

Systematic Digital Twin Reporting

EDT.Community

May 12th 2025



**POLYTECHNIQUE
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About Me



M.Sc. and PhD
McGill University
2011-2018

NECSIS Network: Automotive
academia-industry collaboration

Research stay of two months at GM

Master's: **Evolving game AI**

PhD: **Model transformation verification**



THE UNIVERSITY OF
BRITISH COLUMBIA



UNIVERSITY OF
TORONTO



UNIVERSITY OF
WATERLOO



**Universiteit
Antwerpen**

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

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: Accelerating Knowledge Engineering for Complex Systems

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***

What is a Digital Twin?

Collection of **112 definitions**:
<https://awortmann.github.io/research/digital-twin-definitions/>

Definitions

- ## Definitions
- "An analysis in specific digital model of existing manufacturing entity". B. A. Teitelbaum, M. Clark, W. Schmitt, M. Weirich. A concept in synchronization of virtual production system with real factory based on artificial neural network. In: *Procedia CIRP*, 2018.
 - "An analysis current digital stage of the production system?". D. Dworjag, O. Meike, G. Krasik, M. Weinrich. A digital twin for production planning based on cyber-physical systems. A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin. In: 12TH ORF CONFERENCE ON INTELIGENT COMPUTATION IN MANUFACTURING/ENGINEERING, 2019.
 - "A digital twin is a virtual replica of the printing hardware". J. Murthy, S. J. Debing. An intelligent tool for rapid qualification of 3D printed metallic components. In: *APPLIED MATERIALS TODAY*, 2019.
 - "A virtual mapping of a physical product". A. Delamar, M. Eigner. A digital twin for real-time analysis and product quality monitoring. In: *Proceedings of International Design Conference, DESIGN, 2018*.
 - "In the context of industry 4.0, the Digital Twin is introduced as a framework for ensuring certain aspects of the underlying physical entities in the manufacturing processes". K. Joshi, I. Koca, S. Yigitler, C. Engels. A Digital Twin-Based Multi-Model Adaptation Framework for Assistance Systems in Industry 4.0. In: *Human-Computer Interaction, Design Practices in Contemporary Societies, 2019*.
 - "Digital representation of any real-world counterpart allowing its management". M. Dawid, B. Rudek, G. Pernat. A Distributed Ledger Approach to Digital Twin Secure Data Sharing. In: *Data and Applications Security and Privacy XXXIII*, 2019.
 - "The Digital Twin is a digital asset encompassing CPS data and intelligence; it represents structure, semantics and behavior of the associated CPS providing services to sustain the virtual and physical assets". M. Corvino, M. Ago, S. Morita, G. Dioreo, P. Pedrazzi. A Monocloud-based Middleware for the Digital Factory. In: *Advanced Manufacturing*, 2017.
 - "Digital equivalent to a physical product". G. Averetousis, M. Givoni, P. Pedrazzi. A Networked Production System to Implement Virtual Enterprise and Product Lifecycle Information Loops. In: *RACI PaperCircle*, 2017.
 - "While in the context of smart manufacturing, the term 'digital twin' is more broadly applied to modeling structures and visualization aspects based on various data and data collection during operations, we use it to describe structured or simulated devices that may be connected to an industrial network". M. Zinkert, A. Dierker. A Specification-based State Machine Approach for Digital Twins. In: *Proceedings of the 2018 Workshop on Cyber-Physical Systems Security and Privacy*, 2018.
 - "A digital twin is defined as the predictive and validated model of the manufacturing process with the intention to support remote documentation". T. Zurek-Kloke, A. Sommer, F. Meyerhäuser, M. Moudall, M. Hauer, L. Jähnichen, N. Kowalek, L. Lehmann, R. Eitz, J. Ströbe. Accelerating lifecycle manufacturing by modelling in its favour under the QED and DET approaches developed by authorizes acceptable as well as a digital twin? https://www.researchgate.net/publication/327197770/QED_in_Fabrication. In: *Processes*, 2019.
 - "The DT is a set of virtual information that fully describes a potential or actual physical production from the micro atomic level to the macro operational level". Y. Zheng, Y. Yang, H. Cheng. In-depth exploration of digital twins and its case study. In: *Journal of Ambient Intelligence and Humanized Computing*, 2019.
 - "The Digital Twin of a new manufactured product is a virtual reflection, which can describe the structural, physical and functional properties of the product after the whole life cycle can deliver and receive product information". G. Thoma, S. Winter, M. Eigner. An approach for the implementation of the digital twin in the automotive value chain. In: *Proceedings of International Design Conference, DESIGN, 2018*.
 - "The creation on the basis of stream design software hardware isolation, 'virtual' models of technological units and connecting them via a single integrated 'cloud' model of the production complex called 'digital twin' which in fact represents a virtual projection of the industrial facility onto the 'virtual'. R.R. Vasyunovskiy, V.D. Abukharov, T.T. Arifov, A.A. Voronin. Application of cloud technologies for optimization of complex processes of industrial enterprises. In: *Advances in Intelligent Systems and Computing*, 2019.
 - "The digital twin concept is a functional system of continuous application, which includes physical production together with its digital twin". E. Egnaf, A. Germi, T. Zohou. Application of digitization processes of production enterprise. In: *Management Science in Production Engineering*, 2019.
 - "Digital twins are technological equipment use infrastructure components of production companies at the factory 4.0 technology on the level of cloud computing". O.A. Zakharova, A.V. Starostin, G.R. Muchitsky, I.O. Zhornitskiy. Approaches to industrial modeling models in creating digital twins at the Industry 4.0 company technological equipment. In: *IOP Conference Series: Materials Science and Engineering*, 2018.
 - "The DT is a simulation method that can be used for evaluation and optimization". Y. Tan, W. Yang, X. Huotals, S. Takahawa. Application of real-time simulation for a Cyber physical system. In: *Proceedings of the 2018 IEEE International Conference, ICIP*.
 - "A DT consists of a virtual representation of a production system that is able to use sensing data, connected smart devices, mathematical models, and real-time data elaborations. The DT can be seen on different semantic dimensions that are characterized by the synchronization of virtual and real systems". Y. Tan, W. Yang, X. Huotals, S. Takahawa. Application of real-time simulation to manufacturing systems in cyber physical system. In: *Machines*, 2019.
 - "The first defined Digital Twin concept is to have a digital entity that behaves exactly (or as close as possible) as the real entity". O. Meike, A. Morrow, G. Rade, A. Banerjee. Approximate or exact software for finite element simulation of 3D metal sheet laser cut. In: *International Journal Interactive Design and Simulation*, 2016.
