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Digital Shadow-Based Detection of Blockage Formation in Water-Cooled Electronics

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What is a Digital Shadow vs a Digital Model vs a Digital Twin?

Digital Model:

- No data transfer.
- Passive reflection of the physical system [PS].

Digital Shadow:

- Unidirectional data transfer.
- Cannot directly affect PS.

Digital Twin:

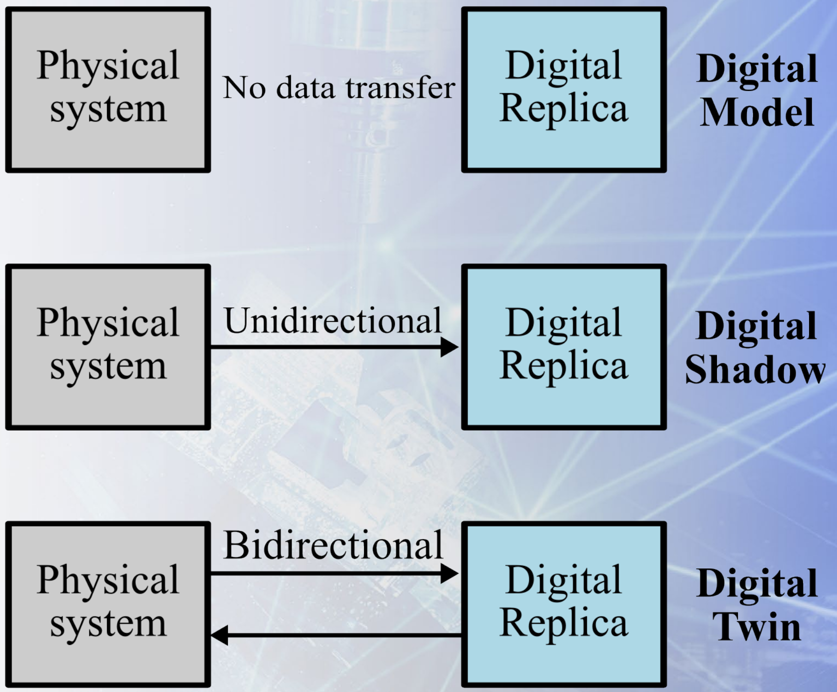
- Closed loop decision making.
- Bi-directional data transfer between models.
- Able to directly affect PS.

Data Transfer:

- Data transfer depends on if online or offline

Offline vs Online:

- Offline = no real time data transfer = .



K. Sado, J. Peskar, A. R. J. Downey, H. L. Ginn, R. Dougal and K. Booth, "Query-and-Response Digital Twin Framework using a Multi-domain, Multi-function Image Folio," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2024.3425276.

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Digital Shadow Integration

Physical Twin:

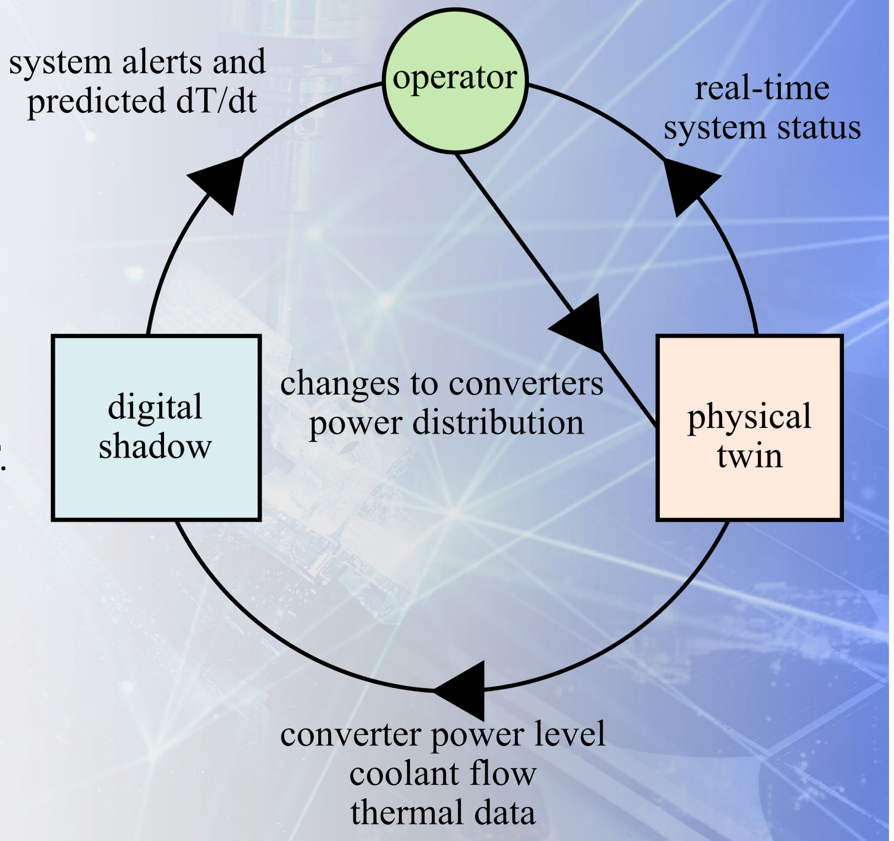
- Real world system.
- Experiments take place on.
- Provides information to digital shadow [DS].

