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Development of a Digital Twin Platform for the Lithium-Based Breeder and Reactor Integrated Test Installation (LIBRTI) Project

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Abstract

Significant international efforts are underway to advance fusion technology from scientific demonstration to a practical source of electricity. One of the key challenges is the fuel cycle, in particular the supply of deuterium–tritium fuel. While deuterium is readily obtained from seawater, tritium is scarce in nature and cannot sustain a power plant without on-site production. The accepted strategy is to breed tritium inside the reactor using lithium-based breeding blankets, which generate tritium when exposed to high-energy neutrons from the fusion reaction. Engineers are designing and testing mock-ups of these systems to demonstrate reliable tritium generation, storage, and handling. To support this effort, a new high-power neutron test facility, LIBRTI, is being established to evaluate candidate tritium breeding technologies. Our contribution is to develop a digital twin of LIBRTI, enabling experimental and simulation data to be integrated and used to train AI models that accelerate design and evaluation. We present preliminary work on a low-code digital twin architecture that leverages Nvidia Omniverse and open-source tools. As a proof of concept, we demonstrate a prototype digital twin of a gas-driven permeation system. This work will interest the fusion community and engineers engaged in hydrogen technologies.

Keywords: fusion energy, tritium breeding, lithium blanket, hydrogen permeation, digital twin, artificial intelligence, experimental facility, low code architecture, simulation, hydrogen economy.

1 Introduction

One of the leading contenders for a first-of-a-kind fusion power plant involves a device that heats a plasma to more than 100 million Kelvin inside a vacuum vessel, forcing the nuclei of hydrogen atoms to fuse. This reaction releases high-energy neutrons, heat, and helium as a by-product. Because the melting points of engineering materials are only in the range of a few thousand Kelvin, the plasma must be kept away from the vessel walls by powerful magnetic fields.

Hydrogen exists in three isotopic forms: protium, deuterium, and tritium. The nuclei of these isotopes contain zero, one, and two neutrons respectively. Although it is theoretically possible to fuse any atom with any other atom, the reaction rate is much higher for light elements such as hydrogen. A mixture of deuterium and tritium has proven to be the most suitable fuel for magnetically confined fusion [1,2], while other isotope combinations are much harder to fuse.

Deuterium is readily available in seawater, where roughly one in every 5000 hydrogen atoms is deuterium. Tritium, by contrast, is radioactive with a half-life of about 12 years and is therefore extremely scarce in nature. Small amounts are produced naturally by cosmic ray interactions in the upper atmosphere, and it can also be generated in human-made systems such as nuclear fission reactors or particle accelerators.

For nuclear fusion to be viable as an energy source, the nascent fusion industry needs a reliable source of tritium fuel. The proposed solution is to generate the fuel directly in the power plant itself. Neutrons released by the deuterium–tritium reaction pass through the reactor structures, depositing heat and interacting with surrounding materials. Engineers are designing a subsystem, that sits between the plasma and the outer shielding. The subsystem comprises components and materials such as lithium that capture neutrons and generate tritium. There are various designs under review that are colloquially referred to as breeder blankets, which line the inside of the pressure vessel like a blanket [3,4].

The design of such blankets cannot rely on a simple design-test-build cycle, since no existing facility can yet reproduce the extreme neutron environment of an operational fusion power plant. Instead, experimental campaigns must be complemented by computer modelling [5] and machine learning [6]. Under the LIBRTI (Lithium Breeding Tritium Innovation) programme, the United Kingdom has invested heavily in establishing a new high-power neutron test facility dedicated to breeder blanket concepts. As part of this effort, the authors are developing a digital twin platform for LIBRTI. The first step is a prototype: a digital twin of a simpler device, a gas-driven permeation system, which serves as a proof-of-concept for the development of the digital twin platform.

2 Methods

Gas-driven Permeation System

In this section, the authors describe the gas-driven permeation system (GDPS), shown in Figure 1, and the development of the digital twin, paying special attention to the various components of the digital twin platform. In this work, a digital twin is defined as a dynamic virtual representation of a physical system that is continuously updated using real-time or near-real-time data and is used to simulate, monitor, and optimize that system [7].

Figure 1: Gas-driven permeation system (left) and sample holder (right).

The GDPS is a self-contained experimental facility that can be hosted in a standard university laboratory equipped to safely handle small volumes of protium and deuterium. It is used to obtain values of the coefficient of permeability of a gas through different materials. A disc-shaped sample, approximately twenty millimetres in diameter and a few millimetres thick, is clamped into the device between two heating elements collectively referred to as the furnace or heating stage. The selected gas is pumped under pressure through tubing that runs through the furnace to the sample. A mass spectrometer is positioned downstream of the sample and is used to measure the type and amount of gas that has permeated through the material.