- The so-called Digital Twin approach, which is a simplified numerical model." T. Benavent, M. Zarzalay. Concept of advanced numerical detection of defect localization heavily using machine learning on standard tests. In: *Diagnostics*, 2019.
- "Digital twin, first of all, is a virtual replica of physical objects (products, processes, or systems) operation conditions". V. Korobov, V. Zhornitskiy, V. Tsukanov. Smart management by IT. M systems: a way to improve the competitiveness in digital economy. In: *IOP Conference Series: Materials Science and Engineering*, 2019.
 - "A product virtual replica is a digital twin that is intended to be to enable manufacturers and their clients to better characterize, monitor, manage and operate it throughout its life cycles, i.e., from the product manufacturing date, through operation and to end-of-life". A.R. Al-Rai, A. Gupta, A.A. Nabais. Cyber physical systems role in manufacturing technologies. In: *IFIP Conference Proceedings*, 2018.
 - "A digital twin is an operational type of CPS where the physical system's components and behaviors are mirrored into the cyber world. A digital twin enables near time monitoring and decision making for various types of applications including maintenance and work optimization". A. Acharya, T. Lawrent, A. Samtse. Cyber-physical System Experiments for Measurement and Analysis of Physical Systems. In: *ELECTRONICS*, 2019.
 - "The basic definition of a Self-aware Digital Twin is that it implements as a self discovery device in the cyberworld processing". M. Shargawi, D. Mansour. Self-aware Digital Twin: a perspective towards specialization. In: *Industry as a Service in Proceedings: 2018 IEEE International Conference on Big Data*. Big Data, 2019, 2019.
 - "Digital twin provides a digital replica of its physical counterpart which is virtually reflecting suitable form its physical form in the sense that it dynamically replicates the behavior and properties of the physical item as well as enriches the replica with additional information about the physical counterpart". The concept model of a digital twin contains three main parts: 1) physical twin in the real world; 2) digital twin in the real world; 3) the connections of input data and output command that has the digital twin and its counterparts together. P. Ozdemir. Finding with Uncertainty in Software Architecture on the Internet of Things with Fogger. Berlin, 2018.
 - "Virtual digital twin of the real network that consists of data from the real network". S. Jiang, C. Shi, W. Han, Y. Li, S. Wu. Cloud Computing for Hybrid CPS Services in Mobile Edge Computing Systems. From Twin to Digital Twin. In: *IEEE Transactions on Wireless Communications*, 2018.
 - "A digital twin is a concept from the product life-cycle management (PLM) domain introduced by Siemens AG in 2010. It is a virtual reproduction of a specific physical product. The abstract idea is that the digital twin should be linked to the physical product throughout the product's life cycle and continuously evolve". R. Birrell, T. Oakes, G. Shaw, M. Jenkins, Y. Chen, J. Wainwright, J. Taylor, G. Chubb, R. Shalton. Defining a Cost Effective Digital Twin of an ICE to Facilitate Faulty Evaluation. In: *Computer Society*, 2018.
 - "A digital twin can be defined as an integrated virtual model of a real-world system consisting of its physical information and functional units". K. Park, Y.W. Nam, H.S. Lee, S.J. Kim, S.D. Nalla, J.Y. Kim, H. Kim. Design and implementation of a digital twin architecture for a compressed natural gas engine. In: *ICATMEE 2018 - 10th Annual IEEE Conference on Information Technology and Mechanically Engineering*, 2018.
 - "More simply, a DTM is a digital replica or virtual counterpart of a real entity, either can be sensors, processes, systems, or even services. After being carried with a physical object, the DTM can perform the functions of the monitoring system and data mining, adding its own logic and enhance the performance before they can occur". S. Shen, N.S. Dong, S. Liu, C.-J. Chen. Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. In: *Structure and Infrastructure Engineering*, 2019.
 - "An integrated model that represents, connects, and synchronizes a part or of the whole physical manufacturing system or process, enabled by historical and real-time data from the physical system/plant/process". G. Shao, D. Ribba. Digital manufacturing: Structures and challenges for implementing digital production. In: *Proceedings - Winter Simulation Conference*, 2019.
 - "The digital twin is an object-oriented digital model of a physical asset that comprises all the data about the asset including system, structure, engineering and technical models". D. Radzinski, N. Kutyrevsky, M. Matyshevsky, V. Gerasimov, V. Ponomarev, A. Vorobyev. Digital twin applications: Design, optimization and prediction. In: *Annals of DAMM and Proceedings of the International DAMM Symposium*, 2018.
 - "Integrated Digital Twin (IDT)" is a digital copy of the real manufacturing systems, which can be created and programmed in real-time directly from the computer application model of the industrial plant". Y. Matsui, I. Ono, T. Takamasa. IDT based on virtual control and simulation of the industrial robotic cell using unsatisfactory. W. Journal of Machine Engineering, 2019.
 - "A digital twin refers to its virtual representation of the real physical system that mimics its state and behavior". N. Karadach, A. Joghlay, S. Mariani, V. Pluchin, D. Padgugur, B. Bandemir. Practical use of meta-intelligence in an EMTP-CPS assembly line. In: *Proceedings: 2018 IEEE International Conference on Advances in Things and Intelligence Systems, ITSAS 2018*, 2019.
 - "Let us consider another model: a digital twin, which can be used throughout the life span of the system it models". N. Khan, M. Elahi, D. Fakheran, M. Rafique. Digital Twin for Legacy Systems: Service Model Based Testing. In: *Kluwer Online. IEEE International Conference on Automation Science and Engineering*, 2018.
 - "Digital twin or DM (Building Information Modeling) [1] [8] is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; depending on setting from capture to demolition". S. Karmann, N. M. Nagel. New for sustainable building evaluation of carbon footprints buildings. In: *Bentley in BIM Environment*, 2018.
 - "Digital Twin (DT) is defined as a very realistic model of the current state of the process and their event between its interaction with their environment in the real world [2]. However, the definition of DT and its requirements are not yet fully established and lack of consensus [3]. This characteristic of DT model might possibly be to widely used in industry remains an open question in the literature". L. Perkowski, C. Szabala, S. Hong, S. Abdel K. Saharoun, S. Zienkiewicz. Digital Twin Requirements in the Context of Industry 4.0. In: *Product Lifecycle Management to Support Industry 4.0*, 2018.

