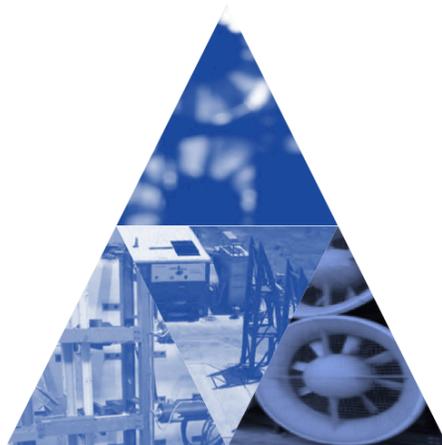


Hybrid Simulation for Multi-hazard Engineering

A Research Agenda

Version 1

Multi-hazard Engineering Collaboratory on Hybrid Simulation



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Executive Summary

As our world becomes more complex and interconnected, engineering experimentation requires greater sophistication. Hybrid simulation methods leverage established knowledge and understanding about the physical world, to gain insight into the behavior of systems that are either too large or too complex to fit in a single laboratory. *Computational substructures* typically encompass the well-known portions of the system, while *experimental substructures* are chosen based on a need to gain new understanding of that component's behavior and its interactions within that system. Actuators and sensors are used to provide needed interfaces between the physical and computational subsystems, *e.g.* to measure physical responses and enforce conditions that enable insight into unknown behaviors by providing a realistic environment. The suite of hybrid simulation methods being developed today represents a disruptive technology that can enable a wide variety of experimental needs for the multi-hazard community as well as several others.

The scientific vision for the hybrid simulation community is to tackle challenging problems in multi-hazard engineering through the execution of high-quality hybrid experimentation with only limited prior knowledge of the physical component. Thus, there is a need for robust methods that are based on a strong theoretical foundation and enable such experimentation under realistic conditions, thus instilling great confidence in the test outcomes. This *research agenda* is meant to document the scientific needs required to advance the application of hybrid simulation methods to a broader range of problems and hazards. The research needs are classified into four main categories: algorithms, fundamental theory, enabling technologies, and learning and community building. This is a living document that will be updated annually to share community priorities and needs, and the steps that are necessary to increase the pace of research in hybrid simulation and enable their use for multi-hazard engineering grand challenges.

This research agenda for hybrid simulation is based on the discussions held at the MECHS Workshop held in San Diego, California December 12-13, 2017. The following committee members and discussion leaders contributed to the development of this research agenda:

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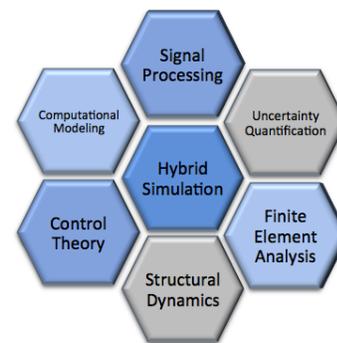
Introduction

Despite our past efforts to establish computational models for complex structural systems under extreme loading conditions, simulation alone is not always sufficient to understand these systems or, moreover, their interactions within a complex structural system. Experimentation is essential, and when the system under consideration is too large to fit in a laboratory, we need to exploit highly creative testing methods.

Hybrid simulation is an experimental method developed within the field of structural engineering. In hybrid simulation, the less understood portions of a structural system may be isolated in an experimental substructure, while the predictable portions of the system are included in the numerical substructure of the system using computational simulation. At the interfaces between the two systems, boundary conditions are enforced to provide realistic behaviors by appropriately inserting reactions and interactions between the two portions. This coupling of a physical subsystem with a computational subsystem according to a suitable partitioning scheme, enables a detailed examination of the complete system while imposing realistic conditions on the selected physical subsystem. Thus, hybrid simulation provides a critical bridge toward advancing and expanding our capabilities in computational modeling.

