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Recurrent neural network-based digital twin of ST40 tokamak dynamics: building system insight into model architecture

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A digital twin for plasma dynamics in a tokamak is useful for optimising and validating experimental scenario proposals, developing plasma control systems and more. Physics-based modelling of the entire tokamak discharge process is challenging due to nonlinear, multi-scale, multi-physics characteristics of the tokamak and demands time from a diverse team of experts as well as computational resources to achieve high-fidelity simulations. Furthermore, simulation-time of physics-based models is prohibitively long for some application types. These challenges invite the use of machine learning (ML) for developing a fast and accurate digital twin. However, a ML-based approach brings its own challenges that need to be addressed –one tends to lose physical intuition about the model behaviour and confidence in its fidelity. This work focuses on building the knowledge of the tokamak sub-systems into the ML-based digital twin architecture as a strategy to a) reduce the risk of unphysical behaviour of the digital twin, b) make surrogate digital twin creation simpler, c) maximise its domain of application and d) define a stepwise process of including more physics into the digital twin. This strategy is to be contrasted with using a single neural net (NN) "black box", such as the one developed for EAST tokamak [1].

A hybrid ML/physics-based digital twin for plasma dynamics in ST40 spherical tokamak [2], employing recurrent neural networks (NN) for time-series prediction is presented. Such NN choice enables simulations with a control system in the feedback loop. Thus far the digital twin incorporates a subset of actuators and measurements that is relevant for the magnetic control. ST40 specifics, such as the merging-compression plasma start-up [3], that guided the choice of the digital twin architecture are discussed.

Representing the ST40 digital twin as a composite model comprised of smaller sub-models proved to be a fruitful strategy, especially for simplifying the development of the digital twin and for increasing the domain of its validity. It is shown that a suitable choice of architecture enables the digital twin to automatically recognise and reproduce plasmaless ST40 operations, plasma startup, plasma flattop dynamics and even some types of disruptions.

The focus on the composite model architecture is complementary to traditional ML approaches that include physics into ML-based models via soft or hard constraints [4], as well as approaches that address fidelity via uncertainty quantification [5]. This project highlights the importance of leveraging the knowledge of the system being modelled into the digital twin architecture and aims to help develop practical strategies and templates.

References:
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