Accelerating Digital Twin Research and Engineering

CAS 782 - Engineering Digital Twins

McMaster University
March 27th 2025

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About Me

POLYTECHNIQUE MONTRÉAL
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M.Sc. and PhD
McGill University
2011-2018

Master's: **Evolving game AI**

PhD: **Model transformation verification**

NECSIS Network: Automotive academia-industry collaboration

Research stay of two months at GM

NSERC CRSNG

IBM

gm

Automotive Partnership Canada

Malina SOFTWARE CORP.

McMaster University

UBC THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

UNIVERSITY OF WATERLOO

1st post-doc

U of Antwerp

Belgium

2018-2021

Functional safety V&V with Siemens and Dana:

Machine Learning-based Fault Injection for Hazard Analysis and Risk Assessment*

Co-simulation configuration with Siemens and Boeing:

HintCO – Hint-Based Configuration of Co-Simulations

DTDesign project with various companies:

Improving Digital Twin Experience Reports

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Université de Montréal

2nd post-doc
U of Montréal
2021-2023

Assisting domain experts in using ML:

Building Domain-Specific Machine Learning Workflows: A Conceptual Framework for the State-of-the-Practice

Tool for ontology construction from NASA JPL:

openCAESAR: Balancing Agility and Rigor in Model-Based Systems Engineering

Continuing Digital Twin work:

EXAMINING MODEL QUALITIES AND THEIR IMPACT ON DIGITAL TWINS

Assistant Prof
Polytechnique Montréal
2023-present

Objective: **A**ccelerating **K**nowledge **E**ngineering for Complex **S**ystems

Tools and techniques: Ontological modelling and analysis, model-based engineering, machine learning, generative AI, co-simulation, 3d game engines

Current Research Focus: *Accelerating and Systematizing Digital Twins Engineering*

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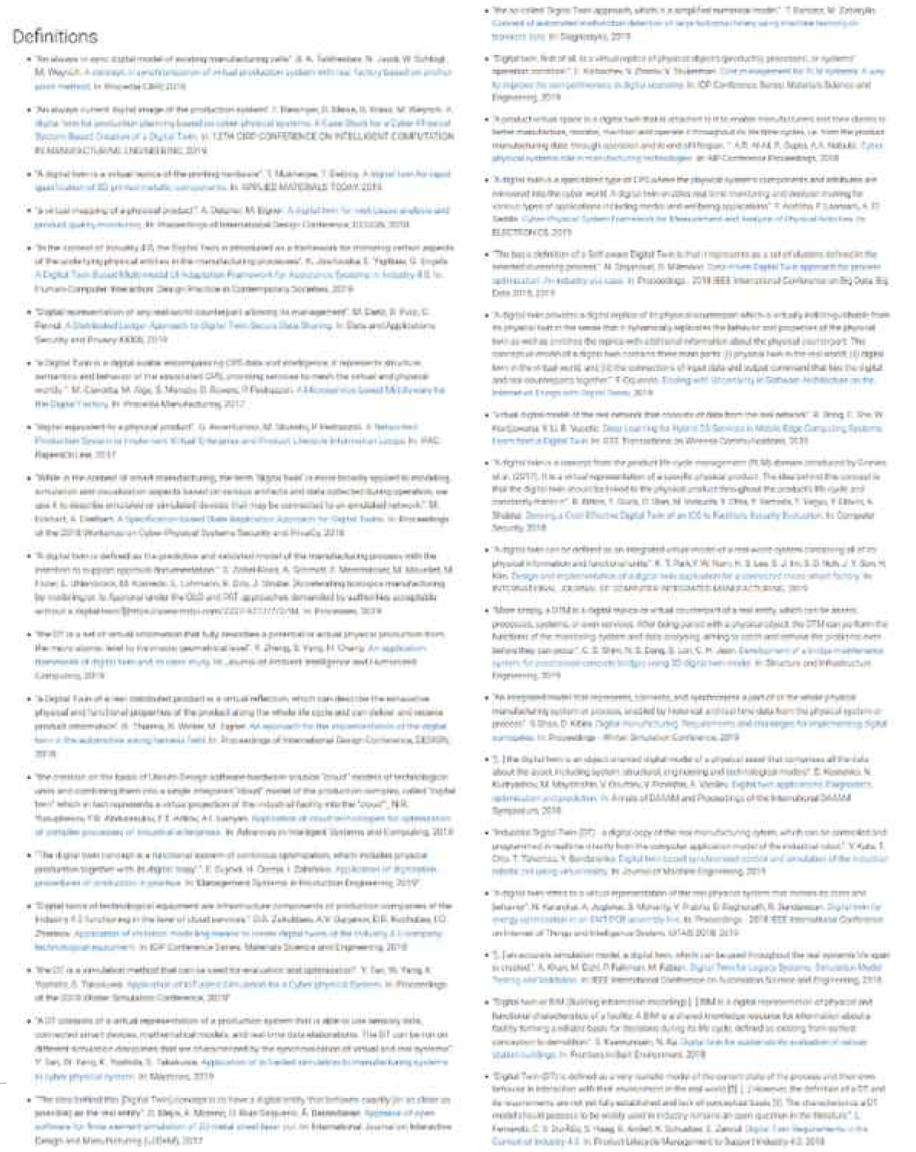
What is a Digital Twin?

“Digital Twin” Definitions

Collection of **112 definitions**:

https://awortmann.github.io/research/digital-twin-definitions/

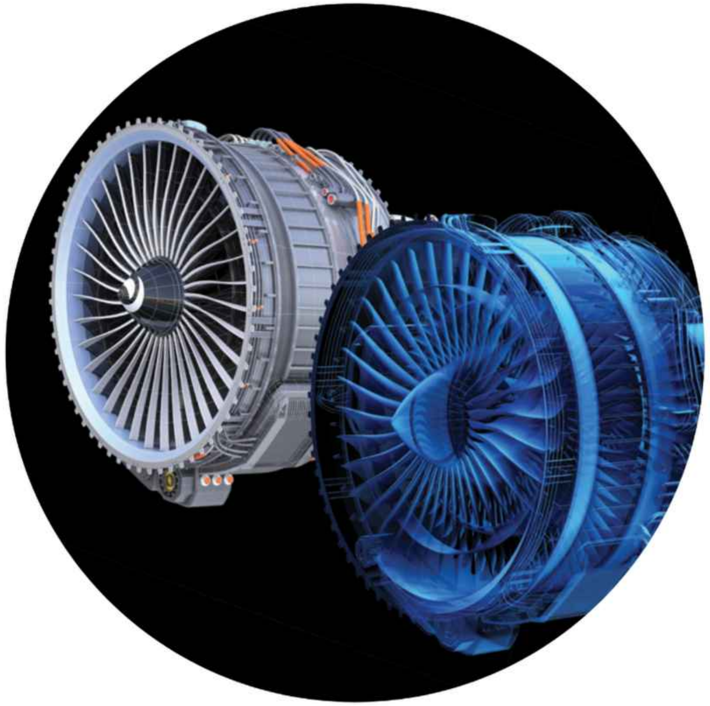

Definitions

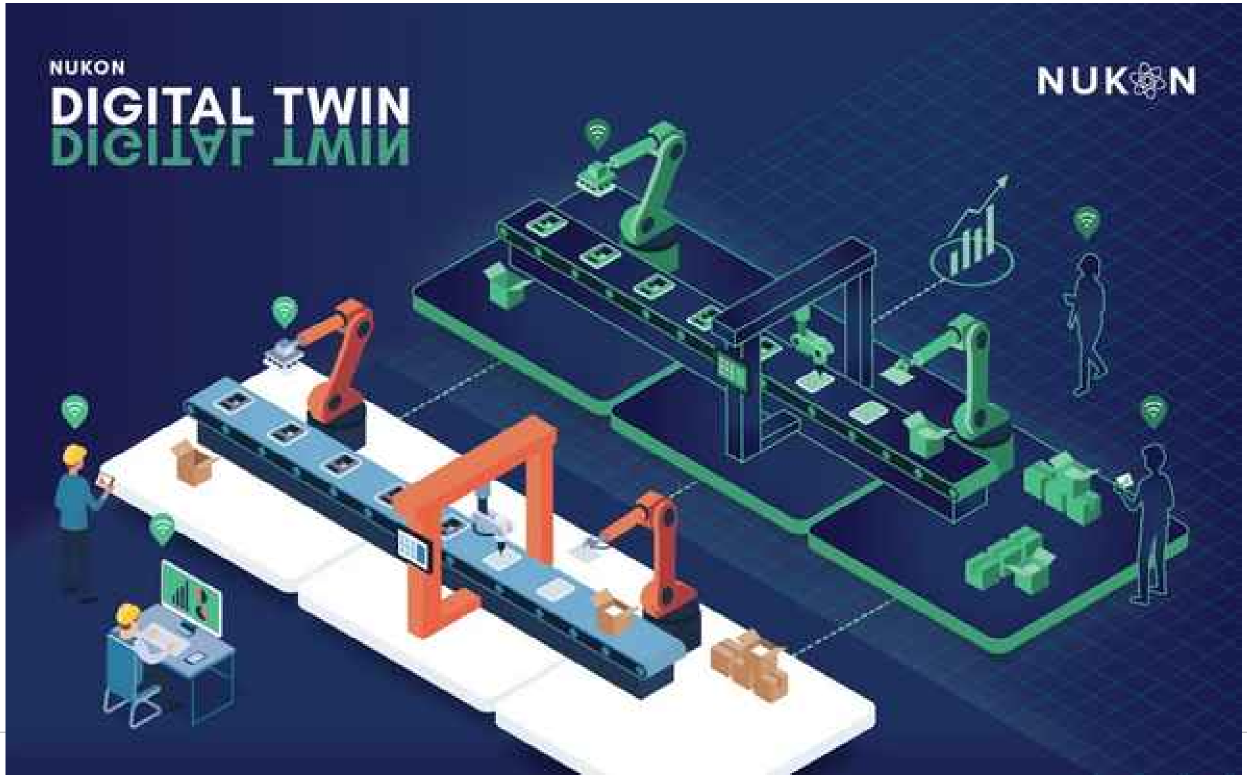
Core Idea: “Twinning”