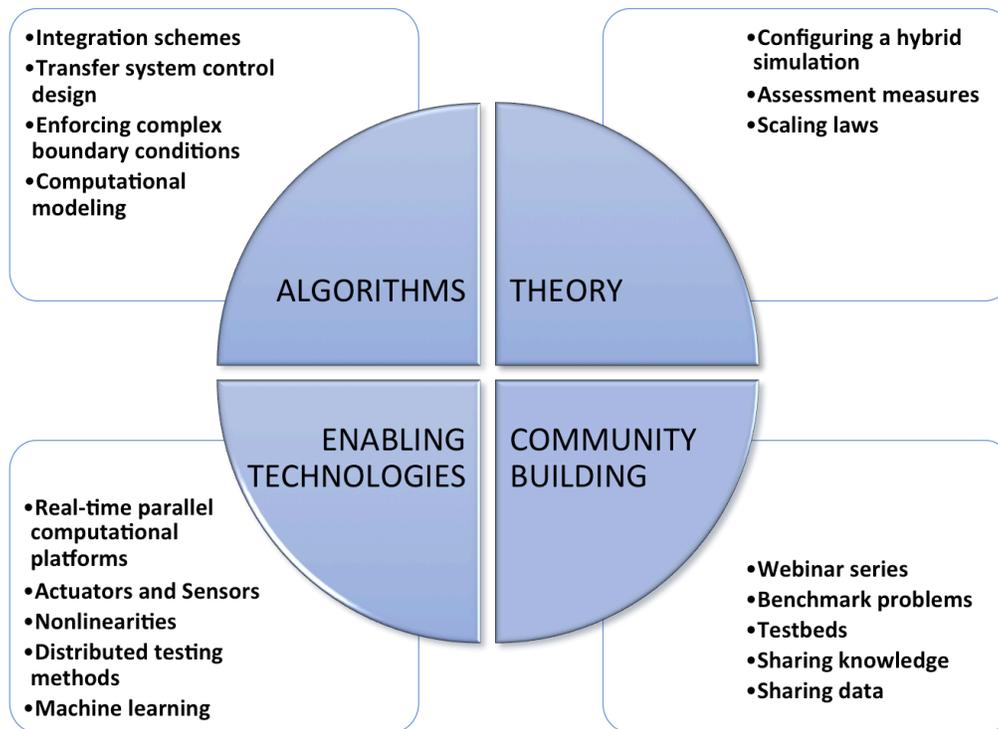
Several classes of hybrid simulation methods have been conducted, each with its own unique challenges and capabilities [2]. *Conventional hybrid simulation (HS)* is conducted at an extended time scale, typically uses higher-order computational models, and is applied when rate-dependence is not present or does not significantly impact the system behavior. *Real-time hybrid simulation (RTHS)* is needed when rate dependence plays a significant role in the dynamics of the physical subsystem, although it requires both high-fidelity control of the actuation system and real-time execution of the computational models and associated supervisory tasks. Furthermore, *geographically-distributed hybrid simulation* and *geographically-distributed real-time hybrid simulation* have been demonstrated in isolated cases to further expand the range of possible experiments by coupling geographically-distributed laboratories.

This research agenda is presented to the multi-hazard community to elicit the breakthroughs necessary to advance hybrid simulation methods and revitalize their use for the multi-hazard community. Here we identify the scientific and technical challenges that must be confronted to develop a next generation of hybrid simulation methods and thus realize its potential by permeating mainstream multi-hazard engineering research [1]. The research needs and technical advances identified herein will enable more realistic and complex experimentation, for instance by their application to new problems (e.g. related to wind and coastal engineering), by explicitly handling complex interactions (e.g., including damage, nonlinear dynamics, aeroelastic effects, or uncertainties), and by expanding the numerical simulation capabilities (e.g. with new integration algorithms, for larger models, with faster rates), all underpinned by strong theoretical foundations (e.g., scaling laws, partitioning, and analysis). Engaging a community of researchers will be essential to address these barriers, and several capacity building activities are also identified herein that would be broadly beneficial. In all of these discussions it is important to remember that hybrid simulation is a highly interdisciplinary topic, and its scientific foundations are rooted in a wide range of disciplines. Techniques such as hardware-in-the-loop have also been exploited in other disciplines. Thus, it will also be helpful to partner with other disciplines and institutes around the world to leverage relevant expertise in making these advances.



