Hybrid Modeling of Mechanical Digital Twin by Finite Element Method and Graph Neural Networks

Branch of study: Technical Cybernetic

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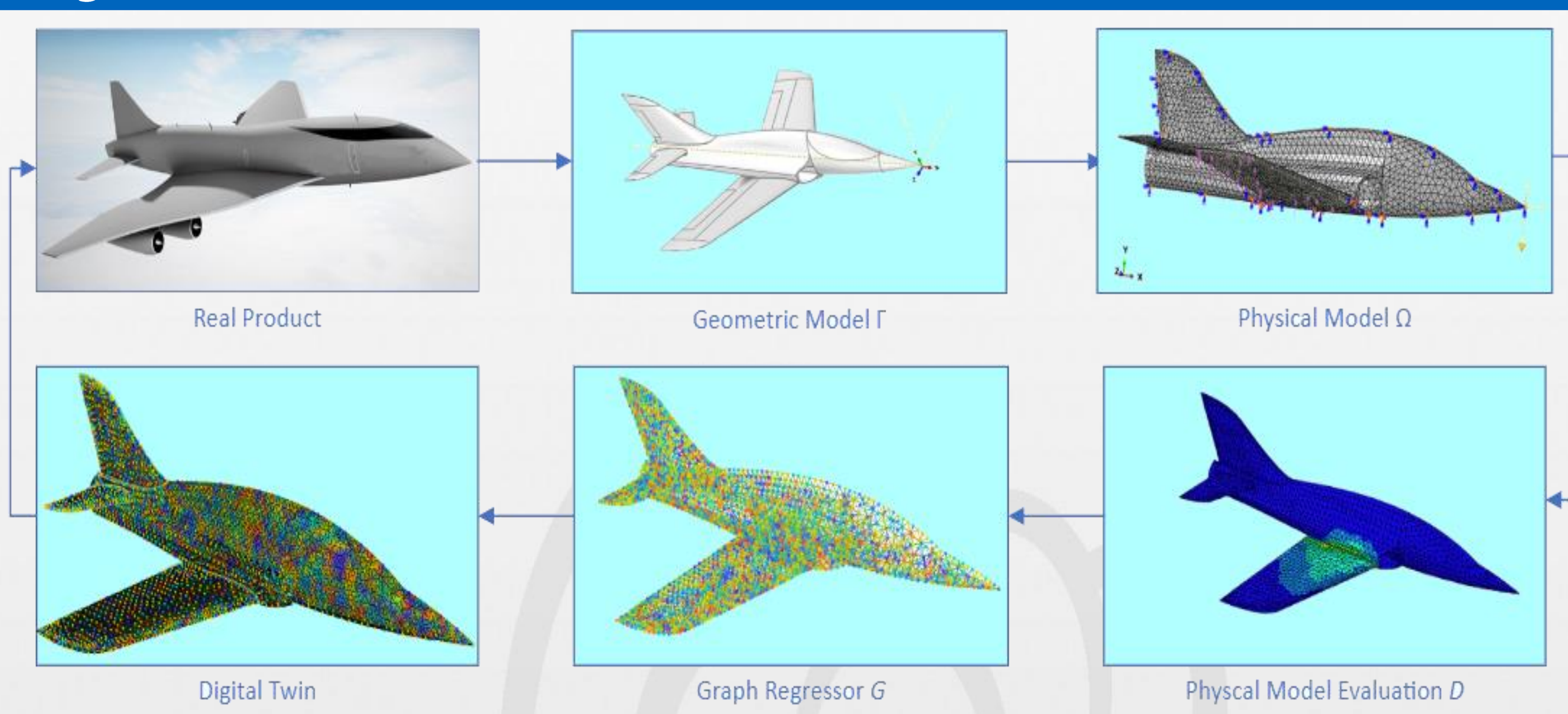
Abstract

This dissertation proposes a hybrid modelling approach for the design of a digital twin of a mechanical structure. The concept integrates the connection of the finite element method and the graph neural network. The advantages of the physical-based method to accurately simulate complex physical and structural behaviour are extended by the possibility of effective data acquisition and, thus, expand the compact understanding of the given mechanical structure. The work's primary goal is to answer whether regressors based on graph neural networks can effectively build a digital twin. Studies supporting this methodology are presented in this work to suggest a perspective on how challenges relate to data acquisition. Designed experiments on the training of a regressor and its validation are addressed to ensure the accuracy and generality of the hybrid model as a whole mechano-digital framework.