Physical Twin
(Object/
system/process)

“twins”

Virtual Representation





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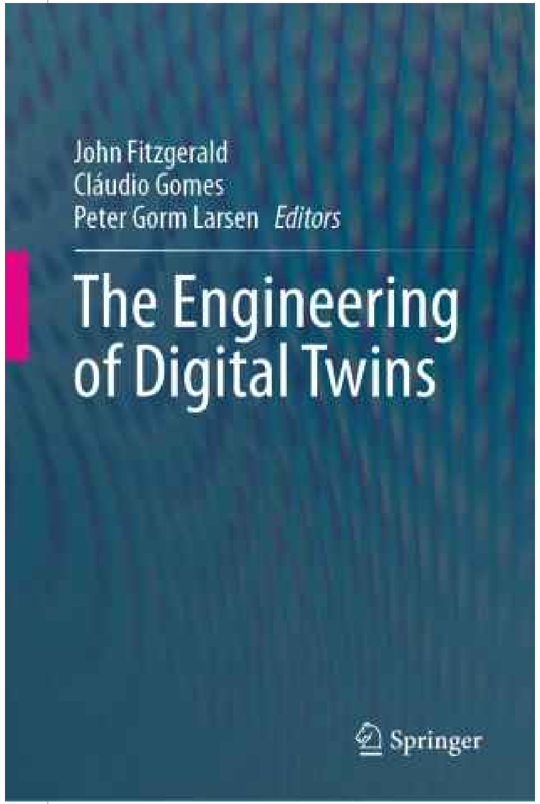
Incubator Example



3.2.1 Tempeh and how to Make it


After Inoculation


Halfway Through Incubation


Final Tempeh "Cake"

"The incubator is a simple system. The goal is to keep the temperature inside an enclosed chamber as **close to as possible to 37.5◦ C**, to promote the fermentation of soybeans to make tempeh."

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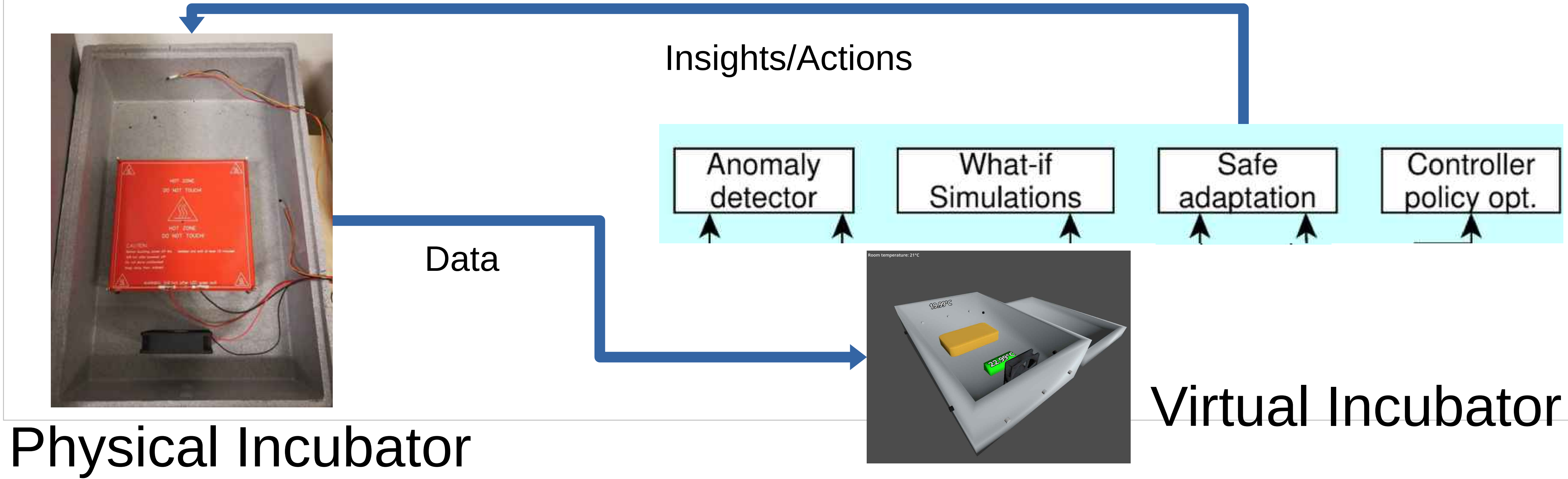
Incubator DT Services

3.2.3 DT-enhanced Tempeh Incubation

1) Present historical data about incubation process to help **spot anomalies**
2) **Energy saving** by adjusting controller settings when lid is open
3) Signalling that **tempeh is ready**, reducing opening of incubator lid
4) Signalling for **maintenance**



Further Digital Twin Services

- **Visualize** system
- **Control** heater
- **Ensure** safety
- Anomaly **detection**
- Find system **improvements**
- Automatic **optimization**
- Predictive **maintenance**
- **Train** users
- Formally **prove** properties
- ...

One More Digital Twin Definition

"dynamic virtual representation of a complex system, for supporting its design and operation"

Digital Twin paradigm =
Modelling and simulation
+ visualization
+ multiple domains
+ real-time/ahead-of-time data/control
+ source of truth for services
+ intelligence (machine and human)
+ integrating and extending as far as possible...

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Systematic DT Reporting

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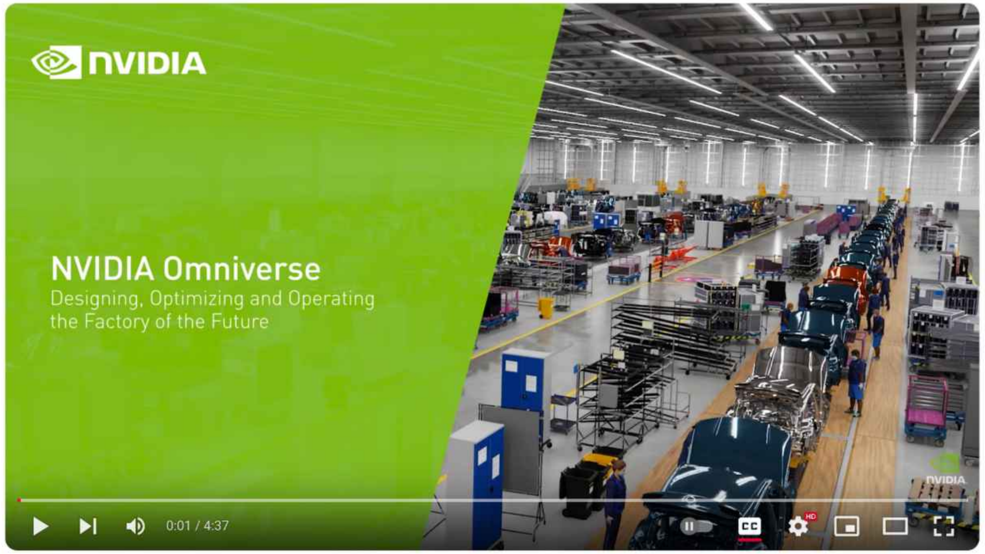
Systematic DT Reporting

Motivation

DT Diversity



NVIDIA Omniverse - Designing, Optimizing and Operating the Factory of the Future

“What Does Your DT Do?”

Instead of arguing about definitions...

Let’s discuss what your DT **is** and **does**

My questions: Is it **real-time**? What are the **services** it provides? How did you **engineer** it?

