A COMPREHENSIVE GUIDE TO DIGITAL TWIN DESIGN, INTEGRATION, AND APPLICATIONS IN DC MICROGRIDS

UNIVERSITY OF
South Carolina
Molinaroli College of
Engineering and Computing

EOL
Energy Optimization Laboratory

INTRODUCTION

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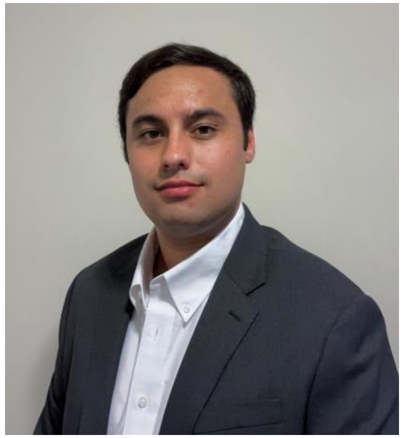

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OUTLINE

- Introduction
- Minimum requirement for a digital twin
- Applications
- Standardizations
- Representation techniques
- Frameworks
- Forecasting via digital twin
- Hands on exercise

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INTRODUCTION TO DIGITAL TWINS

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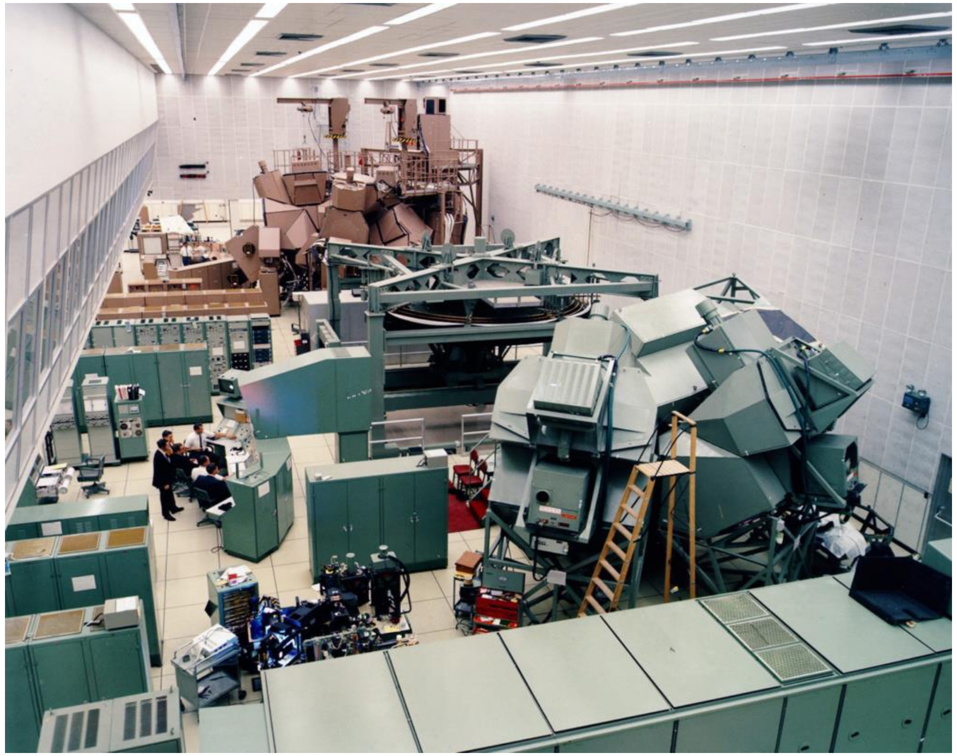
DIGITAL TWIN IDEA

- The idea of a “digital twin” was born at NASA in the 1960s as a “living model” of the Apollo 13 mission.
- Simulators were used to train astronauts and mission controllers.

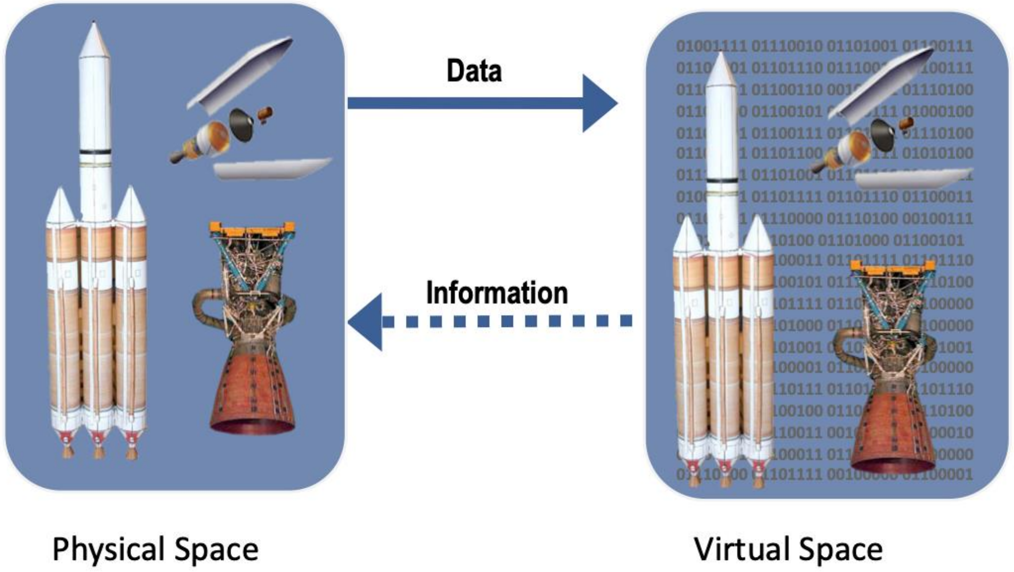


Apollo Simulators at Mission Control in Houston. Image credit: NASA

Allen, B. Danette. "Digital Twins and Living Models at NASA." Langley Research Center, NASA, November 3-4, 2021. https://ntrs.nasa.gov/citations/20210023699.

ORIGINAL DIGITAL TWIN DEFINITION

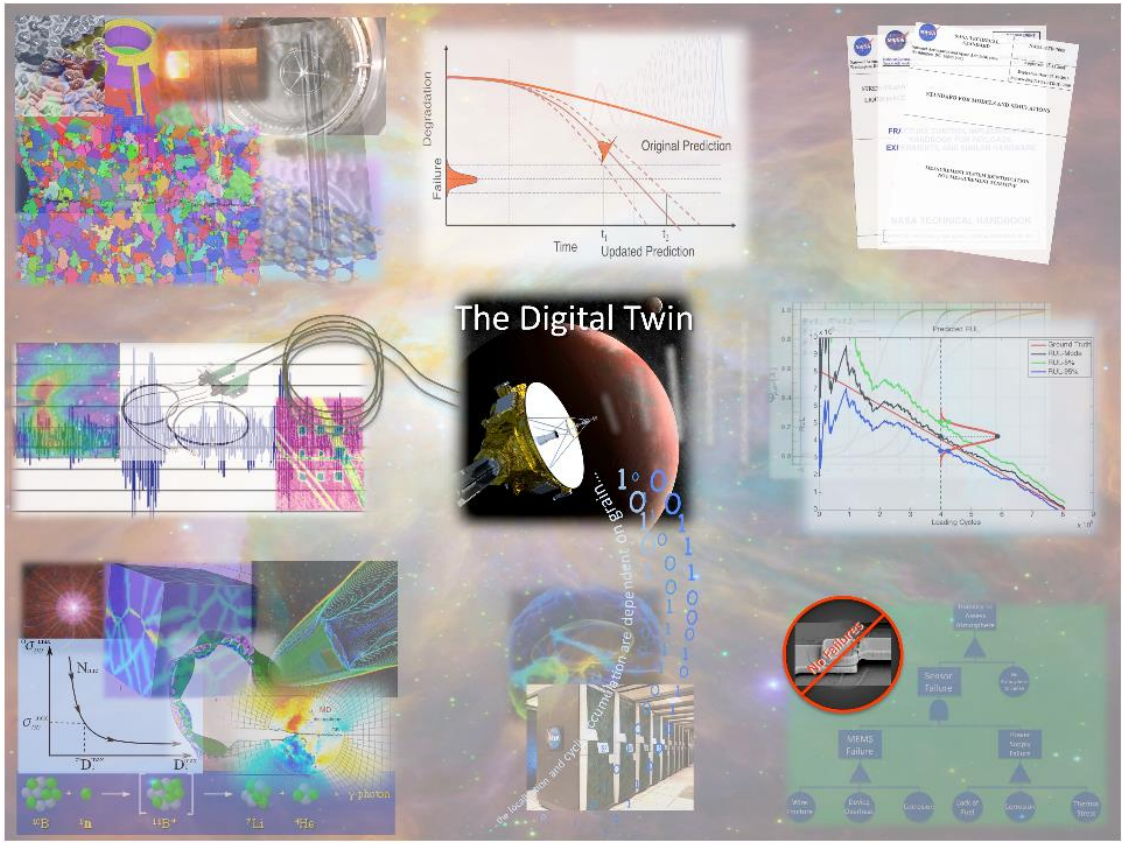
A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.



Grieves, M., Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In: Kahlen, J., Flumerfelt, S., Alves, A. (eds) Transdisciplinary Perspectives on Complex Systems. Springer, Cham. https://doi.org/10.1007/978-3-319-38756-7_4

NASA DIGITAL TWIN DEFINITION

- A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system to mirror the life of its corresponding flying twin.
- The Digital Twin continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success.



Edward Glaessgen and David Stargel. "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles," AIAA 2012-1818. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. April 2012.

NAS REPORT DIGITAL TWIN DEFINITION

- A set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems).
- Is dynamically updated with data from its physical counterpart.
- Has a predictive capability and informs decisions that realize value.

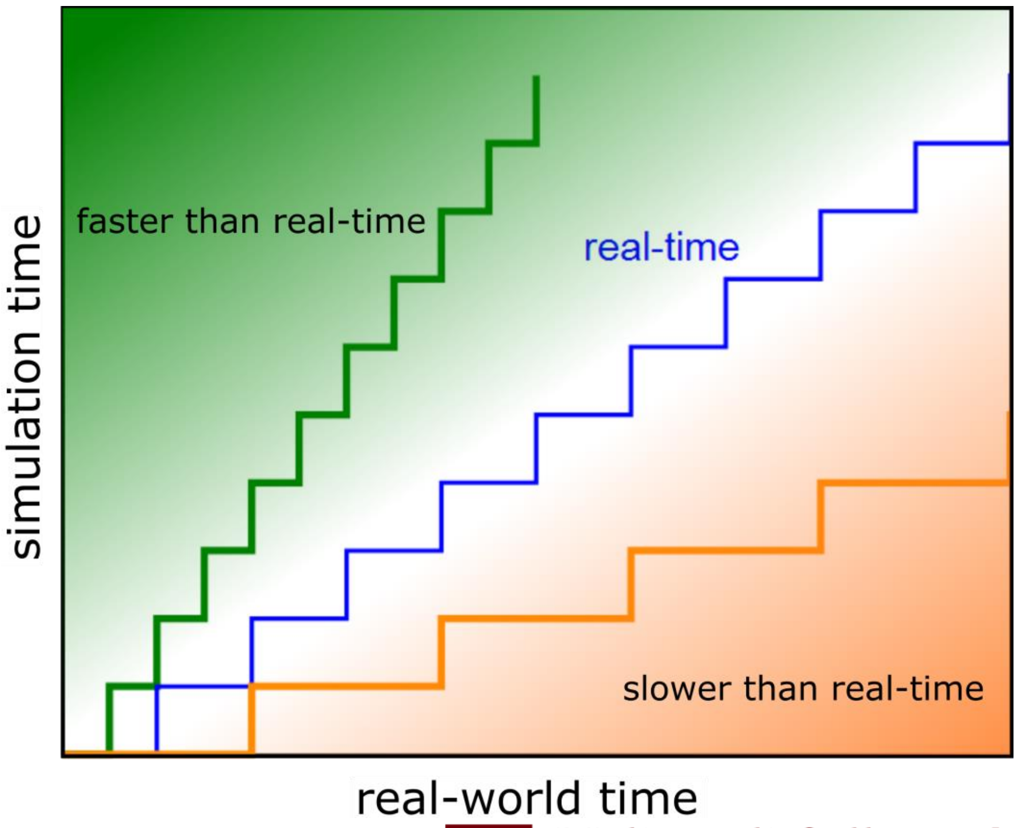
https://resources.sw.siemens.com/en-US/e-book-leverage-closed-loop-digital-twin

National Academies of Sciences, Engineering, and Medicine. 2024. Foundational Research Gaps and Future Directions for Digital Twins. Washington, DC: The National Academies Press. https://doi.org/10.17226/26894.

DIGITAL TWIN TIME SCALES

Digital Twin (DT):

- Is an integrated faithful representation mirroring the life of a physical asset.
- Forecasts performance for upcoming mission segments.
- Operates on any arbitrary timescale.



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DIGITAL MODEL, SHADOW, AND TWIN

Digital Model:

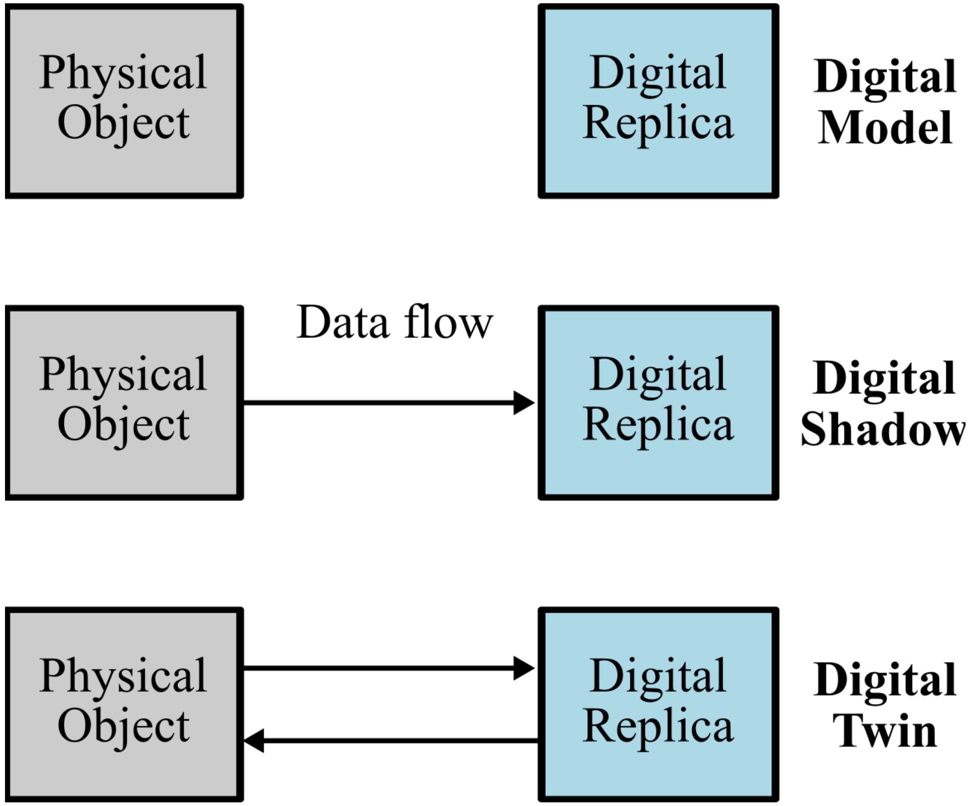
- No data flow and replication of condition.

Digital Shadow:

- Data exchange is unidirectional.

Digital Twin:

- Data exchange must be bidirectional and enables control modification.

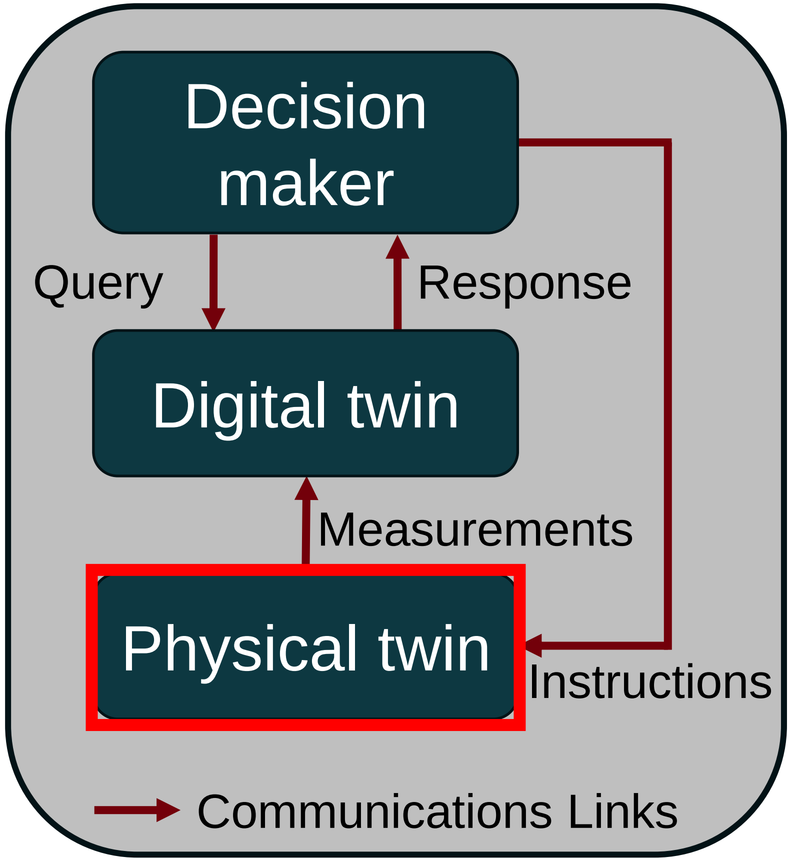


K. Sado, J. Peskar, A. R. J. Downey, H. L. Ginn, R. Dougal and K. Booth, "Query-and-Response Digital Twin Framework using a Multi-domain, Multi-function Image Folio," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2024.3425276.

DIGITAL TWIN ELEMENTS

Physical Twin (PT):

- Is the physical asset under study.
- Can vary in complexity. It might be a machine, a piece of infrastructure, a single component of a system, or an entire, complex system.

