Hybrid Simulation for Multi-hazard Engineering

A Research Agenda

Version 3, October 2023

Multi-hazard Engineering Collaboratory on Hybrid Simulation

The Research Coordination Network in Hybrid Simulation for Multi-hazard Engineering is supported by a grant from the National Science Foundation (CMMI#1661621).

Executive Summary

Hybrid simulation is a *disruptive technology* that is transforming engineering experimentation. As our world becomes more complex and interconnected, engineering experimentation requires greater sophistication. Examining systems and subsystems in isolation may no longer be sufficient.

Although hybrid simulation goes by many names, such as dynamic sub-structuring, cyber-physical testing, dynamic virtualization, pseudo-dynamic testing, the underlying traits common to all of these approaches include: 1) the leveraging of established knowledge and understanding about the physical world, to gain insight into the behavior of physical systems for which we have limited prior knowledge; and 2) the opportunistic coupling of physical and computational models in a way to realistically include their dynamic interactions. Robust methods, with a strong theoretical basis, are needed to enable the most realistic conditions for such experimentation. Taking such a path forward will instill greater confidence in the test outcomes.

An *explosion* in the use of hybrid simulation methods is now taking place. Methods to study the performance of infrastructure systems toward resisting the demands imposed by multiple hazards including wind, tsunami, or storm surge are advancing rapidly. And well beyond that, researchers are also exploring hybrid methods to conduct thermo-mechanical, earthquake-induced fire, fluid-structure interaction, aerospace, automotive, and even biomedical engineering implementations, significantly expanding the scope range of testing that is possible. Cyber-physical testing with linear, pre-determined models is well established. However, the latest advances in nonlinear and adaptive control theory are being applied to tackle especially challenging cases involving damage, failures or strongly changing dynamics. Machine learning is being applied to design and conduct hybrid simulations, supporting greater efficiency and online identification. And hybrid experimentation is now being exploited in selected industrial settings as well.

This *research agenda* is meant to document the scientific needs required to advance the application of hybrid simulation methods to a broader range of scientific problems and hazards. The research needs are classified into four main categories: algorithms, fundamental theory, enabling technologies, and learning and community building. Webinars coordinated by the MECHS virtual community have been useful for engaging new research groups in hybrid simulation methods and use. Benchmark problems have also been developed, and captured the attention of a large group of researchers interested in showcasing their achievements and innovations for RTHS. These community accomplishments are being documented through several special issues of journals.

This *research agenda* is a living document that will be updated periodically 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 and multi-physics engineering grand challenges.

This research agenda for hybrid simulation is based on the discussions held during the MECHS Workshop held in San Diego, California December 12-13, 2017, Joint ETH-MECHS Workshop held in Zurich, Switzerland March 13-15, 2019, 3rd Joint UniValle/MECHS Workshop was held virtually July 15-16, 2021, 4th MECHS Workshop held virtually on March 25-26, 2022, 2022 NHERI Summit Discussion Session held in Washington DC on October 22, 2022, Joint NHERI-WOW+NHERI-RTMD+MECHS Workshop held in Miami, Florida February 7-8, 2023, and the 5th MECHS Workshop held in West Lafayette, Indiana August 8-10, 2023

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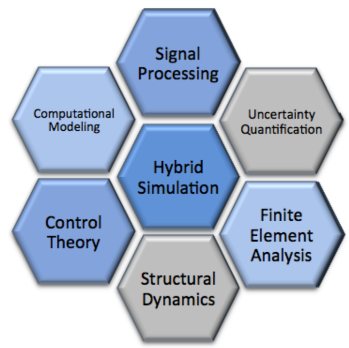
Introduction

Despite all of the past efforts to establish computational models for complex structural systems under extreme loading conditions, simulation alone is not entirely 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 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* [1].

