# Digital Twin for a Multi-Input Multi-Output (MIMO) Process System With Fault Detection Capability

2023 UTK Student Faculty Research Awards

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# 1 Research Narrative

## 1.1 Overview

A Digital Twin (DT) is a virtual model built to accurately reflect a physical system that is coupled to an operating system through data transfer. A DT can be used as an indistinguishable digital counterpart to simulate, integration test, monitor, and enable predictive maintenance for a real system. Although DTs are heavily marketed, there are few actual demonstrations of DTs even for the simplest processes. DTs are proposed across various industries, and are currently the hot-topic in the world of nuclear reactor instrumentation and controls (I&C) for their anticipated benefits including: increased operational efficiencies, enhanced safety and reliability, reduced errors, faster information sharing, and better predictions [1]. In relation to the student PI's current research, and industry interest, the aforementioned benefits can help support the US nuclear energy industry, provide carbon free energy to grid as economically as possible.

## 1.2 Testbed Description

This work proposes to build a DT for a Multi-Input Multi-Output (MIMO) process system. A textbook MIMO process is the coupled two-tank problem. Maintaining constant fluid levels in a tank is a common process control problem. The coupling of the two tanks creates a complex nonlinear system which is difficult to control with traditional methodologies such as a proportional-integral-derivative (PID) controller, which calculates a response using simple arithmetic and "hard-coded" parameters. Using a DT to control this system will provide generalized controls, when compared to a PID controlled system. Any field of study which deals with nonlinear processes are to gain from this type of demonstration.

The project will build a simple two-tank experiment with level measurement, controls, and pumps for circulating new fluid as shown in Figure 1. The system will have a connecting pipe to introduce the nonlinear coupling to the system. A DT will be built and implemented using the Modelica modeling language. This DT will be fully integrated into the two-tank physical system through an Internet of Things (IoT) based architecture, driven by an Nvidia Jetson edge computer. The Nvidia Jetson will receive inputs from the testbed, as well as calculate and send the signal to control the system. Following the construction of the MIMO system and integration with a DT, research will continue into the space of online monitoring and fault detection, fault-tolerant and predictive control, prognostics and health management, and cybersecurity.

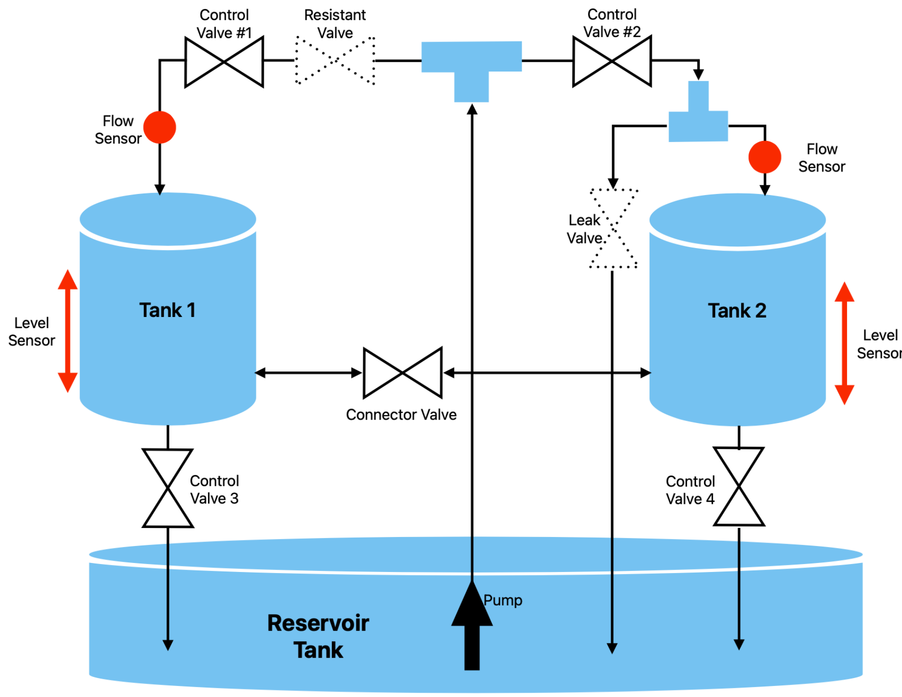


Figure 1: Schematic of Two-Tank Experiment.