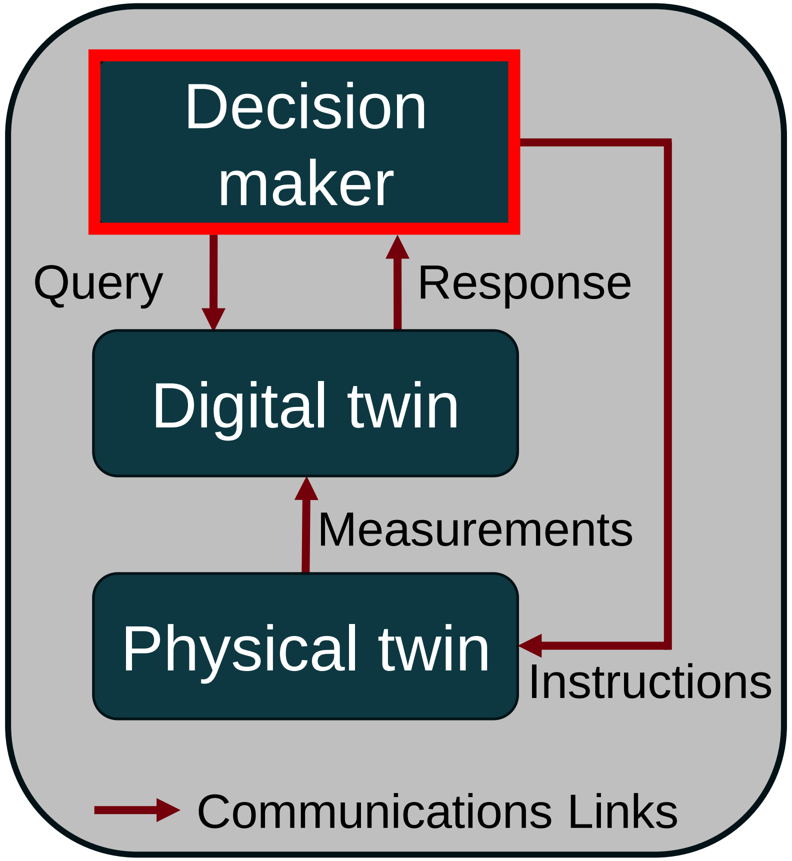


K. Sado, J. Hannum, E. Skinner, H. L. Ginn and K. Booth, "Hierarchical Digital Twin of a Naval Power System," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1514-1521, doi: 10.1109/ECCE53617.2023.10361999.

DIGITAL TWIN ELEMENTS

Decision Maker:

- A control algorithm, an AI, a human-in-the-loop, or a combination of these elements.
- Is the outermost control loop for the system.
- Develops the goal or query for the DT to study.



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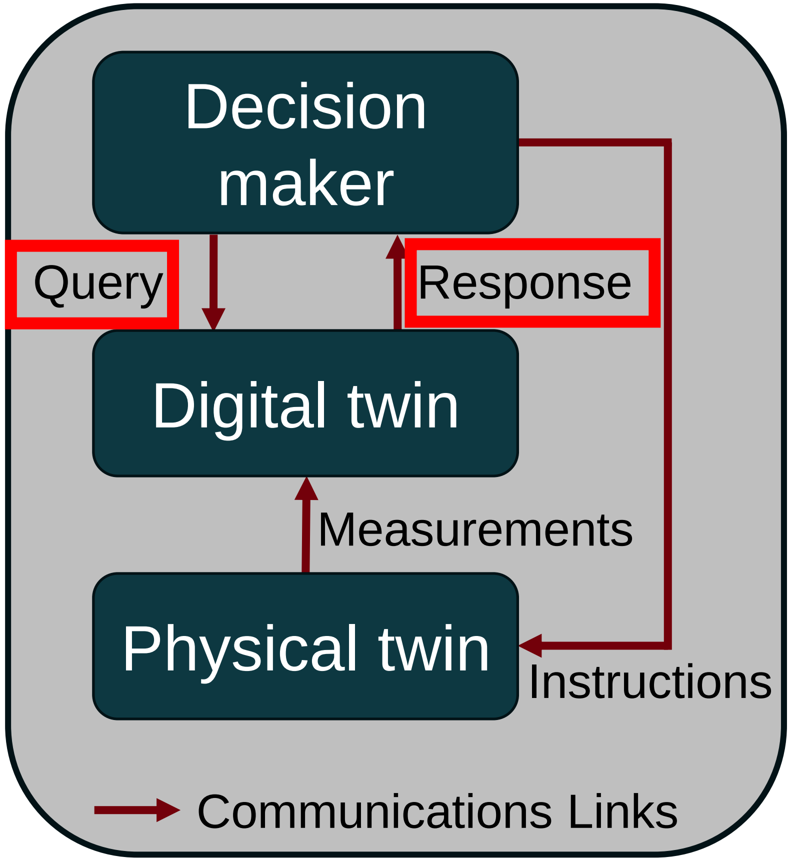
DIGITAL TWIN ELEMENTS

Query:

- Set of instructions sent by the decision maker to a DT.
- Includes parameters or conditions that the DT uses to forecast behaviors to provide decision aids based on the decision maker's objectives.
- Could be predefined or asked in real-time.

Response :

- Insights to the behavior of the physical twin.
- State estimations, forecasted data,..etc.



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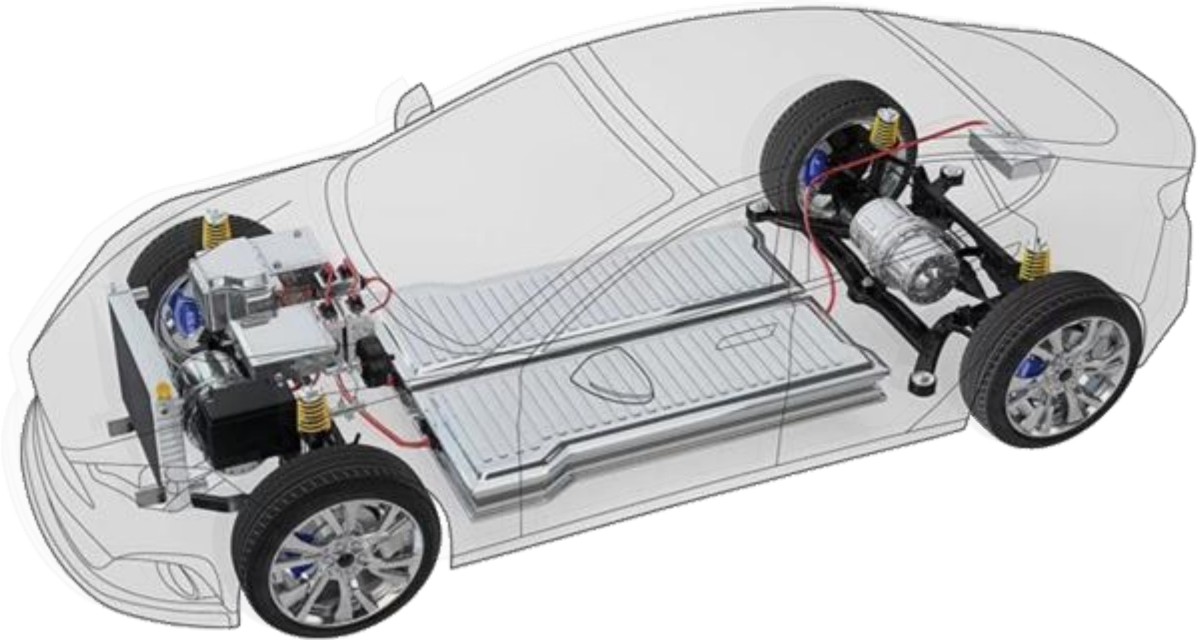

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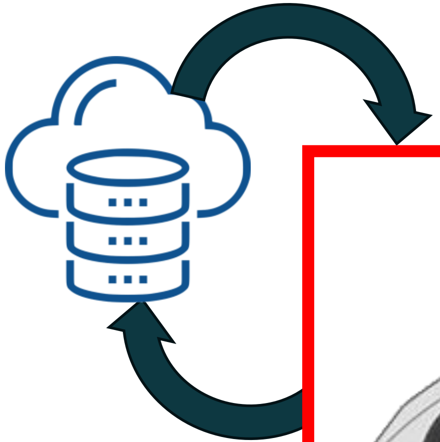
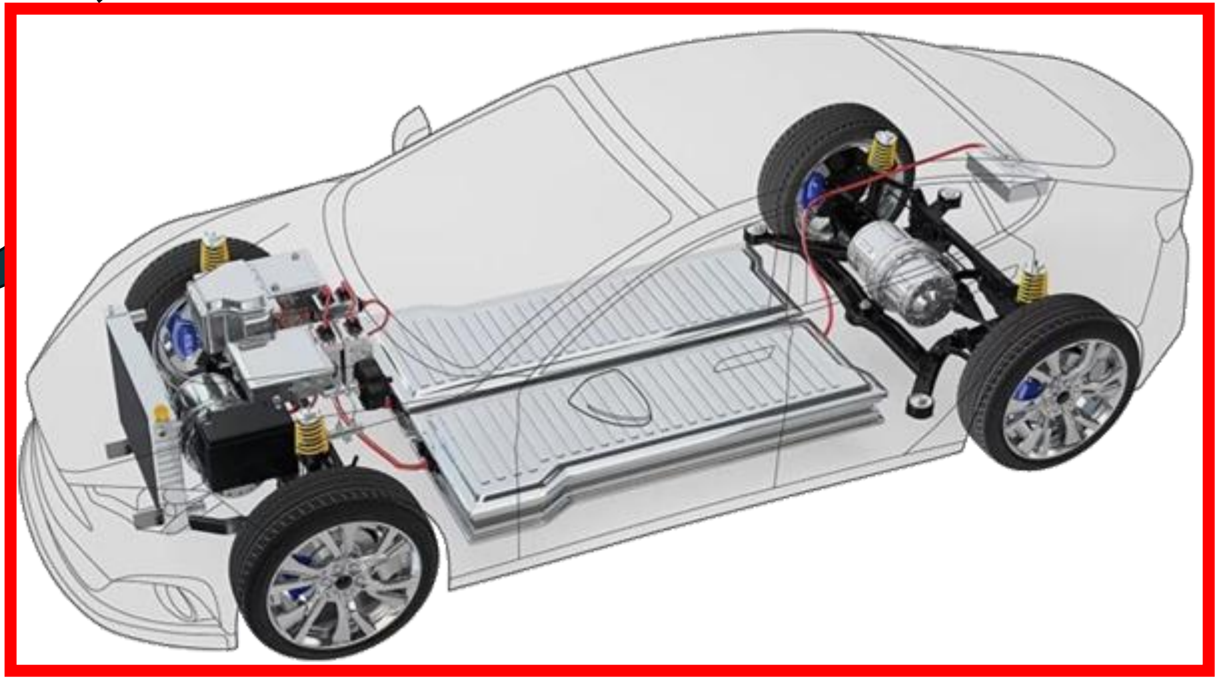
DIGITAL TWIN ELEMENTS



Physical System:

Is the system that encapsulates the physical twin and the computing devices necessary for running digital twins.



K. Sado, J. Hannum, E. Skinner, H. L. Ginn and K. Booth, "Hierarchical Digital Twin of a Naval Power System," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1514-1521, doi: 10.1109/ECCE53617.2023.10361999.

DIGITAL TWIN TYPES

Design Digital Twin

- A virtual representation of a physical product or system, used primarily during the design phase.
- Enables detailed analysis and optimization of designs before physical prototypes are built.
- Reduces the cost and time associated with physical prototyping.

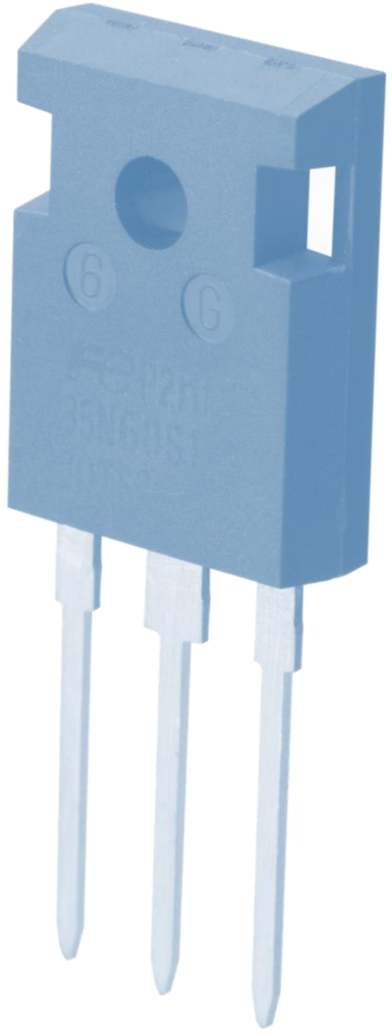
Operation Digital Twin

- A virtual representation of a physical asset that reflects its operating conditions.
- Monitors the operational performance of physical systems.
- Enhances operational efficiency and reliability.
- Improves decision-making based on real-time data.

DIGITAL TWIN FOCUS

Device Digital Twin

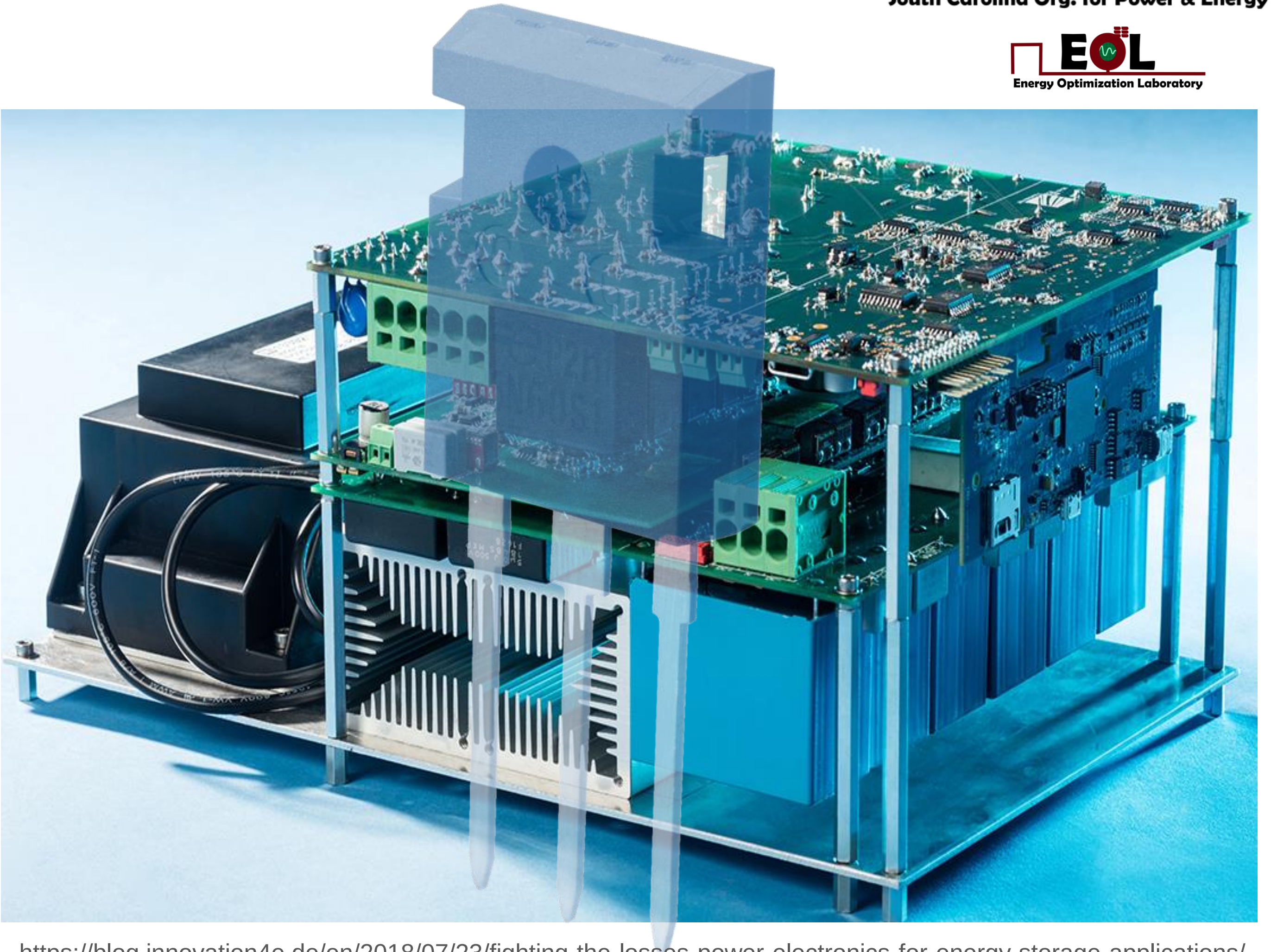
- Represents individual parts of a system, such as semiconductor switches.
- Focuses on modeling integral parts under stress or heat.
- Provides detailed insights into component behavior under various conditions.