Research Agenda

Research is needed in four categories to enable transformative changes in the ability to conduct high-impact hybrid simulations and real-time hybrid simulations, including: algorithms, enabling technologies, fundamental theory and supporting community building and learning. The following sections elaborate on the needs in these areas:



Breaking Barriers – Algorithms and Methods

The complex experiments envisioned will require: new integration schemes specifically designed for hybrid simulation and RTHS; new control strategies for scenarios that require multiple actuators to impose realistic interface conditions; approaches that support implementation of associated control tasks under deep uncertainty; as well as greater flexibility in the computational modeling approaches that can be employed.

Integration schemes should be rigorously assessed in terms of their suitability for linear and nonlinear numerical substructures. Currently, there are two classes of integrators being used in the community: explicit and implicit (predictor-corrector). Explicit integrators are more suitable for RTHS but stability needs to be considered and they can generate high frequency noise in nonlinear systems. On the other hand, implicit integrators are more computationally intensive due to the iterations involved. A new generation of integrators could be developed, for instance based on effective use of energy norms for assessment of stability, considering energy balance and need for controlled numerical damping.

Transfer system control design is hampered in RTHS by uncertainty in the anticipated behavior of the nonlinear physical specimen (e.g., damage or failure) and potential for unpredictable nonlinear behavior in the transfer system (the actuators and other fixtures used to enforce the

correct boundary conditions). In addition, other dynamics must be accounted for in the models and control design, including the effects of interactions between the experimental substructure(s) and actuation system (a.k.a., control-structure interaction), the dynamics/compliance present in test fixtures, the existence of oil-column resonance, etc. In the case of geographically-distributed RTHS, significant communication time delays must also be quantified and accommodated. Although a great deal has been achieved with classical (e.g., proportional-integral-derivative) and modern (e.g., optimal) controllers, to expand the scope of RTHS toward situations involving experimentation on complex systems with nonlinearities, while also increasing the number of degrees-of-freedom and frequency content of the computational models, requires rethinking the ways that we approach this ingredient of an RTHS. The deep uncertainty present in these systems suggests that the future lies in the adaptation of model-based adaptive and robust control methods for RTHS applications. A new generation of transfer system controllers is needed for the complex and multi-dimensional experiments envisioned.

Enforcing complex boundary conditions with requirements that go well beyond defining a single displacement from a hydraulic actuator are a current barrier to what kinds of testing is currently possible. For instance, when boundary conditions require that one impose a rotation, or a rotation combined with a displacement, this is difficult to achieve in the laboratory and simplifications are often made. Also, the use of large actuators may require that compliance in the actuators and/or fixtures be taken into account. Thus, kinematic transformations may be needed, adding complexity to the control and measurement tasks. Additionally, three-dimensional RTHS testing, for instance in the case of asymmetric structures, should be pursued to ensure that RTHS implementations are performed as realistically as is possible from the perspective of the physical specimen. And there may be entirely new interface conditions to enforce in wind and coastal applications, such as distributed loads or displacements, and, depending on the partitioning of the system, new challenges will be encountered in complex wind engineering problems with aeroelastic fluid-structure interactions. In all of these cases, for more complex testing the dynamics of the actuators may be coupled through the physical specimen, and an important task will be in establishing which classes of controllers can be applied more generally to the more complex RTHS scenarios envisioned.

Computational modeling alternatives should be explored. Past hybrid simulations have used finite element method (FEM), as well as convolution integral (CI) and multi-rate methods. FEM subdivides a large computational problem (here, the numerical substructure) into smaller, simpler parts, called finite elements. The CI method was developed to specifically address the challenges associated with model size and the convergence of high-frequency behavior in the numerical substructure. In addition, multi-rate methods have been developed to enable the use of more complex computational models executed at real-time by employing different time-steps in the computational and physical substructures. To extend RTHS to new applications, a variety of modeling approaches could be considered such as the discrete element method (DEM). DEM is an effective method for collapse simulation where discontinuity and loss of elements occur. Such drastic changes in the model during simulation are difficult or not possible in the conventional finite element method. DEM is also suited for problems in granular and discontinuous materials, especially in granular flows, soil and rock mechanics.

