learning curve that is nontrivial. DDDAS applications are usually complicated, getting data is usually difficult, and there is already large scale research ongoing using traditional, take initial data and just run a simulation some period of time, and look at the results.

A community web site, [http://www.dddas.org](http://www.dddas.org), has been developed by Prof. Douglas with help from about 50 other DDDAS-related projects. The site currently has a complete funded project list (from 2000 to 2006), virtual proceedings from workshops from 2000 through 2006, a number of talks on topics that range from disaster management to transportation to homeland security to how a bat flies, news items, pointers to working DDDAS codes, and the January 2006 NSF DDDAS workshop report. Most of the projects listed are from the United States, though a number of the projects have international partners and interest in DDDAS overseas has been increasing.

In the list of projects on the DDDAS community web site are many projects that combine networking, engineering, and sensors (embedded and/or otherwise). Clearly, these are all cyber-physical systems. Some DDDAS projects require a supercomputer whereas some can run on a PDA, smart cell phone, or laptop.

Some questions that this CPS workshop needs to clearly address include the following:

- **What exactly is a CPS?**
- **In what ways can we tell differences between DDDAS and CPS?**
- **Is CPS a superset or subset of DDDAS, or neither?**

**Biographies and Online Sources of Information**

- **Craig C. Douglas** ([douglas-craig@cs.yale.edu](mailto:douglas-craig@cs.yale.edu), [http://www.mgnet.org/~douglas](http://www.mgnet.org/~douglas)) is a professor of computer science and mechanical engineering at the University of Kentucky. He is also a senior research scientist in computer science at Yale University. His community web sites for DDDAS and Multigrid are [http://www.dddas.org](http://www.dddas.org) and [http://www.mgnet.org](http://www.mgnet.org).
- **Robert Lodder** ([lodder@uky.edu](mailto:lodder@uky.edu), [http://www.pharm.uky.edu](http://www.pharm.uky.edu)) is a professor of chemistry, pharmacy, and electrical and computer engineering at the University of Kentucky.
- **Jan Mandel** ([jmandel@math.cudenver.edu](mailto:jmandel@math.cudenver.edu), [http://www.math.cudenver.edu/~jmandel](http://www.math.cudenver.edu/~jmandel)) is a professor of mathematics and computer science at the University of Colorado at Denver. The NSF sponsored wildfire project web site is [http://www.math.cudenver.edu/~jmandel/fires](http://www.math.cudenver.edu/~jmandel/fires).
- **Tony Vodacek** ([vodacek@cis.rit.edu](mailto:vodacek@cis.rit.edu), [http://www.cis.rit.edu/people/faculty/vodacek](http://www.cis.rit.edu/people/faculty/vodacek)) is an associate professor of imaging science at the Rochester Institute of Technology.