Digital Shadow:

- Digital representation of physical twin [PT].
- Calibrated off data from PT.
- Replicates conditions and aspects of PT.
- Provides a digital testbed for experiments that cannot be done to PT.
- Provides operator with system health projections.

Operator:

- Provides initialization data to PT and DS.
- Receives health projections from DS.
- Observes current PT condition.
- Changes PT conditions based on information from DS.
- "Human in the loop"



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Why Is Blockage Detection Important?

Blockage Formation Effect on Systems:

- Blockages in systems can lead to:
  - ➢ Underperformance of systems
  - ➢ Overheating issues
  - ➢ Overall degradation of component`s health and capability

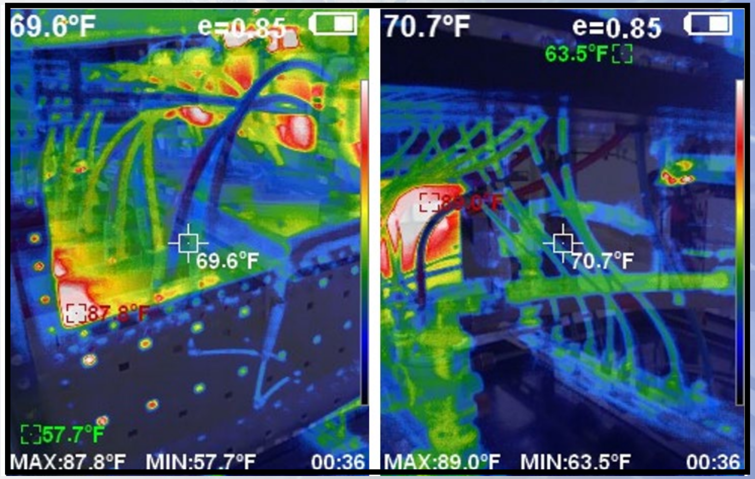
Effect of Blockage Formation:

- If left unchecked, issues can quickly result in potential system failure.
- System failures :
  - ➢ Crew habitation and comfort [e.g., HVAC]
  - ➢ Reduced engine power or engine failure resulting from fuel line or coolant line blockage.
  - ➢ Power electronics [e.g., radar array] failure resulting from coolant line blockage.

Preventive Maintenance:

- Vital that blockages are detected and dealt with before they become critical.

DDG 51 Arleigh Burke class destroyer. Military.com. (n.d.). https://www.military.com/equipment/ddg-51-arleigh-burke-class-destroyer



Method of Blockage detection

MATLAB

How:

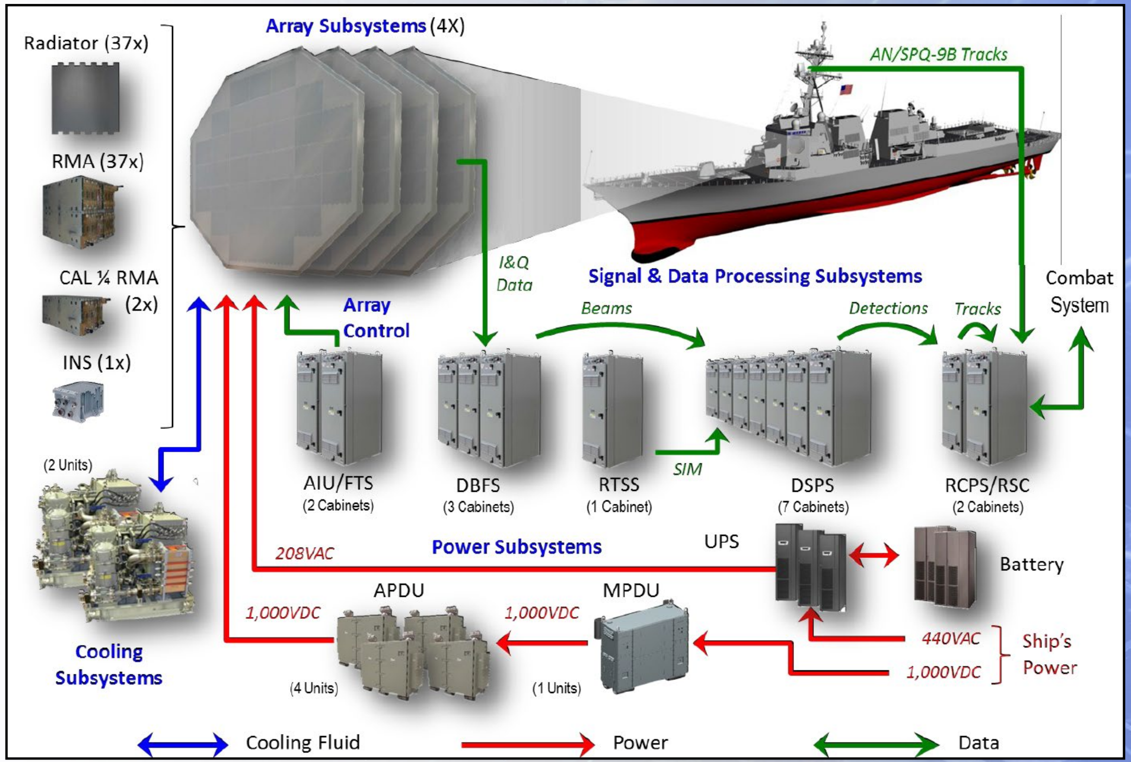
- Implement digital shadow onto real word physical system in conjunction with a digital model.
- Blockage detection and thermal prediction accomplished through use of digital shadow system.
- Digital model designed using MATLAB Simscape.
- Use of offline ‘batch’ data from physical system feed into digital shadow.