DIGITAL TWIN FOCUS

Asset/ Component Digital Twin

- Combines devices to represent an asset.
- Monitors overall performance of combined devices.
- Provides a comprehensive view of asset health and performance.



https://blog.innovation4e.de/en/2018/07/23/fighting-the-losses-power-electronics-for-energy-storage-applications/

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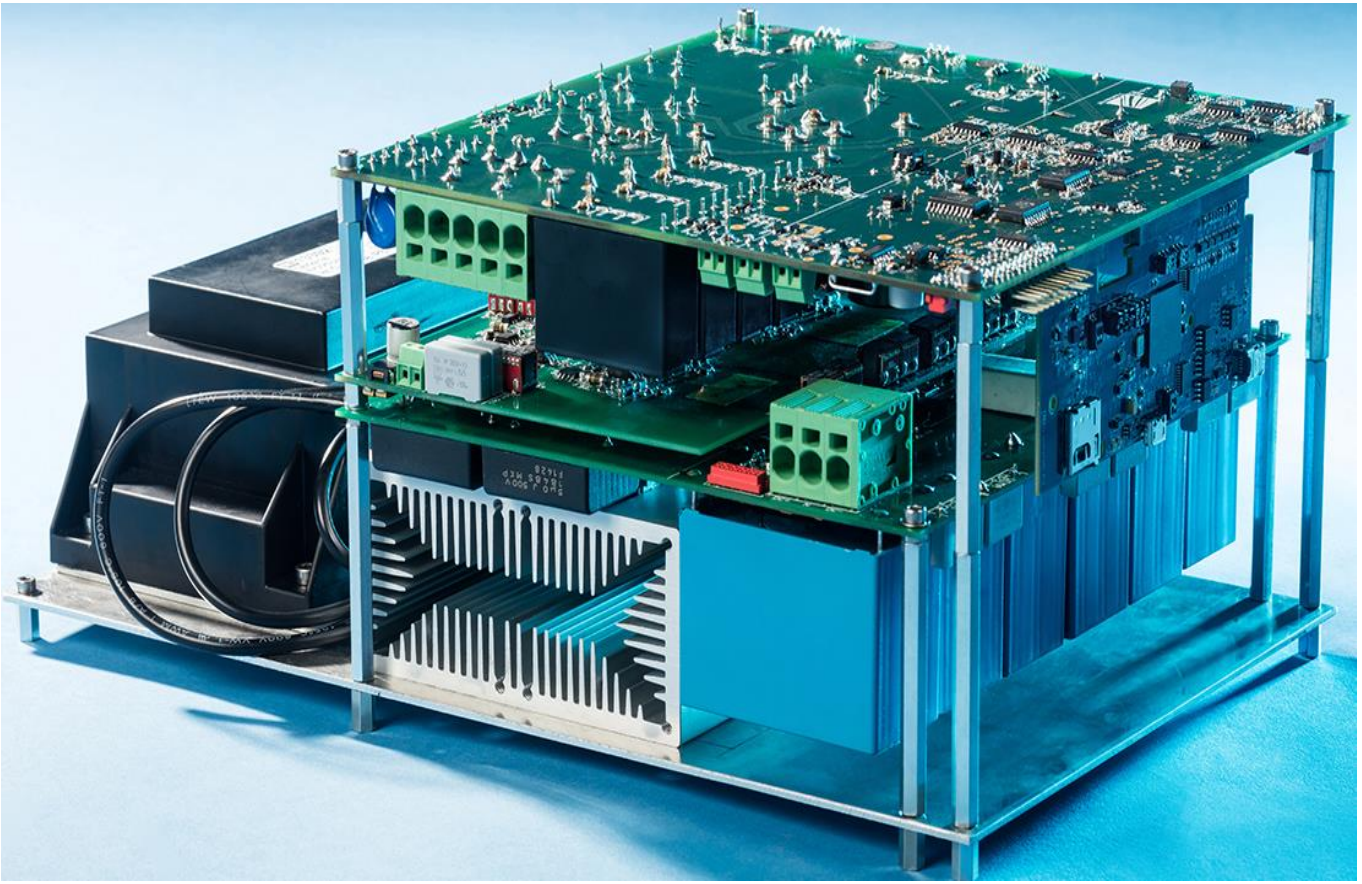
DIGITAL TWIN FOCUS

System Digital Twin

- Represents a system of assets working together.
- Represents the interactions between different assets within a system.
- Enables holistic analysis of complex systems.
- Focuses on the operational performance of systems.



DIGITAL TWIN FOCUS

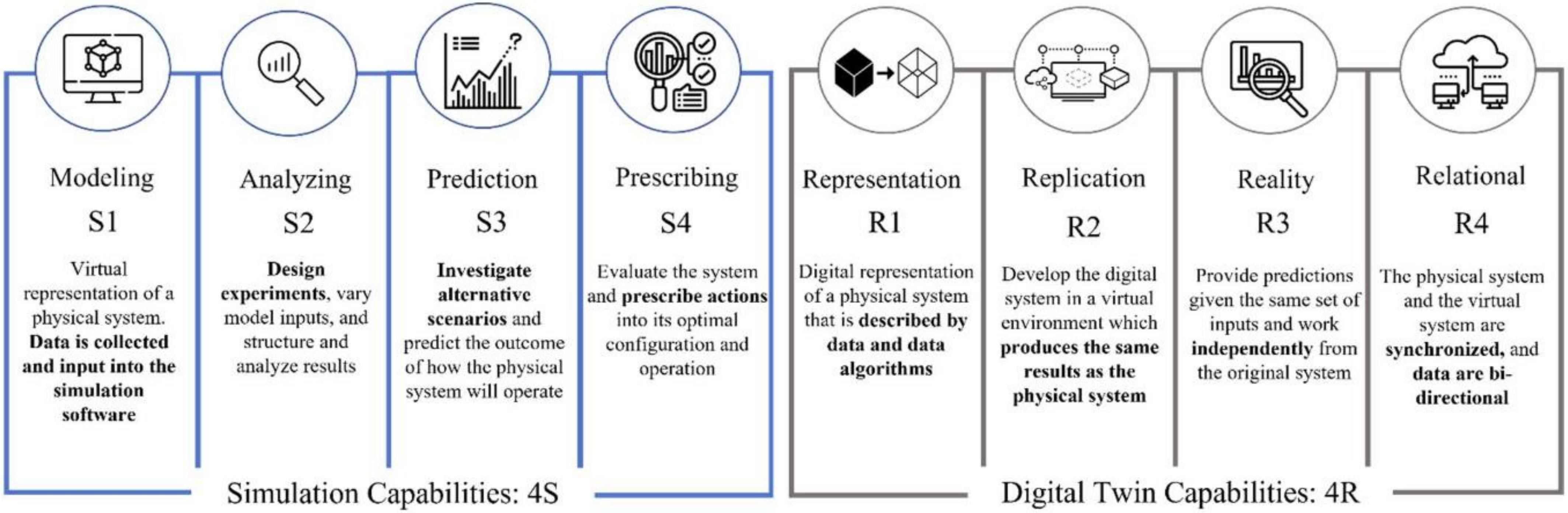
Process Digital Twin

- Digital representation of processes and workflows.
- Represents the entire production facilities to optimize efficiency.
- Represents interactions between different systems and processes.
- Provides insights into process efficiency and bottlenecks.

https://www.royalhaskoningdhv.com/en/twinn/impact-stories/5-digital-twins-helping-nissan-boost-productivity

T. Brockhoff et al., "Process Prediction with Digital Twins," 2021 ACM/IEEE International Conference on Model Driven Engineering Languages and Systems Companion (MODELS-C), Fukuoka, Japan, 2021, pp. 182-187, doi: 10.1109/MODELS-C53483.2021.00032.

SIMULATION OR DIGITAL TWIN?



A. Wooley, D. F. Silva, and J. Bitencourt, “When is a simulation a digital twin? A systematic literature review,” Manufacturing Letters, vol. 35, pp. 940–951, Aug. 2023, doi: 10.1016/j.mfglet.2023.08.014. Available: https://www.sciencedirect.com/science/article/pii/S2213846323000718

MINIMUM REQUIREMENTS FOR A DIGITAL TWIN

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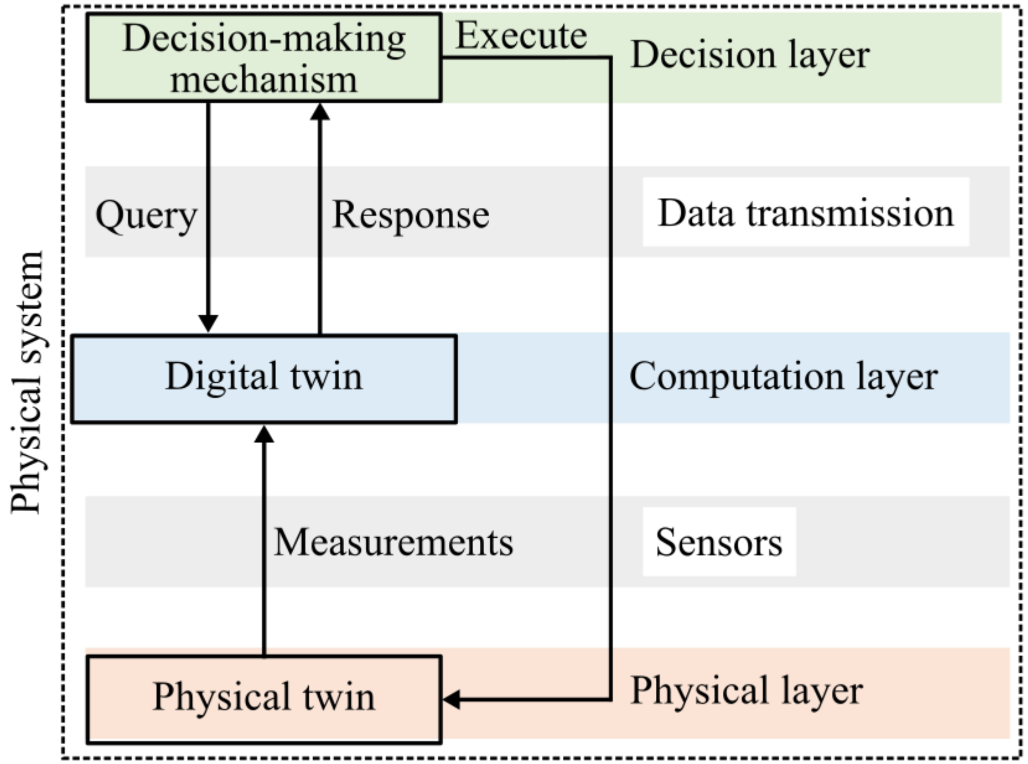
KEY COMPONENTS OF DIGITAL TWIN SYSTEMS

Physical Twin

- Represents the real-world physical entity or system being represented.
- Examples include machinery, buildings, vehicles, or human organs.
- Essential for creating an accurate digital counterpart.

Sensor Data

- Collects real-time data from the physical twin.
- Types of sensors: voltage, current, temperature, pressure, humidity, etc.
- Critical for feeding accurate and up-to-date information into the digital twin.



KEY COMPONENTS OF DIGITAL TWIN SYSTEMS

Data Storage

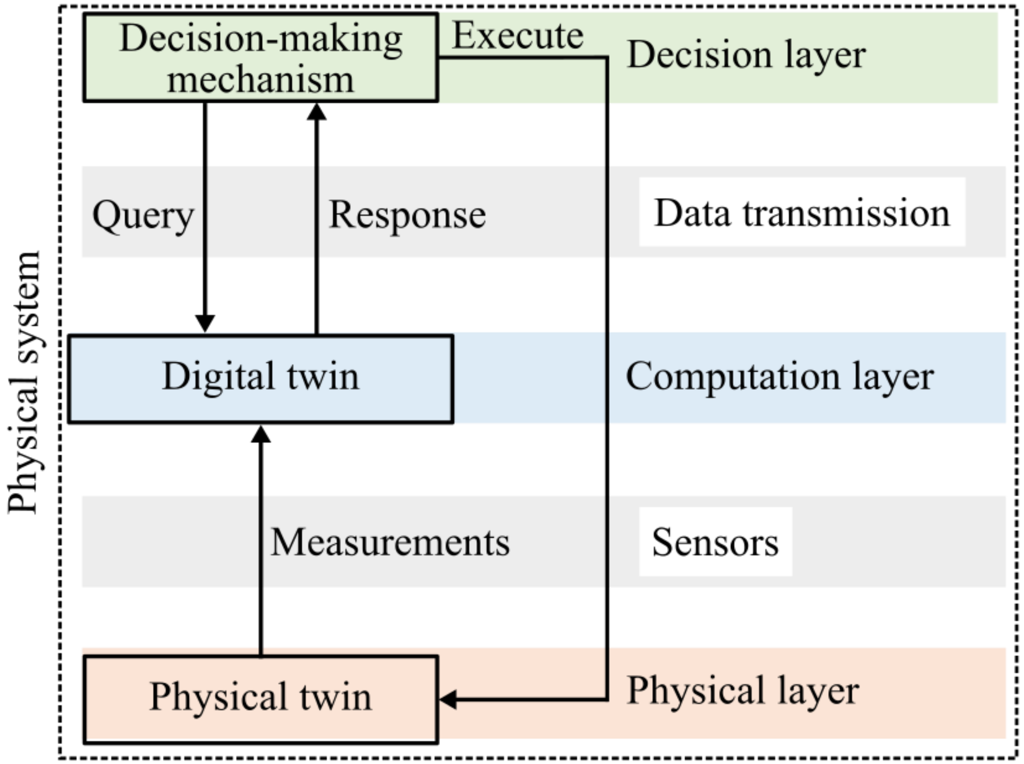
- Handle vast amounts of data generated by sensors.
- Technologies used: cloud storage, databases.

Data Management

- Organizes, maintains, and retrieves data efficiently.
- Essential for enabling real-time data access and historical data analysis.

Data Processing/Computation

- Converts raw data into meaningful insights.
- Essential for predicting future behavior, identifying trends, and optimizing performance.



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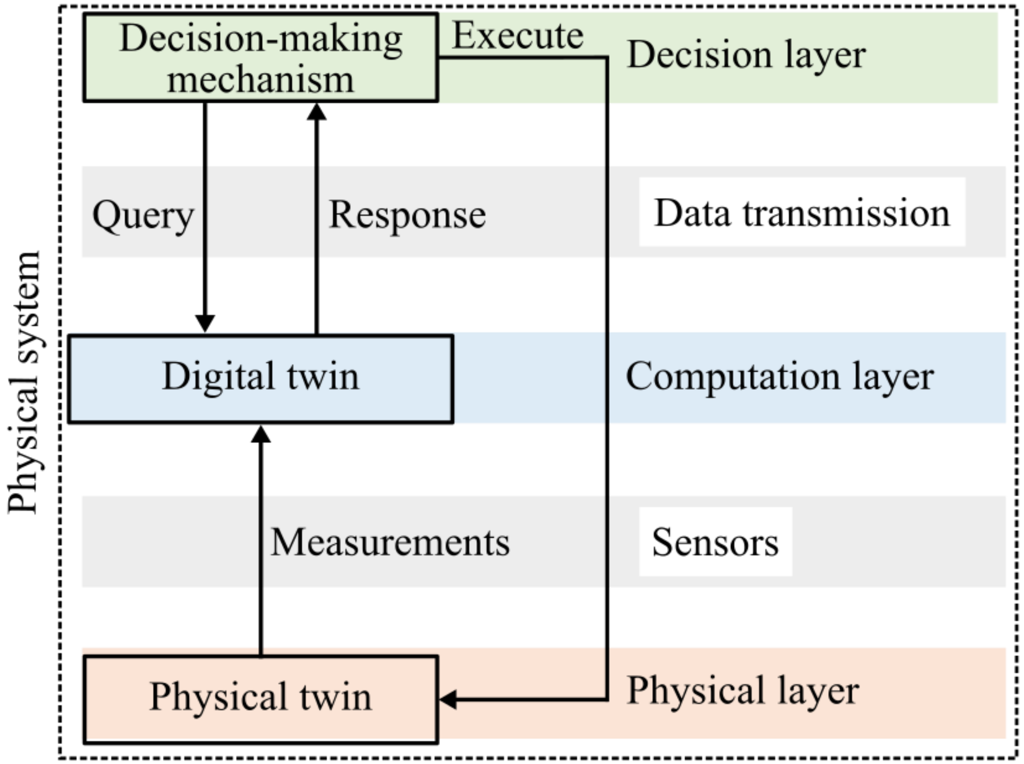
KEY COMPONENTS OF DIGITAL TWIN SYSTEMS

Decision-Making Entity

- Uses insights from data analytics to make informed decisions.
- Can be automated systems or human operators.
- Objectives include optimizing performance, reducing downtime, and improving efficiency.

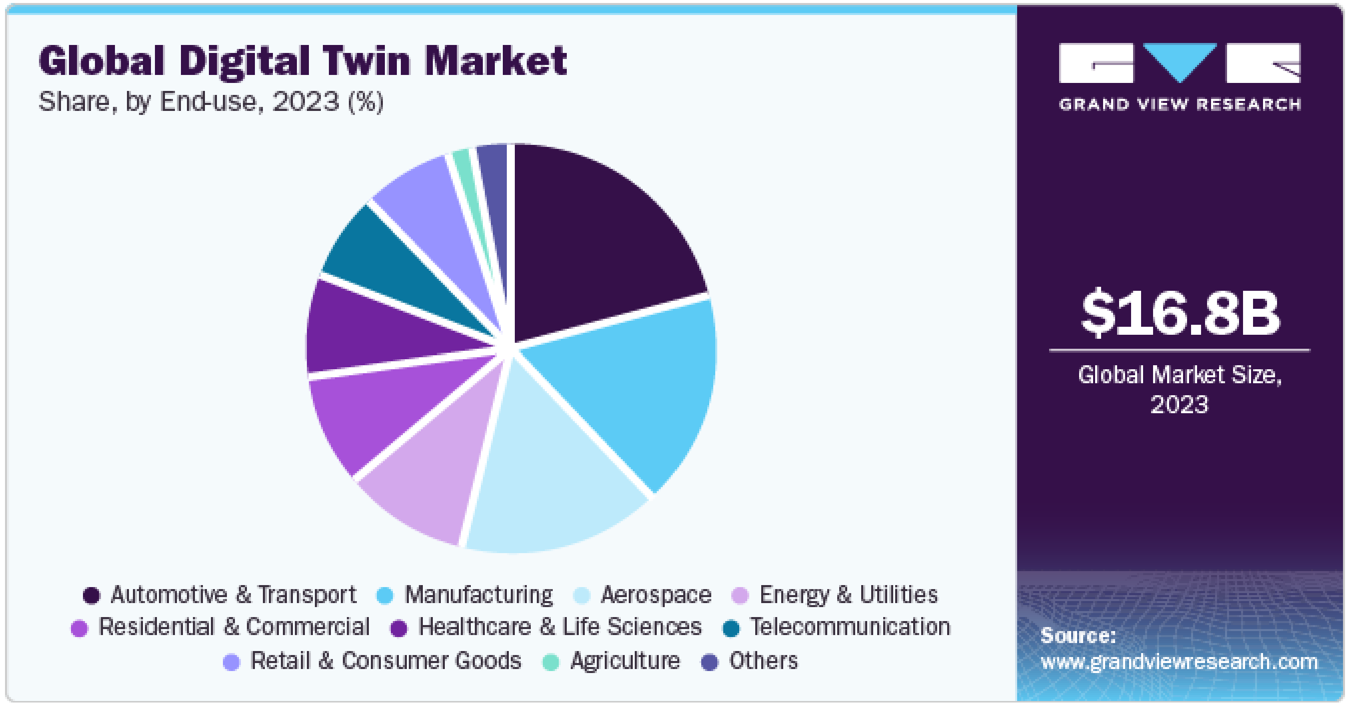
Visualization

- Presents data and insights in an understandable format.
- Tools: dashboards, 3D visualizations, augmented reality.
- Essential for making data-driven decisions and monitoring system performance.