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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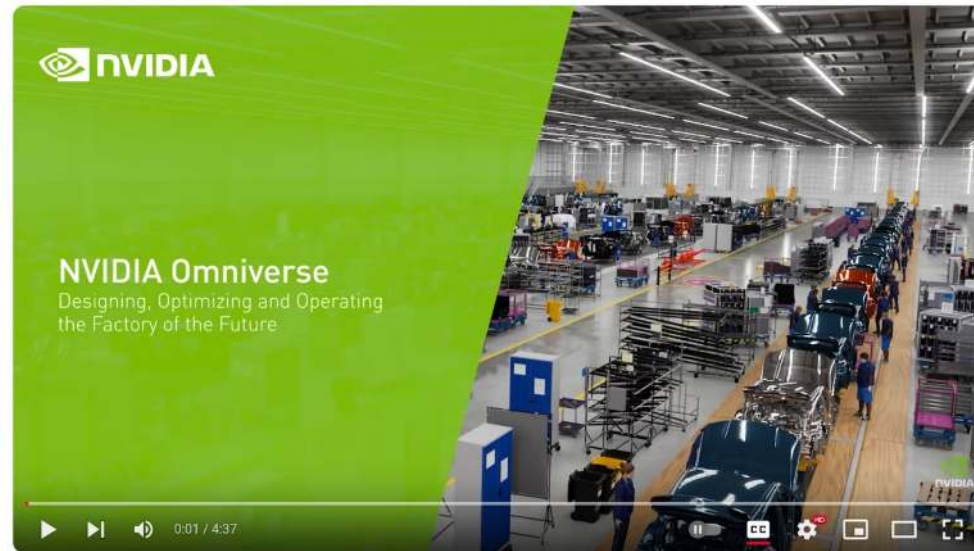
Systematic DT Reporting



Systematic DT Reporting

Motivation

DT Diversity



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



David et al. (2023, October). Digital twins for cyber-biophysical systems: Challenges and lessons learned. In MODELS (pp. 1-12). IEEE.

<https://www.bimcommunity.com/bim-projects/digital-twins-prove-a-game-changer-in-helping-sweco-nederland-deliver-bergen-s-light-rail-extension/>

<https://unity.com/case-study/vancouver-airport-authority>

<https://www.youtube.com/watch?v=6-DaWgg4zF8>

“What Does Your DT Do?”

Instead of arguing about definitions...