Unclear Info in Reports

We argue that due to the lack of standardization in Digital Twins, **essential information is not being adequately reported**

Oakes et al.. (2021). *Improving digital twin experience reports*. MODELSWARD (pp. 179-190).

Digital (Model vs Shadow vs Twin)

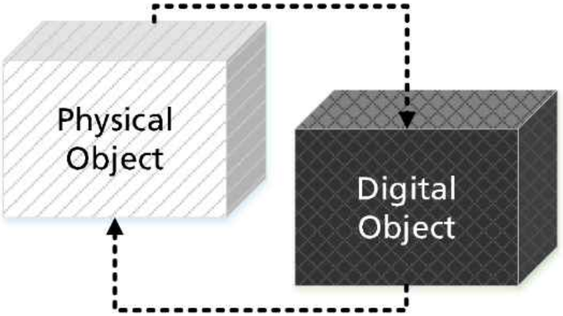


Fig. 1. Data Flow in a Digital Model

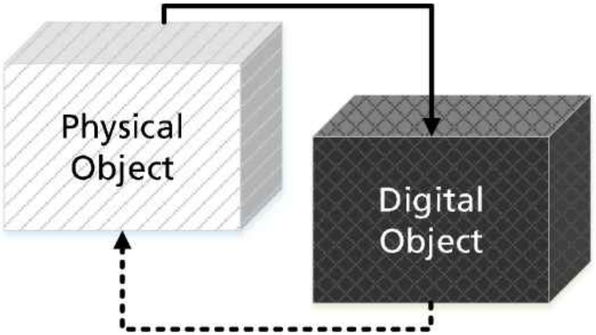


Fig. 2. Data Flow in a Digital Shadow

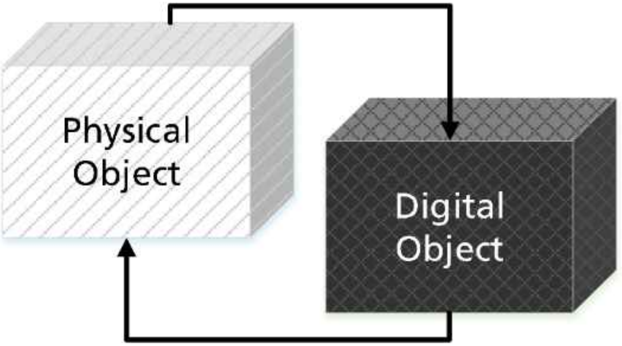
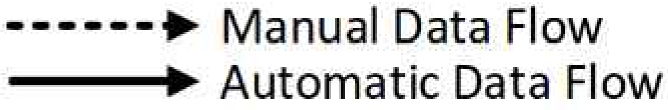
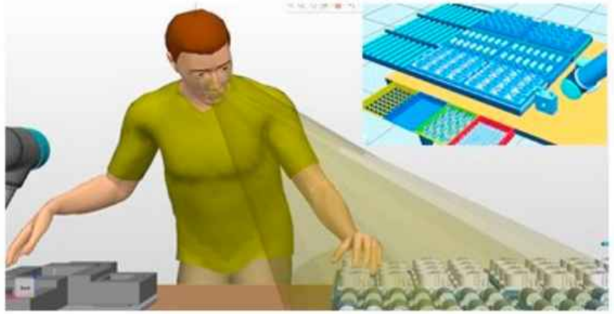


Fig. 3. Data Flow in a Digital Twin

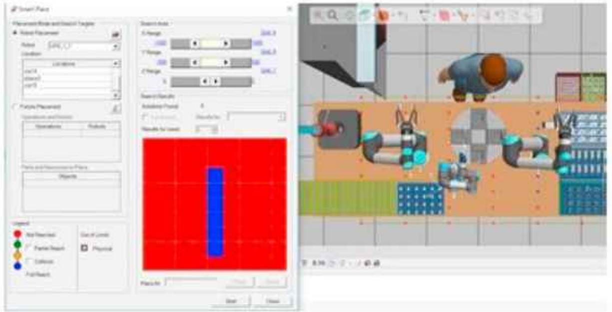


Kritzinger et al. (2018).
Digital Twin in manufacturing: A categorical literature review and classification.
Ifac-PapersOnline, 51(11), 1016-1022.

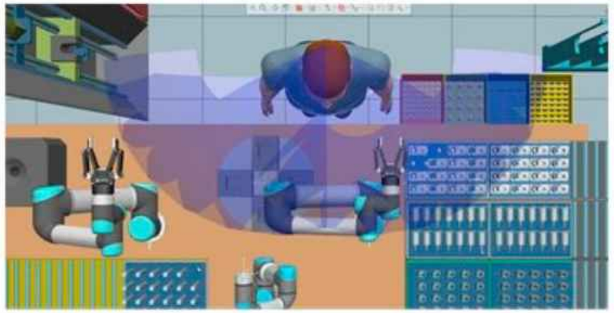
Unclear Info Example



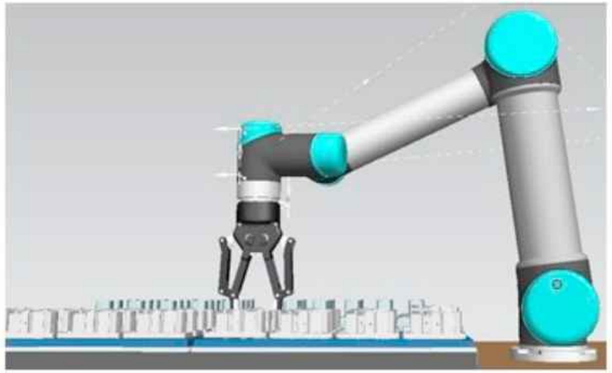
Vision Analysis



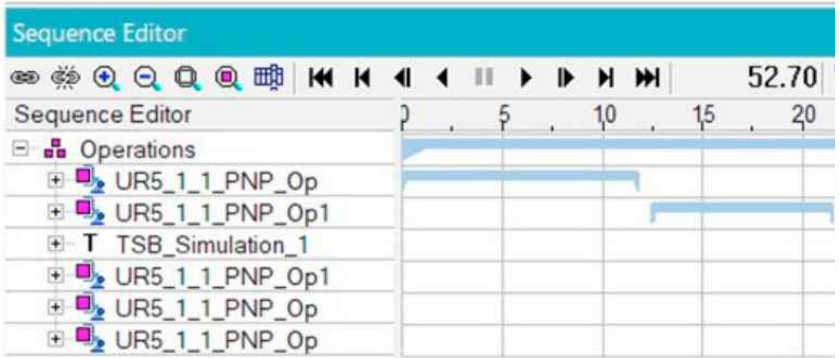
Robot Reach Analysis



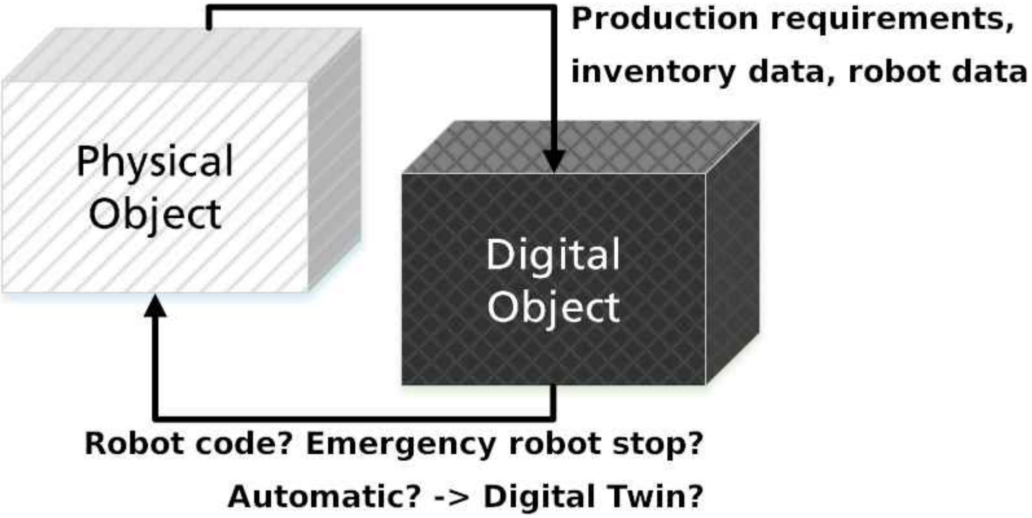
Grasp Analysis



Robot Program



Operation Times



Bilberg & Malik (2019). Digital twin driven human–robot collaborative assembly. CIRP annals, 68(1), 499-502.

Hindering Empirical Research?

Returning to my questions:

What exact **services** are there? What **technology**? What **models**? What were the **engineering milestones** of the DT? Etc.

