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I. Introduction: Designing a Digital Twin Framework for a Tokamak Reactor

This proposal outlines a project to design a digital twin framework for a tokamak reactor that surpasses conventional simulation approaches. Within an initial two-month design period, we will develop a conceptual framework that integrates sensor data, advanced modelling techniques, and machine learning algorithms. This digital twin will enable dynamic plasma control, predictive safety monitoring, and operational efficiency improvements. Lessons from established applications in aerospace, manufacturing, and energy sectors underscore the transformative potential of this approach. The expected impact includes enhanced reactor safety, and cost reductions in maintenance and operations.

Traditional simulators for tokamak reactors rely on models (e.g., free-boundary plasma-evolution and lumped-circuit equations) that, while computationally efficient, are limited in scope. In contrast, digital twins—data-driven virtual replicas of physical systems that continuously integrate sensor-derived data—have become invaluable in industries ranging from aerospace to nuclear energy, offering unprecedented control and predictive capabilities. Developing Physics models in synch with existing software, I design a digital framework twin that serves as a testbed for future integration in control system models for fusion reactors.

II. Technical Description

Overview of the Digital Twin Architecture

The envisioned digital twin will act as a high-fidelity virtual counterpart of the tokamak reactor. It will involve multiple integrated component that collectively replicate the physical, operational, and control aspects of the reactor.

- **Data Integration:**
  Within the initial two-month design period, we will outline the sensor network infrastructure required to collect real-time operational parameters (voltages, currents, magnetic fields, and temperature, among other parameters). Detailed specifications on the data acquisition systems and communication protocols will be documented based on the sensor network architecture that is available at KFUPM during my internship (content of a separate literature review).

- **Modelling Framework:**
  Building on established plasma-evolution models such as the Grad–Shafranov equation and FGE software packages (Degrave, 2022), our design will incorporate machine learning modules for state estimation and error correction. This phase involves:
  - o Conceptual mapping of the hybrid physics-based and data-driven architecture.
  - o Establishing model interfaces to blend first-principles physics with adaptive machine learning algorithms.

    $$\Delta * \psi = -\mu_0 R^2 \frac{dp}{d\psi} - \frac{1}{2}\frac{dF^2}{d\psi}$$

    Equation 1: Grad Shafranov equation for axisymmetric MHD equilibria (Tonetti 1990) The Grad Shafranov Equation is a cornerstone of magnetohydrodynamic (MHD) used to describe magnetically confined plasma in axisymmetric devices such as tokamaks.

- **Implementation Strategy:**
  The design phase will culminate in a detailed technical blueprint covering:

  1. **System Architecture:** Documentation of data flow from sensors to the digital twin, focusing on how collected data is uploaded,

processed, and incorporated into the simulation environment. Instead of continuous streaming, the architecture supports batch or scheduled uploads, ensuring that the digital twin is regularly updated with the latest available sensor data. Feedback mechanisms integrate these updates into the simulation, aligning the model with recent operational conditions.

2. **Model Integration:** The strategy for integrating existing simulation models with data assimilation techniques and machine learning modules.

Interface Design: Preliminary designs for operator dashboards and interfaces to monitor the digital twin's performance. The digital twin will incorporate a closed-loop system whereby simulation outputs inform control system adjustments. This integration enables dynamic optimization of plasma control and proactive maintenance recommendations.

3. Should the initial design be successful, a subsequent extension phase (beyond the two months) is envisioned to develop and implement the system prototype, followed by testing and expert feedback.

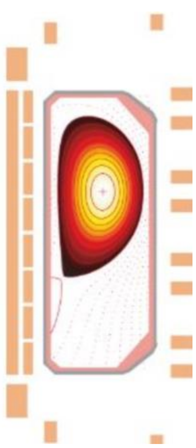

Figure 1: TCV (Tokamak à Configuration Variable) – medium-sized tokamak characterised by a highly elongated, rectangular vacuum.

(Saibene, 2013)

The proposed digital twin will enhance nuclear innovation by serving as a real-time monitoring and control tool for tokamak reactors. Key applications include:

- Enhanced Plasma Control: Dynamic regulation of plasma parameters based on continuous feedback.
- Predictive Safety: Early detection of potential failure modes or plasma instabilities, bolstering reactor safety.
- Operational Optimization: Real-time analysis facilitating maintenance scheduling and improved reactor uptime.

IV. Conclusions

This proposal presents a pragmatic approach to designing a digital twin framework for a tokamak reactor within a two-month timeline. The design phase lays the groundwork for a robust, real-time digital twin system that promises significant advancements in nuclear reactor monitoring, control, and safety. With the potential for extension into prototype implementation and in-field evaluation, this initiative aims to pave the way for the next generation of innovation in nuclear technology.

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