Report on Discussions

Multi-hazard Engineering Collaboratory for Hybrid Simulation: Machine Learning in Hybrid Simulation

Workshop held virtually on March 25th, 2022

Summary

Hybrid Simulation (HS) has reached a stage in its maturity that is enabling the exploration of quite complex problems, such as those that involve nonlinear and degrading phenomena and emergent behavior, as well as novel applications, such as multi-physics problems and distributed loading. As discussed in previous workshops, these new demands on the testing capabilities require further advances in the computational and performance fronts and the control, modeling, and parameter identification strategies.

Machine learning (ML) advances have proven to be useful in a broad class of applications ranging from computer vision to speech recognition. In addition, the inherent ability of these techniques to generate models using input and output measurements can come in handy for specific HS applications. For instance, ML techniques may help to tackle the various challenges related to computationally inexpensive model execution, online model selection and updating, experiment design to optimize the number of tests performed, or modeling large and complex numerical substructures, among other uses.

The objectives of this workshop were to provide researchers, graduate students, and other interdisciplinary participants with a space for discussion on how to leverage ML methods to improve HS techniques. Mainly, our goals were to find ways in which ML can help to understand or reveal structural behaviors from HS experiments, to improve or accelerate our testing, and to extract more information from each test.

See the MECHS page for more activities and resources: http://mechs.designsafe-ci.org

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Introduction

The last MECHS Workshop, "Confronting New Challenges", was held virtually on July 15 and 16, 2021. The key topics discussed during that workshop were two challenges the community must address to advance further Hybrid Simulation: overcoming computational bottlenecks and managing nonlinearities and uncertainties. The 6th MECHS Workshop, "Machine Learning in Hybrid Simulation", held virtually on March 25th, 2022, constituted a follow-up discussion that put on the table a possible solution for the previously identified challenges: the incorporation of Machine Learning (ML) techniques in the Hybrid Simulation (HS) practice. Moreover, potential additional uses of this set of technologies were shown and discussed.

The main goal of this workshop, which brought together researchers, graduate students, international partners, and interdisciplinary collaborators, was to brainstorm and share experiences regarding exploiting ML techniques for the benefit of HS experiments. Pointedly, the discussion was oriented to find out ways in which ML can help to: (1) better understand or reveal the physical behavior of the tested specimens; (2) improve or accelerate HS experiments; and (3) maximize the information coming from HS experimental testing and the associated recorded data.

The first portion of the workshop consisted of a series of presentations showing current advances in ML-HS interaction. One possible application area mentioned is the implementation of reduced-order models for otherwise highly-dense models. For example, neural networks have been used to assess the behavior of a soil-foundation structural system. Another area of application is parameter identification. For example, ML algorithms have been used alongside the digital twin concept to reduce the bias in the physical substructure response due to variations in the type of excitation. Moreover, standard ML techniques, such as Long Short-Term Memory (LSTM) neural networks, can be used to reduce the uncertainty associated with model selection for parameter identification. Finally, the black-box nature of ML, which can be an obstacle in HS applications due to its reduced or absent interpretability, can be alleviated or overcome using cutting-edge methods. An example is the nonlinear static function approximation, which allows tuning typically arbitrary values (number of hidden nodes, initial values, biases) using physically-informed guesses.

The attendees were split into three breakout rooms during the second portion for discussion. A set of suggested questions was provided to the discussion leaders for them to lead the sessions. Among the main ideas and concerns identified by the groups regarding the adoption of ML techniques in the HS practice were: (1) the potential for simulating responses of complex-to-model systems; (2) the possibility of accelerating the execution of HS tests, thus advancing further the quest for actual real-time experiments; and (3) the importance of the management of the datasets used for training of the hypothetical ML models. Regarding the latter point, the participants stressed the need for repositories of high-quality and large enough datasets.

This report is intended to document the aforementioned discussions and is being incorporated into the next Research Agenda on Hybrid Simulation. This report and that research agenda are being posted on the MECHS site for the community: http://mechs.designsafe-ci.org. Adding ML techniques to the current practice of HS can address several of the previously identified obstacles by the community. However, it also creates new challenges and areas of opportunity for these technologies to be successfully implemented. Future research on HS should be oriented towards integrating all these techniques in a useful, well-established tool to understand structural behavior better and increase our infrastructure's resilience in facing multiple hazards.

Discussion Groups

The attendees were assigned to three discussion groups led by a discussion leader as follows:

Group	Discussion Leader	Note Taker
1	Scott Harvey (*University of Oklahoma*)	Mahindra Rautela (*Purdue University*)
2	Gastón Fermandois (*Universidad Técnica Federico Santa María*)	Edwin Patiño (*Purdue University*)
3	Gaby Ou (*University of Florida*)	Lissette Iturburu (*Purdue University*)

The discussion leaders were provided with suggested questions to guide the discussion, but they were free to conduct their groups at will. Here, the discussed topics were organized around the two major concerns identified from the breakout groups: potential applications of ML in Hybrid Simulation and building community to advance ML and HS integration further.