In the present (very typical) laboratory setting, a standard Windows PC is connected to the experimental system. A number of different proprietary software packages supplied by the vendor of the GDPS are used to set up, run, and monitor the experiment. These tools also collect and process the results. In a standard GDPS experiment, the laboratory technician loads a material sample, sets the target furnace temperature and inlet gas pressure. The supplied software is then used to control the experiment and record results across a defined range of conditions. Connecting an instance of the digital twin infrastructure is relatively straightforward due to the limited number of sensors, actuators, and control streams. That said, some work is required to bypass or interface with the proprietary software to access sensor and control data streams directly via hardware or software interfaces.

There are several motivations for building a digital twin of the GDPS. Firstly, the vendor has supplied a turn-key solution that reinforces the tendency for data access to be limited to those with physical access to the experimental facility. Data is siloed, recorded locally on the on-site PC within proprietary software, and human intervention is typically required to retrieve it. A digital twin aims to make data accessible to authorised users, including AI agents. Secondly, integration with other components of a broader digital twin ecosystem enables design of experiments, automation of experimental campaigns, and AI-driven control of the system. Thirdly, this simple platform provides an ideal testbed for building a minimum viable product—a prototype for a new digital twin architecture that supports the fusion of data from multiple sources. In addition to permeability data, the material samples will be studied using other characterisation techniques such as microscopy and tomography. The ultimate test of the platform will be its scale-up for the LIBRTI facility.

Digital twin platform

The digital twin platform for the GDPS is designed to mirror the physical experiment as closely as possible while enabling remote access, monitoring, and control.

A central server hosts most of the digital twin architecture, collating, storing and assessing data to provide command and control to simulations and experiments. In the laboratory, server commands are translated into hardware instructions and telemetry data is streamed to the server. The on-site computer for the system is a Raspberry Pi, which runs lightweight containers of firmware for portability and ease of deployment. The firmware can run on a variety of systems, including microcontrollers, enabling a per-sensor deployment in larger systems. On the GDPS system, these sensors include pressure transducers located upstream and downstream of the sample, a mass flow sensor to regulate the gas flow rate, thermocouples positioned at three points on the Carbolite furnace, and a mass spectrometer for detecting permeated gases. The digital twin architecture uses MQTT (Message Queuing Telemetry Transport), a lightweight messaging protocol used to transmit and receive data between all the elements of the digital twin; allowing easy extension of the distributed architecture.

The Comodo controller on the remote server provides both a command-line API via MQTT messages and a browser-accessible graphical user interface. These interfaces enable users to configure experimental parameters and initiate experiments remotely.

On the server side, a standard open-source software stack is used to handle telemetry data. An external application called Telegraf listens for MQTT messages, including time series data from all sensors, and writes this information into a high-performance time series database known as InfluxDB. The experimental data stored in InfluxDB can then be visualised using Grafana, a web-based dashboard tool that enables users to monitor live experiments or review past runs through interactive graphs.

The geometric representation of the system is created using a custom application developed with the Nvidia Omniverse SDK. This digital model serves not only as a visualisation environment but also as an interactive control interface. Scripts implemented using the SDK allow seamless access to data stored in InfluxDB, enabling real-time interaction between the virtual twin and the physical experiment. The Omniverse application may also serve as a user entry point for setting up and launching experiments, offering a unified environment for both control and visualisation. A high level overview of the architecture is shown in Figure 2.