Two fault modes have been added into the design to allow for non-invasive representation of component failures. A tee-connected and manual valve have been added to manually divert water directly back into the reservoir, resembling a ”leaking valve”. The second fault mode is a simulated pump degradation, which is manually induced with the ”resistance valve”. We hope to identify these faults in real time and design a control system that is capable of compensating for the leak and sluggish pump to maintain the water level at the setpoint. In practice, at a commercial nuclear power plant, identifying and classifying faults can help improve safety and economics.

The Nvidia Jetson hardware will allow complete integration of the measurement and control devices of the two-tank system, as well as the DT. This MIMO system utilizes the same computational methodologies as the Oak Ridge National Laboratory (ORNL) Nuclear Thermal Propulsion (NTP) mock reactor. Benefits will flow between ORNL and UT, as ORNL can provide assistance and expertise setting up the IoT, and UT will prove the benefits and limitations of DT in a complex nonlinear system. By having both the NTP mock reactor and the two-tank system, preliminary I&C/DT/online-monitoring developments can be implemented at UT before being translated to ORNL's system and ultimately to fielded systems.

### 1.3 Available Resources & Feasibility

At the current state, a significant amount of resources and knowledge are available to allow this facility to be successfully built and operated. First, there already exists a Modelica model of the two-tank problem (Figure 2), which would only need to be adapted to the specific parameters of our system and altered to act in accordance with the physical system. Secondly, there is expertise available for the integration of the physical components with the IoT. The student PI has experience in this regard with the NTP mock reactor [2] from a summer internship, and online resources are readily available online due to the open source nature of the IoT components. Third, a framework has already been developed for fault detection by the student PI [3]. The two-tank experiment could validate these methods, as well as test the effectiveness of fault detection using the DT. Third, there is sufficient space to house the facility in the faculty PI's Zeanah Engineering Complex laboratory space. Lastly, a significant amount of resources are currently available for use in this project. Four-motor operated valves (MOVs) and a submersible pump are available from previous testbeds and can be used for this facility. These components make the testbed economically feasible. Further, if awarded this $5,000, Dr. Coble will be able to supplement additional costs from her RIF to complete the proposed testbed.

### 1.4 Conclusion

This project presents a compelling opportunity to harness the potential of DTs for controlling nonlinear systems and detecting faults. By building a DT for the MIMO process system, this research endeavor aims to achieve several significant outcomes. These include enhanced

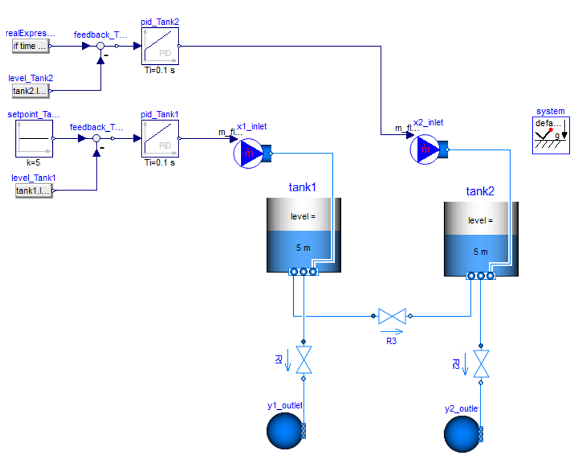


Figure 2: Modelica model of two-tank problem.

process control, real-time fault detection, fault-tolerant control strategies, and insights into predictive maintenance. The expected outcomes of this proposal align perfectly with the current industrial demand for increased operational efficiency, safety, and reliability. This project not only offers a gateway to transformative technology but also positions us as pioneers in the application of DTs to real-world, nonlinear systems, fostering innovation and advancements that will have a profound and lasting impact on multiple industries.

# 2 Impact on the Professional Development of the Student PI

There is a shortage of nuclear engineering graduates with instrumentation and control (I&C) experience. The next generation of advanced nuclear reactors are relying on more automatic and autonomous control systems. David was able to find his interests in this area of research during his summer internship at ORNL. He has since met with industry workers that are very interested in hiring students with I&C expertise, especially with nuclear specific knowledge. This project will allow for David to gain hands-on experience in building a complete digital twin of a system comparable to what will be found in all advanced reactor operations. The ability to integrate the interdisciplinary expertise into a fully functioning DT will provide David with a new skill set that currently is too new to have active academic training programs. More importantly, this work will allow for David to pay forward the knowledge gained to other students and to demonstrate a digital framework for building DTs of any laboratory experiment at UTK.