APPLICATIONS IN MODERN ENGINEERING

- Manufacturing:
  - Optimize production process.
- Healthcare:
  - Personalized patient care.
- Automotive:
  - Vehicle lifecycle.
- Urban Planning:
  - Efficient urban management.

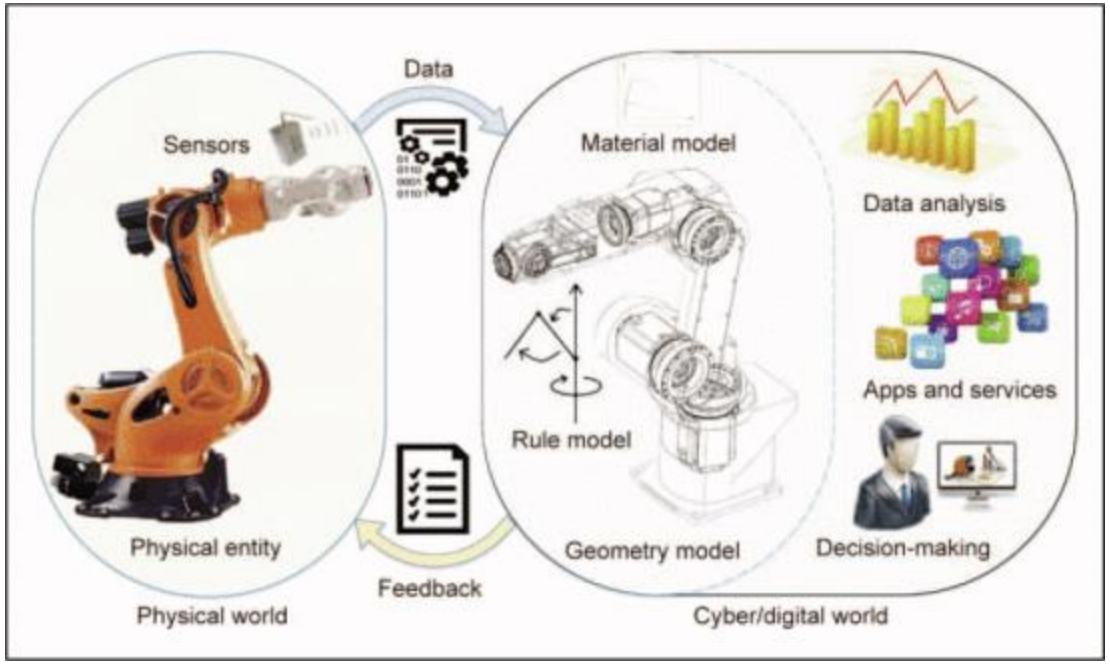


Digital Twin Market Size, Share And Growth Report, 2030 (grandviewresearch.com)

APPLICATIONS ACROSS INDUSTRIES

Manufacturing:

- Enables self correcting behavior to robotics.
- Improves robustness and agility of the manufacturing process through reverse control.
- Streamlines production and improves quality.

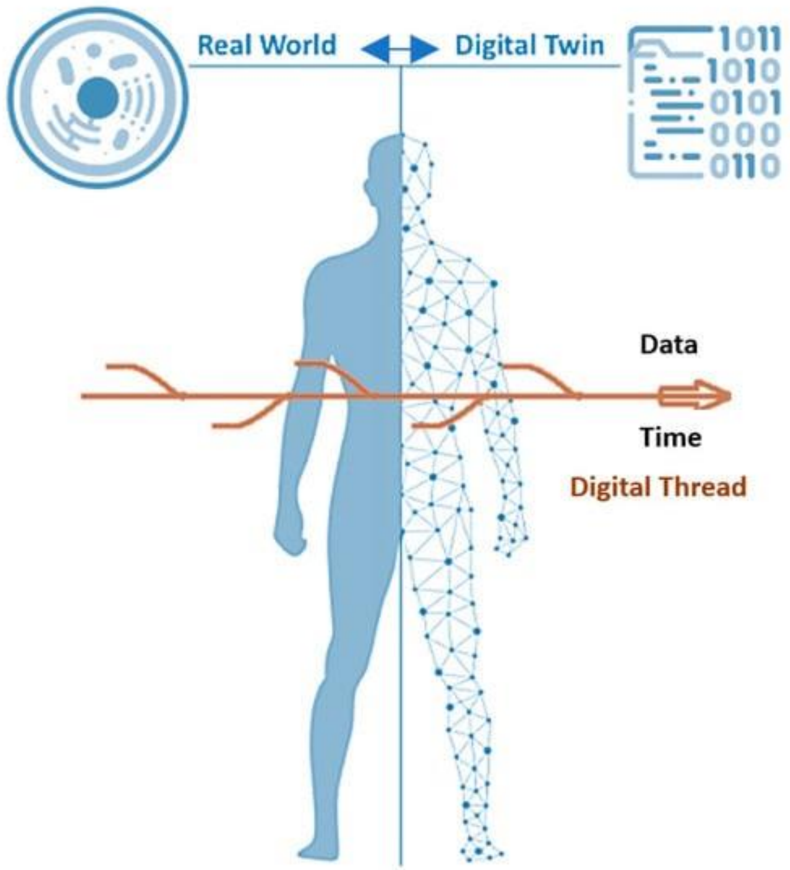


X. Zhang, B. Hu, G. Xiong, X. Liu, X. Dong and D. Li, "Research and practice of lightweight digital twin speeding up the implementation of flexible manufacturing systems," 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI), Beijing, China, 2021, pp. 456-460, doi: 10.1109/DTPI52967.2021.9540104.

APPLICATIONS ACROSS INDUSTRIES

Healthcare:

- Monitors patient health and optimizes treatment plans.
- Personalized medicine based on individual patient data.
- Simulations for disease progression and intervention outcomes.

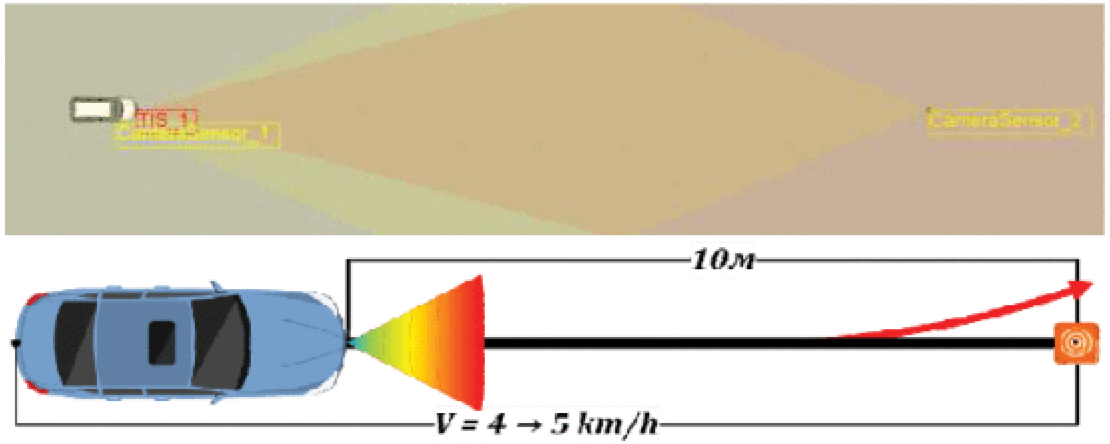


Kamel Boulos, Maged N., and Peng Zhang. 2021. "Digital Twins: From Personalised Medicine to Precision Public Health" Journal of Personalized Medicine 11, no. 8: 745. https://doi.org/10.3390/jpm11080745

APPLICATIONS ACROSS INDUSTRIES

Automotive:

- Enhances vehicle design and manufacturing efficiency.
- Predictive maintenance by monitoring operation of components.
- Optimizes performance and reliability throughout the lifecycle of the car.

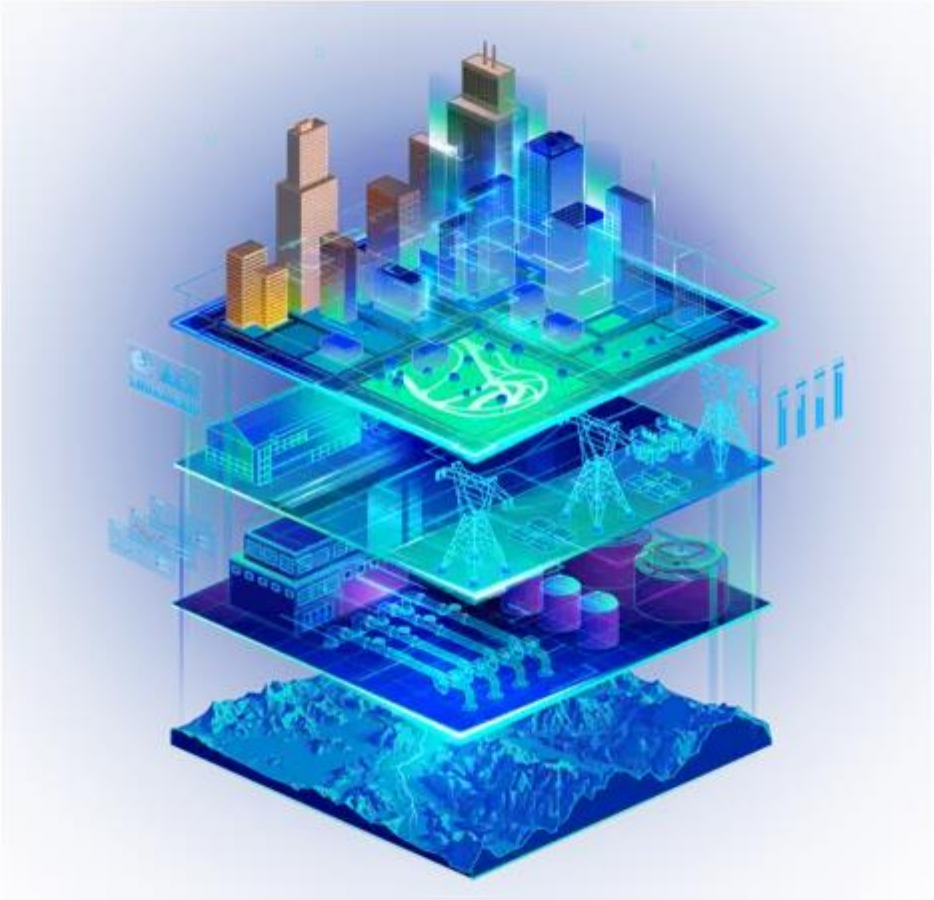


S. S. Shadrin, D. A. Makarova, A. M. Ivanov and N. A. Maklakov, "Safety Assessment of Highly Automated Vehicles Using Digital Twin Technology," 2021 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED), Moscow, Russian Federation, 2021, pp. 1-5, doi: 10.1109/TIRVED53476.2021.9639110.

APPLICATIONS ACROSS INDUSTRIES

Urban Planning:

- Assists in designing smart cities and infrastructure.
- Optimizes traffic management and transit routes.
- Resource allocation to optimize energy and water usage.
- Optimal space utilization considering population growth/ economic development.



Tessel Elisabeth Kaal Optimization of Buildings Energy Demand-Supply for Local Energy Source Design with Minimum Burden on the Grid https://www.gdmc.nl/publications/2024/MScThesisTesselElisabethKaal.pdf

STANDARDIZATION

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BENEFITS OF STANDARDIZATION

Interoperability: Ensures that digital twins from different vendors can work together.

Reliability: Provides a consistent framework for developing and deploying digital twins.

Scalability: Facilitates the scaling of digital twin solutions across industries and applications.

Digital Twin

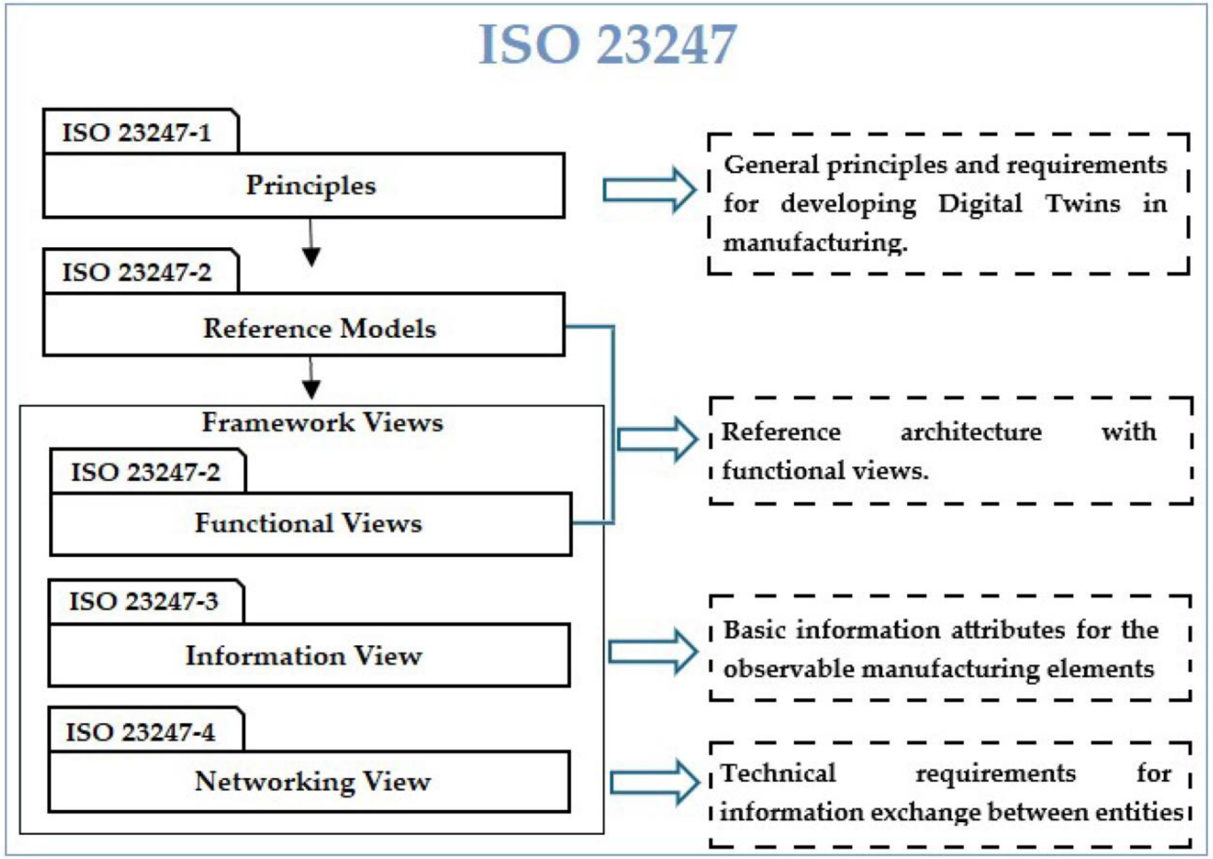
CHALLENGES IN STANDARDIZATION

- Diverse Applications:
  - Digital twins are used in various industries, making standardization challenging.
- Rapid Technological Advancements:
  - Keeping standards up-to-date with fast-paced technological changes.
- Global Coordination:
  - Ensuring collaboration and agreement among international stakeholders.

ONGOING STANDARDIZATION EFFORTS

ISO 23247 Standardization

- Proposes a reference architecture for digital twins in manufacturing.
- Addresses digital twin terminology and definitions.



ISO TC 184/SC 4; Automation Systems and Integration-Digital Twin Framework for Manufacturing—Part 1: Overview and General Principles. ISO: Geneva, Switzerland, 2021. Available online: https://www.iso.org

ONGOING STANDARDIZATION EFFORTS

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- Industry Consortia
  - Digital Twin Consortium: A global consortium driving the adoption and standardization of digital twin technology.
  - Industrial Internet Consortium (IIC): Promotes the growth of the Industrial Internet, including digital twins.

digital twin® CONSORTIUM

Industry IoT Consortium®

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DIGITAL TWIN REPRESENTATION TECHNIQUES

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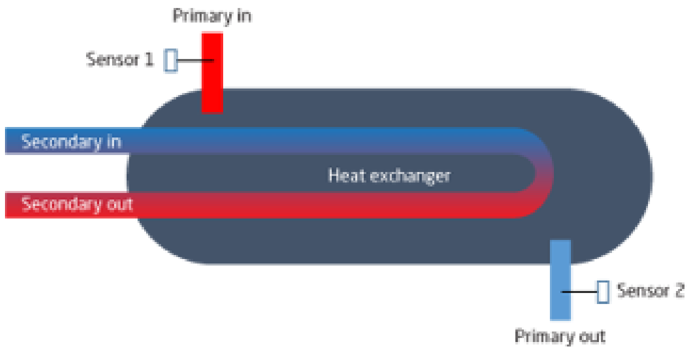
DIGITAL TWIN REPRESENTATION TECHNIQUES

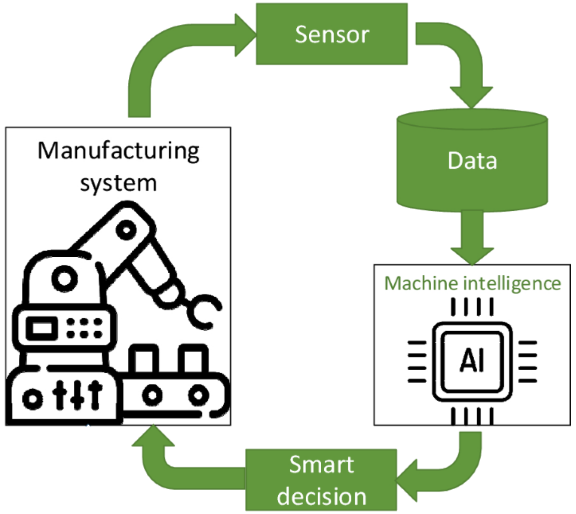
Physics-Based Modeling

- Uses mathematical models to represent physical properties and behaviors. Example: Thermal analysis of a heat exchanger.