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

My questions:

- What are the **services** it provides?
- Is it **real-time**?
- 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)

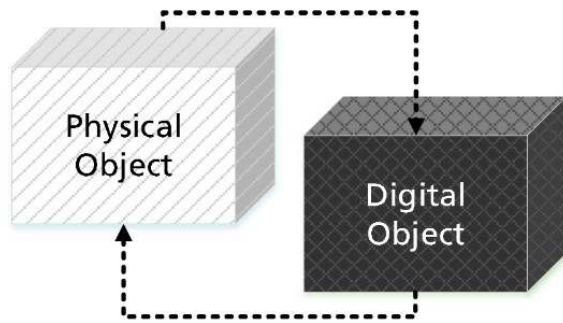


Fig. 1. Data Flow in a Digital Model

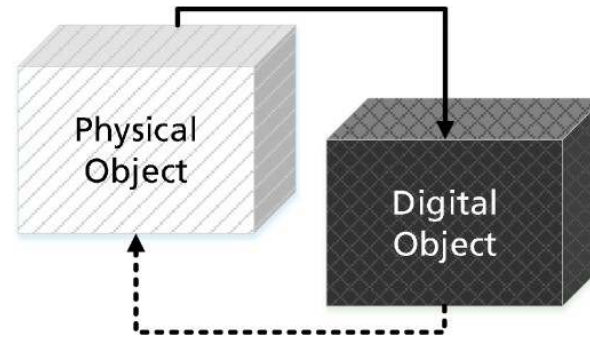


Fig. 2. Data Flow in a Digital Shadow

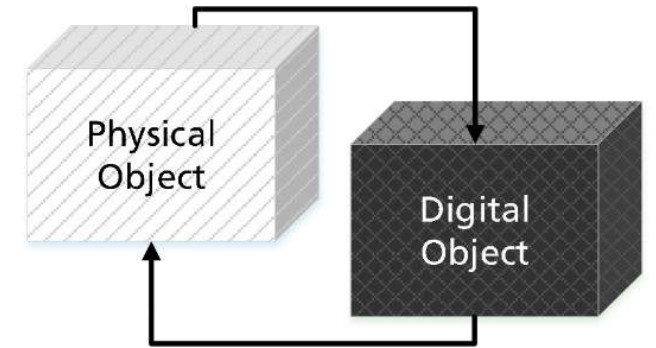


Fig. 3. Data Flow in a Digital Twin

-----➔ Manual Data Flow
————➔ Automatic Data Flow

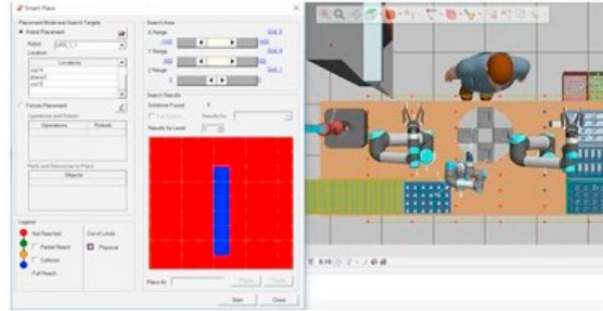
Kritzinger et al. (2018).

