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Novel Variable Input Observer for High-Rate State Estimation

Laflamme, Simon
IOWA STATE UNIVERSITY
1350 BEARDSHEAR HALL
AMES, IA,
US

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Simon Laflamme

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
IOWA STATE UNIVERSITY
1350 BEARDSHEAR HALL
AMES, IA
US

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Dr. Simon Laflamme

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INTRODUCTION

The development of microsecond Structural Health Monitoring (μSHM) systems is critical for the reliable operation of next generation high-speed complex structures (e.g. hypersonic air vehicles, space structures, and weapons). High amplitude impacts may induce damage, or change the configuration of the structure, and therefore, alter the underlying system configuration thereby create changes in the dynamic response of these systems. While state-of-the-art structural health monitoring (SHM) systems allow for constant measurement of gradually changing structures on the order of seconds to minutes, there are no real-time methods that can detect, and characterize, damage in the microsecond time scales. Additionally, there are no experimental test suites which can evaluate the robust performance of the high-rate monitoring algorithms.

To address the technology gap and need for microsecond detection of state changes, the objective of this project were to (i) extend the current capabilities of adaptive observers for microsecond state estimation and monitoring of nonlinear time-varying mechanical systems; and (ii) develop a time-varying experimental system and corresponding analytic models for validation, evaluation, and implementation of the μSHM methods on nonlinear time-varying mechanical system structures.

Both of these objectives were successfully achieved by our group at Iowa State University (ISU) and in collaboration with Dr. Jacob Dodson at the AFRL/RW to complete these objectives.

The rest of the report is organized as follows. Section I summarizes discoveries with respect to each technical objective, and links to published articles in peer-reviewed international journals. Section II summarizes research products, including educational outcomes.

I - DISCOVERIES

The technical objectives of this research were to:

Objective 1: Extend the current capabilities of adaptive observers for microsecond state estimation and monitoring of time-varying mechanical systems.

1.1 Extend current adaptive observers through a combination of model-based methods to estimate the current and future state of a system on microsecond timescales.
1.2 *[Joint AFRL/ISU Task]* Integrate high-rate estimators developed in task 1.1 (AFRL/RWMF) with adaptive input space methods (ISU) for a high performing, rapidly converging state detection method.

Objective 2: Experimentally and analytically validate, and evaluate, the microsecond state estimation and monitoring methods on a nonlinear time-varying system.

2.1 Develop
    a. tunable experimental nonlinear time-varying system
    b. corresponding analytic nonlinear time-varying models
    for the implementation, assessment, and validation of high-rate state estimation and μSHM algorithms.
2.2 Develop performance metrics for validation, evaluate the algorithms, and quantify the performance of microsecond state estimation and health monitoring.
2.3 *[Joint AFRL/ISU Task]* Investigate the sensitivity of performance in the high-rate adaptive observers to environmental and structural variables such as the rate of change of a dynamic system (e.g. boundary conditions and structural damage), and the number and location of sensors on the structure.

Under Technical Objective 1.1, we have developed the theoretical foundations of a variable input observer (VIO) to estimate NLTV time series. In particular, we have:

- Introduced the research problem of high-rate state estimation [J1].
- Demonstrated opportunities in crafting the input space of machine learning representations [J2, C1-C3].
- Investigated performance of the VIO for wavelet reconstruction of 3D representations [J3] and control applications [J4].
- Optimized the VIO architecture for high-rate state estimation [J5].
- Investigated the role of physical knowledge in machine learning convergence for high-rate systems [J5].

Under Technical Objective 1.2, we have integrated the VIO-based methodology for hybrid observers. In particular, we have:

- Developed model-based observers (C4-C6, J10, J12]
- Developed hybrid observers [C7, C9, J13]
- Extended developed knowledge to the problem of physics-informed prognostics of lithium batteries [J8, J11].