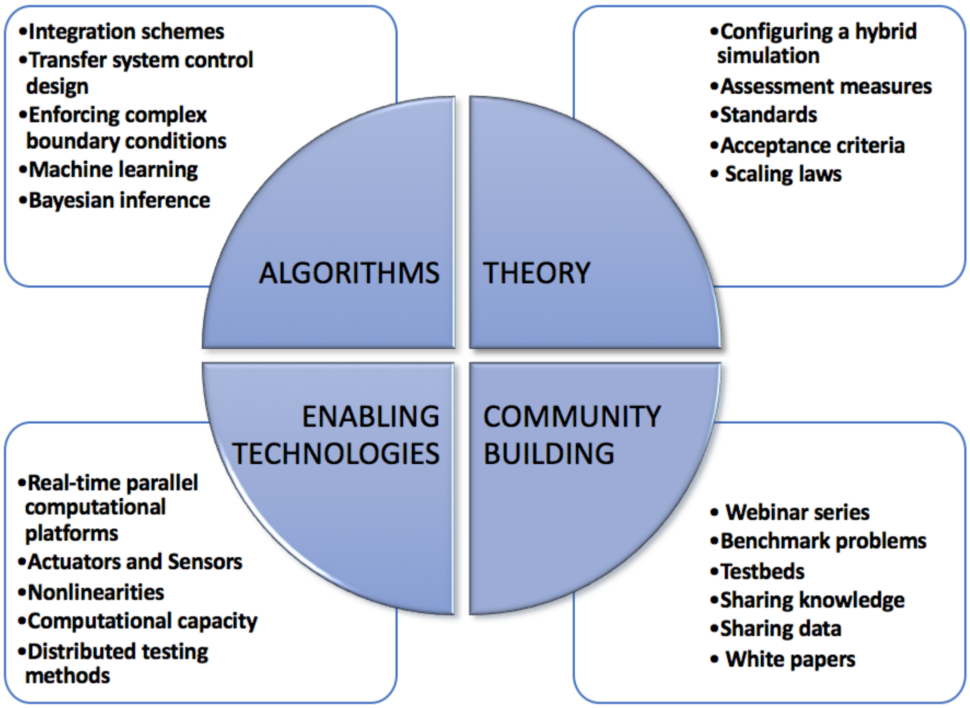


This research agenda is presented to the multi-hazard community to elicit the breakthroughs necessary to advance hybrid simulation methods and revitalize their use for the multi-hazard community. Here we identify the scientific and technical challenges that must be confronted to develop a next generation of hybrid simulation methods and thus realize its potential by permeating mainstream multi-hazard engineering research [2]. 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, thermal effects, or uncertainties), and by expanding the numerical simulation capabilities (e.g. with new integration algorithms, using multiple cores and FGPAs, with faster clock speeds), all underpinned by strong theoretical foundations (e.g., scaling laws, partitioning, and analysis). Key enabling technologies are also identified as being critical to expanding the scope of hybrid testing to exploit these methods in the manner originally envisioned. One such technology is the ability to reliably perform complex computations while meeting real time constraints, and do so for a variety of scenarios – each test is certainly unique. The community has identified many problems in which it is necessary to incorporate machine learning, parallel computation, adaptive control, online model updating, and predictive surrogate models into these tests. However, running such complex scenarios, at real time (usually ~1000 Hz) or faster than real time (which is needed for scaled cases such as wind and fluid engineering), is not even remotely possible at this time.

Engaging a broad community will be essential to address these barriers. This community should include relevant hazard engineering disciplines, as well as computer scientists, control experts, and practicing engineers. Several capacity building activities are also identified herein that would be broadly beneficial, and the sharing of open-source resources such as data, codes and benchmark problems that will accelerate the transfer of knowledge. 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 and human-in-the-loop have been exploited in several 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

The research needs are described in terms of 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 and needed for supporting research 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 and result in nonlinear behavior and even failures; approaches that support implementation of associated control tasks under deep uncertainty; as well as much greater flexibility in the computational modeling approaches that can be employed [13].

Integration schemes should be rigorously assessed in terms of their suitability for both linear and nonlinear numerical substructures [14]. Currently, two classes of integrators are 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. Advances in computing techniques (parallel computing) and hardware (new generations of CPU), algorithms with iterations may also be enabled through real-time computing. A new generation of integrators could be developed, perhaps with a goal of being more computationally efficient.