- Important for both **researchers** and **practitioners** (to know best practices)

- Having all details **explicitly reported** would allow for more detailed empirical research

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Systematic DT Reporting

Reporting Framework

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Reporting Framework Goal

- Define **DT characteristics** to be reported/discussed
- Move towards **common language** (textual and graphical)

- Not to be **enforced** on authors, simply guidance
- Characteristics must be **flexible** and change as needed

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Constructive Intention

Reporting framework is intended to **support** improvement, **not criticize** DT researchers or their papers

Reporting Framework Progress

Oakes et al. (2021). *Improving digital twin experience reports*. MODELSWARD (pp. 179-190).

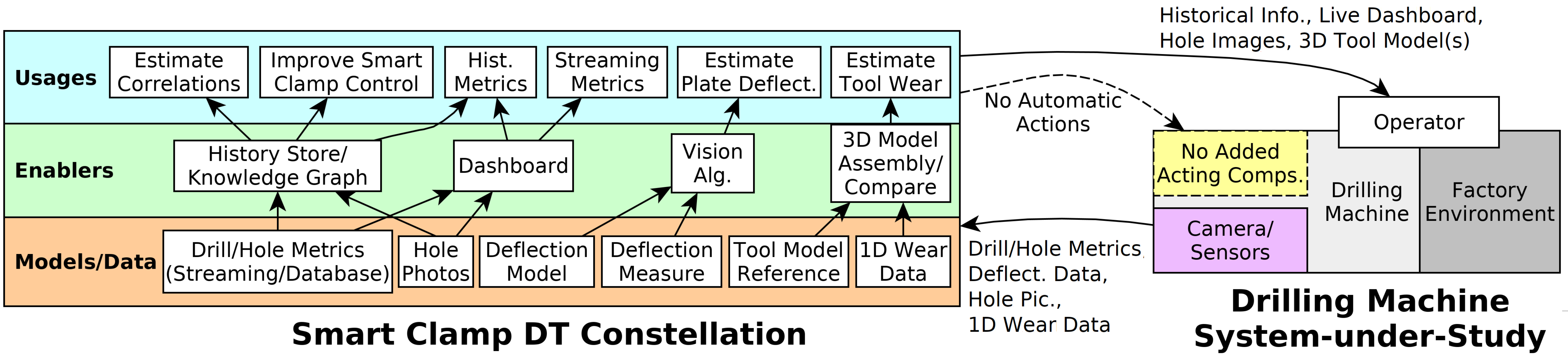
- Defines characteristics to be reported, and ‘constellation’
- Five DTs examined in paper, further fifteen online
- Classification differences found with other papers

Insights / Actions	I: Boat info., service recommendations & offers A: Posting to social networks(?).	I/A(?): AGV code.	I: Performance reports A: Drill control signals.	I: "Analysis data" and recommendation info. A: Control instructions.	I: Production schedule, list of bottlenecks, flow observation.	I/A(?): Production rates suggestions /commands(?).	I: Decision support, prognostics. A: Emergency shutdowns, graceful degradations.	I: None(?) A: Part flow path.	I: Simulated performance, product line design changes A: None	I: Timing mismatch, design for product line, fault warnings.	I/A: Fault detection and localization, quality inference (?).

Reporting Framework Progress

Oakes et al. (2023). *A digital twin description framework and its mapping to Asset Administration Shell*. Selected extended papers of MODELSWARD (pp. 1-24). Springer.

- Expanded description of characteristics
- Application to industrial DT of a “smart clamp” (holds drilled piece steady)
- Mapping of framework to Asset Administration Shell



AAS Mapping

Table 1: Support for the characteristics by the AAS

Characteristic	Support by the AAS
C01. System-under-study	●
C04. Multiplicities	●
C09. Models and Data	●
C10. Constellation	●
C05. Data Communicated	◑
C06. Insights and Actions	◑
C13. Life-cycle Stages	◑
C14. Evolution	◑
C02. Acting Components	◐
C03. Sensing Components	◐
C07. Usages	◐
C08. Enablers	◐
C11. Time-Scale	○
C12. Fidelity Considerations	○

● Explicit support ◑ Partial support ◐ Implicit ○ No support

- Mapping of **explicit/partial/implicit AAS support** for characteristics
- Different concerns: AAS meant for technical/implementation concerns, while reporting framework meant for reporting

DT Systematic Reporting Framework

Gil, Oakes, et al. (2024). *Toward a systematic reporting framework for digital twins: a cooperative robotics case study*. Simulation.

- **18 fundamental characteristics** and **three cross-cutting characteristics** for reporting DT case studies
- Formed by systematically **merging three frameworks** from Oakes, Dalibor, and Jones
- Reports **robotics, mobile robotics, and incubator case studies**

Merging Frameworks

Table 1. DT Characteristics proposed by Oakes et al.[7].

Characteristic	Description
C1: System-Under-Study (SUS)	The PT, its environment, and any agents present
C2: Acting Components	Any additions and modifications to the SUS which enables communication from the DT to the SUS
C3: Sensing Components	Any additions and modifications to the SUS which enables communication from the SUS to the DT
C4: Multiplicities	How many systems and DTs are involved in the DT ecosystem and their relationships
C5: Data Transmitted	The data transmitted from the SUS to the DT
C6: Insights/Actions	The information from the DT to agents in the SUS, or the automatic controlling actions from the DT to the SUS
C7: Services	The activities that the DT is used for. This could also be termed the *capabilities* or *usages* of the DT
C8: Enablers	Computational components which take models and data, and support the services of the DT
C9: Models and Data	The input and output for the enabler components, with some data coming from the SUS
C10: Constellation	The conceptual relationships within the DT of the models/data, enablers, and services
C11: Time-scale	The time-scale of the communication between the DT and SUS, and the computation within the DT. Includes data, insights, actions, and any simulations
C12: Fidelity Considerations	For each DT service, the considerations for fidelity (how the DT represents the SUS)
C13: Life-cycle Stages	The stages of the SUS (*ideation*, *realization*, *utilization*, etc.) which the DT is used for. If the scope of the SUS changes, this should also be reported
C14: Evolution	The evolution of the DT throughout its development (milestones, publications)

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Table 2. DT Dimensions proposed by Dalibor et al.[14].

Dimension	Description and subfeatures
Requirements Dimension	This dimension covers the basic constituents and characteristics of the DT under study. It is characterized by the subfeatures *Counterpart*, *Multiple Representation*, *Usage Phase*, *Representation Phase*, *Asset Interaction*, *Optimization*, and *Consist Of*
Realization Dimension	This dimension reports on how the DT is implemented and which tools and processes are used for the DT development. It is characterized by the subfeatures *Implementation*, *Tools*, and *Process*
Deployment Dimension	This dimension reports on hosting the DT and its connection to the real world. It is characterized by the subfeatures *Hosting* and *Connection*
Operation Dimension	This dimension reports on the operational features of the DT while it is running. It is characterized by the subfeatures *Horizontal Integration*, *Decision Making*, *Inputs and Events*, and *Outputs*

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Table 3. DT Themes proposed by Jones et al.[18].

Theme	Description
Characteristics	
Physical Entity	A real-world artifact, i.e., a PT
Virtual Entity	A computer generated representation of the physical artifact, i.e., a DT
Physical Environment	The measurable real-world environment within which the PT exists
Virtual Environment	Any number of virtual worlds or simulations that replicate the state of the physical environment and designed for specific use-case(s)
Fidelity	The number of parameters transferred between the physical and virtual entities, their accuracy, and their level of abstraction
State	The current value of all parameters of either the physical or virtual entity/environment
Parameters	The types of data, information, and processes transferred between entities
Physical-to-Virtual Connection	The connection from the physical to the virtual environment. Comprises of physical metrology and virtual realization stages
Virtual-to-Physical Connection	The connection from the virtual to the physical environment. Comprises of virtual metrology and physical realization stages
Twinning and Twinning Rate	The act of synchronization between the two entities and the rate with which synchronization occurs
Physical Processes	The physical purposes and process within which the physical entity engages
Virtual Processes	The computational techniques employed within the virtual-world
Knowledge Gaps	
Perceived Benefit	The envisaged advantages achieved in realizing the DT
DT across the Product Life-cycle	The life-Cycle of the DT – (whole life cycle, evolving digital profile, historical data)
Use-Cases	The applications of the DT
Technical Implementations	The technology used in realizing the DT
Levels of Fidelity	The number of parameters, their accuracy, and level of abstraction that are transferred between the virtual and physical twin/environment
Data Ownership	The legal ownership of the data stored within the DT
Integration between Virtual Entities	The methods required to enable communication between different virtual entities

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Merging Detail

Table 4. Merge of the reporting frameworks by Oakes et al.[7], Dalibor et al.[14], and Jones et al.[18]. *In bold*: Fundamental characteristics. *In italics*: cross-cutting characteristics.