Offline Data Transfer:

- Offline = ‘batch’ data transfer.

Result:

- Effective emulation of physical system in digital environment where blockage detection.



Ryan White, By, & White, R. (2021, February 25). *Report to U.S.Congress on U.S. Navy DDG-51 and DDG-1000 destroyers*. Naval Post- Naval News and Information. https://navalpost.com/report-to-congress-on-ddg-51-ddg1000-usnavy/

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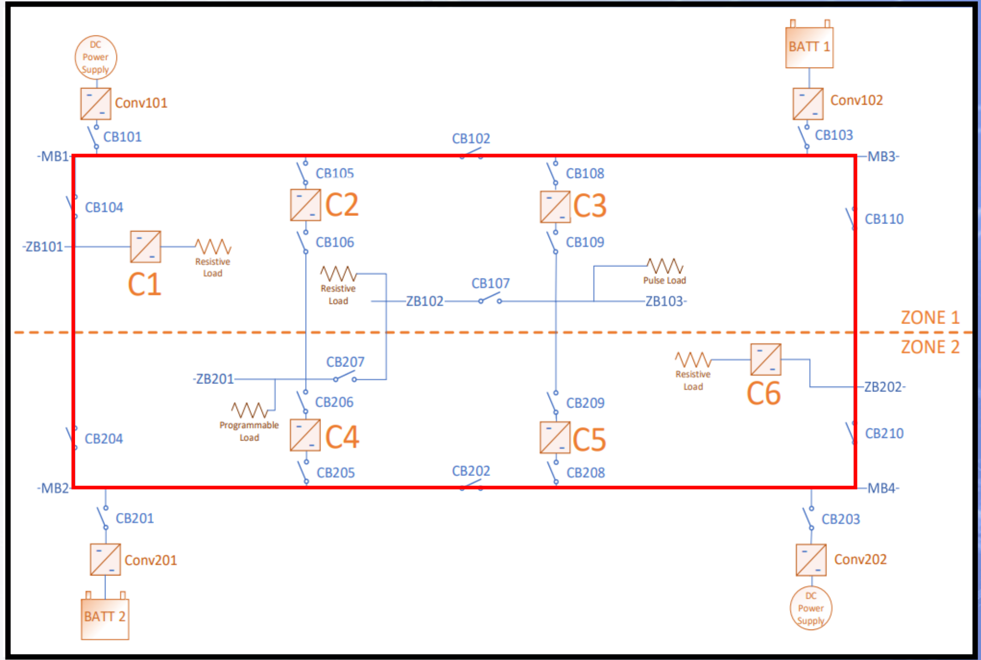
Electrical Network for SCEPTER lab Testbed

Power Converters:

- Set of Six.
- Receives power from generator and batteries.
- Act as “Buck” and “Boost” DC power transformers.
- Boost converters supply power to major systems.
- Buck converters supply power to minor systems.
- Work in conjunction with other electrical system to create a microgrid emulator of ship`s systems.
- Examples: propulsion, energy weapons, radar, etc.

Waste Heat:

- Produces waste heat due during operation.
- Water cooled for higher cooling capacity vs air.
- Example input electrical power: 2kW.
- Example efficiency ~95%
- Waste heat production: 190 W.



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Physical Testbed Overview

Assembly:

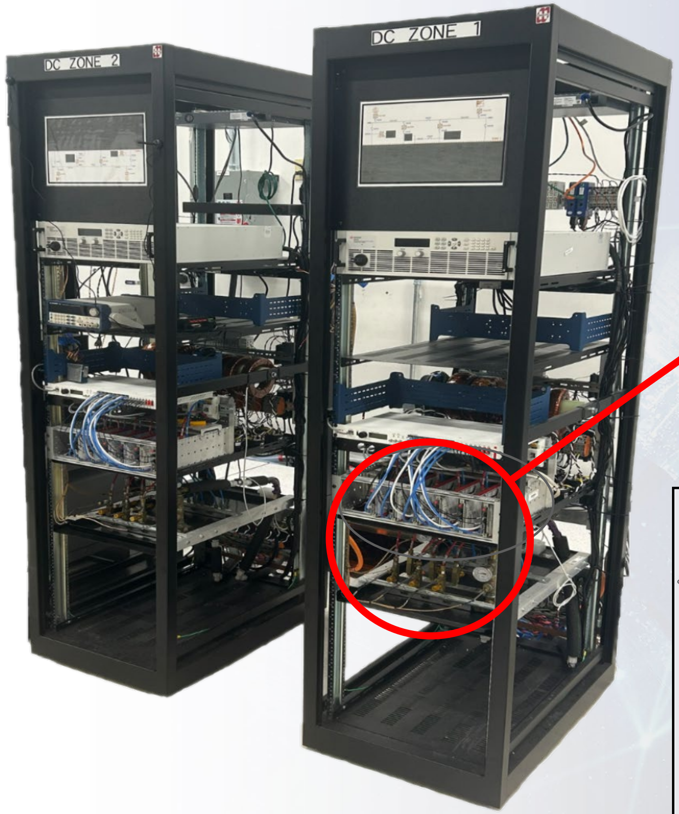
- Power converters.
- Coolant distribution manifolds.
- Temperature sensors.
- Flow gauges.
- Balancing valves.

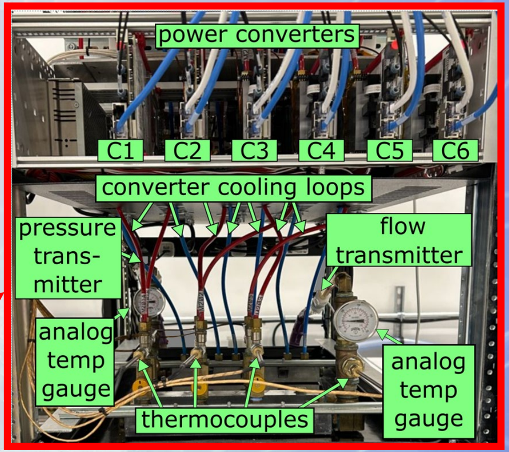
Sensors:

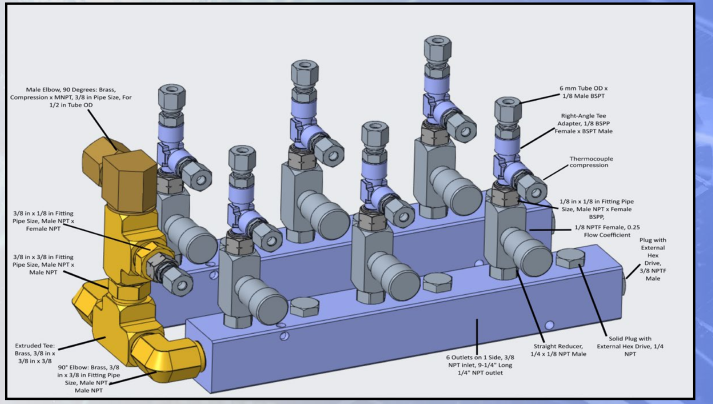
- Set of eight thermocouples:
  - Seven on return.
  - One on send.
- Records the change in temperature of coolant..

Flow Control:

- One proportional needle valve for each converter.
- Allows for flow balancing.
- Can perform experiments on individual converters.







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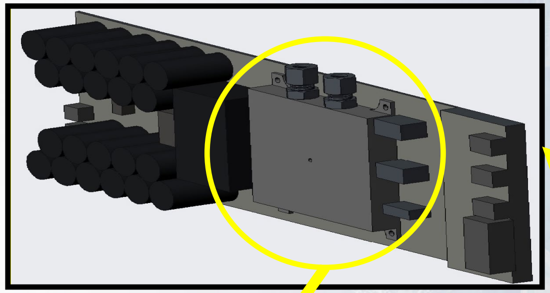
Power Converter Cooling Diagram

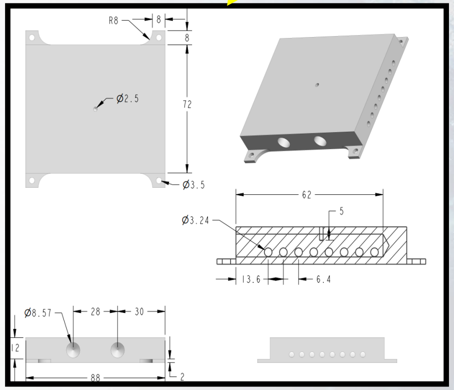
Thermal Loop:

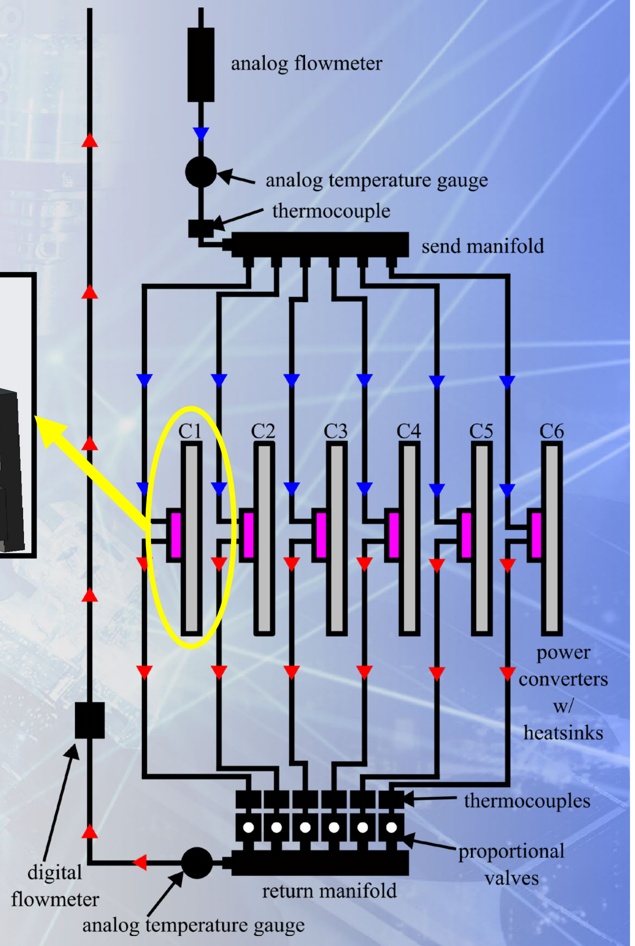
- Coolant moves through each loop for each converter, absorbing heat generated by semiconductor switching devices.
- Typical losses ~ 150 W per converter operating at full capacity.

Overheating of Power Converter:

- Safe operating temperature for power converters: up to 80°C (measured at heatsink).
- Automatic shutdown occurs if temperature exceeds 80°C.
- Operating above 80°C can damage the power converter and reduce its lifespan.
- Serious damage to the power converter and overall system may occur if overheating continues.







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Digital Shadow Simulation

Purpose:

- The digital shadow identifies blockages early to mitigate risks of downtime or damage.

Detection:

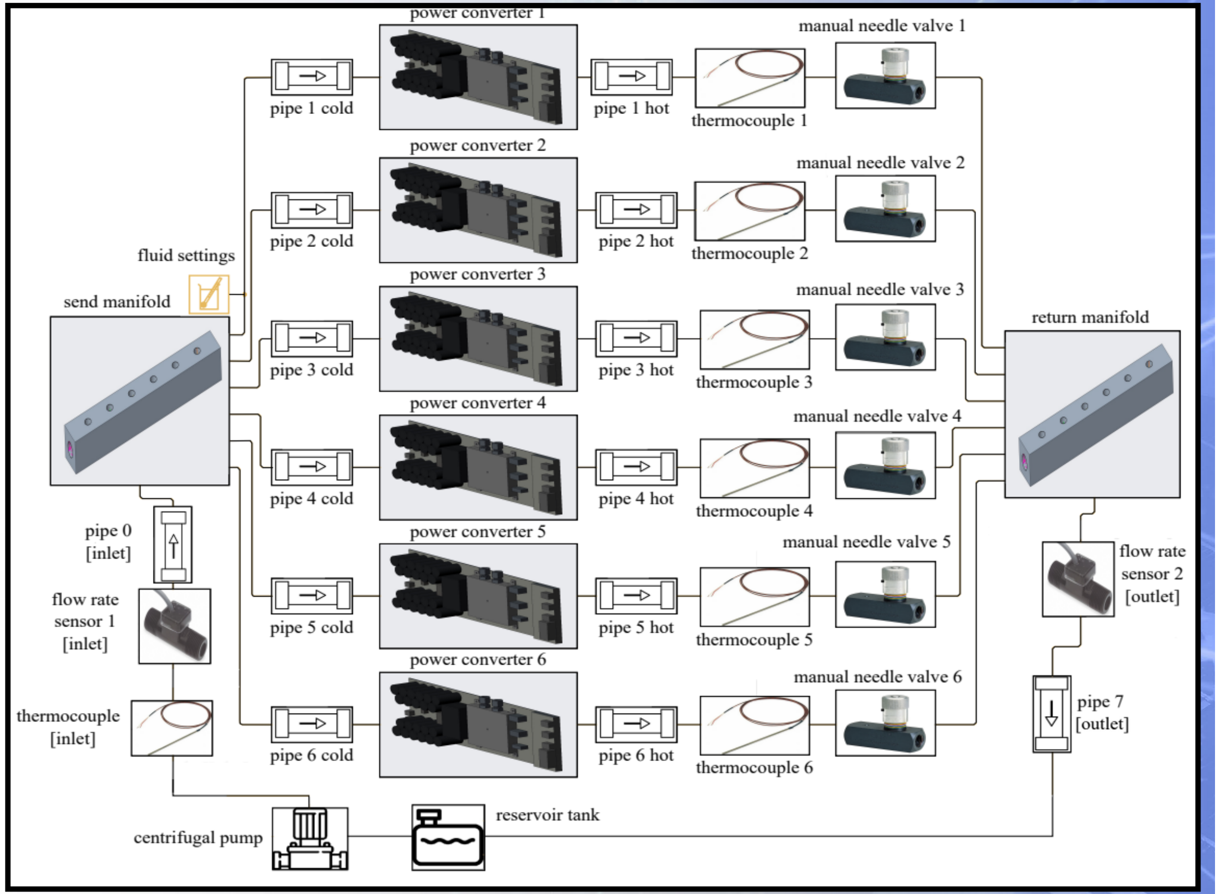
- Monitors abnormal temperature change rates (dT/dt); alerts operators if it exceeds a threshold.