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

Unclear Info Example



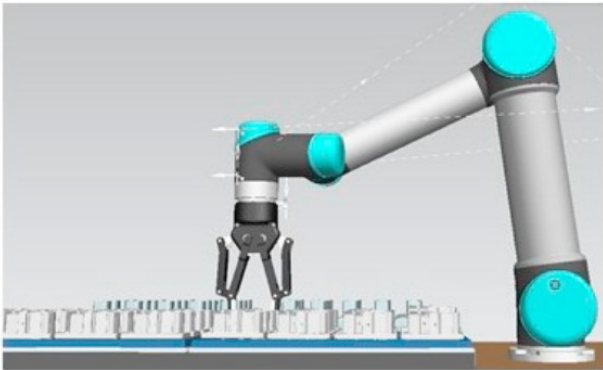
Vision Analysis



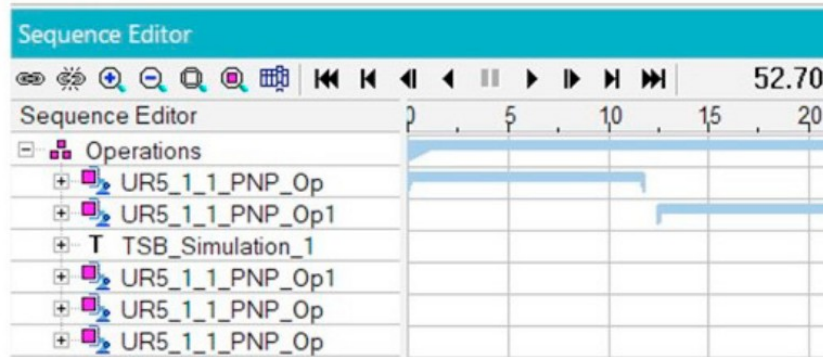
Robot Reach Analysis



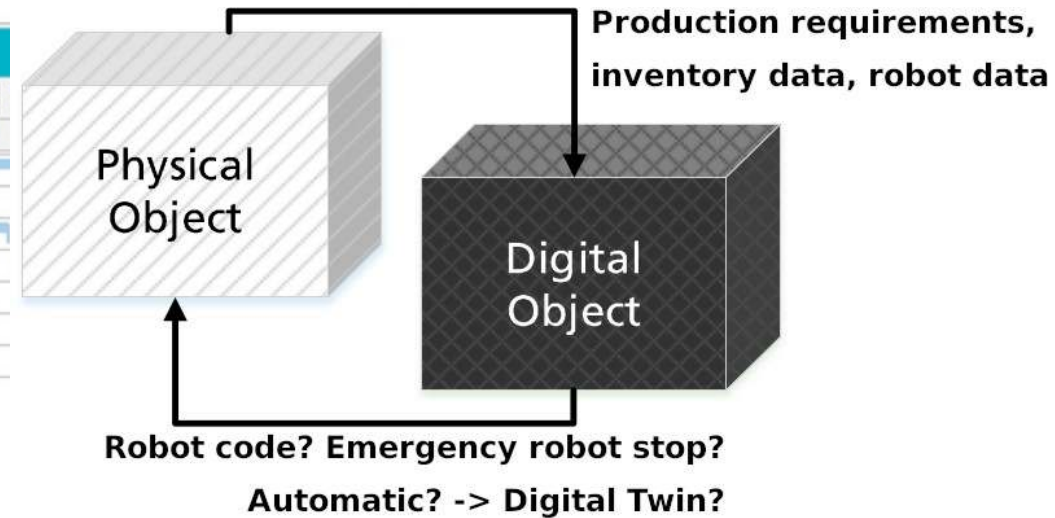
Grasp Analysis



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
 - <https://www2.sigsoft.org/EmpiricalStandards/docs/standards?standard=CaseSurvey>

Systematic DT Reporting

Reporting Framework

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



Constructive Intention

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

1st Paper on Reporting Framework

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

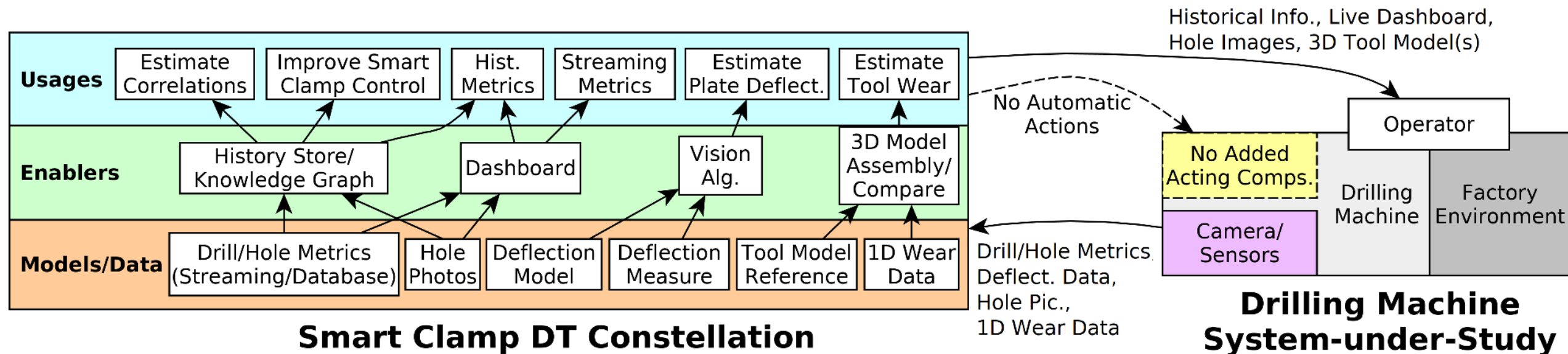
- Defines characteristics to be reported, and ‘constellation’
- Five DTs examined in paper, further fifteen online
- Classification differences found with other papers

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 (?).
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2nd Paper on Reporting Framework

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



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 <i>capabilities</i> or <i>usages</i> 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 (<i>ideation, realization, utilization</i> , 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 <i>Counterpart</i> , <i>Multiple Representation</i> , <i>Usage Phase</i> , <i>Representation Phase</i> , <i>Asset Interaction</i> , <i>Optimization</i> , and <i>Consist Of</i>
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 <i>Implementation</i> , <i>Tools</i> , and <i>Process</i>
Deployment Dimension	This dimension reports on hosting the DT and its connection to the real world. It is characterized by the subfeatures <i>Hosting</i> and <i>Connection</i>
Operation Dimension	This dimension reports on the operational features of the DT while it is running. It is characterized by the subfeatures <i>Horizontal Integration</i> , <i>Decision Making</i> , <i>Inputs and Events</i> , and <i>Outputs</i>

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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. Comprised of physical metrology and virtual realization stages
Virtual-to-Physical Connection	The connection from the virtual to the physical environment. Comprised 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