Potential Applications of ML in Hybrid Simulation

Group 1 summarized areas where ML techniques can come in handy for hybrid simulation purposes, for instance: in simulating nonlinear responses, especially when the underlying models are highly uncertain; for modeling complex numerical subsystems; and for parameter identification. Moreover, they consider that ML can help to accelerate HS techniques in two ways: by accelerating the experiments themselves, providing the tests with the ability to run larger models in real-time at relatively low computational demand, and by taking forward the frontier on the modeling side, that is, allowing the HS community to model more complicated phenomena in less time. As an example of this last issue, the question of how to use ML capabilities to test unconventional environments, such as spatial structures and habitats, was left open.

Group 2 suggested looking further into the potential adoption of ML methods for feedback control purposes. They also discussed the nature of the conventional ML tools as black-box models, which is a constraint regarding interpretability and tuning. A workaround for this difficulty is the use of physics-informed neural networks.

Finally, **Group 3** proposed to use ML for choosing appropriate setups, *i.e.*, for the selection of models and development of numerical or physical components. This approach would also allow uncertainty management in two ways: first, by propagating uncertainty into the numerical models, and second, by reducing the undesired uncertainty coming from a model selection. They also discussed the possibility of using ML to represent regional variations of the tested structure, which might be particularly helpful for wind simulation. ML can also help choose which tests to perform, which would further economize HS experiments. Overall, the group concluded that ML should alleviate the computational burden of the tests, allowing the execution of more complex behaviors, such as nonlinear, extreme, and degrading phenomena.

Action Items and Future Research Needs

- Development of nonlinear, extreme, and degrading-systems benchmark problems that allow the testing of different ML-based strategies for:
    - parameter identification;
    - feedback control;
    - uncertainty propagation.
- Rigorous assessment of the computational performance of ML models as opposed to conventional numerical substructure models.
- Development of a model-selection framework using ML.
- Educational:

- Update the recommended course curriculum to include basic notions of ML techniques.
- Organize webinars and record educational videos on the principles of ML and their application in HS.

Building community to advance ML and HS integration

The three groups agreed that successfully adopting ML techniques into the HS community largely relies on our ability to integrate data and shared code repositories.

Group 1 suggested the creation of a GitHub repository for the individuals working in HS to post their data, either coming from experiments or generated through numerical models. They also stressed the importance of this kind of workshop and discussion spaces to develop new implementation ideas. One of the participants mentioned the possibility of connecting with the undergraduate-level community by offering shake-table training for them to get involved with HS techniques. The final goal would be to attract students to pursue PhDs in related areas.

Group 2 remarked the need for benchmark data for training models and recommended making clear to the community that we are not advancing further nor developing new ML methods but using the existing ones to facilitate the execution of HS tests. They also stressed the importance of us being aware that a critical limitation of these techniques is the need for varied and large datasets. These can be easily obtained from finite element or reduced-order models, but the dataset is likely to be small if the data is collected from the test itself. This kind of situation constrains the use of ML models for extrapolation.

Group 3 commented on possible sources of the training data. For instance, they suggested using data from the Natural Hazards Engineering Research Infrastructure (NHERI) Data Depot (https://www.designsafe-ci.org/data/browser/public/). However, it was mentioned that not all the datasets in the depot satisfy the quality requirements for ML purposes. Moreover, most data lack extreme or corner cases that are valuable for modeling nonlinear phenomena. Therefore, they proposed to create a framework for managing, cleaning, and unifying datasets provided by the community.

Action Items and Future Research Needs

- Development, management, and maintenance of a dedicated MECHS repository for training datasets.
- Development of guidelines for acceptance of datasets to ensure the quality of data.
- Get more Computer Science scholars, either graduate students or faculty, involved in the HS community. Some actions that can be performed:
  - reach out to the undergraduate Computer Science community by offering basic training in experimental civil engineering methods;
  - involve researchers currently working on physics-informed neural networks and related topics.

Appendix A: Agenda of the 6th Workshop

Multi-hazard Engineering Collaboratory for Hybrid Simulation (MECHS)

AGENDA

Machine Learning Workshop
March 25th, 2022, 3:00pm – 5:00pm Eastern US Time (held virtually)

The goal of this workshop is to stimulate a discussion on the potential for Machine Learning to enhance Hybrid Simulation. The workshop will consist of short informal vision talks, followed by a group discussion to generate new research ideas.