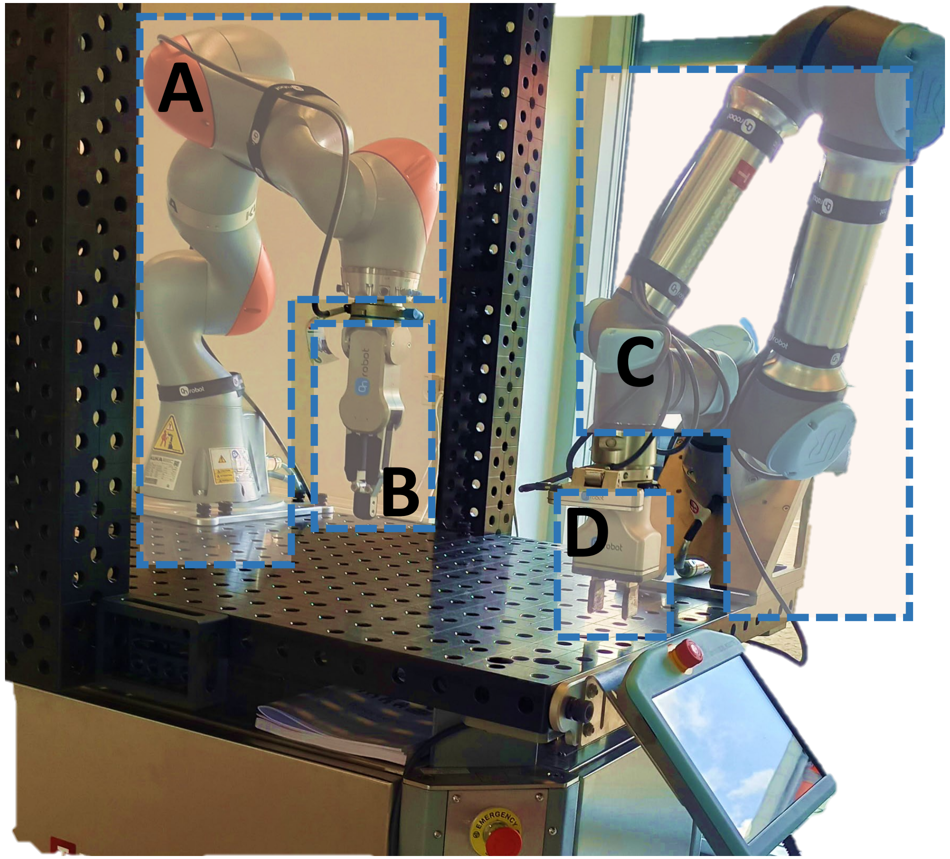
Oakes et al.	Dalibor et al.	Jones et al.	Resulting Characteristic	Description
System-under-Study	Counterpart	Physical Entity; Physical Environment; Physical Processes	**MC1: System-under-Study**	Describes the SUS, i.e., the PT, of the system of interest.
Acting Components			**MC2: Physical acting components**	Describes the available acting components in the DT constellation, i.e., the mechanisms the DT can use to act on thc PT.
Sensing Components			**MC3: Physical sensing components**	Describes the available sensing components in the DT constellation, i.e., the mechanisms the PT can use to transfer data to the DT.
Data Transmitted	Inputs and Events	Technical Implementations; Physical-to-Virtual Connection; Parameters	**MC4: Physical-to-Virtual Interaction**	Describes the interactions from the physical world to the virtual world, i.e., the data transmitted from PT to DT, including inputs and events that the DT processes.
Insights / Actions	Outputs; Asset Interaction	Technical Implementations; Virtual-to-Physical Connection; Parameters	**MC5: Virtual-to-Physical Interaction**	Describes the interactions from the virtual world to the physical world, i.e., the data transmitted from DT to PT, including outputs the DT generates as part of its services.
Services	Optimization	Perceived Benefits; Use Cases	**MC6: Digital Twin Services**	Describes the services, such as optimization, task planning, and visualization, which the DT provides to the users and the physical system.

...

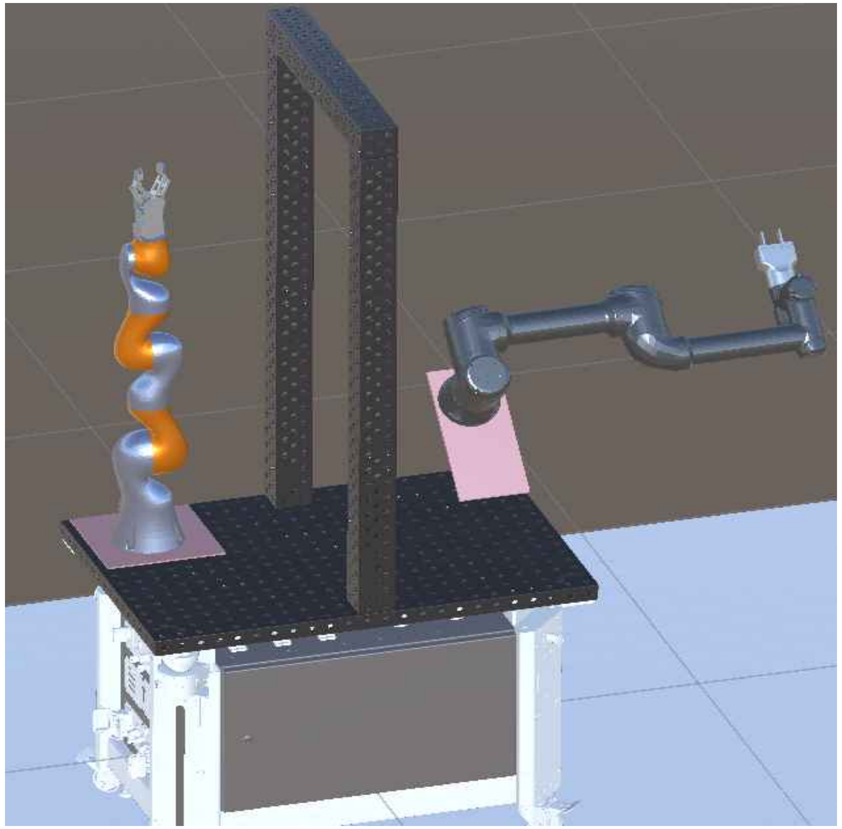
Main Idea: DT Constellation

- DTs:
  - connected in loop with PT
  - provide **services** (top)
  - operate on **models/data** (bottom)
  - Have **enablers** (in-between)
  - Data flows through DT

Robotics Case Study



PT: Manufacturing cell with independent assets
(2 robotic arms, 2 grippers)



DT: what-if simulation, trajectory visualization, discrete working space commands, and deviation checking

Robotics Constellation

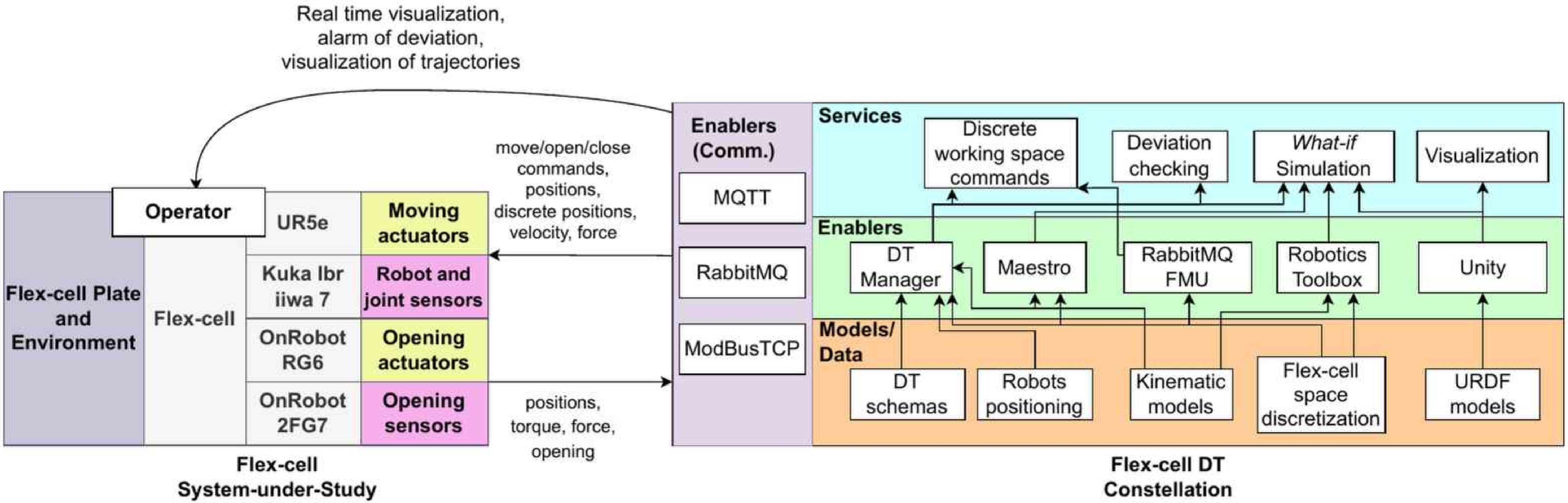


Figure 5. Constellation[7] of the flex-cell DT, detailing the composition of the DT and the data flow.