Merging Detail

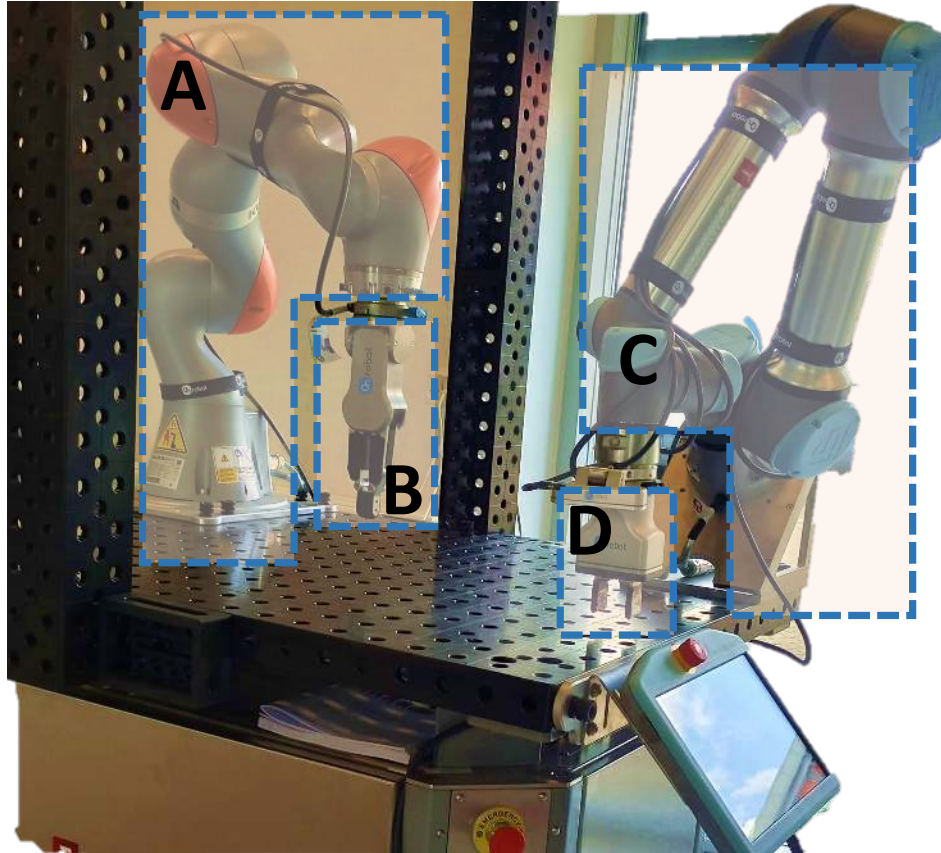
Table 4. Merge of the reporting frameworks by Oakes et al.⁷, Dalibor et al.¹⁴, and Jones et al.¹⁸. *In bold*: Fundamental characteristics. *In italics*: cross-cutting characteristics.

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 the 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.

