An Information Technology Initiative on

Data Transmission and Massive Data Analysis Challenges

(Computer-Aided Experimentation and Telemetry)

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Abstract

The proposed initiative is a multi-disciplinary effort involving the colleges of engineering and basic sciences. It has a dual long term goal: (a) to develop and implement telemetry suited for challenging environments capable of high throughput, and (b) to develop data analysis and visualization tools on parallel architectures capable of efficiently interfacing with experiments and processing massive experimental data sets in real time. The combined realization of these goals will allow engineers and scientists a multidimensional glimpse into the physics and functions of complex systems with the capability of local intervention.

Introduction

With the advent of modern sensors, instrumentation and measuring techniques, and a growing need for optimized designs and the monitoring/control of processes in several application fields it has become necessary to acquire, transmit, analyze and digest vast quantities of data generated either from experimental simulations or directly from the field. This is particularly true for complex engineering and biological systems in which transport processes (mass, momentum, energy) are essential. The effective analysis and utilization of massive amounts of experimental data requires direct and speedy links of the instrumentation to massively parallel computing resources and specialized algorithms tailored for the task. It is only recently with the development of advanced experimental techniques such as Phase-Doppler Analysis, Refractometry, Particle Image Velocimetry, Stereo-Particle Image Velocimetry, and Holography that the demand for computational power in experimentation has increased by orders of magnitude. These experimental techniques utilize algorithms and discretizations that are very often identical to those used in numerical simulations. In addition the volume of experimental data, which can easily be as formidable in size as numerically generated data, requires advanced post-processing and visualization tools in order to be useful. Advanced experimental techniques are currently utilized at LSU and elsewhere and are in dire need of support by multiprocessor, parallel computing capabilities. In addition, expertise in linking experiments into a parallel computation environment is required.

In many cases where the environment of interest is harsh (combustors, incinerators and turbines), remote (engineered structures in the transportation system), delicate (the human body), or severely space limited (micro-systems) the information must be passed from its source to a processing and/or control unit without physical links. Thus telemetry properly adapted to the particular environment is a critical need. The importance of telemetry is accentuated in cases where large numbers of very small-scale sensors and/or actuators are used. These devices are becoming feasible as a result of recent research and development efforts in the Micro-Electro-Mechanical Systems (MEMS) areas. Distribution of such micro-devices in systems of interest will provide information or action on the spatial and temporal dimensions of the system. Telemetry capable of handling bi-directional flow of a considerable volume of data will make such implementation useful.

Below we describe several specific projects that are currently in progress, revealing the broad range and cross-disciplinary impact of the proposed topical initiative. Support of this effort with suitable resources will set the stage for further inter-disciplinary efforts on a larger scale.

Relevant Projects of Current Interest

1. Control of Gas Turbine Systems

Control and monitoring of gas turbine engine processes is a major research thrust area of the Turbine Innovation and Energy Research (TIER) Center in the Mechanical Engineering Department at LSU. Some current objectives of the ongoing effort are to:

- Develop active control strategies in order to manipulate non-equilibrium dynamics of flow, combustion and heat transfer in different components of gas turbine systems, and optimize performance measures of these systems by combining control theory and process dynamics.
- Develop and implement micro-scale sensors, actuators, and communication technology for harsh environments, enabling significant improvements of gas turbine performance through local active control.

Succeeding in accomplishing these objectives requires successful integration and operation of micro-systems within harsh environments. This poses challenges in sensor, actuator and micro-electronics design and fabrication as well as in process and materials development.

Given the robustness requirements of the application, the current strategy is to avoid exposing critical components to the harsh environment. To this effect, a four-part, modular architecture is adopted, comprising of (a) Sensing/Actuation, (b) Transduction, (c) Communications, (d) Signal Processing and Control (SP&C) modules (Fig. 1). The first two modules will necessarily reside on the host component (e.g. rotating blade or fixed vane). The transduction module will be shielded and/or actively cooled, but the sensing/actuation module will be designed to withstand exposure to the harsh environment (up to 1700C). For this reason resistive-element sensing and modulated Wheatstone bridge transduction (Fig. 1) will be pursued for improved noise performance, and avoid using temperature-limited integrated circuits (IC).