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DT Characteristics

C1: System-under-Study	C10: DT Models and Data
C2: Physical acting components	C11: Tooling and Enablers
C3: Physical sensing components	C12: DT constellation
C4: Physical-to-virtual interaction	C13: Twinning process and DT evolution
C5: Virtual-to-physical interaction	C14: Fidelity and validity considerations
C6: DT services	C15: DT technical connection
C7: Twinning time-scale	C16: DT hosting and deployment
C8: Multiplicities	C17: Insights and decision making
C9: Life-cycle stages	C18: Horizontal integration

C19: Data ownership and privacy
C20: Standardization
C21: Security and safety considerations

Legend:

Reqs/Concept/Design
Realization
Deployment
Operation

- 18 characteristics are "essential"
- 3 characteristics are "cross-cutting"

- Characteristics are (multi-) labelled with four system life-cycle stages

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Robotics Table Summary

Table 6. Summary of the flex-cell DT case study through the characteristics of our proposed DT description framework.

Merged Characteristic	Flex-cell case study
MC1: System-under-Study	Manufacturing cell with independent assets (2 robotic arms, 2 grippers).
MC2: Physical acting components	Controllers of the robotic arms, grippers, and safety system.
MC3: Physical sensing components	Sensors of the robotic arms and grippers, including 117 observations for the UR5e, 31 for the Kuka lbr iiwa 7, and two for each gripper.
MC4: Physical-to-Virtual Interaction	The PT to DT interaction is managed by the DT Manager with the methods `getAttributeValue` on either a periodic basis or on event.
MC5: Virtual-to-Physical Interaction	The DT to PT interaction is managed by the DT Manager with the methods `setAttributeValue` for parameter update and `executeOperation` for direct actions.
MC6: Digital Twin Services	The flex-cell DT provides services for *what-if simulation*, *trajectory visualization*, *discrete working space commands*, and *deviation checking*.
MC7: Twinning Time-scale	The DT-to-PT synchronization is on demand, on a periodic basis, or on incoming events. The DT supports slower-than-real-time, real-time, and faster-than-real-time services.

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Robotics Prose

4.2.14. MC14: fidelity and validity considerations. As for quality assurance, the validation of the flex-cell DT has been carried out through experimental validation as follows: The motion speed of behavioral models has been tuned so they approximate to the actual motion trajectory.

...

Some of the limitations in terms of model fidelity are as follows:

- The kinematic models do not include the kinematics for the grippers.
- The trajectory generation with the kinematic models provides certain time behavior based on an assumed motion speed (which can be tuned during operation). However, it does not consider the actual

Characteristics 1/6

Characteristic	Description	Flex-Cell Summary
C1: System under Study	Describes the SUS, (Physical Twin), of system of interest	Manufacturing cell with independent assets (two robotic arms and two grippers)
C2: Physical Acting Components	Describes acting components, i.e., mechanisms DT can use to act on PT	Controllers of the robotic arms, grippers, and safety system
C3: Physical Sensing Components	Describes sensing components, i.e., the mechanisms PT can use to transfer data to DT	Sensors of robotic arms and grippers, including 117 observations for UR5e, 31 for Kuka lbr iiwa 7, and 2 for each gripper
C4: Physical-to-Virtual Interaction	Describes interactions from physical world to virtual world, i.e., data transmitted from PT to DT, including inputs and events that DT processes	PT-to-DT interaction is managed by the DT Manager with the method *getAttributeValue* on periodic basis or on event

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Characteristics 2/6

Characteristic	Description	Flex-Cell Summary
C5: Virtual-to-Physical Interaction	Describes interactions from virtual world to physical world, i.e., data transmitted from DT to PT, including outputs DT generates as part of its services.	DT-to-PT interaction is managed by the DT Manager with methods *setAttributeValue* for parameter update and *executeOperation* for direct actions
C6: Digital Twin Services	Describes services, such as *optimization*, *task planning*, and *visualization*, which DT provides to users and physical system.	flex-cell DT provides services for *what-if simulation*, *trajectory visualization*, *discrete working space commands*, and *deviation checking*
C7: Twinning Time-Scale	Describes time-scale use and time rates for DT services and DT-to-PT synchronization.	DT-to-PT synchronization is on demand, on periodic basis, or on incoming events. DT supports slower-than-real-time, real-time, and faster-than-real-time services
C8: Multiplicities	Describes multiplicities, i.e., internal twins that compose the DT system, which can be implemented in a centralized or decentralized way.	Each independent asset has its own DT and composition is enabled. There is no multiplicity of same DT class

Characteristics 3/6

Characteristic	Description	Flex-Cell Summary
C9: Life-cycle stages	Describes lifecycle and representation phases in which DT takes place, i.e., as designed (ideal), as manufactured, or as operated	DT services include *design*, *manufacturing*, and *service* life-cycle phases. Within *service* phase, it supports *creating*, *executing*, *analyzing*, *saving*, and *terminating*. DTs cover system *as-designed* and as *operated*.
C10: Digital Twin Models and Data	Describes DT components, including available models and data, and their role in DT constellation	Data models initialized from DT schemas using AAS meta-model, structural models for visualization with URDF format, and behavioral models as FMUs for robotic arms kinematics. Data in DT are related to robot positioning.
C11: Tooling and Enablers	Describes tools or enablers that are used to achieve DT goals, i.e., they enable DT to provide services.	DT Manager for interfacing and service access, Robotics Toolbox and UniFMU for behavioural models, URInterface for UR5e robot, KukaIbrinterface, ModbusTCP, MQTT, and RabbitMQ for connectivity, Maestro and RMQFMU for co-simulation, URSim, Unity, ZeroMQ, and URDF for viz, and DTaaS for cloud execution
C12: Digital Twin Constellation	Describes orchestration of the DT system, components, and services as a whole. (also show the constellation figure!)	Orchestration of the system-as-a-whole is defined, and in multiple scenarios for provided services. Configuration files and scripts for components. (Figure 5 is the constellation)

Characteristics 4/6

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Characteristic	Description	Flex-Cell Summary
C13: Twinning Process and DigitalTwin Evolution	Describes engineering process involved in DT implementation, including development process, quality assurance, and definition of requirements. Also informs on milestones of DT engineering process over time and intended upgrades	DT was engineered based on an existing manufacturing cell with a set of own requirements. The evolution presents 12 milestones (*described in paper)*
C14: Fidelity and Validity Considerations	Describes fidelity and validity considerations behind models in DT, including verification and validation mechanisms, uncertainty, and errors	DT contains sufficiently accurate models for the robotic arms and overall execution. Low coverage of models for the grippers. Flex-cell DT has been experimentally validated and provides mechanisms for consistency checking
C15: Digital Twin Technical Connection	Describes technical network connection details between PT and DT, including network protocols and architectures	Connection to the physical assets needs to be done on a LAN. Several communication protocols are used for the whole system deployment
C16: Digital Twin Hosting/Deployment	Describes technical hosting aspects of the DT and associated technology	Flex-cell DT can be deployed on a LAN or on the DTaaS platform in the cloud

Characteristics 5/6

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Characteristic	Description	Flex-Cell Summary
C17: Insights and Decision Making	Defines insights and decision making, i.e., indirect outputs of DT, which have no direct effect on PT, such as update of parameters, plans, and so on.	Flex-cell DT can provide insights in the form of simulation-based analysis and semantic reasoning
C18: Horizontal Integration	Describes information exchange with external information systems not limited to other DTs.	horizontal integration with flex-cell PT and infrastructure services of DTaaS Platform. The flex-cell DT is able to exchange information with other information systems not limited to other DTs

Characteristics 6/6

Characteristic	Description	Flex-Cell Summary
C19: Data Ownership and Privacy	Refers to ethical and technical aspects regarding data ownership and data privacy. *Is the data owned by the PT owner or by DT service provider?*	Not considered in the case study
C20: Standardization	Refers to standards being followed for engineering of the DT and its components.	Behavioral models conform with the FMI Standard Version 2. Twin schemas conform with the AAS meta-model (IEC-63278-1)
C21: Security and Safety Considerations	Refers to ethical and technical aspects regarding data cybersecurity and safety on operation. Can a DT execute operations remotely on a PT where there may be accidents with humans?	Security aspects inherited from the DTaaS Transport Layer Security (TLS). Safety aspects regarding remote operation for accidents and collisions

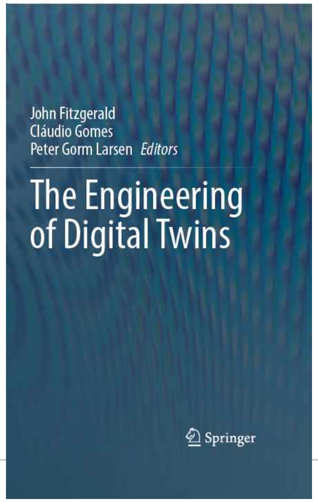
Cross-cutting characteristics

Suggested Framework Usage

- Report on these characteristics as precisely as possible
  - In detail and/or tabular form
- Draw the constellation figure

- Nothing set in stone, make changes if needed
- Out of room? Place table in appendix or online

- For guidance, paper offers three DT reports
  - **Flex cell**
    - In detail and in table
  - **Robotti mobile robotics**
    - In table form
  - **Tempeh incubator**
    - In table form
- DT book also provides *Gunnerus* ship DT (in older framework version)



Tempeh Incubator

MC4: Physical-to-virtual interaction	The controller in the PT sends sensor and actuator data on a periodic basis over RabbitMQ.
MC5: Virtual-to-physical interaction	The DT sends new parameters of the controller, or desired temperature, to the controller in the PT.
MC6: Digital Twin services	*Heater state estimation*, *real-time (and historical) visualization*, *anomaly detection*, *what-if simulations*, *reconfiguration according to state of the lid*, and *controller parameters optimization*.