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, the potential for changing behavior in the studied specimens, 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 use of model-based adaptive and robust control methods for RTHS applications that make use of models of the transfer system but allow significant uncertainty in the test specimen without loss in control performance. Furthermore, phenomena that impose drastic behavior changes on the studied specimens, such as damage and degradation, may require nonlinear or switching control strategies to ensure the fidelity of the experiment. A new generation of transfer system controllers is needed for the complex, multi-dimensional and multi-physics experiments envisioned and benchmark problems could support this pursuit [11, 12].

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 [12, 13]. 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. As the scope of our applications grow, the interactions between numerical and physical substructures also become more complex. For instance, multi-physics problems, like those involving extreme temperature variations or fluid-soil interactions, would require different types of actuators that may not be readily available. Digital twins (DT) technologies may be leveraged to artificially impose boundary conditions without the need of specific actuator types.

Computational modeling alternatives should be explored. The choice of a computational model is linked to the purpose of the simulation, and thus, to the granularity and accuracy of information that is to be extracted from the results. The use of more detailed computational models is typically associated with greater computational time requirements, limiting the rate at which RTHS can be conducted. 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 a method used 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. Data-driven approaches, such as neural networks (NN) or machine mearning (ML), offer a flexible modeling approach that may reduce the computational demand and capture complex behaviors. Thus, data availability becomes a challenge that can be addressed by the creation of public databases and repositories.

Breaking Barriers – Enabling Technologies

One class of hybrid simulation, RTHS has many special challenges. The technologies needed to achieve the types of complex testing that are desired within the multi-hazard community just do not exist at the present time. Researchers seek to conduct RTHS tests that have tremendous computational needs, requiring access to real-time parallel processing, adaptive controllers, uncertainty quantification, 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 of the new technologies that may be needed to perform such advanced tests have been identified in the following discussion.

Real-time computational platforms that can truly leverage parallel processing capabilities with reliable and appropriate scheduling techniques are a high priority to expand the scope of RTHS. 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 for wind or fluids). Significant computation may also needed for the control action determination, as well as for state or parameter estimation, continuous model updating, or prediction tasks. As is clear from many of the other topics in this research agenda, researchers are eagerly working to advance these techniques beyond a few degrees-of-freedom, beyond reduced linear models, and beyond pre-determined identified models. These are critically necessary if RTHS are to realize the vision, but a major barrier impeding real applications of all of these promising paths forward is the limited amount of computation that is possible today. In both hydrodynamics and aerodynamics, the rate dependent nature of the problem demands a real-time test environment. Thus, when scaling down physical specimens, the speed of the loading and of the test generally increases considerably. Thus, the computations are much more demanding and enforcement of real-time constraints may be more critical to the success of the test than in some seismic applications. 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. Additionally, underwater actuators are needed to facilitate new classes of hydrodynamic hybrid testing. 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. Experiments involving temperature changes require the use of thermal actuators and associated components such as chillers or thermal panels. The identification, control, and state estimation techniques for these components are needed to include them in the RTHS community toolbox.

Nonlinearities must be a priority of future research to develop advanced RTHS methods. Nonlinearities represent a major challenge to RTHS methods, because the ultimate goal is to consider damage and failures in structural engineering when the specimen itself is actually unknown. This is the central vision behind the purpose of hybrid simulation – *testing the unknown*. However, as is often the case with nonlinear systems, each case is unique and may require an entirely different approach be applied. Thus, nonlinearities pose challenges to several aspects of an RTHS, including: computational demands, control performance, uncertainty quantification. For instance, nonlinear computational models require a significant increase in the processing demands, and typically are implemented using implicit integration schemes. Furthermore, nonlinear physical specimens require robust (and possibly adaptive) control techniques that are able to deal with the complex and uncertain behaviors exhibited. 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. Other possible applications include seismically-induced fire with structural instabilities, thermo-mechanical coupled tests, and contact problems which are used in a wide variety of engineering fields. And due to the large uncertainty in each of these cases, significant effort should be put into quantifying that uncertainty based on the data available to predict future behavior and inform testing choices. Research focusing on how to conduct tests that involve geometric nonlinearities, material failures and instabilities will offer insight into the broad future for HS/RTHS to consider such complex issues.