Predictive Capability:

- Provides alerts on potential blockages before they become critical, maintaining safe thermal limits and converter reliability.

Integration:

- Integrates with the physical twin for informed decision-making.



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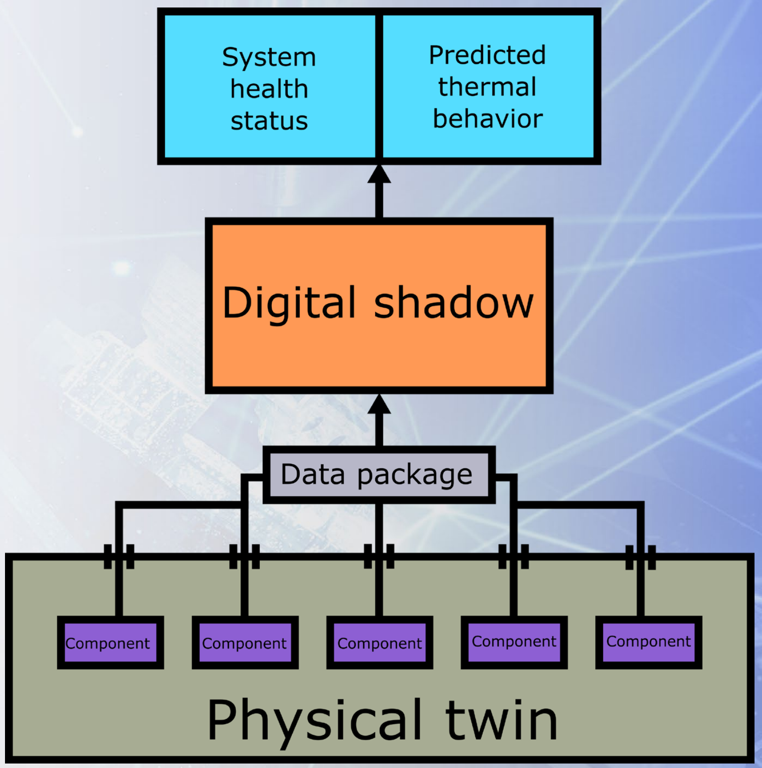
Digital Shadow Characterization and Calibration

Characterization:

- Digital shadow must accurately replicate the thermal behavior of the PT.
- Inaccurate digital shadow model = inaccurate thermal behavior prediction = Failure to find potential blockages in PT.

Calibration:

- Calibration drift over time affects accuracy of digital shadow.
- Periodic recalibration of the system must be done to maintain accurate emulator.
- Currently done manually but automatic optimization programs may be used – Particle swarm optimization (PSO).



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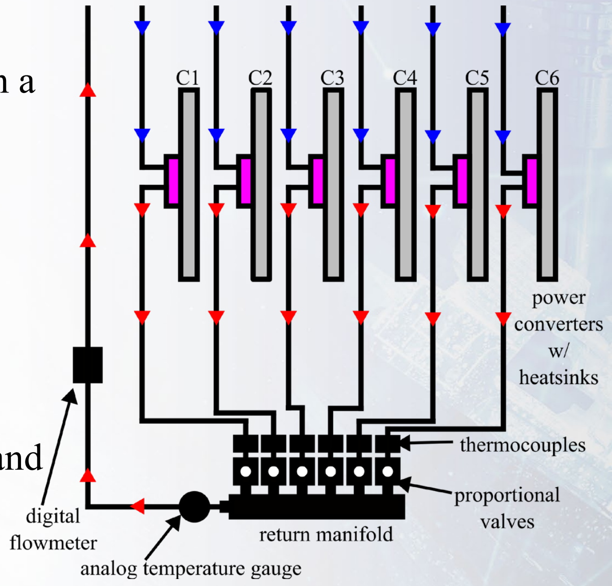
Experiment Procedure and DS Characterization