Breaking Barriers – Enabling Technologies

One class of hybrid simulation, RTHS has certain unique challenges. The technologies needed to achieve the types of testing that are desired do not fully exist at the present time. Researchers seek to conduct RTHS tests that have significant computational needs, requiring parallel processing

and great flexibility in test execution. These often require rapid changes in the computational models, instrumentation and control settings used, and the capabilities for such testing do not exist today. Thus, some new technologies that are needed to perform such advanced tests have been identified in the following discussion.

Real-time computational platforms that can truly leverage parallel processing capabilities are a high priority to expand the scope of RTHS by exploiting parallel computing. RTHS involves large amounts of computation for the real-time numerical simulation (for instance, a FEM of a structural subsystem, or a computational fluid dynamics (CFD) model) and for the control action determination, as well as for estimation and model updating tasks. Each test is unique, and a platform that allows rapid switching among controllers or computational models is essential. Also, these computations are generally coupled, and at this time there are severe limitations on the processing capacity that is possible in real-time. Real-time platforms with parallel computing capabilities are needed which would provide researchers with the tools to truly execute the massive amounts of computations that are needed for high fidelity testing of complex system. Additionally, immediate data processing and analysis would open up opportunities to integrate more realistic conditions into each test. Performing analysis and verification of data in parallel with the test could inform the test in real time, and may even enable the use of a broader set of sensors as feedback measurements (e.g. pressure sensors in the wind tunnel).

Actuators and sensors available today have certain limitations. When RTHS is necessary, existing barriers are often related to the dynamics of the actuators and/or sensors being used and the ability to control those dynamics. For instance, hydraulic actuators have a large force capacity, but this comes at the expense of slower response times. In certain applications there is a need to apply a distributed force over a length or area, rather than a point force. Also, pressure sensors commonly used in boundary layer wind tunnel experimentation exhibit lags or delays due to their dynamics and acquisition/processing times. Pressure tubing also induces distortion in amplitude and phase of pressure signals in wind tunnels (real-time correction of which poses challenge). Large actuators with faster reaction times and sensors with faster response and processing times are needed, and there may be opportunities to work with industry toward these goals. For coastal research, actuators and sensors that can withstand wet environments may also be needed. For RTHS tests in a wind tunnel, low profile or modified actuators and sensors may be needed to reduce the influence of the presence of an actuator on the test results. To extend these methods to certain aerospace or mechanical systems, the testing bandwidth may need to exceed a few hundred Hertz.

Nonlinearities represent a major research area in structural engineering, although they also pose a particular challenge to many of the hybrid simulation methods. And as is often the case with nonlinear systems, each case is unique and may require an entirely different approach be applied. For instance, nonlinear computational models require significant processing time and typically implicit integration schemes, while nonlinear physical specimens require robust control techniques that are able to deal with the complex behaviors. For instance, sudden failures due to wind loading are not understood and cannot be explained, while progressive failure is a topic of great interest to earthquake engineers. Moreover, failure of components is challenging to replicate in the lab in a manner that realistically represents the behavior in the field. Research focusing on how to conduct a test that involves nonlinearities and material failures will offer insight into the broad future for HS/RTHS to consider such complex issues.

Distributed testing methods that involve multiple facilities may be needed to consider certain hazard scenarios, such as hurricane wind and storm surge. Future research could couple facilities to simultaneously conduct a single test. This approach has been used in a limited number of cases for seismic HS and for seismic RTHS, and there is interest in developing a new approach to do

this in wind/coastal engineering. For instance, a test that couples wave simulation and wind simulation facilities would have high potential.

Machine learning offers possibilities for enhancements to existing methods. Some thought needs to be given to where and how machine learning methods can be appropriately applied to support the design, conduct and assessment of an HS/RTHS, including data analysis tasks. Also, to develop and verify the use of these methods to support testing, a large quantity of data from past HS/RTHS test configurations will clearly be essential.