Machine learning offers a range of opportunities to advance many of the existing RTHS methods. For instance, surrogate models can be developed for a range of purposes, for instance to reduce computational demands or offer predictive capabilities. Experimental design can be enabled by using machine learning to classify and cluster similar inputs (e.g. earthquake records) or even responses and behaviors (e.g. structural responses or failure modes). Machine learning is already being used for sequential selection, with the goal of designing an experiment to minimize the number of simulations needed to achieve a predetermined level of dispersion in the results. In future RTHS applications, model updating and state estimation will be critical for conducting reliable RTHS experimentation as the nonlinear and uncertain nature of the test specimens, as well as the noise and fixturing, will require that updating of the knowledge of the condition of the test specimen be known to properly apply control and enforce boundary conditions. Software to enable these should be developed, and could leverage past. Parallel computing, FPGAs and GPUs may need to be exploited with such software to realize real-time requirements when using machine learning techniques. 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.

Distributed testing methods that involve multiple facilities may be needed to consider certain multi-hazard scenarios, such as hurricane, wind and storm surge. Future research could couple facilities to simultaneously conduct a single test. While this vision has been imagined for over twenty years, this approach has only been used in a limited number of cases for seismic HS and for seismic RTHS, and work has started on this to couple wind and wave simulations. There is potential for developing advanced to do this type of testing in wind/coastal engineering or in multi-physics problem.

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 uncertainties are present in my test, how can I quantify them, and how sensitive is my setup to these? What are the advantages and disadvantages in conducting this test at 500Hz or 2000Hz? What is the impact of this design decision on the results obtained and knowledge gained? How 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 a 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?

Uncertainty has been investigated and, to some extent, rigorously examined in HS/RTHS. Hybrid simulation studies are no longer being viewed in a deterministic manner. Researchers are more aware of the uncertainties that do exist in the sensors, actuators, physical specimens, couplers, input/disturbance, and the entire experimental setup. Fixturing issues, slop, backlash, misalignment, noise, etc. still may pollute a test, and these sources may accumulate and even magnify due to the closed loop nature of the test. As we move forward with this technology, it would be beneficial to incorporate the latest work being done in uncertainty quantification/propogation and parameter estimation so that the errors that are present when using RTHS can be quantified and understood. The challenge here in RTHS methods is that it is generally difficult to do so without a reference for comparison. Tools from scientific machine learning and data science should be proposed and applied to establish rigorous methods to explain how all sources of uncertainty propagate through the hybrid system response. Some key questions that need to be addressed are: which are the sources of uncertainty that are sensitive to the hybrid system response; how many experiments are required to characterize the probabilistic response of the hybrid system; and, can the bounds of uncertain variables that define artifacts and still yield high fidelity results be defined? The acquisition and transfer of such knowledge regarding practical considerations is critically needed to expand the scope of HS/RTHS. The inverse problem is also worthwhile to investigate: given a reduced number of tests, how can we isolate and quantify the uncertainty of the studied phenomenon?

Scaling laws that can systematically be applied to conduct RTHS experiments are needed. Scaling methodologies such as similitude are used in the isolated fields, and are well established with their limitations being understood. For example, in hydrodynamics, Froude scaling is applied to preserve the dynamic effect generated by water wave; in aerodynamics, Reynolds scaling is similarly applied. However, when RTHS is used and multiple scaling procedures may be relevant, it is not generally obvious how to apply these methods to a given problem. Additionally, this concern is particularly relevant and increasingly complex when geometric or material nonlinear behaviors are to be considered.

Appropriate assessment measures and acceptance criteria should be established for use in hybrid simulations. Assessment measures would be used to understand how well a particular HS test is emulating the behavior of the whole structure, and acceptance criteria will define requirements for the design of controllers to achieve a specific level of performance. Knowing more about the performance of these tests toward a given objective will also serve 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.