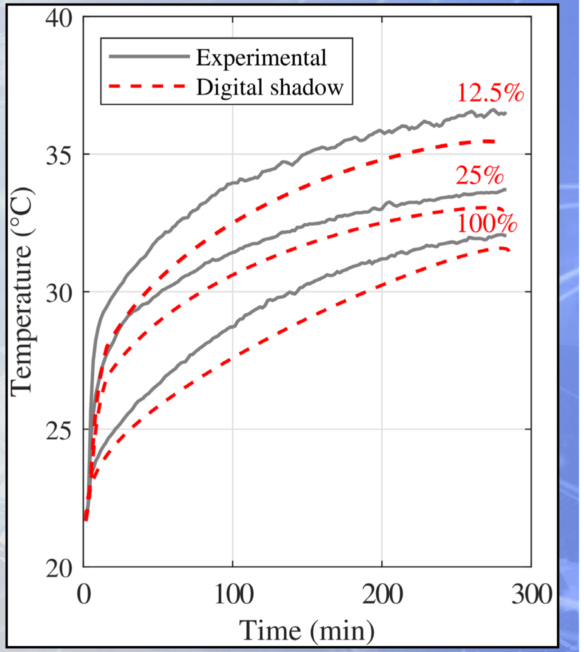
Purpose:

- Study effects of partial blockages on power converters under heat load.
- Determine temperature increase due to blockage in a single power converter.

Procedure:

- Simulated blockage by progressively reducing C2 valve opening by 12.5% over eight tests.
- Each test started with water coolant circulation at 2.46 lpm and ambient temperature of 22°C.
- C1, C2, C3, and C4 each supplied 2 kW; C1, C3, and C4 served as controls. C5 and C6 remained unpowered.
- C2's valve manipulated to simulate blockage.
- Testing lasted ~ five hours until reaching a quasi-steady state.
- Coolant temp returned to room temp before next valve reduction.





Unoptimized characterization results

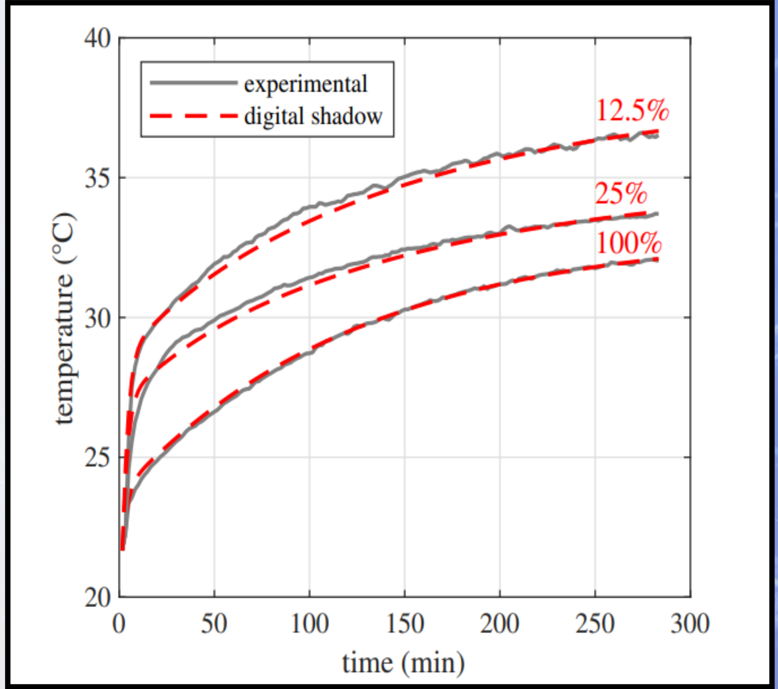
Results: Comparison of Simulation vs Physical Testbed Experiments

Experiment Overview:

- Results from reducing C2 converter valve opening from 100% to 12.5% at 2 kW.
- Lower percentages indicate increasing blockage.

Results:

- Simulation and physical tests show good agreement.
- Increased dT/dt and steady state as valve percentage decreases.
- Reduced cooling ability due to blockage formation resulting in loss of coolant flow.



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Results: Blockage Formation Effect on Heating Behavior

Temperature Change Analysis:

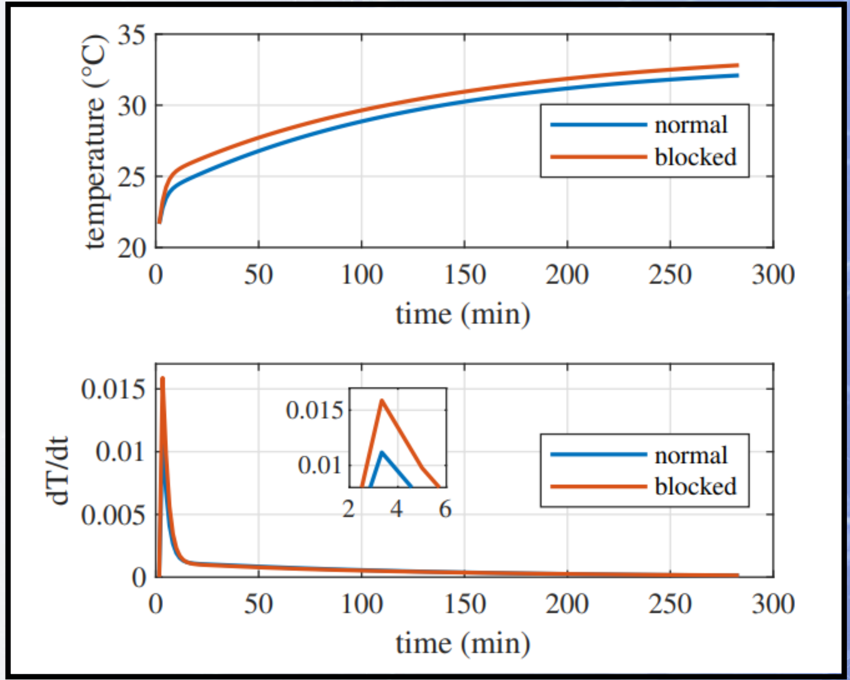
- Illustrates the abnormal rate of temperature change.
- Experimental data characterize normal dT/dt under operational conditions.
- Under no blockage, coolant temperature rises from ~22°C to ~24°C, reaching a steady state at ~33°C.
- With a 37.5% valve opening (blockage condition), temperature increases sharply to ~26°C, stabilizing at ~34°C.