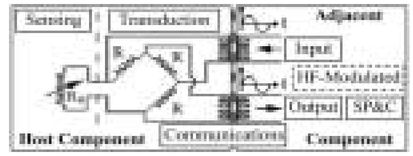

Figure 1: Modular Sensing Architecture

Fluidic actuation will be used as it requires no direct contact of moving parts with the harsh environment and can be designed so that they are not susceptible to electromagnetic interference. The initial focus will be on jet actuators for flow control. Several such devices have already been demonstrated on a proof-of-concept level and have the advantage that the actuating element is shielded from the environment by a flexible membrane. Piezoelectric and electrostatic devices will be considered for transduction of the control signal.

The communications and SP&C issue will be approached through the innovative multilevel scheme of Fig. 2, which effectively addresses the problem of signal transmission across modular components in a noisy environment. Close-proximity, inductive-coupling telemetry will be used to pass input (e.g. power, control) and output signals from the host component (e.g. rotating blade or fixed vane) to intermediate components (e.g. hub, shroud) within the engine while radio-frequency (RF) telemetry will be used to eliminate physical connections to the main controller. Digital signal processing will be performed as necessary on each stage using SiC electronics, pioneered at NASA GRC, silicon on insulator (SOI) or traditional VLSI technologies depending on local temperature (Fig. 2).

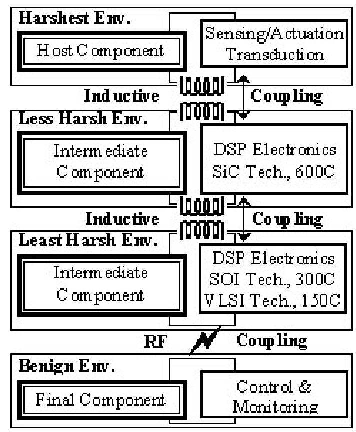

Figure 2: Communication Strategy

We will partner with NASA-Glenn to leverage their recent work on high-temperature sensors and electronics.
Current Sponsors: NASA, DoD, NSF
Potential Sponsors: DoD, NASA, NSF, Gas-Turbine Industry.

2. Fluidic/Thermal Systems for DNA Assay and Bio-Analysis Applications

The goal of this research project is to develop integrated micro-instrumentation for molecular biological applications using High Aspect Ratio Microsystems (HARM) and Micro-Electromechanical Systems (MEMS). Current efforts are directed specifically towards "lab-on-a-chip" devices for clinical diagnostics (DNA), genotyping and DNA sequencing. The instruments under development have unique but common attributes - namely, small instrument footprint (~25 cm x 30 cm), minimal manufacturing costs, the ability to mass produce various components, and the capability of performing the assay from sample preparation to detection with nano-fluid handling and detector optics integrated directly on a small platform. The devices currently being fabricated include:

- *Fast thermal cyclers for PCR amplification of DNAs in nanoliter volume chambers.*
- *Microfabricated cell sorters for isolating cells of fixed size with on-chip cell lysis chamber.*
- *Free flow electrophoresis devices for isolation of specific intra-cellular materials.*
- *Micro-electrophoresis devices containing multiple separation channels for the high speed processing of DNAs for genotyping applications.*
- *Ultrasensitive near-IR fluorescence instrumentation using solid-state components.*
- *DNA immobilization and hybridization chips for LDR mutation analysis (diagnostics).*
- *Fully integrated microfabricated capillary electrochromatography system with conductivity detection and micromachined supports for immobilizing bonded phases.*
- *Injection molding of miniaturized plastic devices for minimizing fabrication costs.*
- *Near-IR fluorescent probes appropriate for use with miniaturized near-IR detectors.*
- *Micro-pumps for fluid handling in pressure driven systems.*