Data-Driven Modeling

- Leverages historical data to create models that predict behavior of the asset.
- Example: Predictive maintenance/ fault detection for industrial machinery.

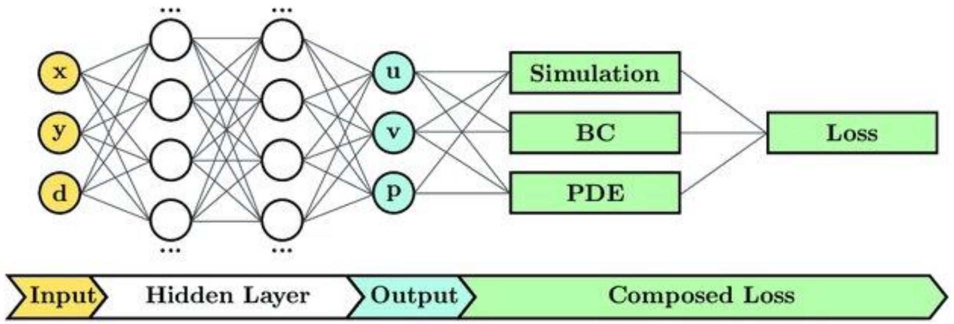


Xu, K., Li, Y., Liu, C. et al. Advanced Data Collection and Analysis in Data-Driven Manufacturing Process. Chin. J. Mech. Eng. 33, 43 (2020). https://doi.org/10.1186/s10033-020-00459-x

DIGITAL TWIN REPRESENTATION TECHNIQUES

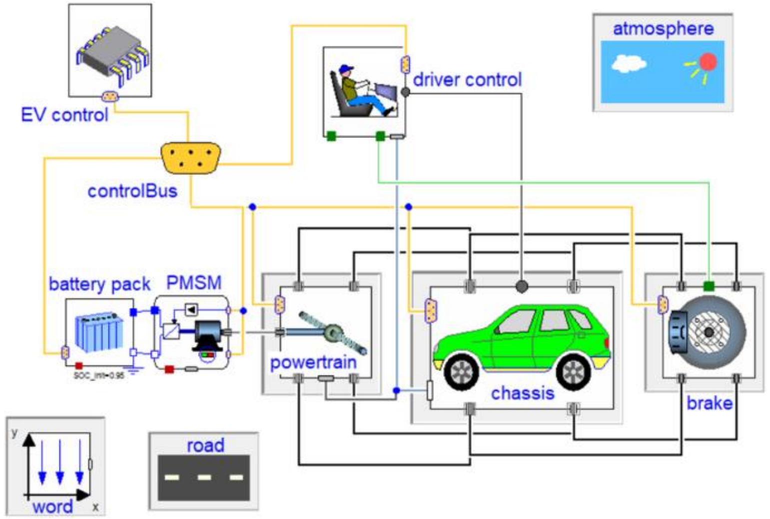
Hybrid Modeling

- Combines physics-based and data-driven approaches for more accurate and robust models.
- Applications: Complex systems where both physical laws and data trends are important.



Simulation-Based Modeling

- Uses simulation software to create a virtual replica of the system.
- Applications: Testing and validation, scenario analysis.
- Example: Simulating the behavior of an electric vehicle powertrain.



Pioch, Fabian & Harmening, Jan Hauke & Müller, Andreas Maximilian & Peitzmann, Franz-Josef & Schramm, Dieter & el Moctar, Ould. (2023). Turbulence Modeling for Physics-Informed Neural Networks: Comparison of Different RANS Models for the Backward-Facing Step Flow. Fluids

Qin, D., Li, J., Wang, T. et al. Modeling and Simulating a Battery for an Electric Vehicle Based on Modelica. Automot. Innov. 2, 169–177 (2019). https://doi.org/10.1007/s42154-019-00066-0

DIGITAL TWIN REPRESENTATION TECHNIQUES

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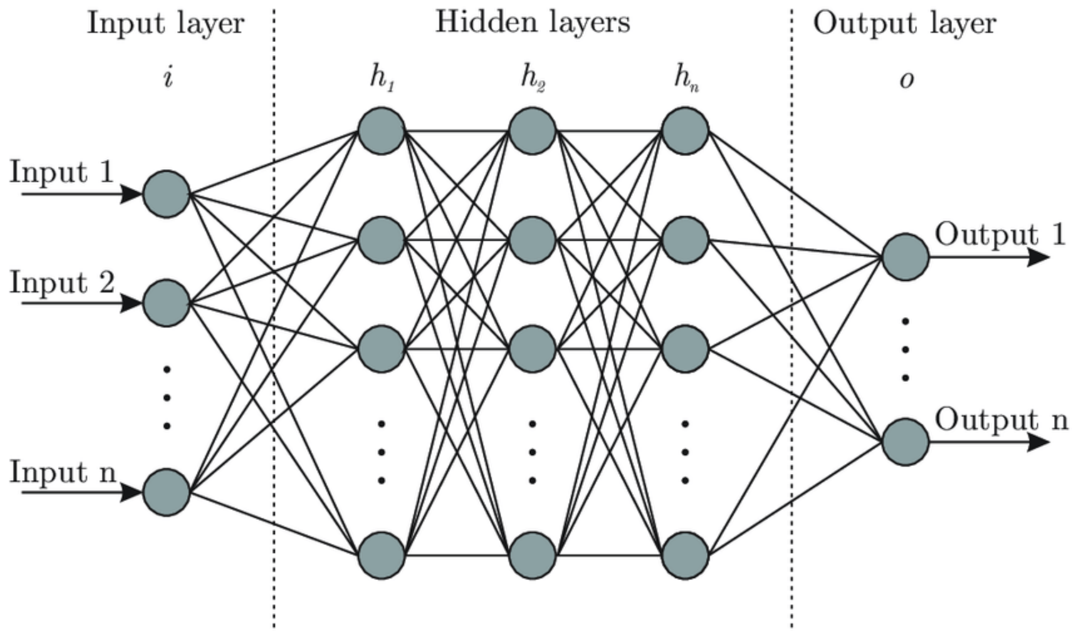
AI and Machine Learning Modeling

- Utilizes AI and machine learning algorithms to improve model accuracy and provide predictive insights.
- Example: Anomaly detection in power converters.



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FRAMEWORK AND ARCHITECTURE

Digital Twin Structures and Cyber-physical Integration

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CHALLENGES & PROPOSED SOLUTIONS

Challenges:

Singular Digital Twin

- ❑ Computational burden.
- ❑ Scalability.
- ❑ Interoperability.
- ❑ Maintenance &reconfigurations.

Proposed solution:

Hierarchical Digital Twin

- ✓ Distributed processing.
- ✓ Continuous integration.
- ✓ Standardization.
- ✓ Modular approach.

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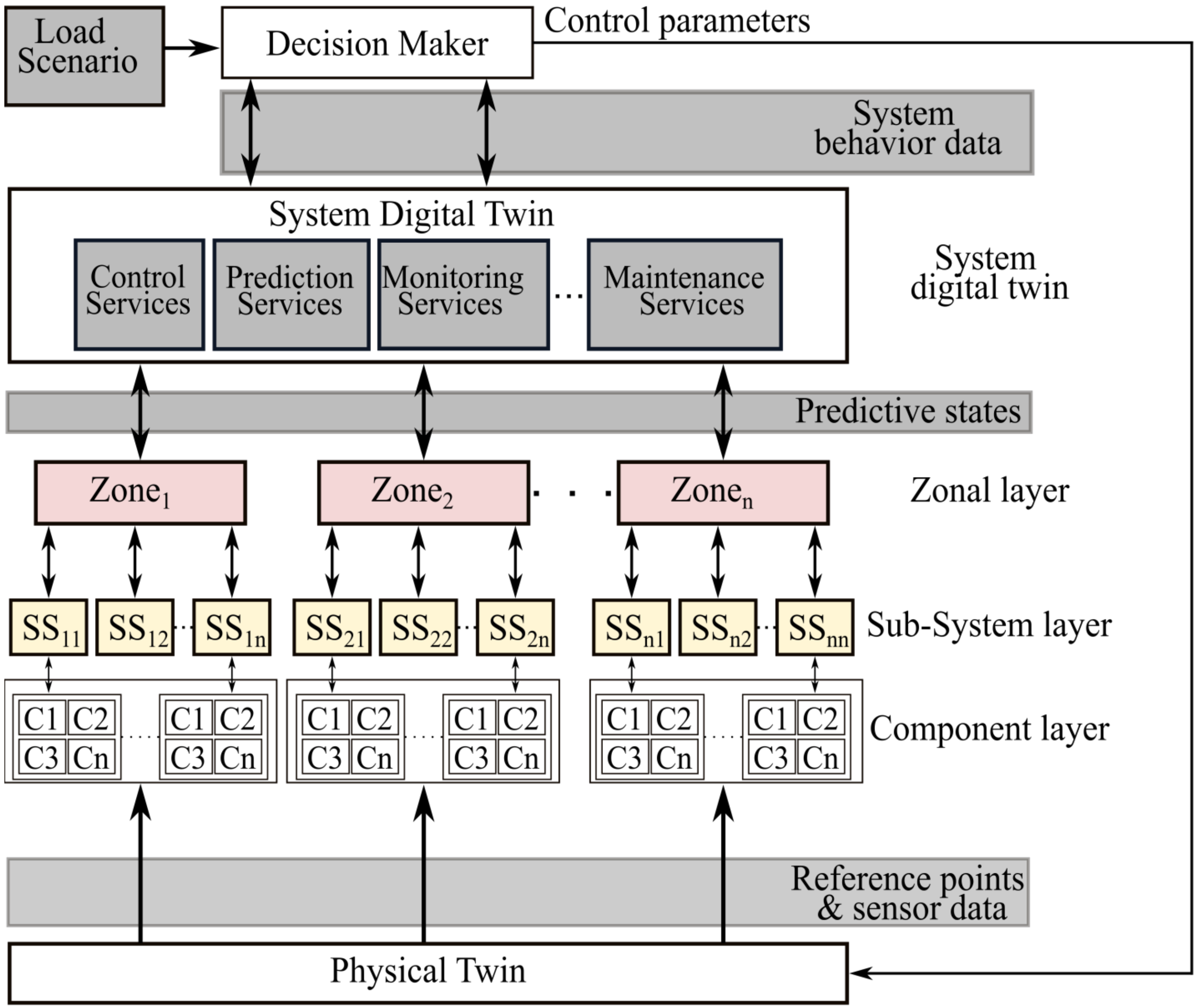

HIERARCHICAL DIGITAL TWIN

- ✓ Distributed processing.
- ✓ Continuous integration.
- ✓ Standardization.
- ✓ Modular approach.

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UNIVERSITY OF SOUTH CAROLINA

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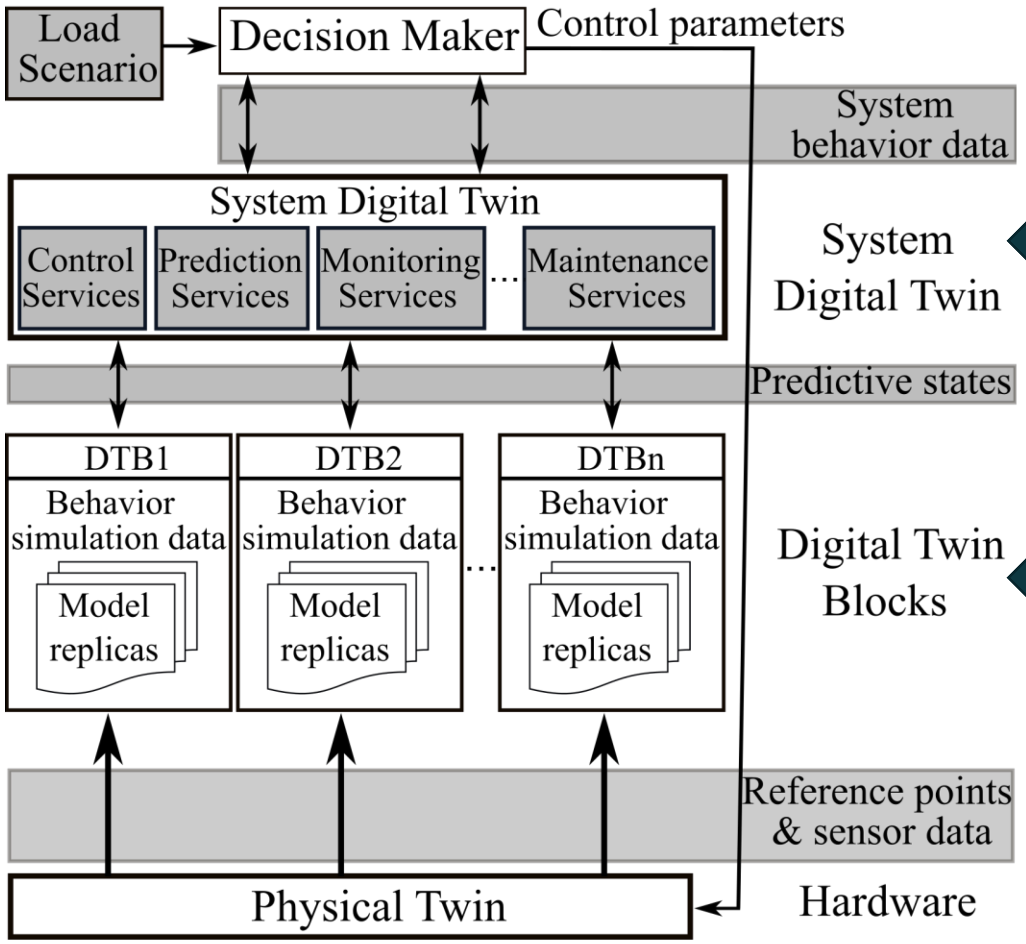
TWO-LAYERED HIERARCHICAL DT

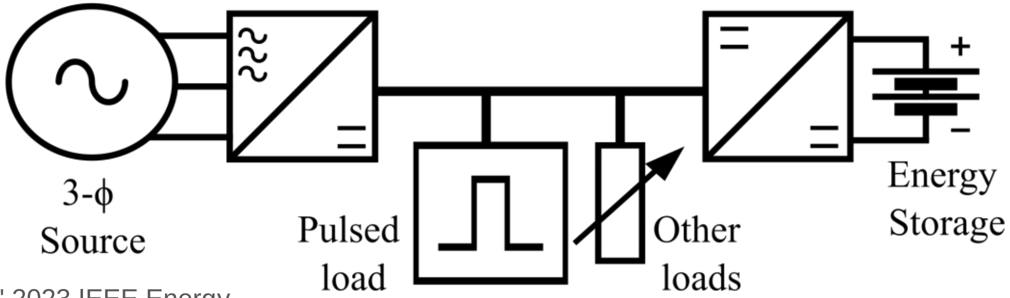


System Digital Twin (SDT):

- Communicates with DTBs and interacts with a decision maker.

Digital Twin Blocks (DTBs):

- Represents one or more system components or subsystems.



K. Sado, J. Hannum, E. Skinner, H. L. Ginn and K. Booth, "Hierarchical Digital Twin of a Naval Power System," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1514-1521, doi: 10.1109/ECCE53617.2023.10361999.

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NEW DEFINITIONS

Multi-function DT:

- Handles a wide range of representation tasks.
- Uses different types of fidelities to achieve different objectives and outcomes.

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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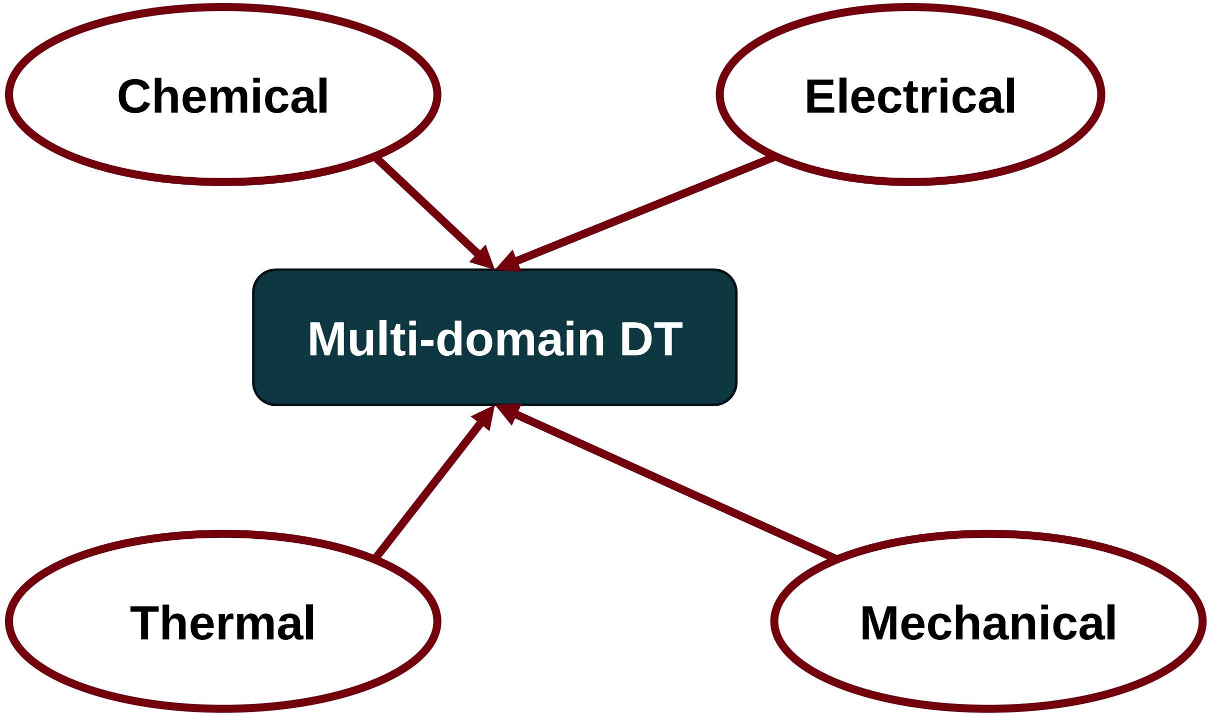
NEW DEFINITIONS

Multi-domain DT:

- Represents the behavior of the asset across multiple physical domains.
- includes electrical, mechanical, thermal, or other domains, depending on the nature of the physical asset.