Under Technical Objective 2.1, we have developed a numerical model for a tunable NLTV system (developed by the AFRL) used in the assessment of the VIO method. In particular, we have:

- Introduced the DROPBEAR (Dynamic Reproduction Of Projectiles Ballistic Environments for Advanced Research) experimental testbed [J6, C8, C10].
- Develop an analytical model for DROPBEAR [J7].
- Studied opportunities in processing DROPBEAR data in the frequency domain [J9].

Under Technical Objective 2.2, we have developed performance metrics for validation, evaluation, and quantification of the performance of the VIO method for high-rate state estimation. In particular, we have:

- Introduced a set of performance metrics to analyze computation speed and time-series estimation and prediction performance [J5, J9].

Under Technical Objective 2.3, we have investigated the performance of the high-rate adaptive observer in realistic high-rate environments. In particular, we have:

- Demonstrated the performance of the hybrid algorithm at predicting stiffness states on high-rate systems [J13-15].
- Summarized the general research program on high-rate state estimation and discoveries from this research project [B1, T1].

II - PRODUCTS

Publications

- 15 articles published in peer-reviewed journals (see *References*), among those (see Table 1):
  - 40% published in top 20% journals
  - 53% published in top 25% journals
  - 40% published in journals with an impact factor above 5
  - 80% published in journals with an impact factor above 2
  - 33% published in open access journals
- 10 conference papers
- 1 book chapter
- 1 invited talk to the topic
- Yearly presentations to workgroup on high-rate state estimation (led by Dr. Jacob Dodson, AFRL/RW)

Table 1: Journal metrics

	# pubs	EF*	IF**	Open Access
Power Sources	1	99	8.247	
Engineering Structures	1	94	2.528	
Mech. Systems & Signal Processing	3	89	8.934	
Reliability Eng. & Sys. Safety	1	84	5.040	
Automation in Construction	1	77	5.669	
Neural Computing and Applications	1	77	4.774	
Structural Control and Health Monitoring	1	60	3.499	
Shock and Vibration	1	43	1.59	yes
Sensors	2	29	3.275	yes
Applied Sciences	1	26	2.474	yes
Materials Evaluation	1	15	0.48	
Vibration	1	NA	NA	yes

* Eigenfactor (eigenfactor.org); top xx% journal in the field

** Impact Factor

Educational Accomplishments

- 4 Ph.D students supported (all graduated):
  - Jonathan Hong (now research engineer at ARA)
  - Austin Downey (now assistant professor at U. South Carolina)
  - Jin Yan (now research engineer at PARC)
  - Vahid Barzegar (now structural engineer at Thornton Tomasetti)
- 1 M.Sc student supported (graduated):
  - Matthew Nelson (now structural engineer)
- 2 AFRL summer interns at Eglin AFB
- An educational partnership agreement (EPA) between ISU and AFRL/RW (expired 2021).
- Research discoveries integrated in a special 1-hour lecture on high-rate state estimation:
  - within the course *Structural Health Monitoring* taught at ISU; and
  - within a mini-course on structural health monitoring taught at the University of Perugia in November 2020 (attended by 20+ researchers).

Other Outcomes

- Discoveries were used as the building blocks for:
  - NSF projects #1937460 and #1937535 *RTML: Small: Collaborative: A Programming Model and Platform Architecture for Real-time Machine Learning for Sub-second Systems* ($500,000, led by Simon Laflamme and co-lead by Austin Downey, former student), 9/19-9/23.
    - This project is to co-design software and hardware to empower real-time learning

    capabilities in the sub-millisecond realm.

- AFOSR YIP *Real-time Model Updating for Structures in Shock Environment* (led by Austin Downey, former student)
    - This project is to develop physical model updating capabilities to establish the condition of structures in shock environments.
- DEPSCoR project *Topology-Aware Learning and Modeling of High-Rate Dynamic Systems* (led by Chao Hu, co-led by Simon Laflamme), 9/22-9/25.
    - This project is to study the integration of topological data analysis theory in machine learning to improve on the speed of convergence, targeting high-rate systems.

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