Thesis Objectives

1. **Design a methodology to establish a Digital Twin (DT) architecture of a mechanical system by hybrid modelling.**
2. **Extract information from a Finite element model (FEM) for compilation suited for further training of a regressor.**
3. **Train a graph neural network (GNN) regressor optimally so that they can be used to perform regression tasks on nodes of graphs reflecting a physical-based model.**
4. **Define diagnostic tools to evaluate the DT model to avoid false system predictions in the regular operation of the physical asset**

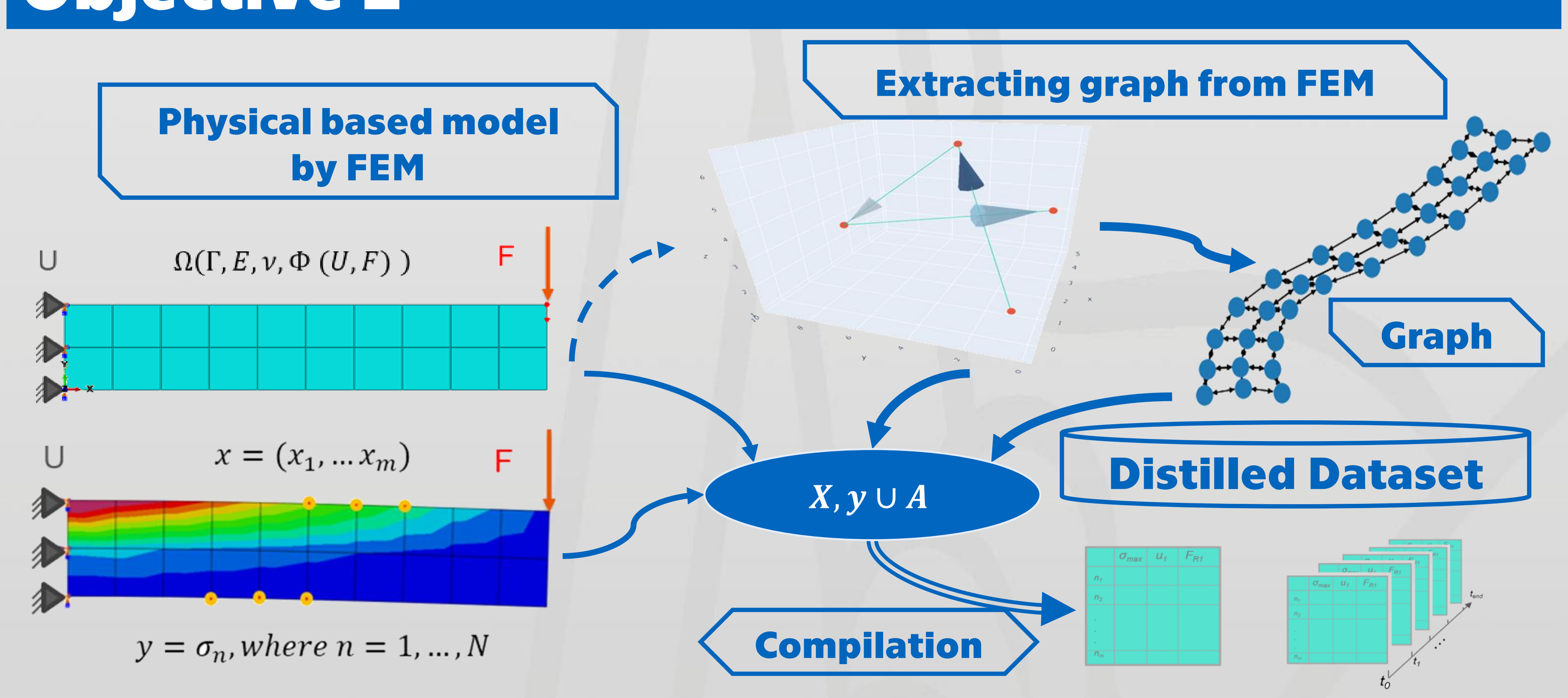
Objective 1



Lifecycle to create Digital Twin Model by Finite Element and Graph methods can be summarized in following steps:

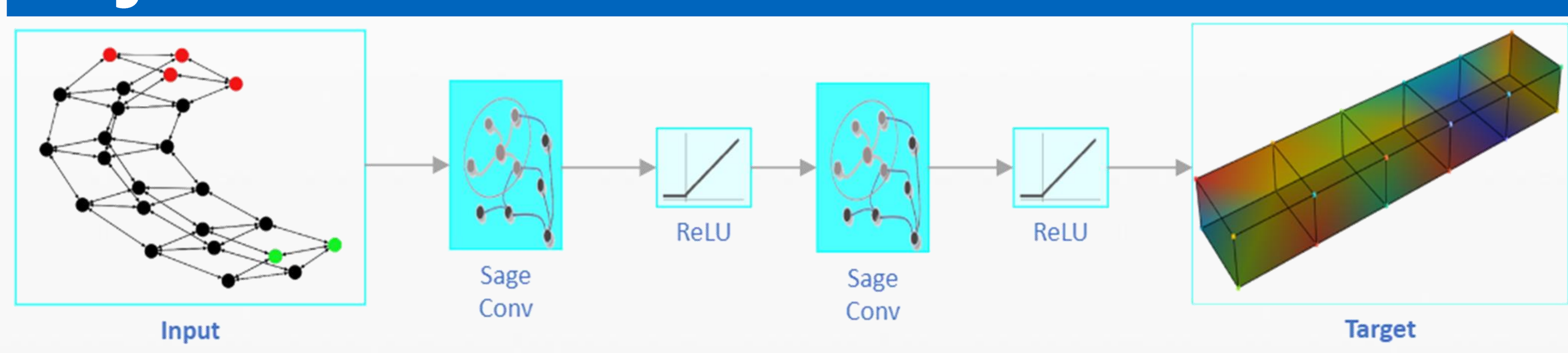
1. **Identify physical phenomena to model and monitor on product**
2. **Define geometrical model to required spatial precision**
3. **Create FEM based on requirements of first and second step**
4. **Extract calculated physical attributes of converged FEM**
5. **Train and validate graph regressor**
6. **Replace FEM by DT based on GNN**
7. **Optimize Graph by reduction of digital twin complexity**