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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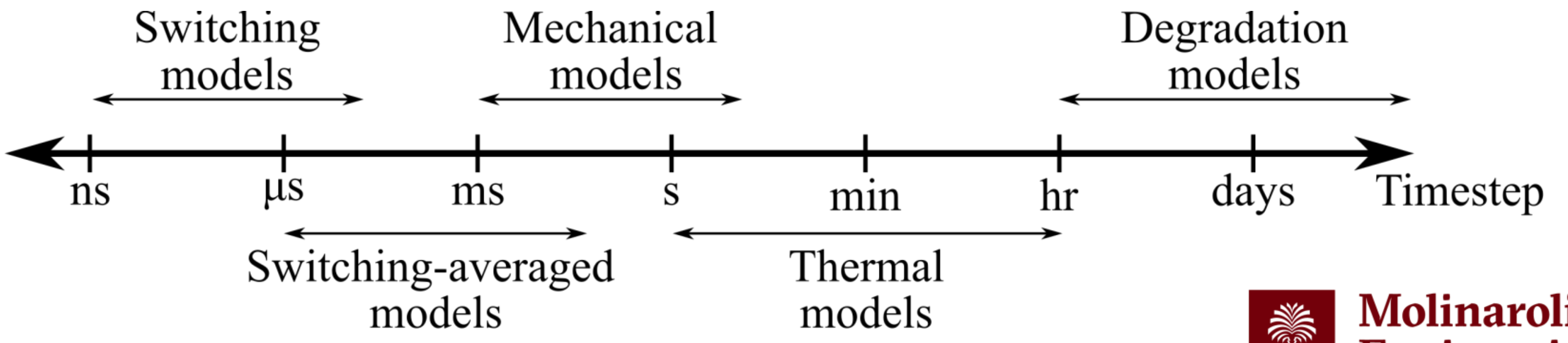
BALANCING FIDELITY AND DOMAINS

- It is desirable for DTs to support a variety of queries.
- A one-size-fits-all DT representation increases computational costs due to its inability to scale down for simpler queries.
- Combining multiple domains or abstraction levels at similar timescales may result in computational inefficiencies and timestep-related inaccuracies.



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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DEFINITION OF DIGITAL IMAGES

- Individual representations that capture varying levels of detail specific to segments of the PT.
- Ensure each domain or segment has a specialized representation within the unified DT framework.
- Grouped within a DT.
- Can be selectively activated by the decision maker for targeted queries.

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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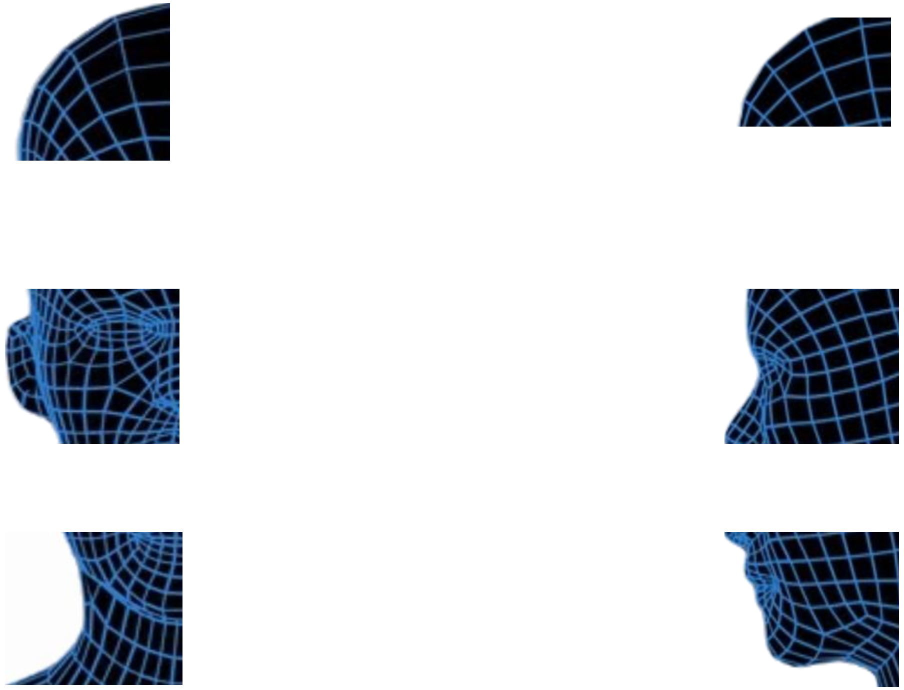

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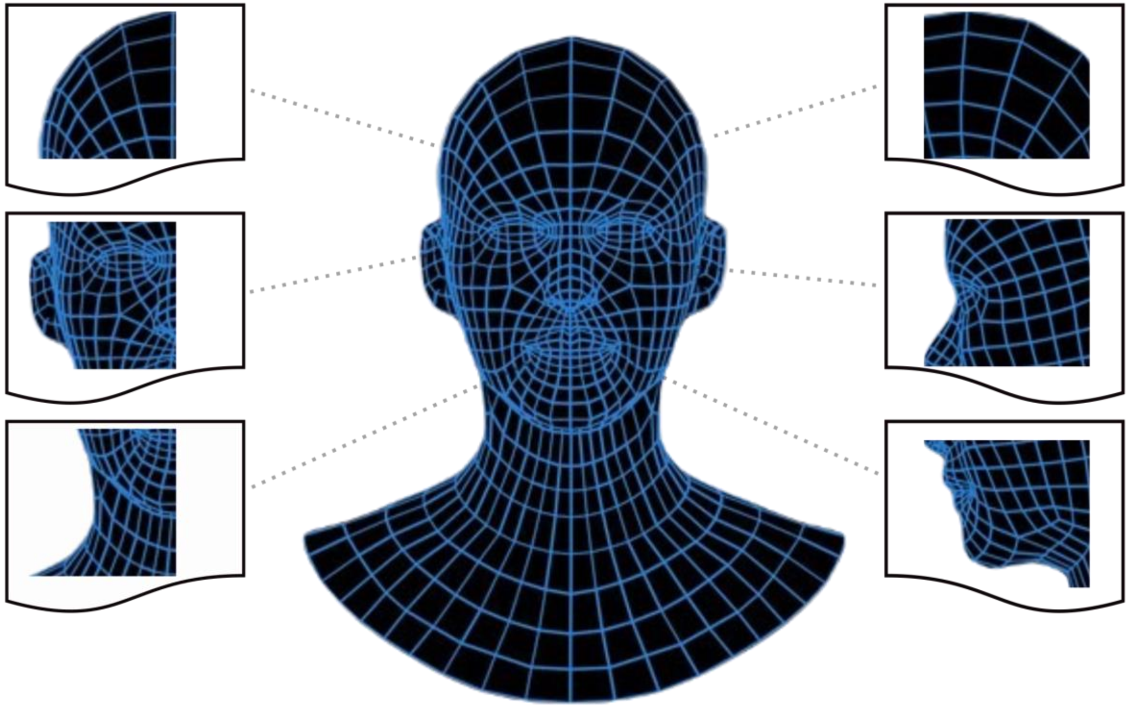

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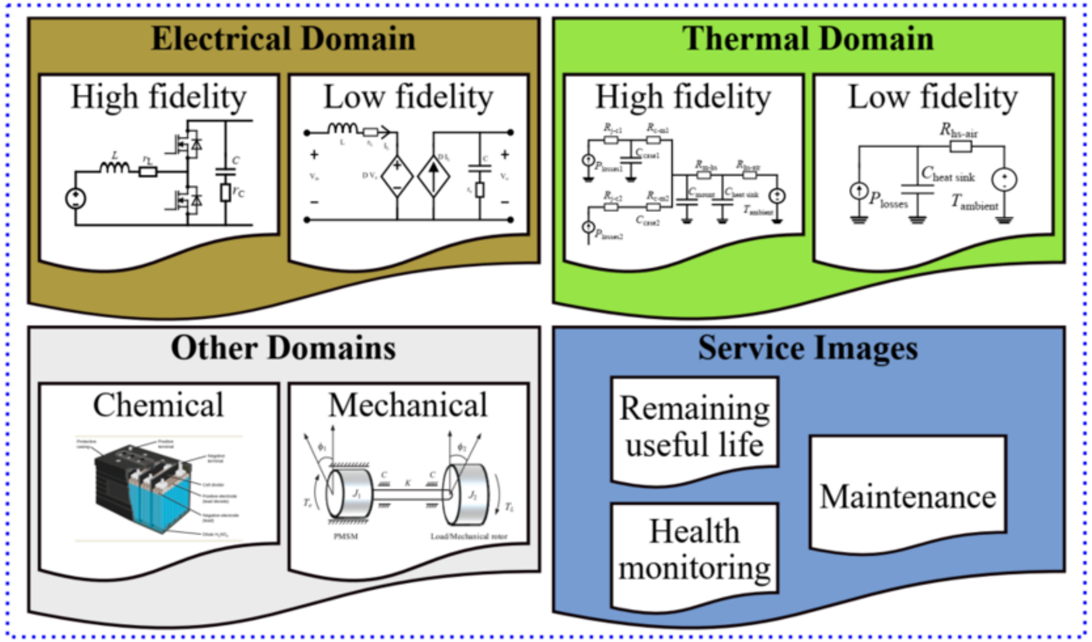
DIGITAL IMAGE FUNCTIONALITY

- Multiple digital images can be uploaded to a DTB to provide responses to queries.
- A digital image can vary in fidelity and/or physical domain.
  - Electrical images.
  - Thermal images.
  - Service images.
- A folio of digital images creates a holistic representation set of a component or subsystem.



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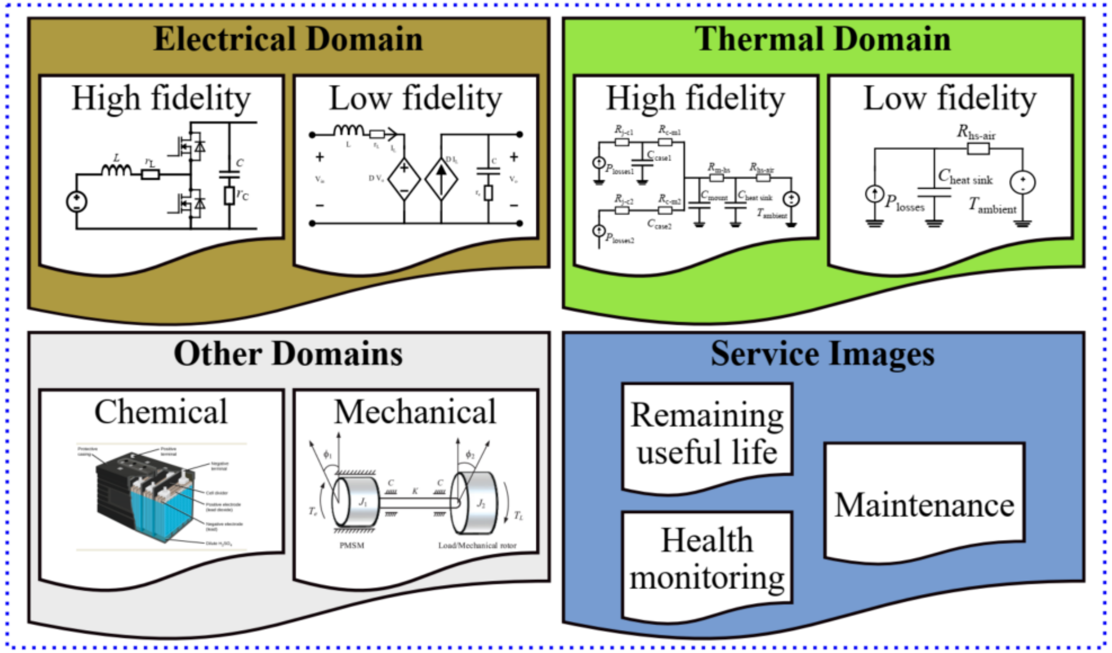
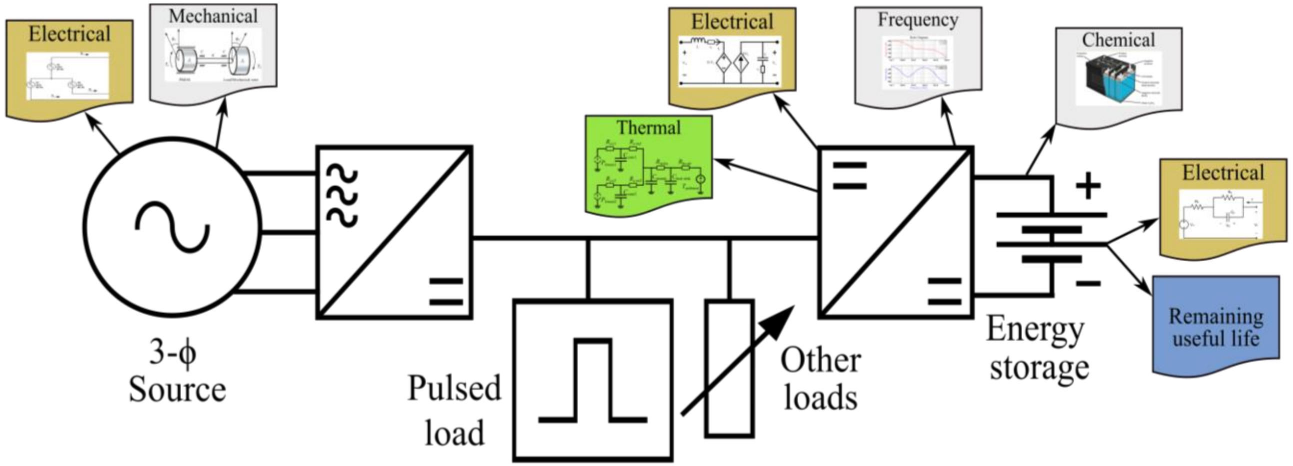
BUILDING A FOLIO OF DIGITAL IMAGES





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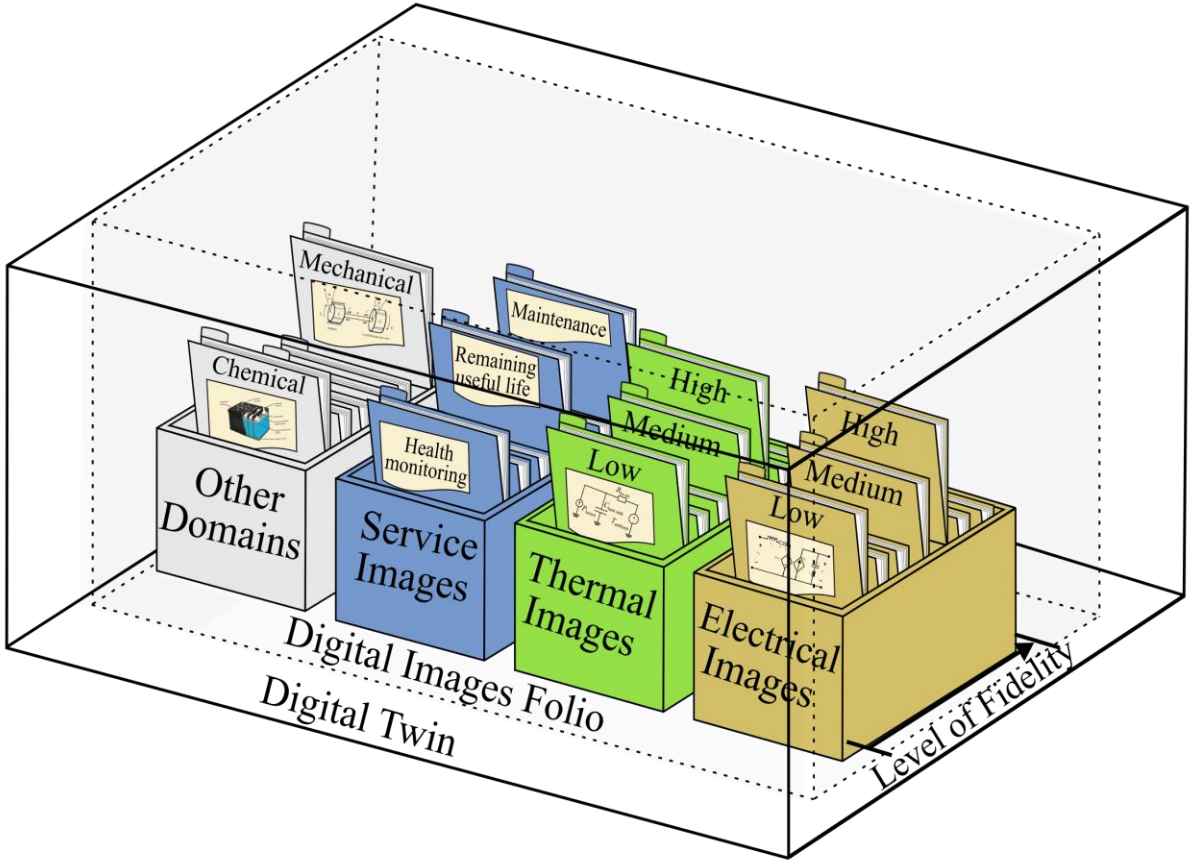
BUILDING A FOLIO OF DIGITAL IMAGES

- A folio of digital images creates a holistic representation set of a component or subsystem.
- Digital images can calculate quantities that are not typically measured in the hardware.
- Digital images can run independently, in a sequential order, or in parallel, depending on the specific query.