Breaking Barriers – Fundamental Theory

The foundations of hybrid simulation and RTHS mainly reside in the traditional disciplines of structural engineering, computer engineering (high performance computing, digital electronics), mechanical engineering (actuators/sensors), and control engineering (control theory). However, the integration of these requires a new perspective be taken, and the development of theoretical foundations that consider this unique interdisciplinary topic. Questions that might be addressed about an individual test through such a theoretical foundation include: *Which computational model would best meet the objectives of this test? What new knowledge can I extract if I use each of these two possible models? What are the advantages and disadvantages in conducting this test at 500Hz or 2000Hz? What is the impact of this decision on the results obtained and knowledge gained? How accurate or robust does my actuator controller need to be for this case?*

Future directions needed toward the theoretical foundations that underpin hybrid simulation methods include:

Configuring a hybrid simulation should be done systematically, with the objectives of the test in mind. The complexity of the specimen, the choice of partitioning and associated boundary conditions, the reproduction of the loading, and the sensors used to measure the responses, will all play a significant role in the ability to conduct a test that meets the needs of the researcher. The capabilities of the controller and the presence of computational time delays and actuator dynamics, as well as the physical coupling of multiple actuators, all currently pose challenges to the researcher interested in implementing more complex hybrid simulations. Models (linear and nonlinear) that are able to characterize these individual mechanical and electrical components, and methods that are capable of analyzing this complete system of systems, are needed to capture the behavior and influence of each of these individual components. Such models and methods will provide the means to consider the trade-offs to be made in configuring a particular test. And perhaps more generalized approaches are needed for splitting the system of interest into the numerical and experimental subsystems to address new and challenging problems. For instance, (i) in wind engineering experimentation, a HS/RTHS test may not apportion only the structure as more complex representations of the system will be needed, or (ii) in a HS/RTHS test that considers soil-structure interaction, how can one best represent the interactions present for different types of testing objectives?

Appropriate assessment measures should be established for use in hybrid simulations. These measures would be used to understand how well a particular HS test is emulating the behavior of the whole structure, and will serve as information to guide future development of methods. Both offline (after the test) and online (during the test) assessment measures are worth considering and have complementary purposes. Offline results enable post-test assessments, and can determine how well the test met the intended goals. Online assessments provide information that can be used to redirect a test that may suffer from noticeable errors. Furthermore, data from a large number of tests can also be collected and mined to determine what situations are particularly

challenging to HS/RTHS methods, and to rigorously identify the sources of and propagation of error in HS/RTHS tests.

Scaling laws that can systematically be applied to conduct RTHS experiments are needed. Scaling methodologies used in the isolated fields are well established and their limitations are understood, for instance for wind tunnel testing, for reinforced concrete structures, etc. However, when HS is used and multiple scaling procedures may be relevant, it is not generally obvious how to apply these methods to a given problem. This concern is particularly relevant when geometric or material nonlinear behaviors are to be considered.

Building Capacity – Supporting Community Building and Learning Resources

There can be a substantial learning curve associate with this highly multi-disciplinary field to gain access to hybrid simulation methods. Experience may be required with numerical simulation, control theory, hydraulic systems, high-performance computing, numerical methods and integration algorithms, embedded systems, etc. However, the community can share resources, and leverage experience and knowledge to simplify this process and identify and prioritize those most essential for getting started. Thus, to broaden access to the various classes of hybrid simulation methods and support a community of researchers that can tackle a broad range of problems in multi-hazard engineering, several avenues should be pursued:

Shared/Published Resources: An online presence has been established for this community using the NHERI Design-Safe cyberinfrastructure portal. Information is being posted including technical reports, dissertations, journal paper abstracts, open source software/tools, sample learning tools and virtual simulations, and documented experimental data. The latest research papers on HS/RTHS are not useful for novice users and researchers because they do not describe the basic steps with enough detail. However, historical reports and papers exist that describe the basics of hybrid testing and the essential procedures to be used in great detail. Additionally, the community would benefit from building community libraries containing shared control schemes, integration algorithms, actuator and frame models, collections of case studies, and lessons learned with troubleshooting tips. Common platforms, such as Matlab/Simulink would be ideal as a format for ready use within the research community.

Instructional Webinars/Video Tutorials: A series of webinars (~30 minutes each) should be organized and delivered to the multi-hazard engineering community interested in various hybrid simulation methods. An initial list of topics that could be presented would include: Conventional hybrid simulation 101, Real-time hybrid simulation 101, anatomy of a hybrid experiment, configuration of an experiment, design of an actuator compensator, online model-updating, issues with nonlinear specimens, shake table RTHS implementation, and wind tunnel RTHS.