As part of this effort, micro-fluidic networks consisting of channels etched into plastics, which are arranged in "T's" and crosses, as well as more complex integrated micro-fluidic systems such as cell-sorters and free flow electrophoresis devices are being built. Currently, electrokinetic pumping is used for valving and, while this is an appropriate vehicle for some devices, the ability to implement pressure or hydrodynamic pumping is required as well. This being the case, new valving strategies will have to be developed to handle pressure-driven fluid movement in these networks. Future application of similar fluidic systems for 'lab-on-a-scope' and implantable clinical diagnostic instruments will require flows in sub-micron (nano) channels. In addition to the analytical instrumentation, development of an intravenous oxygenator based on massive micro-bubble formation is currently underway in collaboration with physicians at LSUMC-Shreveport. To develop these fluidic micro-systems, fluid dynamic observations and measurements in micro-channels and flow elements will be required. The current major need is to possess the capability to locally measure the transport of fluids through the micro-fluidic networks in order to design them. Recently a micro-Particle Image Velocimetry System (PIV) has been designed and implemented to the micro-scale flow geometries of interest with funding from NSF. Particle image velocimetry application on such a small scale faces many challenges, one of which is poor signal quality and the scarcity of tracer scatterers. This difficulty can only be overcome with computationally intensive image processing algorithms and very large numbers of realizations (of the order 10^4 to 10^5). The image processing and PIV algorithms are very conducive to parallelization and such an adaptation would cut down processing and analysis times from the order of days to hours.

In addition to the diagnostics needed to guide design it is also necessary to interrogate and transmit the bio-analysis relevant signals between sensors on these micro-devices and a separate central processing and control unit during operation. Given the smallness of the devices and the future plans for developing ones that can be inserted or implanted into the human body, innovative telemetry schemes need be developed and implemented.

Current Sponsors: NIH, NSF, NASA/LaSPACE

Potential Sponsors: NIH, NSF, DoD, NASA.

3. Multiphase Flows: Measurement and Control

Multiphase flows are of critical importance to many engineering and biological systems. Examples are numerous: chemical reactors involving gas, liquid and/or solid phases; combustors and incinerators fueled by liquid or solid fuel dispersions and other combustibles; materials synthesis reactors and processes utilizing solid-gas and/or liquid-solid dispersions; fire-suppression systems utilizing liquid and powder suppressant dispersions; oil and gas drilling and production systems involving gas, solid and liquid phases; biological fluids consisting of continuous and dispersed phases including macromolecules; pharmaceutical systems utilizing powder or droplet dispersions in drug manufacturing and dispensing; and the list goes on. The examples outlined are representative of ongoing projects at LSU relevant to multiphase flows. Optimization of design and control of multiphase-based systems is a formidable engineering and scientific challenge that can only be addressed through state-of-the-art experimentation and simulation. During the last fifteen years experimental and numerical techniques have been developed that permit a more detailed local and instantaneous look into the physics of these challenging flows. Because of the multiple phases involved and the associated interfaces both simulations and experimental data analysis are extremely intensive computationally. Typical three-dimensional experimental datasets of variable fields adequate for an accurate statistical view of multiphase processes are of the order of 10^2 Gigabytes. As diagnostics evolve into providing time-resolved, three-dimensional field information, datasets may increase by two more orders of magnitude. Clearly, analysis and visualization of such datasets require massively parallel computing capabilities with significant storage and random access memory capacity, as well as development of associated algorithms.

Current Sponsors: NASA, LaSPACE, LaBoR LEQSF

Potential Sponsors: NSF, NIH, DoD, NASA, EPA.