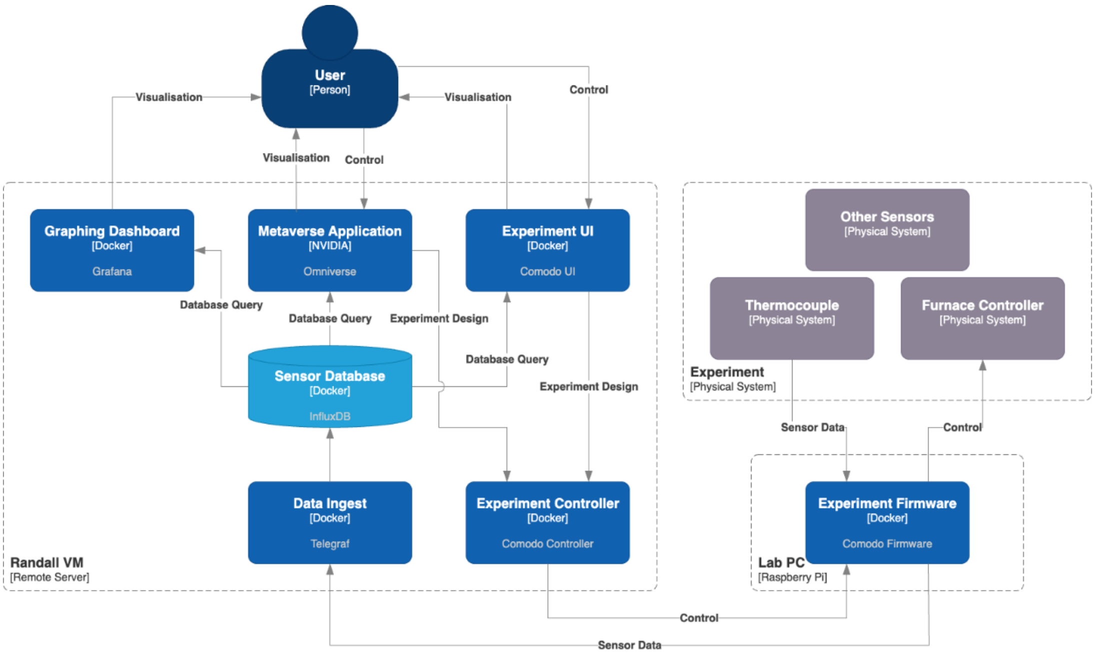

Figure 2: Overview of the digital twin platform.

To enhance the utility of the digital twin, physics-based modelling capabilities are being integrated using the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework. Additionally, Galaxy workflows are employed to automate data processing tasks. Together, these tools allow point-wise sensor data to be transformed into full-field model predictions that are continuously fitted to the experimental results, enabling predictive simulation and deeper insight into the physical processes governing gas permeation.

Digital twin extensions

In addition to the live command and control features of the digital twin platform, many other services have been integrated. Because the system uses MQTT messages to control operations and enable communication between components, it is straightforward to expand and add services that can subscribe to and publish specific message streams. As a result, we have developed and incorporated a system called Randall. This automated provenance capture system utilises knowledge graphs and RO-Crates to help experimentalists review experimental campaigns more easily and promote better data sharing and accessibility, aligning with the FAIR data principles. This data can also be used to check experimental requirements against current values to ensure experimental safety, and log who did what, where, and when, ensuring accountability and traceability.

3 Results

Digital Twin Geometry

The authors received a 2D technical drawing from the GDPS hardware vendor. This provided the dimensions and other details required to produce a 3D CAD geometry. The geometry was converted into Universal Scene Description (USD) format for display in Nvidia's Omniverse platform. USD is a file format and framework for describing, composing, simulating, and collaborating on 3D scenes. It is an open-source, extensible ecosystem developed by Pixar, and is becoming a standard for 3D visual media production and other industries. Material textures from the Omniverse built-in library were applied before rendering the scene shown in Figure 3.

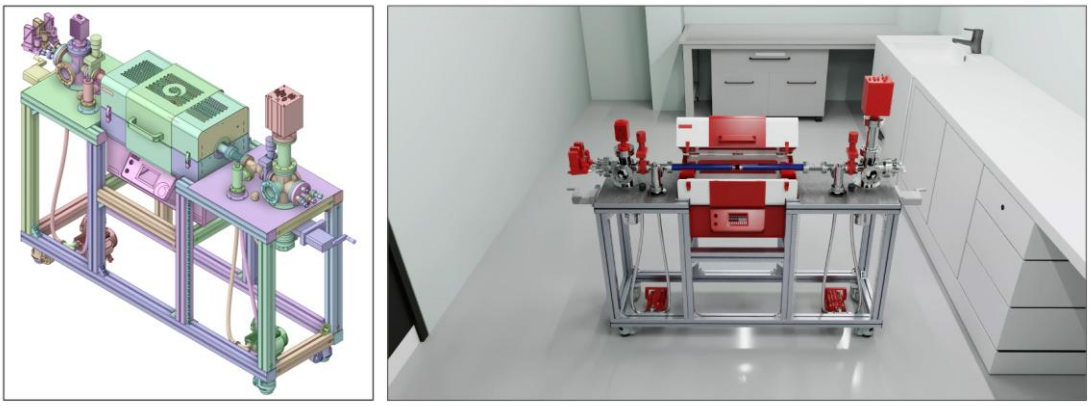

Figure 3: CAD geometry of the GDPS (left) rendered in Nvidia Omniverse (right).

The Omniverse supports physics engines and rigid body mechanics. These were applied to the scene so that the end user could perform actions such as opening and closing the furnace lid. The USD scene can also be configured as a high-level interactive user interface to display sensor data, experimental data and simulation results, for example as in Figure 4.

Several web browser-based user interfaces have been implemented. Figure 5 shows an example that allows the end user to design, configure and launch experimental campaigns. The authors have also implemented graphing tools for results visualisations. The common thread is that the software tools and stored data are distributed, allowing a verified end user to retrieve and interrogate results from any location. It is not necessary to be physically in the laboratory.