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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QUERY-IMAGE MAPPING ALGORITHM

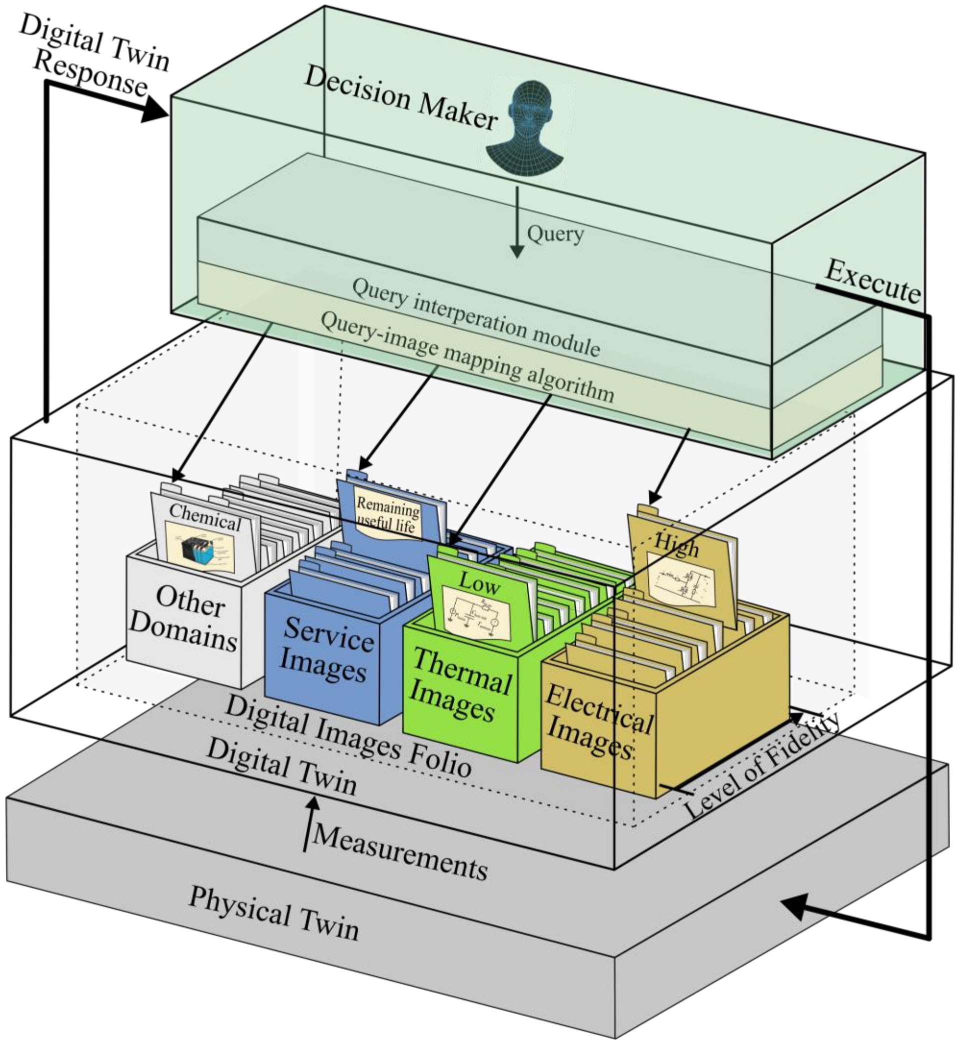

Image Activation:

- Unique identity.
- Database of keywords & context.
- Query interpretation module.
  - Natural language processing.
- Query-image mapping algorithm.
  - Dependency mapping.
  - Composite query handling.
  - Activation.

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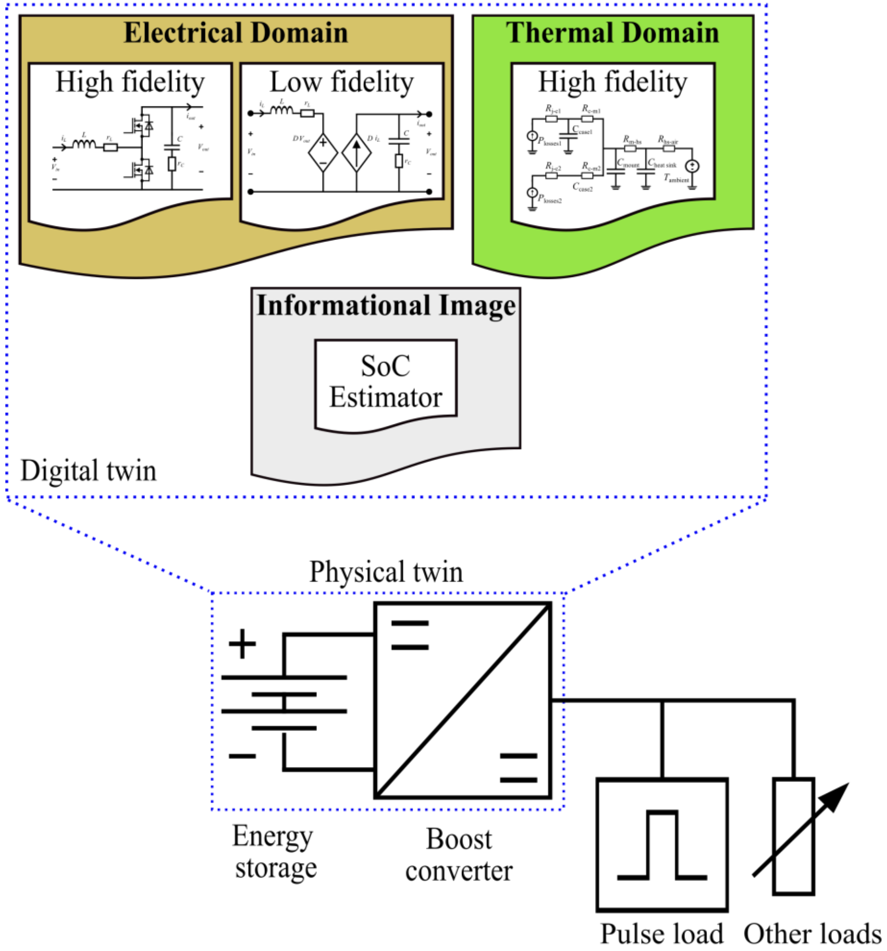
DEMONSTRATOR

- In this demonstration, the DT contains a folio of four images with the following abilities:
  - Replicates the thermal behavior of the converter.
  - Estimates the State of Charge (SoC) of the energy storage through indirect measurements.
  - Responds to written queries from the decision maker.



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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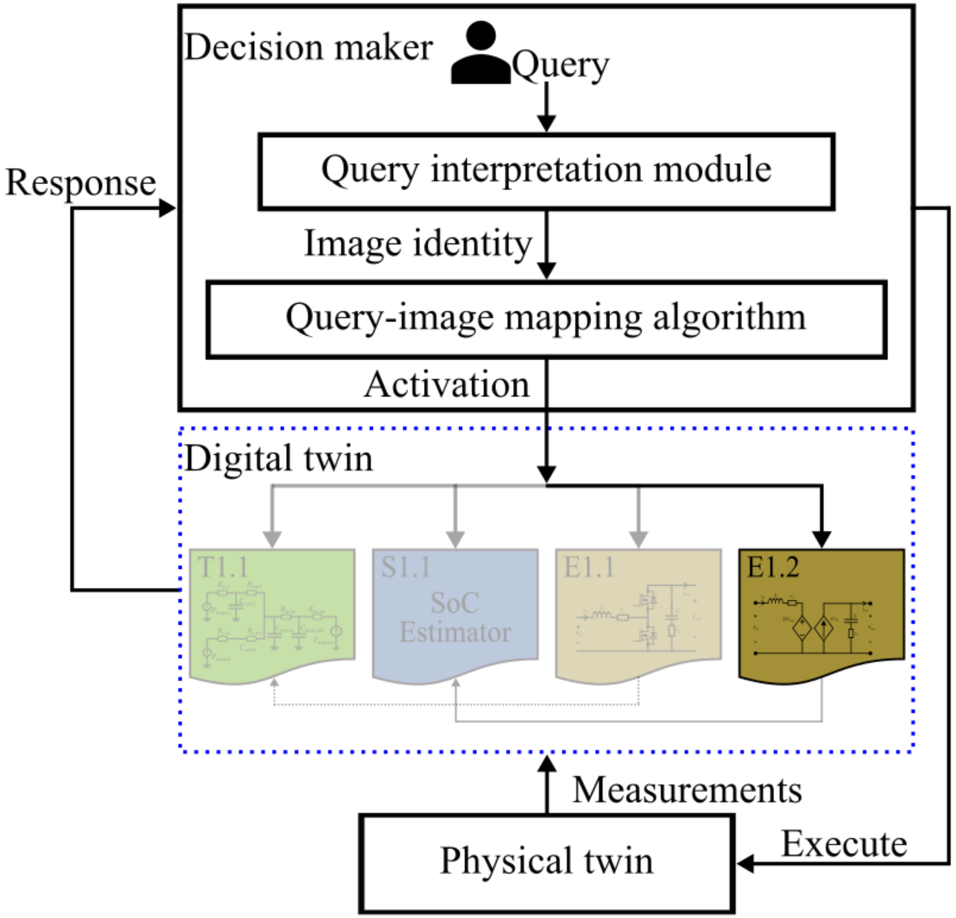
EXAMPLE QUERY

Digital Images Assigned IDs, Dependency & Context

Digital image	Assigned ID	Keywords	Context	Dependent image ID
Electrical domain high fidelity switching	E1.1	Electrical	Switching	None
Electrical low fidelity switching-averaged	E1.2	Electrical	Low	None
State of charge estimator	S1.1	Charge	State	E1.2
Thermal domain high fidelity	T1.1	Thermal	Behavior	E1.1



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EXAMPLE QUERY

Query: "***Display the thermal behavior of the converter.***"

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Electrical domain high fidelity switching	E1.1	Electrical	Switching	None
Electrical low fidelity switching-averaged	E1.2	Electrical	Low	None
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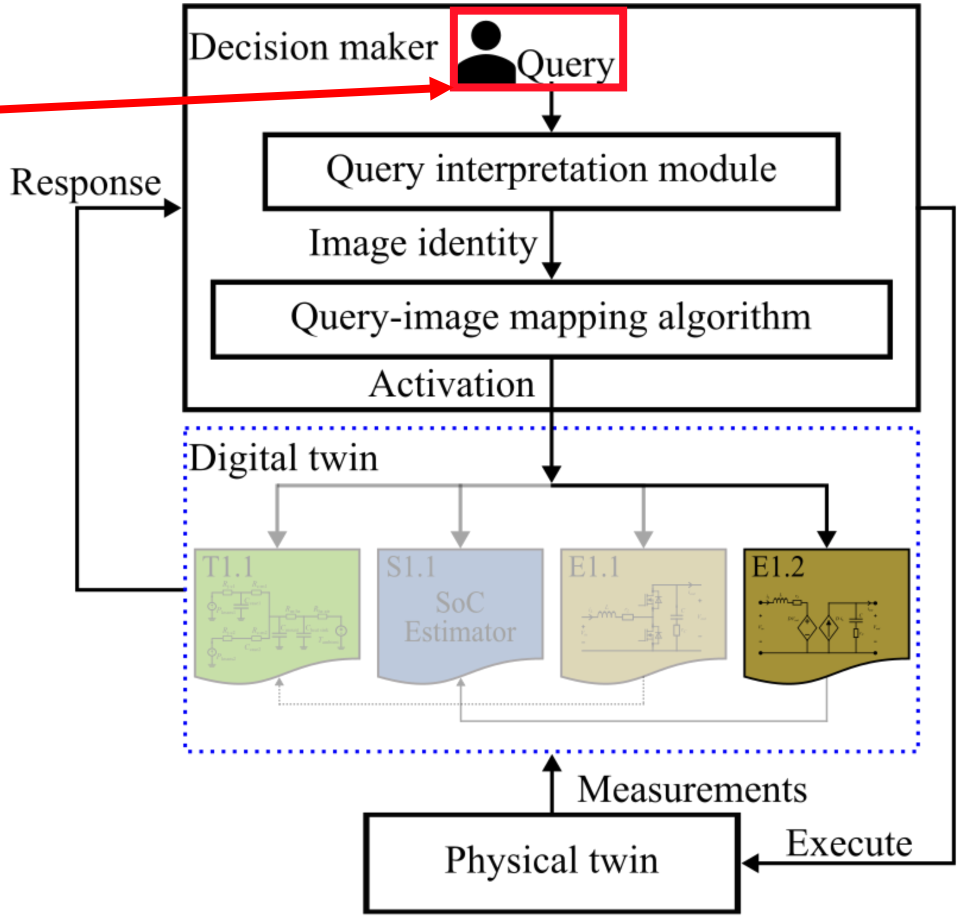
Thermal domain high fidelity	T1.1	Thermal	Behavior	E1.1



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EXAMPLE QUERY

***Query*: "*Display the thermal behavior of the converter.*"**

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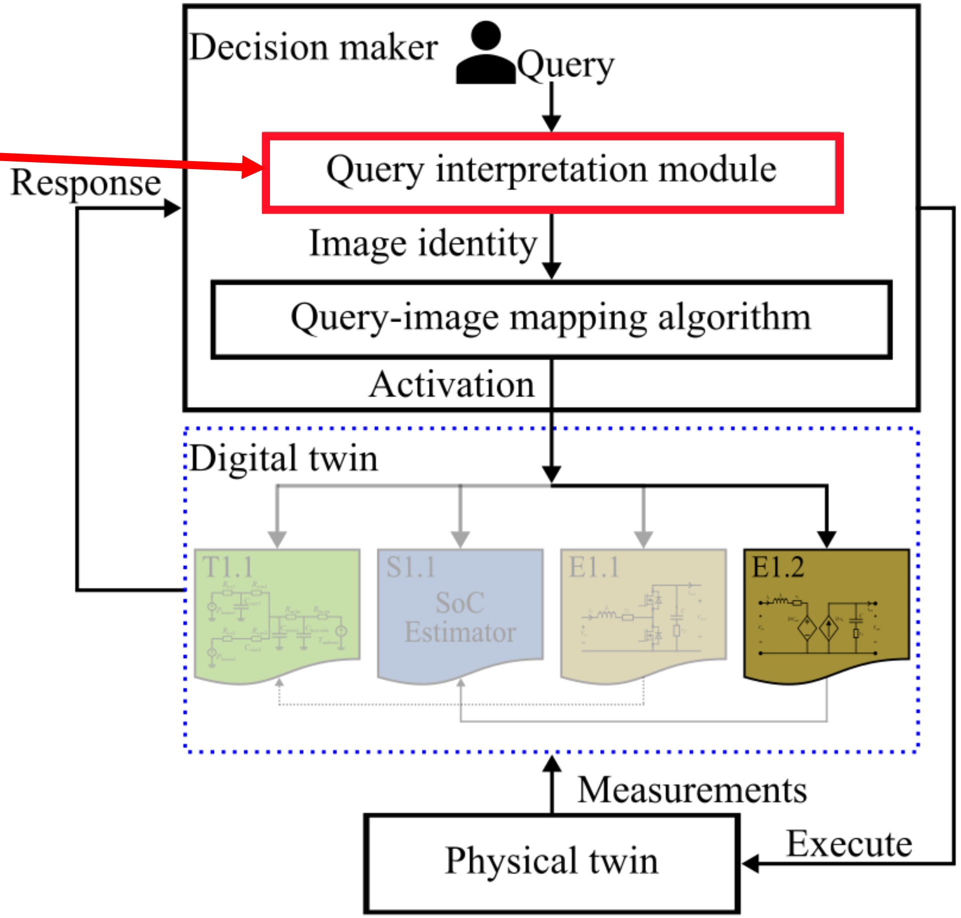

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EXAMPLE QUERY

***Query*: "*Display the thermal behavior of the converter*."**

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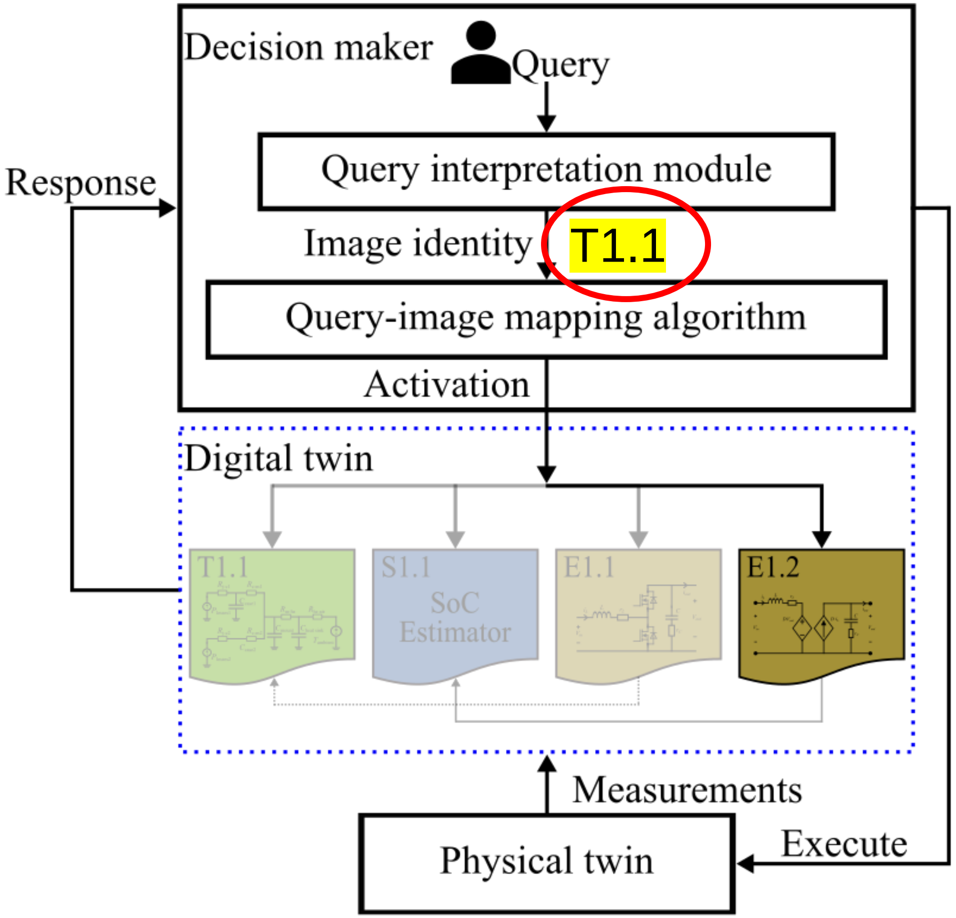