Building Capacity – Supporting Community Building and Learning Resources

A substantial learning curve is associated 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. The development and continued growth of the MECHS web portal and publication library has been a great resource for this growing community. To further broaden access to the various classes of hybrid simulation methods and support this community of researchers as they tackle a broad range of problems in multi-hazard engineering, several avenues should be continued:

Shared/Published Resources: An online MECHS website is available for this community through the NHERI Design-Safe cyberinfrastructure portal under "community" in the menu. Information posted includes technical reports, dissertations, journal paper abstracts, open source software/tools, sample learning tools and virtual simulations, instructional videos, curriculum suggestions, and documented experimental data. Also, a growing *Publication Library* is available on the MECHS website, to share the latest research results in a single location. These easily accessible publications on HS/RTHS are useful for knowledgeable users and researchers. However, novice users will also benefit from the historical reports and papers that describe the basics of hybrid testing and the essential procedures to be used in greater detail. A recommended curriculum built from existing YouTube videos has also been posted for those new to these topics. 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. Special efforts should be made to include (and to expand) *open-source tools, publications, and resources*.

Instructional Webinars/Video Tutorials: A series of webinars have been initiated and posted for the multi-hazard engineering community members interested in hybrid simulation methods. The initial list of topics in this Hybrid Simulation 101 series included: Anatomy of a hybrid experiment, Pseudo-dynamic hybrid simulation, and configuration of an experiment. Hybrid Simulation 201 series went deeper into wind RTHS methods, hydrodynamic RTHS, dealing with uncertainty, configuring an RTHS, and nonlinear control techniques, among others. Future ideas include: fluid-structure interaction, shake table RTHS implementation, and wind tunnel RTHS. In addition, a few short educational videos (~5 minutes each) were created to provide background information for students new to hybrid simulation. Topics included: hydraulic actuators, and PID controller design.

Community 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. Two benchmark problems in real-time hybrid simulation are now available [11, 12], and the research community was invited to apply the most promising techniques to this community problem. Special issues have been organized on these problems. 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 and Reference Data Sets: 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 reference data sets would be attractive components of young investigator/career proposals, publishable in a suitable data repository. 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 value of these methods to other researchers and to practitioners. As an example, EUCENTRE and other labs have done extensive experimentation with large bearing devices using Simulink. Data from these experiments 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 these could serve a role 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 such data and metadata were 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.

Guidelines, Standards and Acceptance Criteria: An analogy exists between the needs for guidelines in hybrid simulation methods and those discussed in FEMA 461 *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components.* This document made some progress on standardizing conventional component testing techniques, and there is potential for a set of guidelines such as "FEMA 461-HS" to be developed to recognize HS/RTHS as standard test methods. Acceptance criteria can also exploit modern uncertainty quantification methods to predict or estimate distributions using available data.

Establishing Subcommittees: To further build community, it could be effective for this virtual organization to develop some subcommittees in various application areas that might lead white papers and promote hybrid technologies within their specialties.

Concluding Remarks

The MECHS community has held several workshops to discuss progress and to update this research agenda. Current priorities focus on the need for advances in the methods to deal with the wide variety of *nonlinearities* as well as *uncertainties*. Nonlinear behavior is the eventual result of extreme loads within multi-hazard engineering, such as damage, instabilities, contact problems, and even collapse. Uncertainties are prevalent in all experiments conducted to consider the unknown, and recent advances in uncertainty quantification provide a range of tools that can be adapted to this problem. For instance, experimental design can enable more efficient testing and the extraction of more information from fewer tests. All of these advanced methods do, however, rely greatly on the ability to acquire data through hardware and perform an enormous amount of *computation* within a less than millisecond time step. Thus, inexpensive options for parallel computing, as well as FPGAs and GPUs, that can exploit the interconnected structure of these computations are critically needed to realize all of the items in 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 data model, such as the one originally developed in NEES for hybrid simulation project data and later adopted by NHERI, 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 the loading on prosthetic limbs that dynamically interact with the human body, 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.

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