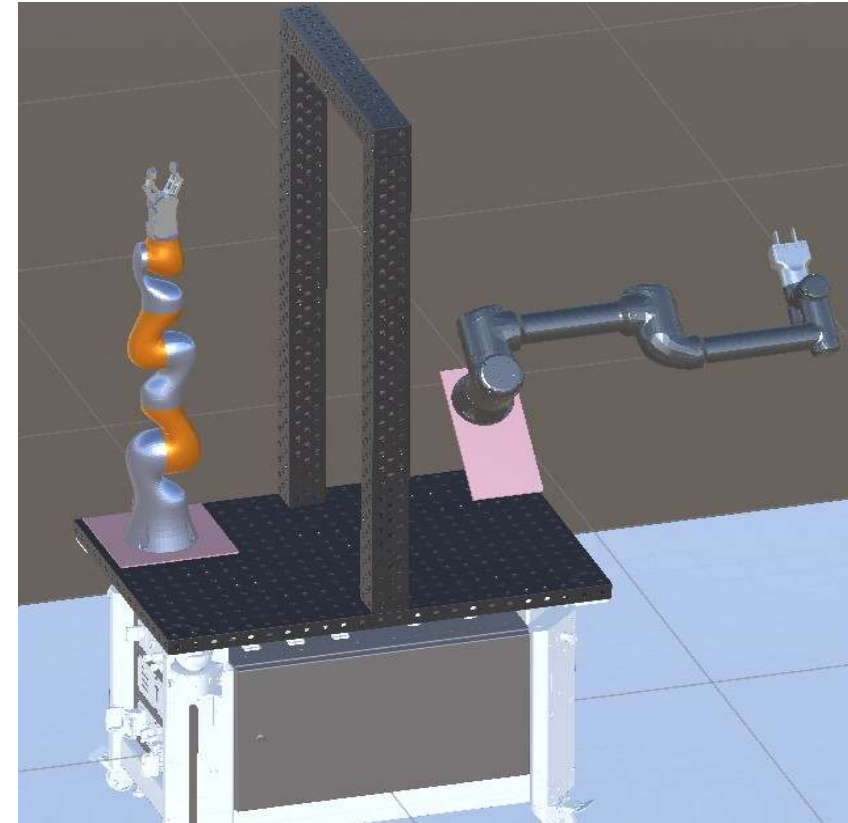
Main Idea: DT Constellation

- 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

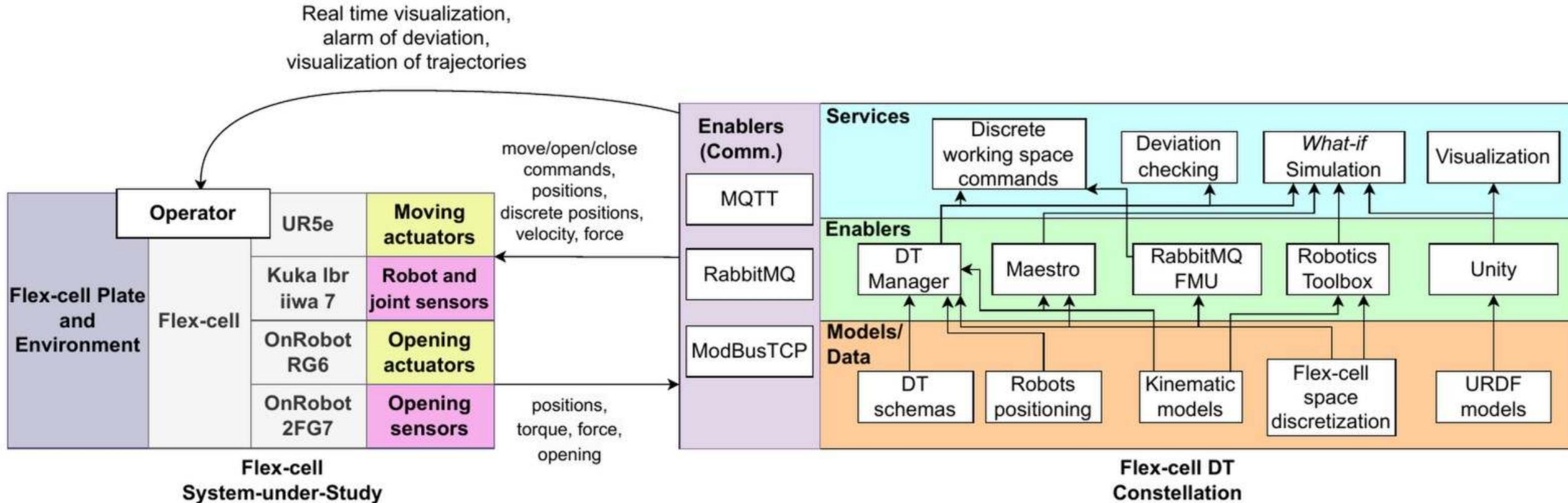


Figure 5. Constellation⁷ of the flex-cell DT, detailing the composition of the DT and the data flow.

DT Characteristics

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

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	

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 <code>getAttributeValue</code> 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 <code>setAttributeValue</code> for parameter update and <code>executeOperation</code> for direct actions.
MC6: Digital Twin Services	The flex-cell DT provides services for <i>what-if simulation</i> , <i>trajectory visualization</i> , <i>discrete working space commands</i> , and <i>deviation checking</i> .
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.

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 Ibr 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 <i>getAttributeValue</i> on periodic basis or on event

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 <i>setAttributeValue</i> for parameter update and <i>executeOperation</i> for direct actions
C6: Digital Twin Services	Describes services, such as <i>optimization</i> , <i>task planning</i> , and <i>visualization</i> , which DT provides to users and physical system.	flex-cell DT provides services for <i>what-if simulation</i> , <i>trajectory visualization</i> , <i>discrete working space commands</i> , and <i>deviation checking</i>
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 <i>design, manufacturing, and service</i> life-cycle phases. Within <i>service</i> phase, it supports <i>creating, executing, analyzing, saving, and terminating</i> . DTs cover system <i>as-designed</i> and <i>as operated</i> .
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, KUKAInterface, 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

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 (<i>described in paper</i>)
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

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
<i>C19: Data Ownership and Privacy</i>	<p>Refers to ethical and technical aspects regarding data ownership and data privacy.</p> <p><i>Is the data owned by the PT owner or by DT service provider?</i></p>	Not considered in the case study
<i>C20: Standardization</i>	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)
<i>C21: Security and Safety Considerations</i>	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

Missing Characteristics?

Discussion: Can you propose any
crucial missing characteristic?

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)

John Fitzgerald
Claudio Gomes
Peter Gorm Larsen *Editors*

The Engineering
of Digital Twins

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.

Desktop Robotti

MC1: System under study

MC2: Physical acting components

MC3: Physical sensing components

MC6: Digital Twin services

MC11: Tooling and enablers

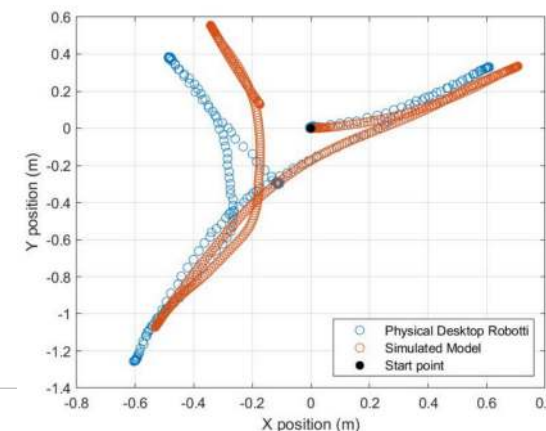
Small prototype of a field (agricultural) robot. A mobile robot.

Motors for each wheel.

RPLidar A1, IMU (Inertial Management Unit), and wheel encoders.

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.*

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 injection⁶⁶ and runtime model swapping.⁶⁷ RViz for visualization.



