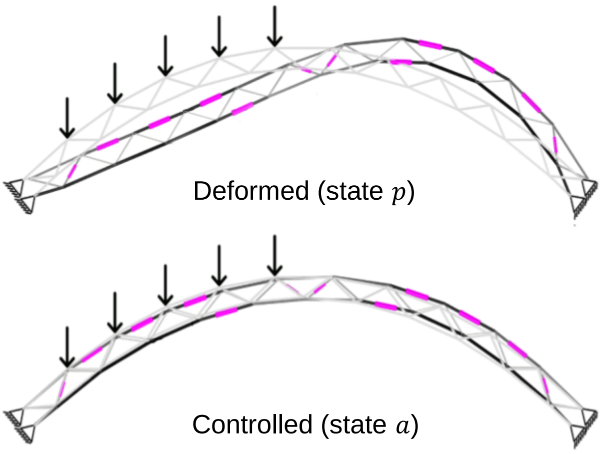
Adaptive Control Strategies through Knowledge-Infused Reinforcement Learning

MSc project

Adaptive structures can modify their shape and internal forces through sensing and actuation to counteract the effect of external loading (e.g., stress, deformation). Adaptation allows manipulation of the structural response to satisfy required limits in material strength and stiffness. Hence, passive resistance through material is replaced by actuation energy. Well-designed adaptive structures can achieve significant savings in material mass and in whole-life energy/carbon compared to conventional passive structures [1]. The active components are typically linear actuators strategically placed on some of the structural elements. Several methods for static and dynamic compensation have been successfully developed and tested. However, the optimal placement of actuators remains a challenging task due to its combinatorial nature and can become prohibitive for structures made of many elements. In addition, little attention has been given to methods that enable "learning" from experience to improve the control model over time as well as to deal with geometric and material nonlinearity that might occur after damage.



The goal of this MSc project is to develop a new strategy based on reinforcement learning to control adaptive structures. Given the structural state under loading (state p), and a target state (state a, for example, defined by a target shape and limits on the internal forces), the controller is responsible to provide actuator commands to change the structural state from p to a. During damage, however, one or more actuators might not work at full capacity and one or more structural elements might have collapsed. This scenario will be considered to train the control model to mitigate the effect of damage by redirecting the stress away from critically stressed elements.

The method to design the controller will be based on reinforcement learning while using existing knowledge of the system. An actor-critic framework will be adopted to learn the "policy" and the "value" functions. Among other actor-critic methods, Deep Deterministic Policy Gradient [2] will be tested since it is particularly suited for continuous action spaces (i.e., control commands). The structure-control system will be represented through graph neural networks (GNNs) with an appropriate embedding and propagation operator in combination with reinforcement learning [3]. To incorporate knowledge of the structure-control system, graph neural networks (GNNs) will be employed to encode information about the structural layout (e.g., topology, element sizing, etc.) as well as the actuation layout (actuator position). Different propagation operators will be tested to pass messages (such as displacements and forces or actuator states) along the graph elements. For example, using graph spectral theory, a convolution operator can be defined based on the eigendecomposition of the graph Laplacian [4]. The convolution operator will be employed to aggregate information from the graph structure and convert it into a latent vector that can be used for learning. The use of GNNs will enable learning optimal placement (i.e. topology) of actuators, which could then be applied to different structures without retraining saving significant computation time. In addition, the use of GNNs will make the overall framework more interpretable, facilitating the inclusion of additional knowledge.

Supervision, writing, and examination will be carried out in English.

Supervision

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Key requirements

- Bachelor's degree in civil engineering, architecture, SimTech and/or computer science.
- Knowledge of structural mechanics including dynamic analysis.
- Knowledge of (or a strong interest to learn) machine learning.
- Knowledge of (or a strong interest to learn) mathematical and structural optimization.
- Knowledge of (or a strong interest to learn) MATLAB/Python programming language.
- Advanced spoken and written English.

References

[1] G. Senatore, P. Duffour, and P. Winslow, 'Synthesis of minimum energy adaptive structures', *Struct Multidisc Optim*, vol. 60, no. 3, Art. no. 3, 2019.
[2] T. P. Lillicrap *et al.*, 'Continuous control with deep reinforcement learning', no. arXiv:1509.02971, 2019.
[3] C. Kupwiwat, K. Hayashi, and M. Ohsaki, 'Deep deterministic policy gradient and graph convolutional network for bracing direction optimization of grid shells', *Frontiers in Built Environment*, vol. 8, 2022.
[4] J. Zhou *et al.*, 'Graph neural networks: A review of methods and applications', *AI Open*, vol. 1, pp. 57–81, 2020.