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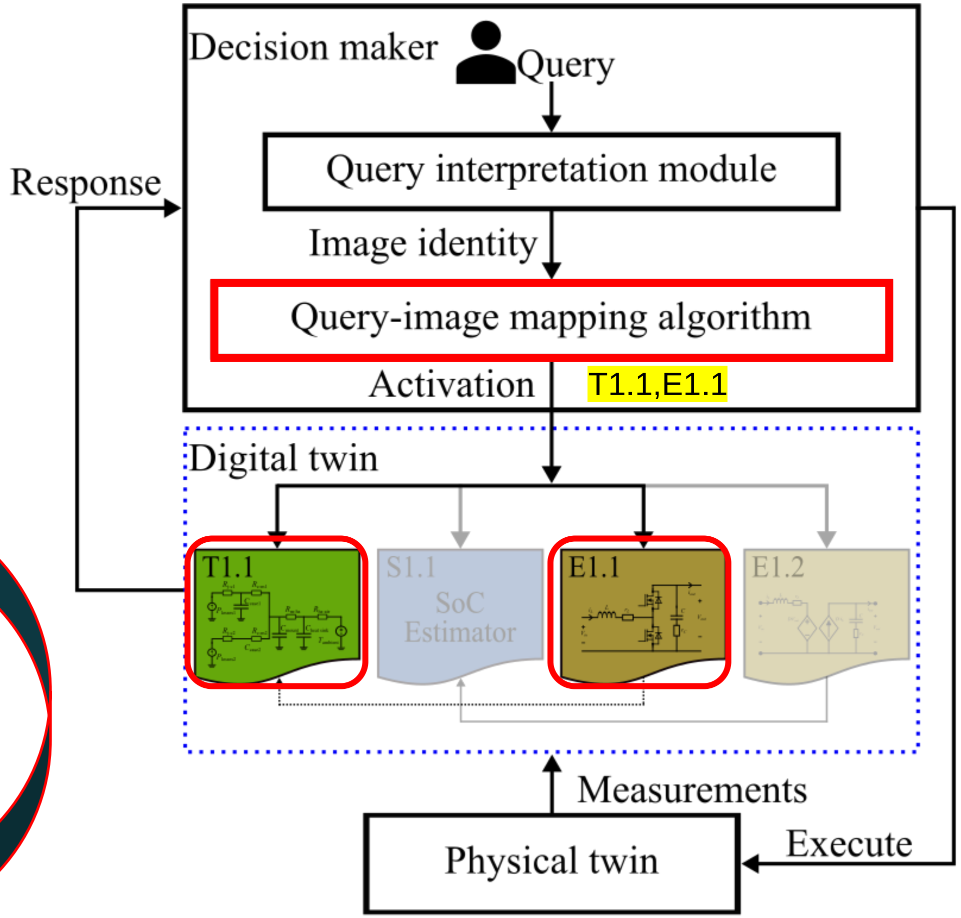

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FORECASTING USING DIGITAL TWINS

Requirements and assumptions

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Molinaroli College of Engineering and Computing

Energy Optimization Laboratory

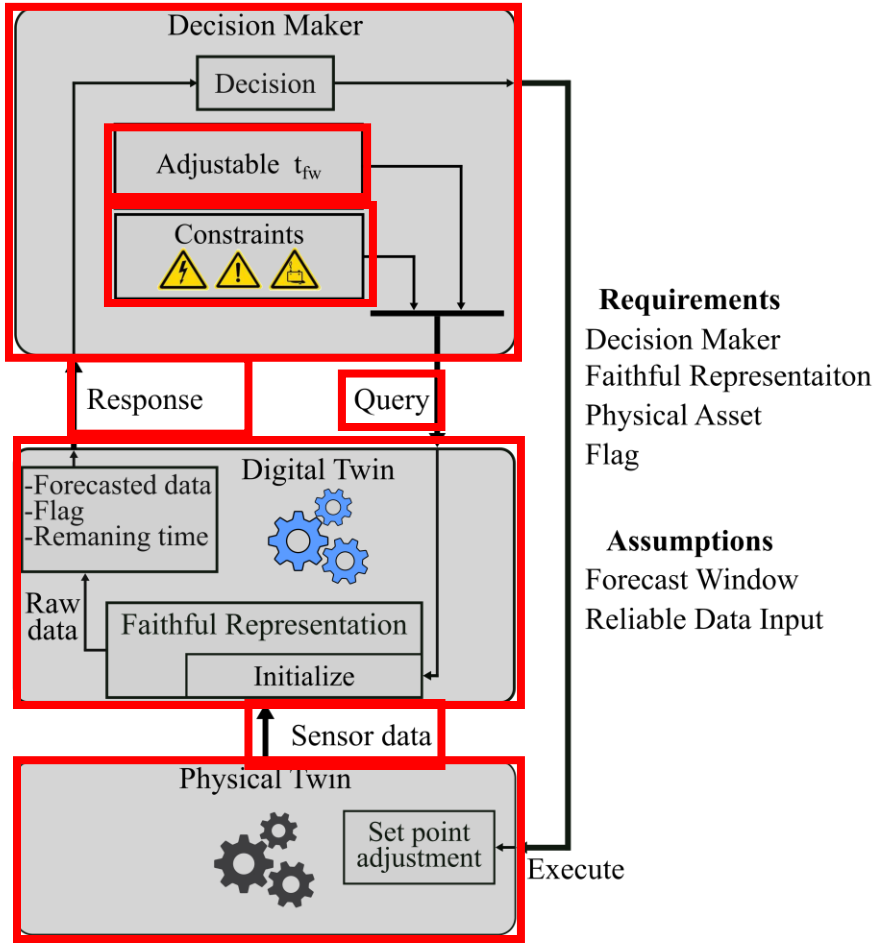
FORECASTING USING DIGITAL TWINS

Design requirements:

a) A physical asset to monitor.
b) Faithful representation of the asset.
c) A decision maker.
d) Forecasting window, t_{fw}.
e) Flag.

Design assumptions:

i. Monitoring a constraint.
ii. Reliable Data Input.
iii. Adaptable forecasting window.



Kerry Sado, Jarrett Peskar, Austin Downey, Jamil Khan, Kristen Booth. Forecasting Framework for Digital Twins , 01 July 2024, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-4570932/v1]

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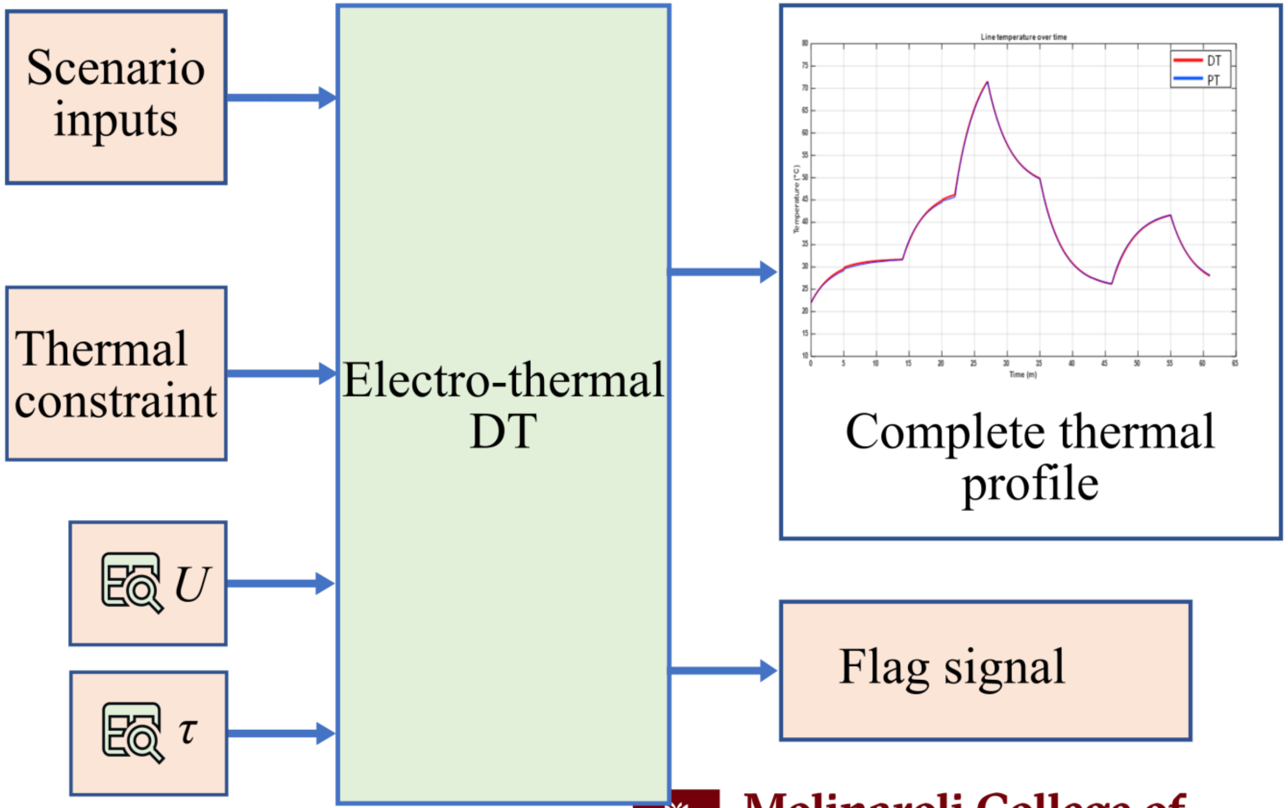
ELECTRO-THERMAL DIGITAL TWIN OF CABLE

- Potential mission segments are provided to the DT.
- A thermal profile is generated.
- A flag alerts the decision maker if constraints are exceeded.



K. Sado, R. Hainey, J. Peralta, A. Downey and K. Booth, "Digital Twin Model for Predicting the Thermal Profile of Power Cables for Naval Shipboard Power Systems," 2023 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 2023, pp. 299-302, doi: 10.1109/ESTS56571.2023.10220549.

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FORECASTED PROJECTION EXAMPLE

SCOPE
South Carolina Org. for Power & Energy
EOL
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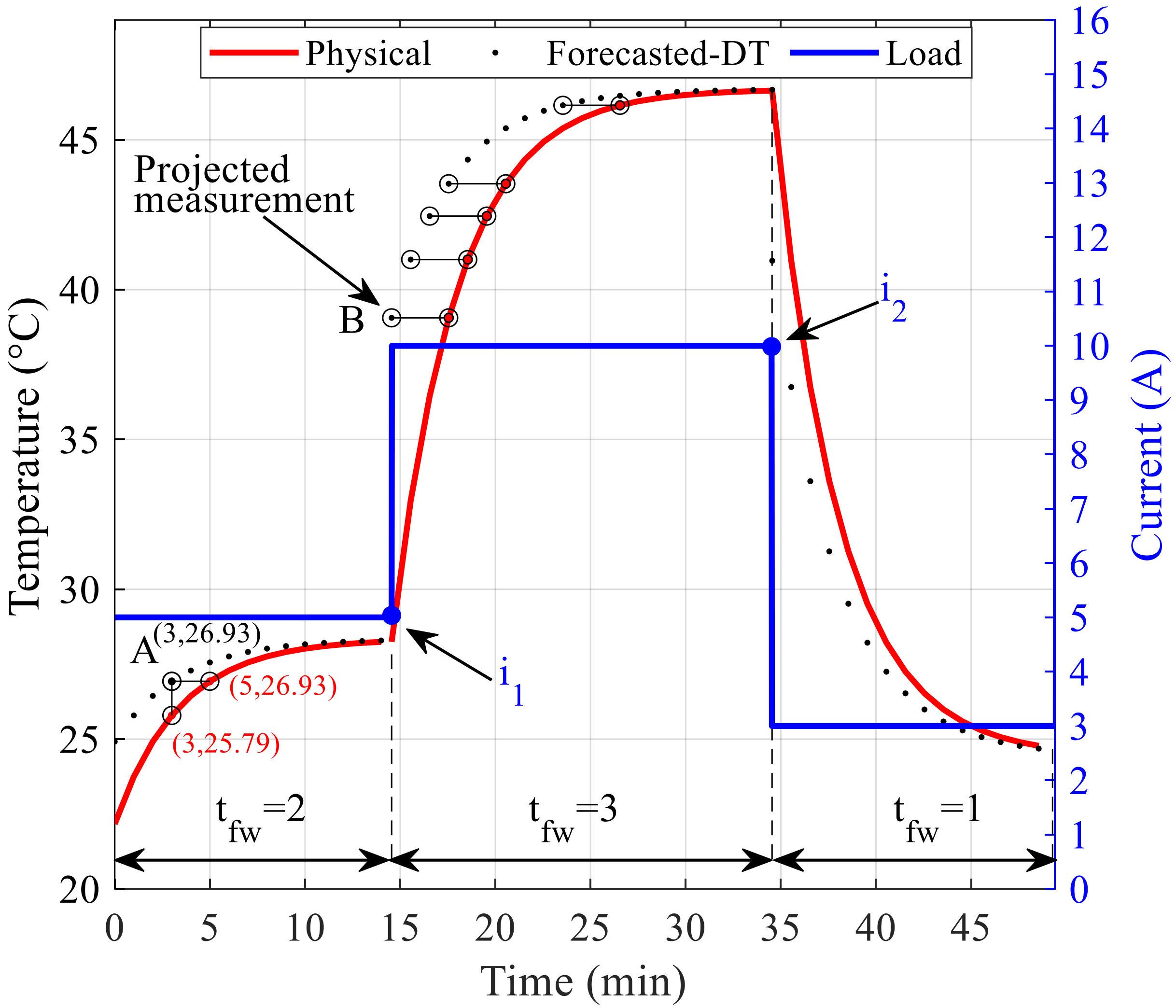

Point A is forecasted data.

- Forecast window, t_{fw}, set for 2 minutes.
- Horizontal line is the forecasting window.
- Vertical line is the instantaneous difference between measured data and the projection.

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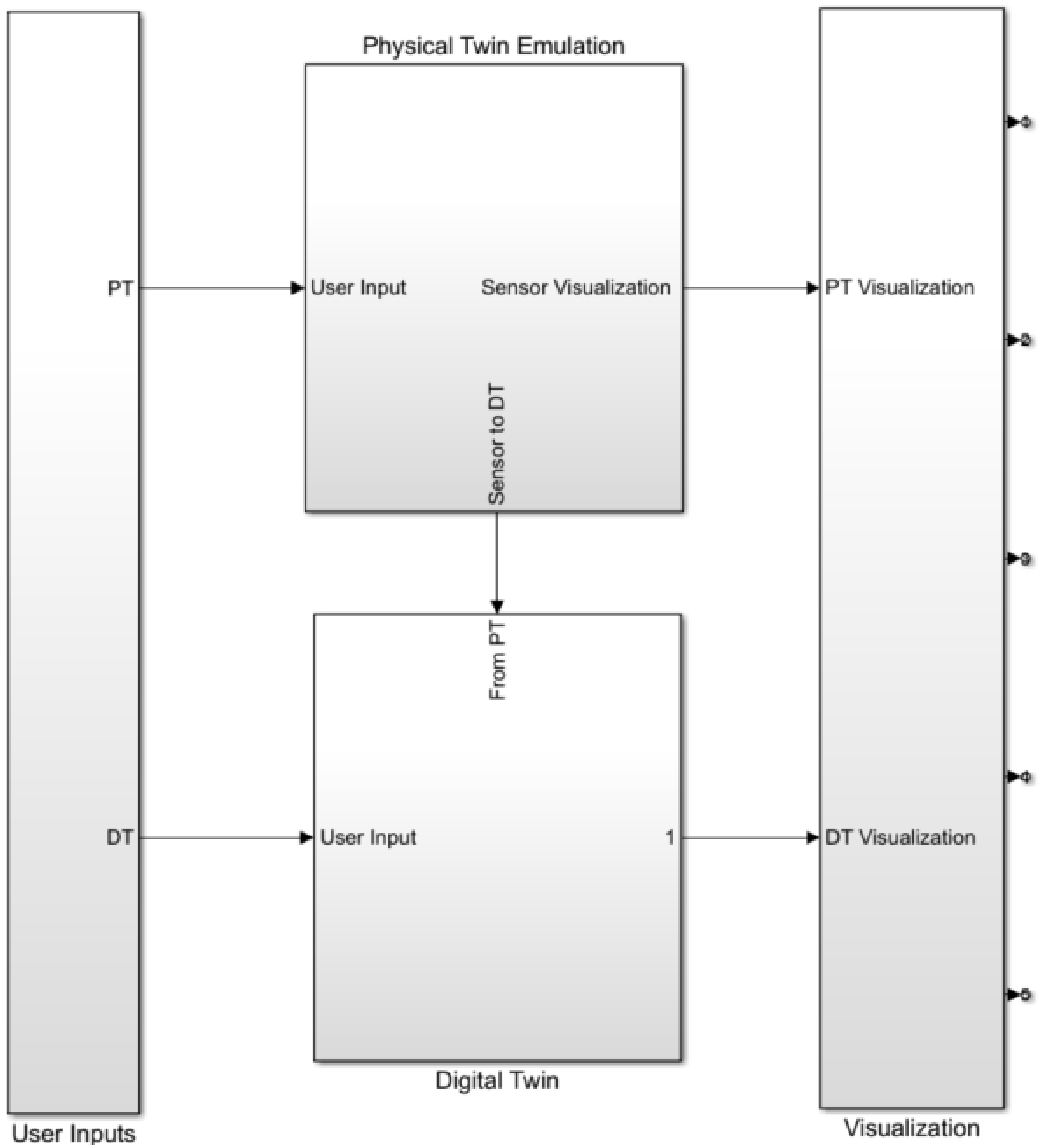
HANDS ON

Forecasting via digital twin:

- Thermal digital twin of a heating pad.
- Forecasts the thermal behavior in real-time.

HANDS ON


Physical Twin Emulation
PT
User Input
Sensor Visualization
Sensor to DT
From PT
DT
User Input
1
PT Visualization
DT Visualization
User Inputs
Digital Twin
Visualization

THANKS!

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