Rate of Change:

- Maximum temperature spike under normal conditions: ~0.011°C/s.
- With 37.5% valve opening: ~0.0155°C/s, indicating blockage severity.

Result:

- Temperature increase is distinct enough to detect potential blockage formation.



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Conclusion and Future Work

Validation and Support:

- Results validate thermal digital shadow, replicating cooling system's behavior and supporting exploration of coolant blockage impacts.

Efficiency and Monitoring:

- Model enables real-time monitoring and prediction of blockage issues, enhancing proactive management and reliability of water-cooled systems.

Operational Impact:

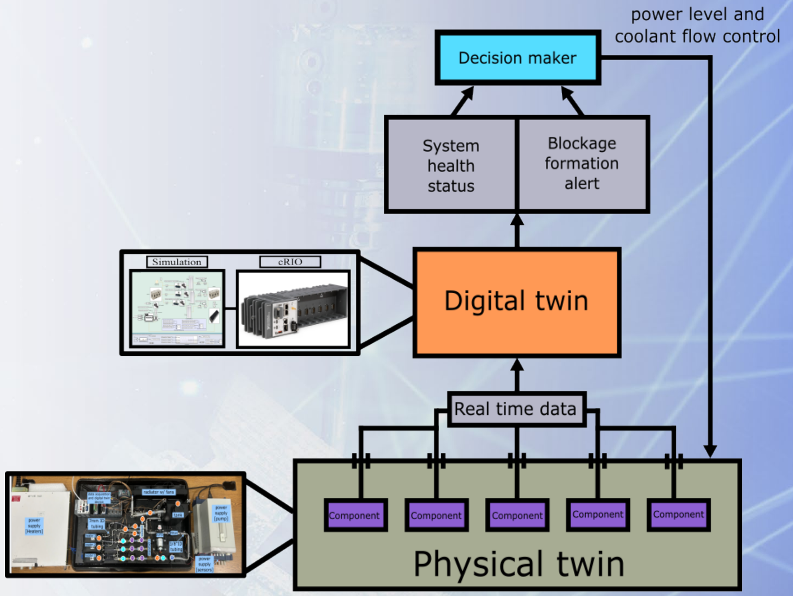
- Ensures efficient power rerouting to cooled components, minimizing downtime and overheating, improving reliability and efficiency of power electronic systems.

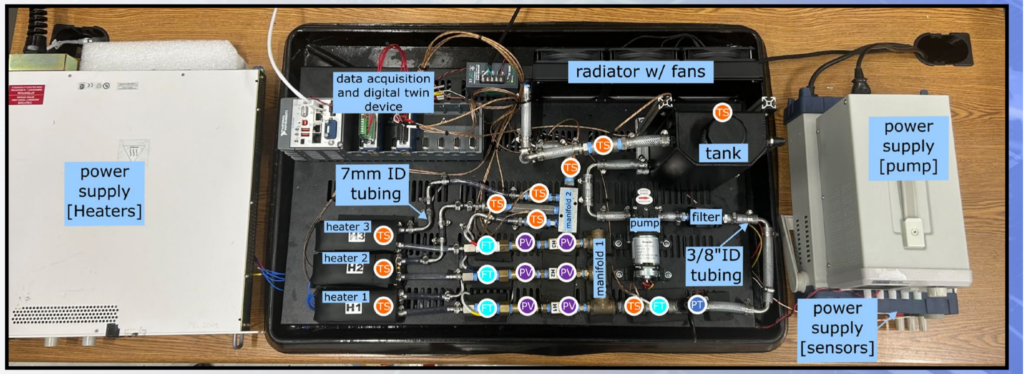
Future Development:

- Plans to develop digital shadow into a fully operational digital twin, enabling online data transfer and supporting human-in-the-loop decision-making.

Progress:

- Testbed title: BDPD (Blockage Detection & Power Distribution).





Thank you

This work was supported by the Office of Naval Research under contract NOs. N00014-20-C-1106, N00014-22-C-1003, and N00014-23-C-1012. The support of the ONR is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Navy.

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