# 3 Relevance to the Faculty's Expertise and Research Agenda

This research is directly related to Dr. Coble's expertise and research agenda. She has an active research program applying data analytics and machine learning for robust and integrated decision making in nuclear power systems. She has previously worked with researchers at GE-Research and GE-Hitachi to develop DT technologies for monitoring and maintenance scheduling in the BWRX-300 reactor design, a design that is conceptual and has not been built. In this work, the DT technology could not be validated in an operational system.The proposed two-tank loop would support demonstration of DT technologies in a well-understood, but still complex system. It would also support future research endeavours, including online monitoring, equipment condition assessment and prognostics, advanced control systems, and cybersecurity. A completed testbed with an associated DT model would support not only Mr. Anderson's research, but the research of many future students in the nuclear engineering, energy science and engineering, and data science and engineering programs. Dr. Coble has an active research group with funded research from DOE-NE, NSF, and Y-12 security complex. These funded projects focus on applications of data analytics and machine learning for degradation detection, classification, prognostics, and controls. None of her currently funded research is investigating the development and demonstration of digital twins. The proposed two-tank system would provide a complementary capability to the largely simulation-based research her team is currently performing.

# 4 Itemized Budget

| NAME | NUM. | PRICE | TOTAL PRICE | LINK |
|---|---|---|---|---|
| Cylindrical Open Top Tank | 2 | \$125 | \$250 | *US PLASTIC CORP* |
| Open Top Reservoir Tank | 1 | \$450 | \$450 | *US PLASTIC CORP* |
| Motor Operated Valve | 1 | \$550 | \$550 | *GRAINGER* |
| Level Transmitters | 2 | \$500 | \$1,000 | *GRAINGER* |
| Mass Flow Sensor | 2 | \$220 | \$440 | *GRAINGER* |
| Manual Valves | 3 | \$20 | \$60 | *HOME DEPOT* |
| Nvidia Jetson | 1 | \$150 | \$150 | *AMAZON* |
| Framing | 1 | \$1,000 | \$1,000 | ESTIMATION |
| Piping and Fittings | 1 | \$300 | \$300 | ESTIMATION |
| I&C Components | 1 | \$800 | \$800 | ESTIMATION |
| | | Total Cost: | \$5,000 | |

Table 1: Itemized budget for construction of two-tank system.

# 5 Projected Timeline

Following the acceptance of this grant, the procurement process can begin and parts can get ordered to the Zeanah Engineering Complex (ZEC), where the two-tank system will be constructed and operated in ZEC G104. Procurement of components will being with a finalization of components sizes and layout, allowing for the ordering of framing, piping, and all the components. Upon completion of construction, there will not be any additional costs unless additional features are desired by the PI or the student PI for a different project.

The full timeline is shown in Table 2. The student PI anticipates completing his M.S. degree in December, 2024 and availability of this facility would significantly improve the outcomes of his thesis research.

| TIME SPAN | ACTIVITIES |
|---|---|
| Now - End of Year | Procurement and development of Modelica model. |
| Janurary - February 2024 | System assembly. Connecting IoT. |
| March - April 2024 | Initial demonstration of DT. |
| May 2024 - Summer 2024 | Assessment of fault detection using existing systems. |
| Following Summer 2024 | Fault detection utilizing DT. Further experimentation. |

Table 2: Project timeline.

# References


[1] U.S. Nuclear Regulatory Commission. "The State of Technology of Application of Digital Twins". In: (2021). URL: https://www.nrc.gov/docs/ML2116/ML21160A074.pdf.

[2] David Anderson and Wesley Williams. "Flexible Instrumentation and Control Testbed for Nuclear Thermal Propulsion and Microreactor Systems". In: 2023 IEEE Aerospace Conference. 2023.

[3] David Anderson and Jamie Coble. "Implementing Component Degradations Into a Modelica Model of an iPWR System to Develop Health Monitoring Techniques". In: 13th Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies (NPIC&HMIT 2023). 2023.