4. Mixing Control through Passive and Active Forcing

Mixing and the ability to control it is a critical factor in many processes of practical interest. Chemical and biological reactor and combustor performance, and gas-turbine component cooling are typical examples of application areas where mixing control is important. Two approaches to controlling mixing are currently pursued at LSU under this project. One approach is to employ passive means through geometry manipulation of the system of interest; for example, in combustors/reactors this can be achieved using spatially-distributed micro-injector arrays and/or non-conventional complex nozzle geometries that take advantage of non-axisymmetric instability modes. Another approach is to actively introduce local or global perturbations in the time and/or space domain and at appropriate phases to bring about the desired result. Typically this strategy requires distributed sensors and actuators

on scales comparable to those of the flow. Both active and passive strategies involve complex geometries and consequently complex flow and temperature fields spanning a broad spectrum of spatial and temporal scales. Thus, proper investigation and development of such strategies requires fully three-dimensional information with time resolution. Recent developments in flow and thermal diagnostics have made it possible to obtain such information. However, as the challenges in properly implementing these state-of-the-art diagnostics are overcome, one has to contend with a staggering volume of data (of the order of 10^2 Gigabytes per experiment), which often need computationally intensive post-processing and visualization, to become useful. Much of the post-processing required to make these datasets useful is very conducive to parallelization. Hence, massively parallel computer architectures in combination with appropriately adapted post processing algorithms are equally necessary as in numerical simulation applications.
Current Sponsor: NASA
Potential Sponsors: DoD, NASA, NSF, EPA.

5. *Flow-Structure Interactions Under Extreme Wind Conditions*

The research objectives of this project are: (1) to study the performance of buildings and large coastal bridges under strong hurricane-force winds (2) to examine the behavior of large-coastal bridges under heavy traffic loading as it is likely to occur in a scenario of hurricane hazard mitigation; (2) to investigate the possibility of utilizing traffic patterns or installing temporary mass dampers to reduce bridge vibration and thus increase the opening time of the bridge when needed; (3) to advance the state-of-the-art of aerodynamic analysis of large bridges under strong winds; and (4) to develop a safety analysis procedure of hurricane-shelter-designated buildings and large bridges in hurricane hazard mitigation.
In order to successfully address the objectives of the project, it is necessary to perform extensive tests both in the wind tunnel laboratory as well as in the field. Laboratory tests utilizing modern variable-field (2D, 3D) measuring techniques are faced with the same challenges and needs outlined in items 2, 3 and 4 above. Acquisition and evaluation of data obtained from a large number of strain, vibration, pressure and flow sensors installed on instrumented full scale bridges under field conditions requires sophisticated high-throughput telemetry.
Current Sponsors: LaBoR LEQSF, Jefferson Parish.
Potential Sponsors: NSF, LaBoR.

6. *Jet-Propelled Roadable Vehicle for Field Data Collection and Surveillance*

The objective of this project is to develop a Vertical Take-Off and Landing, jet-propelled, small-scale vehicle that is instrumented and remote-controlled or programmed for environmental field data collection (e.g. pollutant sensors, weather data during storms) or surveillance (e.g. monitoring disaster areas during or after hurricanes/floods, military intelligence). The vehicle has to rely on telemetry for bi-directional communications and a link to the Global Positioning System (GPS) for navigation. Thus expertise and resources in telemetry are critical.
Current Sponsor: NASA
Potential Sponsors: DoD, EPA, NASA.

Resources Requested

As noted above, there is significant ongoing activities in mechanical engineering in the area of biological computing. There is also potential for significant collaboration with the biological sciences group at LSU, the medical group at LSU Medical Center, and the computational sciences group in Physics and Computer Sciences at LSU. We are therefore requesting that our activities in this area be strengthened and enhanced by providing additional resources in the following areas:

1. Additional faculty lines in engineering and basic science specializing in:
    a) large data set management,
    b) advanced numerical algorithms,
    c) application of parallel computer systems to data acquisition and real time analysis,
    d) high-throughput telemetry,
    e) micro-telemetry to support micro-sensors and actuators tailored for harsh environments
2. Post-doctoral and graduate assistant positions to work in the areas listed above.
3. Additional space, and resources to establish a state of the art, high performance, parallel computing facility in engineering specifically designed to interface with experimental measuring systems and provide real time data analysis and visualization.