General information:

Note that the MECHS Collaboratory site can be found at:
https://mechs.designsafe-ci.org

Content collected there includes:

- Past Webinar recordings
- *A Publication Library*
- Instructional materials for those new to hybrid simulation
- Curriculum suggestions

Teleconference Instructions Using Purdue Webex System:

Meeting name: MECHS Machine Learning Workshop
Date: Friday, March 25, 2022 | 3:00 pm Eastern US Time
Link: https://purdue.webex.com/purdue/j.php?MTID=m24bb83db8c1a956d2980e147f6f7e940

Meeting number: 2623 200 7393
Meeting password: spring2021

Join by phone
+1-855-282-6330 US TOLL FREE
+1-415-655-0003 US TOLL

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

AGENDA

3:00 – 3:45 MECHS and Workshop Introduction

3:00 – 3:10 *Welcome and introduction*
Shirley Dyke

3:10 – 3:45 Vision talks to stimulate discussion

James Ricles, Lehigh University
Multi-Natural Hazards Performance Assessment of Soil-Foundations Structural Systems using Real-time Hybrid Simulation and Machine Learning-Trained Neural Networks

Jin-Song Pei, University of Oklahoma
Interpretable Machine Learning for Nonlinear Static Function Approximation

Ali Imanpour, University of Alberta, Edmonton
Multi-element Seismic Hybrid Simulation Combining Hysteresis Modeling and Recursive Model Updating

Mao Cheng, University of California, Berkeley
Model updating using LSTM for initial selection

3:45 – 3:50 *Move to Breakout Rooms*

3:50 – 4:30 *Breakout Rooms*

4:30 – 4:35 *Return to Main Room*

4:35 – 4:55 *Summaries from Breakout Discussions*

4:55 – 5:00 Closing

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Appendix B: Pictures from the 6th Workshop

Figure B1. Presentations of the four speakers.

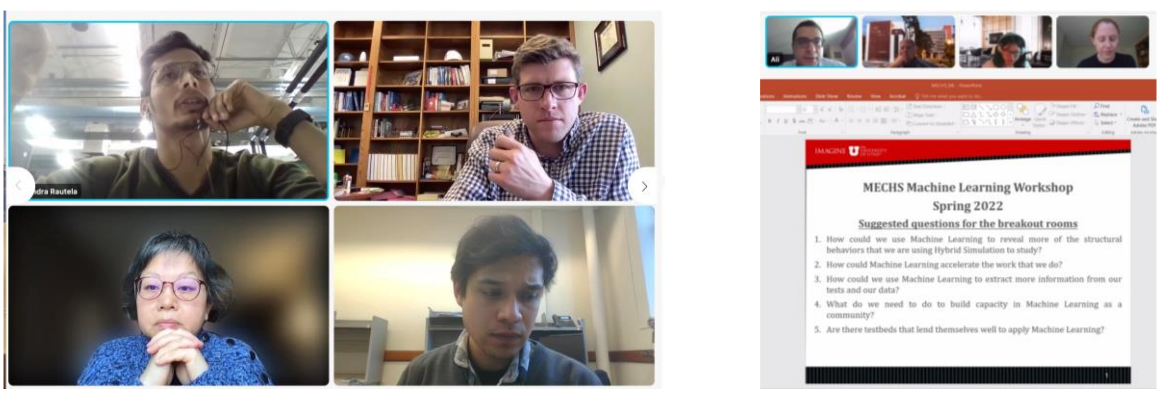

Figure B2. Breakout rooms.

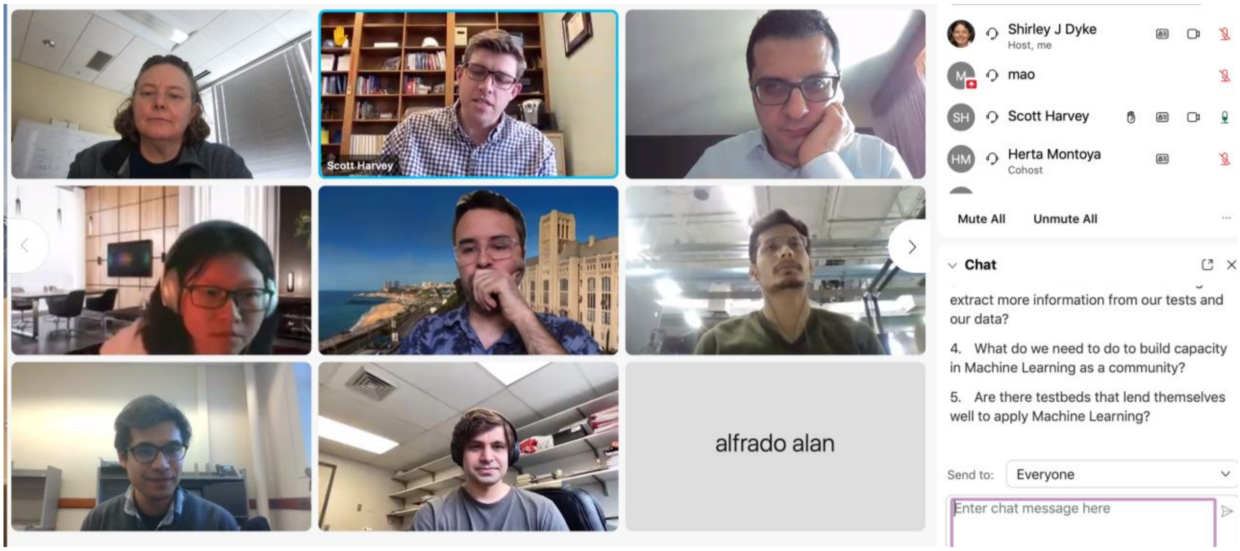

Figure B3. Summary of discussions.