Benchmark Problems and Shared Testbeds: Opportunities for researchers to explore the boundaries and weigh the capabilities and limitations of newly developed methods must be pursued to advance our understanding of the most effective use of hybrid simulation methods. Numerical and physical benchmark problems would offer the opportunity for various researchers to tackle a carefully designed problem with common objectives that is based on realistic models of the components and physical constraints. This approach has been quite successful in the structural control and health monitoring communities. Shared laboratory testbeds also provide a resource for a community of researchers to leverage a single physical setup for multiple uses. For instance, a facility and test structure might be available for users to propose experiments, with the facility sharing information with the potential participants regarding some of the items that users new to HS/RTHS are not typically familiar with such as: i) the coupling of the numerical model

and physical subsystem; ii) the communication between hardware and software; iii) the role of controllers, sources of instabilities, when they occur, and how they exhibit in the hardware; and iv) the sources of uncertainties and errors, and how to minimize those.

Case Studies: Sharing experiences and lessons learned, both successful and unsuccessful, in the form of case studies would be particularly helpful to researchers across the community. Such a collection of case studies would have at least two purposes: First, a collection of validation case studies comparing hybrid simulation and shake table test results (develop testbed cases) could be valuable for conveying the power of these methods to other researchers and to practitioners. For example, EUCENTRE and other labs have done extensive experimentation with large bearing devices using Simulink. Data can be made available to validate numerical models of actuators and improve the understanding of actuator dynamics (tracking and delays). The second purpose is that this could act as a sort of trouble-shooting manual. Collecting relevant data, identifying and documenting challenges and lessons learned in each step will help researchers to understand and overcome difficulties that they are having in their own testing. It would be best if it is searchable to allow researchers to find similar situations.

Distribution List and Newsletter: An email distribution list [mechs@purdue.edu] has been established to share developments and disseminate information of interest to the MECHS virtual community. A periodic newsletter will also be established to broadly circulate such information and to recognize noteworthy accomplishments toward these research goals.

Concluding Remarks

Over the next few years, the MECHS community will hold one workshop each year to discuss progress and update this research agenda. To have an impact on the broad use of hybrid simulation and the development of the next generation of methods, it will also be essential for the community to *share resources* such as: documented and complete public data sets from past and future experiments, reports and publications, open source simulation models of testing equipment, demonstration codes, and educational materials designed for young researchers. Resources and data will also be shared through the NHERI Design-Safe cyberinfrastructure portal. Data documentation and sharing will play a key role in advancing hybrid simulation and RTHS, and building capacity. Extracting new knowledge from the data will only be possible if details are documented about the actuators, sensors, hardware, integration methods, all used to conduct each test so that they can be examined and generalized to inform future experiments. A suitable data model, such as the one developed in NEES for hybrid simulation project data, should be adopted, especially for sharing data from case studies. The data model may need to be slightly expanded to include test equipment characteristics, and thus address new needs of wind/coastal engineering to fully document the test conditions and facility settings, as well as a similar effort to document the characteristics and settings of hydraulic actuators used for seismic studies with RTHS. Promotion of hybrid simulation methods as an opportunity for experimental investigation and verification of new concepts or structural components will increase awareness and acceptance of this method.

Finally, hybrid simulation is not isolated to civil engineering, nor is it subject to geographic borders. This is both an *international* and an *interdisciplinary* discussion, and rapid advances will require sharing of knowledge and experiences with international counterparts and interdisciplinary collaborators. In mechanical engineering researchers are simulating automobiles under harsh road conditions, in aerospace engineering researchers might investigate the behavior of systems beyond the earth by emulating low-g environments, or in electrical engineering researchers might use a variation of such experimentation to understand the performance of certain components when they are integrated into a national power grid infrastructure.

References

- [1] NHERI (2017). *NHERI Five-year Science Plan*, posted at DesignSafe-CI, (Last viewed: January 19, 2018).
- [2] NEES Hybrid Simulation Task Force (2014). *Hybrid Simulation Primer and Dictionary*, posted at DesignSafe-CI (Last viewed: April 19, 2018).