MC13: Twinning process and Digital Twin evolution	The DT was engineered based on a joint engineering approach. For the evolution, 10 milestones have been defined: identifying the physics for the PT, building the plant models with, characterizing the heating power, building the first physical prototype, experimentally refining the parameters for the plant model, creating the controller model, deploying the controller code into the physical controller, deploying the visualization service, providing services for state estimation and anomaly detection, and providing the service for optimizing the control policy.
MC14: Fidelity and validity considerations	The models have been calibrated against experimental data and the predictive accuracy of the best model is within 2°C. The models have been validated in a controlled environment.

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Desktop Robotti

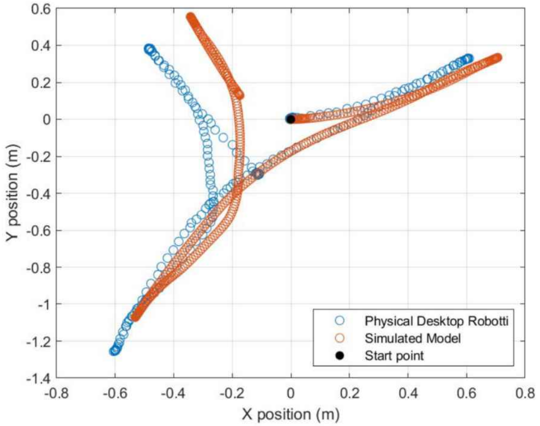
MC1: System under study — Small prototype of a field (agricultural) robot. A mobile robot.

MC2: Physical acting components — Motors for each wheel.

MC3: Physical sensing components — RPLidar A1, IMU (Inertial Management Unit), and wheel encoders.

MC6: Digital Twin services — The Desktop Robotti DT provides services for *monitoring: distance-to-obstacle, collision avoidance for two cooperative Desktop Robottis, Parallel operation: comparing real and predicted location data, Fault injection with hardware in the loop*, and *Runtime model swapping*: swapping FMUs during operation to extend functionality.

MC11: Tooling and enablers — RabbitMQ and the Robot Operating System (ROS)[65] for communication and interfacing. Maestro and RMQFMU to run the co-simulation scenarios. The Model Swap and Fault Injection plug-ins to run the DT services related to fault injection[66] and runtime model swapping.[67] RViz for visualization.



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Gunnerus Research Vessel

- Owned by Norwegian University of Science and Technology (NTNU) for marine research and exploration

- C7: Services:
- what-if simulations, real-time visualization, estimate effect of environmental disturbances, anomaly detection and estimation of Remaining Useful Life (RUL)

- C8: Enablers
- Open Simulation Platform (OSP)

C2: Acting Components and C5: Data Transmitted

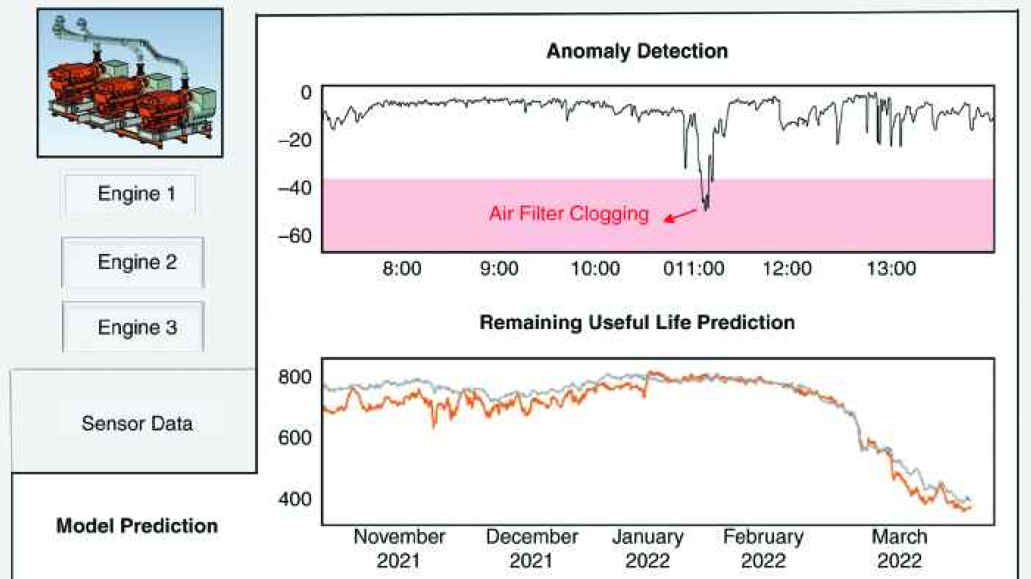
- cellular 4G/5G connection with Message Queuing Telemetry Transport (MQTT)

Table 12.3: Data channels sensed onboard the R/V Gun

Signal	Channels	Unit
GPS	Latitude	ddmm.mmmm
	Longitude	ddmm.mmmm
	Surge velocity	knots
	Sway velocity	knots
	Course angle	deg
	Speed over ground	knots
MRU	Heading angle	deg
	Heading rate	deg/s
	Roll angle	deg
	Pitch angle	deg
	Heave displacement	m
	Roll rate	deg/s
	Pitch rate	deg/s
	Heave rate	m/s
Wind sensor	Wind direction	deg
	Wind speed	knots
Thruster	Port thruster rotational speed	%
	Port thruster angle	deg
	Starboard thruster rotational speed	%
	Starboard thruster angle	deg
	Tunnel thruster rotational speed	%

Table 12.5: TwinShip articles and their topic.

Year	Topic	Citation
2019	Estimating useful life predictions	[3]
2020	Co-simulation framework to simulate Gunnerus case-study	[15]
2020	Gunnerus DT within a co-simulation environment	[16]
2021	Development of a ship trajectory predictor	[20]
2022	Improving trajectory prediction with a physics-based model	[22]
2023	Refining models between different ship size	[21]
2023	Enabling technologies for the Gunnerus DT	[39]

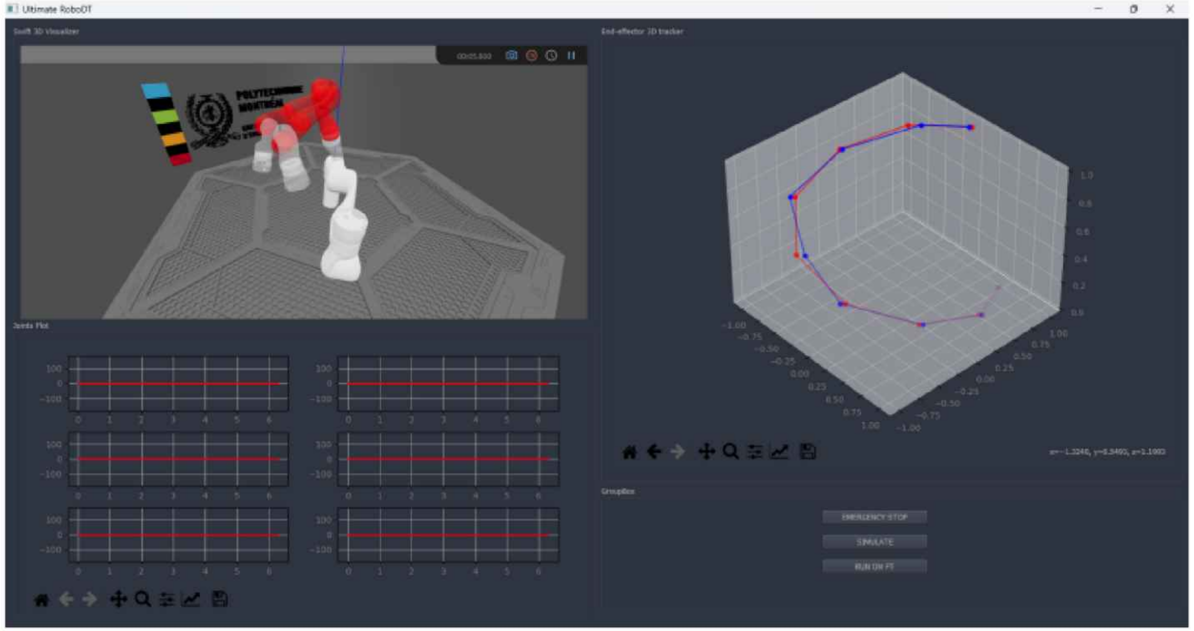


Ongoing DT Reporting Work

- Validation on further case studies

Proposed DT characteristics:

C1	System under study	7-Dof Kinova 3 robotic arm
C2	Acting components	Human-in-the-loop control
C3	Sensing components	ActuatorFeedback API already implemented by Kinova
C5	Data transmitted	Joint position information Motor temperature and status information
C6	Insights/Actions	Warning to the operator of the SUS, visualized temperature, status and position information to the operator of the SUS.
C7	Services	- Deviation-checking service notifies the operator if the joint position of the robot deviates beyond a set threshold from its given instructions. - Visualized temperature and other status monitoring service display intuitive visualization of joint temperature and status - Visualized arm position - Simulation of arm movement



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Systematic Reporting Framework Conclusion

- DT research and engineering held back by **incomplete reporting**
- Framework has **21 characteristics** to report as precisely as possible
- Case study examples provided

Gil, Oakes, et al. (2024). *Toward a systematic reporting framework for digital twins: a cooperative robotics case study*. Simulation.

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Systematic DT Construction

EDTconf 2024 Paper

Towards Ontological Service-Driven Engineering of Digital Twins

Bentley Oakes, Claudio Gomes, Eduard Kamburjan, Giuseppe Abbiati, Elif Ecem Bas, Sebastian Engelsgaard

🏆 Best Short Paper

Proposal - Start Top Down

Multiple DT construction approaches start at bottom layer

Instead, leverage DTs as a constellation

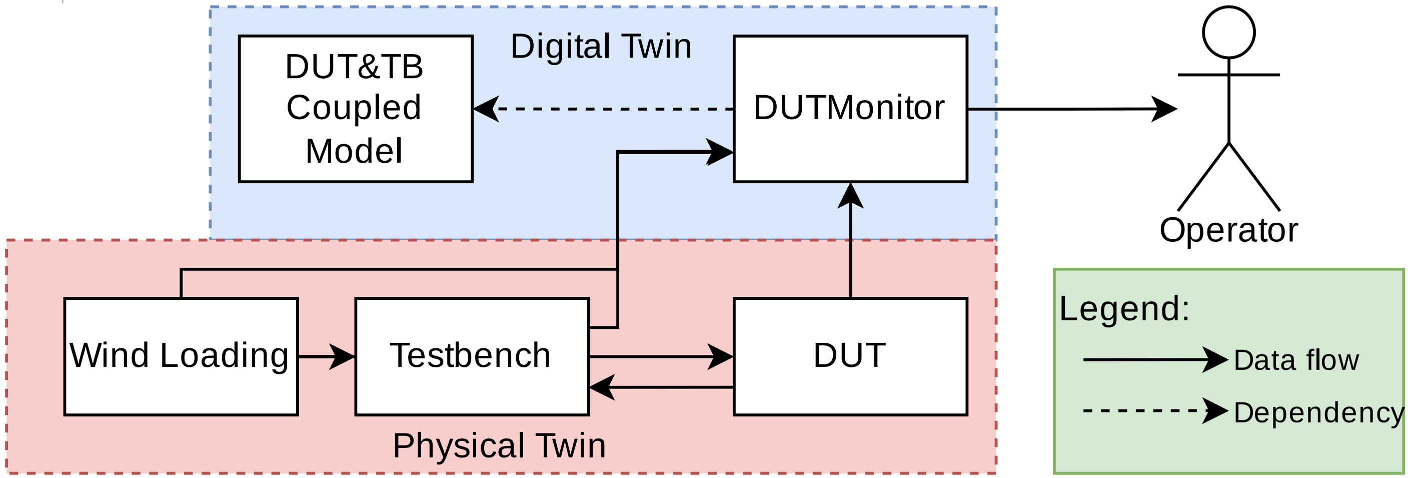
- **Pick desired service**, then **recommend components**
- **Guide** users in selection, modelling, deployment
- Focus on **non-software engineering experts**

Wind Turbine Testing

With Aarhus U., U. of Olso, R&D Test Systems, LORC

- Representative testbench for bending/torquing turbine nacelle

Problem: Detect mismatches between dynamics model and testbench, as failure can cause *structural damage*



Menu of Services

- Is it possible to create a **menu of DT services**?
- Where user can pick and choose service(s), and DT is **assembled together (semi-)automatically**

Proposed Approach

Ontological Basis

Multiple ontologies in **Ontological Modelling Language (OML)**, built in openCAESAR

- This slide is a selection of the ontologies
- Total concepts: 42+, Total relations: 25+

Ontology concepts:

1) Specific: Artifact, Simulator, ODEModel, DeployedModel

2) DT/Roles: System, ConstellationElement, ServiceRole

3) Process/notebook: Process, Step, DeployStep, ProduceArtifact, Decision

Step 2) Role Recommendation

Recommendations are stored in knowledge graph, typed by ontologies

- **Recommend roles** for the service to be found or created
- **Connect** to workflows (next step)

- Can query knowledge graph to find roles not yet filled

- Further work: Connect to repository, additional role constraints (validity, fidelity)

Step 3) Service Eng. Workflows and Ontology-aware Tooling

- Workflows as **guided steps** for user to find/model/test/deploy components
- Modelled in ontology, enacted in **Jupyter notebook**
- Concepts: Steps, decisions, artifact production/consumption, simulation steps
    - Model management problems

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Ongoing Work

- Connect with existing DT/Industry 4.0 ontologies
  - Process modelling, sensors, ...

Ontologies in digital twins: A systematic literature review

Erkan Karabulut [a,*], Salvatore F. Pileggi [b], Paul Groth [a], Victoria Degeler [a]

Table 1
Usage of ontologies in the different layers as per reference architecture.

Layer/Context	Usage
Physical	Physical entities, actions and processes
Communication	Protocols, access parameters
Digital	Generic DT concepts, real or abstract/derived digital terms, assets and operations
Application	Ranges between task-specific terms (e.g., CNC (Computer Numerical Control) cutting machine optimization app) to domain-independent application terms (e.g., top-level requirements validation app)
Organizational context	Production lines, facilities, client and order info, project management, bridging DT and non-DT parts

- Evaluation and validation with expert users

- Determine menu of services

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DT Construction Conclusion

- Can leverage DT constellations and services
- Ontologies for heterogeneous/flexible/rich modelling and model management
- Role/workflow/notebook approach welcomed by practitioners

Towards Ontological Service-Driven Engineering of Digital Twins

Oakes, Gomes, Kamburjan, Abbiati, Bas, Engelsgaard

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Conclusion

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Lab Members and Topics

PhDs

Carlos Pambo
- Recommendations and guided workflows
Application: Wind turbine testing DT

Lei Zhao
- Empirical foundations for DT engineering
Application: Permafrost DT

Open position:
- Consistency framework
Application: Advanced Air Mobility

Master's

Kérian Fiter
- DT reporting
- DT engineering using LLMs

mitacs

Globalink Research Intern

Angelica Portocarrero
Universidad Autónoma de Occidente, Colombia
- DT engineering using LLMs

Conclusion

1) Systematic DT reporting
2) Ontology-based DT engineering

Takeaways:
1) DT engineering and reporting must become **more systematic**
2) Many opportunities for model-/ontology-based techniques to **structure DTs and guide users**

Thank you!

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OML and openCAESAR

- Ontological Modelling Language (OML):
  - Essentially a DSL over OWL, removes accidental complexity
  - Vocabulary (like meta-model) and descriptions (like model)
  - Consistency checking and inference rules, a-posteriori typing
  - Text-based for version control, federation of ontologies
  - Trick: Closes world for analysis, becomes specification model

openCAESAR:
- OML editor (Rosetta)
- Fuseki server for knowledge graph

```
concept Mission :> base:IdentifiedElement
concept Objective :> base:IdentifiedElement
relation entity Pursues [
    from Mission
    to Objective
    forward pursues
    reverse isPursuedBy
    asymmetric
    irreflexive
]
```

Elaasar et al (2023, October). openCAESAR: Balancing agility and rigor in model-based systems engineering. In 2023 MODELS-C (pp. 221-230). IEEE.