Objective 2



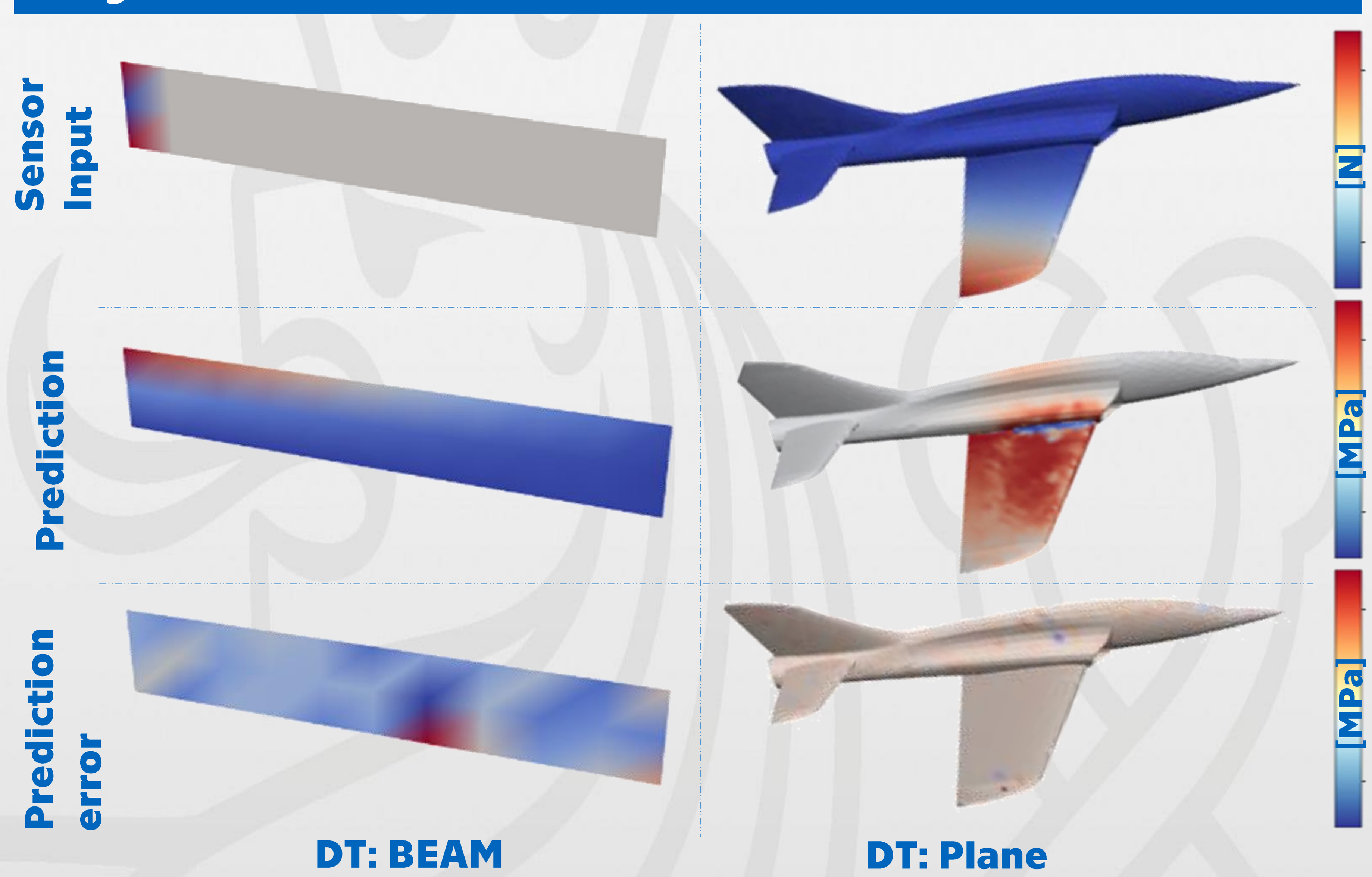
The Finite Element Model, once defined geometrically and spatially, is documented computationally to establish a graph model. This model ensures logical adherence to the original FEM, with nodes acquiring data from the converged FEM. Input parameters X simulate distributed sensors for reaction F at selected node n, while the output y represents structural mechanical stress for all nodes. This approach was introduced in [1].

Objective 3



Various frameworks were suggested, including simpler model frameworks like Multilinear Regression and Feed Forward Neural Networks, alongside GNN-based frameworks. Multiple experiments aimed to accurately estimate model performance, reducing randomness and enhancing understanding. GNN architecture showed superior predictive performance for complex datasets, while simpler models excelled on smaller ones [2, 3].

Objective 4



Various tools were utilized to evaluate DT based on regressors, highlighting the importance of visualization for operators in decision-making. One of many tools is chosen ground truth Visualization on original model geometry for critical assessments.

Conclusion

The proposed methodology dealing with how to design a Digital Twin of Mechanical Structure by hybrid modelling with combination FEM and GNN accomplishes all thesis objectives. It is capable of distilling high-value knowledge regarding mechanical structure for further precise and effective system control responses. The methodology is well-tested on the established datasets.

List of selected author's publications

[1] Ciklamini, "Graph neural network preprocessing for purpose of digital twin of mechanical system," in New Methods and Practices in the Instrumentation Automatic Control and Informatics 2020. Czech Technical University at Prague, Sep. 2020, ISBN ISBN 978-80-01-06776-5

[2] Ciklamini, Gf dataset: Mesh-based graphs dataset for a digital twin of a mechanical systems," in 2023 24th International Conference on Process Control (PC). IEEE, Jun. 2023, doi: 10.1109/pc58330.2023.10217603

[3] M. Ciklamini and M. Cejnek, "Enhancing digital twin accuracy through optimizing graph reduction of finite element models," in Graph Theory-based Approaches for Optimizing Neural Network Architectures. Springer Nature Optimization and Engineering, submitted in Jan 24, in review.

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