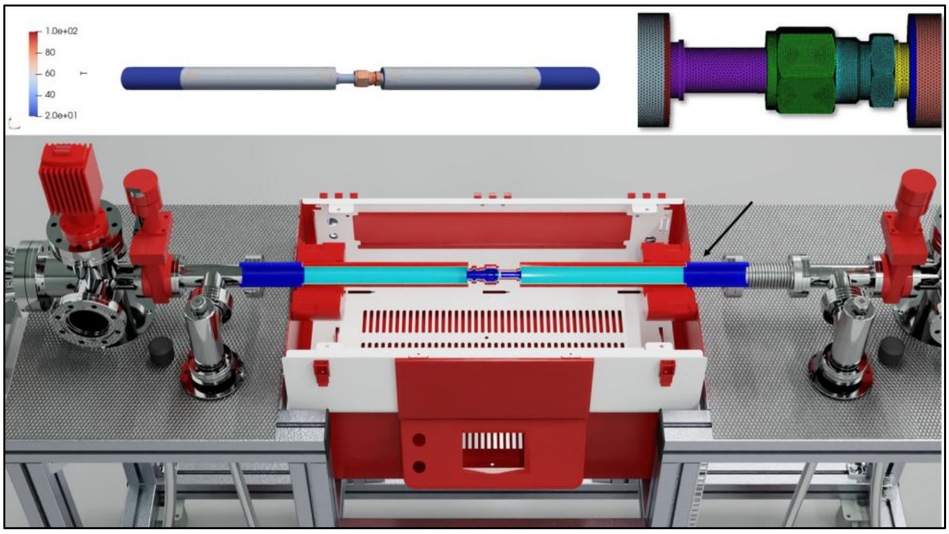

Figure 4: Display of finite element results in the Nvidia Omniverse.

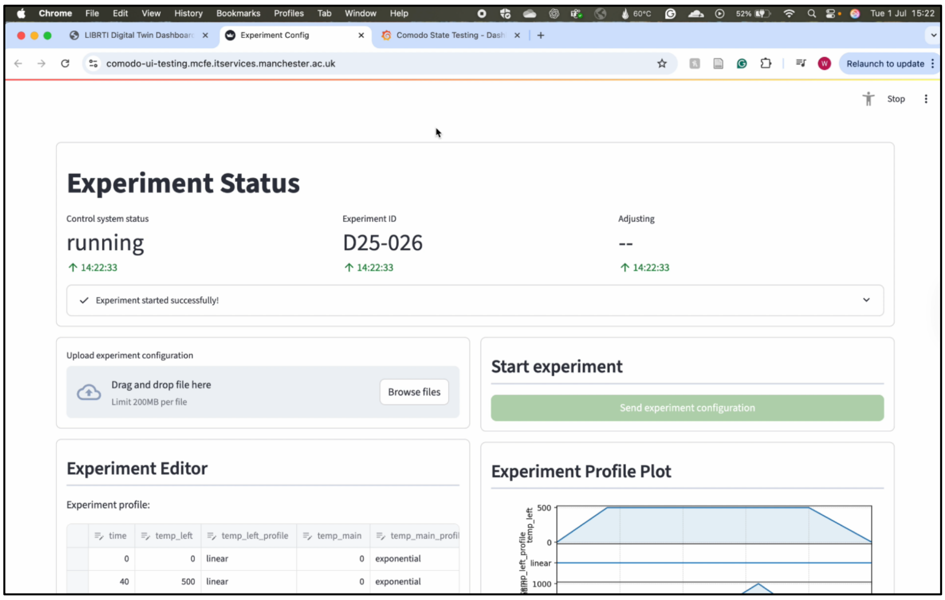

Figure 5: Web-based dashboards.

4 Conclusions and Contributions

This work presents the development of a prototype digital twin for a gas-driven permeation system, serving as a foundational step towards a full-scale implementation for the LIBRTI high-power neutron test facility. The prototype demonstrates how distributed sensing, open-source data infrastructure, and advanced visualisation through Nvidia Omniverse can be integrated into a low-code, remotely accessible platform. By incorporating real-time telemetry, automated workflows, and physics-based modelling, the system enables continuous synchronisation between physical experiments and predictive simulations. The approach enhances data accessibility, facilitates AI-driven experiment design, and provides a scalable architecture adaptable to other fusion-relevant testbeds. Beyond technical implementation, the platform supports FAIR data principles, improving traceability and collaboration across geographically distributed teams. The results indicate that digital twin methodologies can accelerate design cycles and de-risk large-scale fusion infrastructure projects, positioning LIBRTI as a leading facility for breeder blanket and tritium cycle R&D.

Acknowledgements

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