Gunnerus Research Vessel



Photo: Fredrik Skoglund

- 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)

Table 12.5: TwinShip articles and their topic.

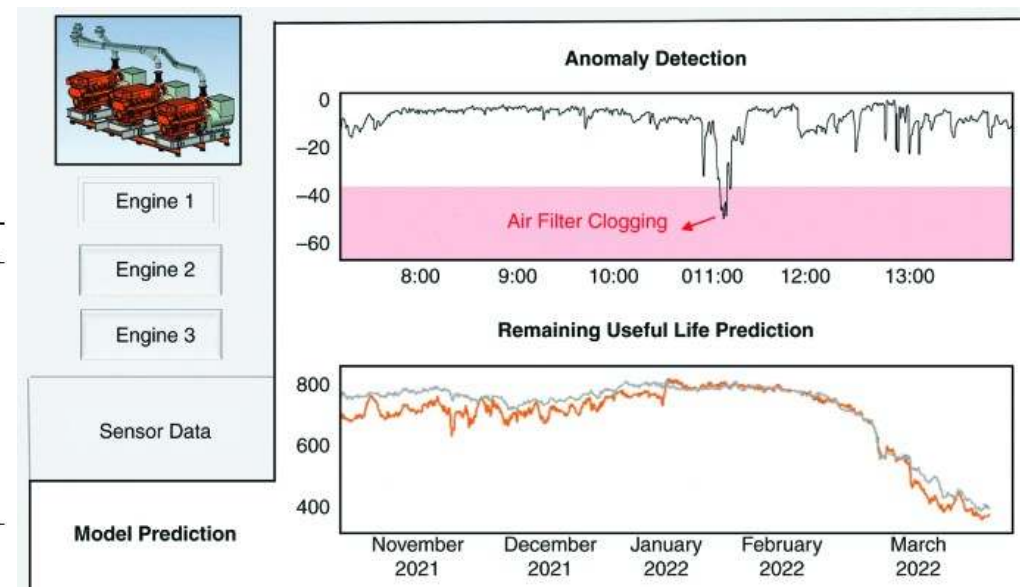
Year	Topic	Citation
2019	Estimating useful life predictions	[3]
2020	Co-simulation framework to simulate Gunnerus case-study	[15]
2020	Gunnerus DT within a co-simulation environment	[16]
2021	Development of a ship trajectory predictor	[20]
2022	Improving trajectory prediction with a physics-based model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

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 Gunnerus

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 direction	deg
Wind sensor	Wind speed	knots
	Port thruster rotational speed	%
Thruster	Port thruster angle	deg
	Starboard thruster rotational speed	%
	Starboard thruster angle	deg
	Tunnel thruster rotational speed	%

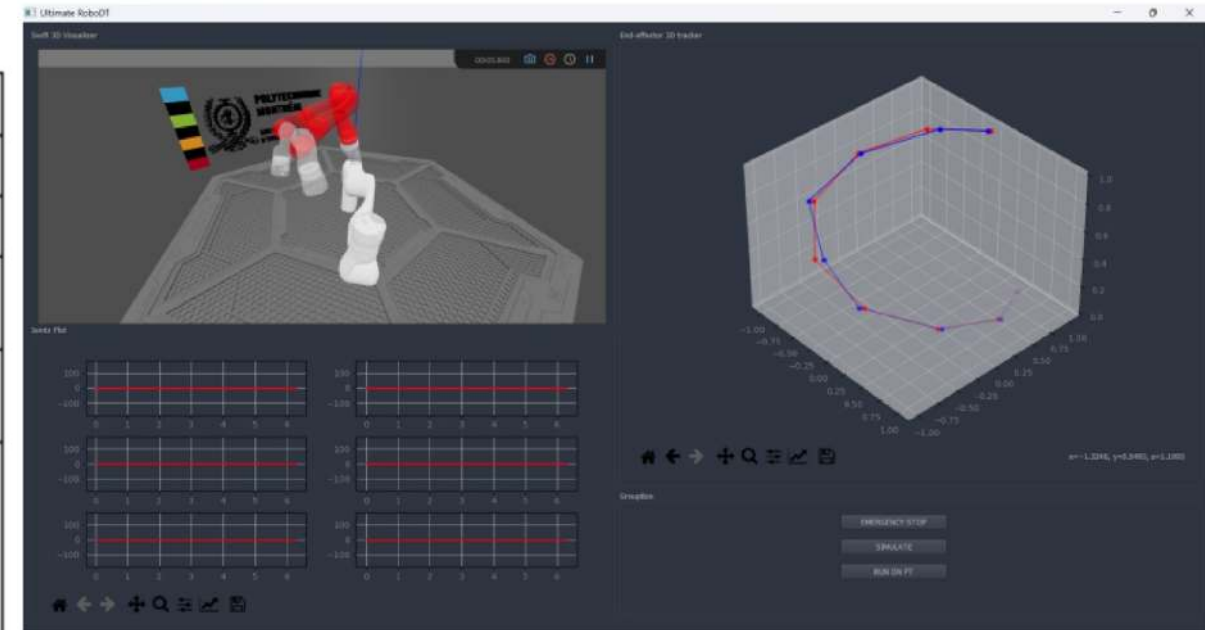


Ongoing DT Reporting Work

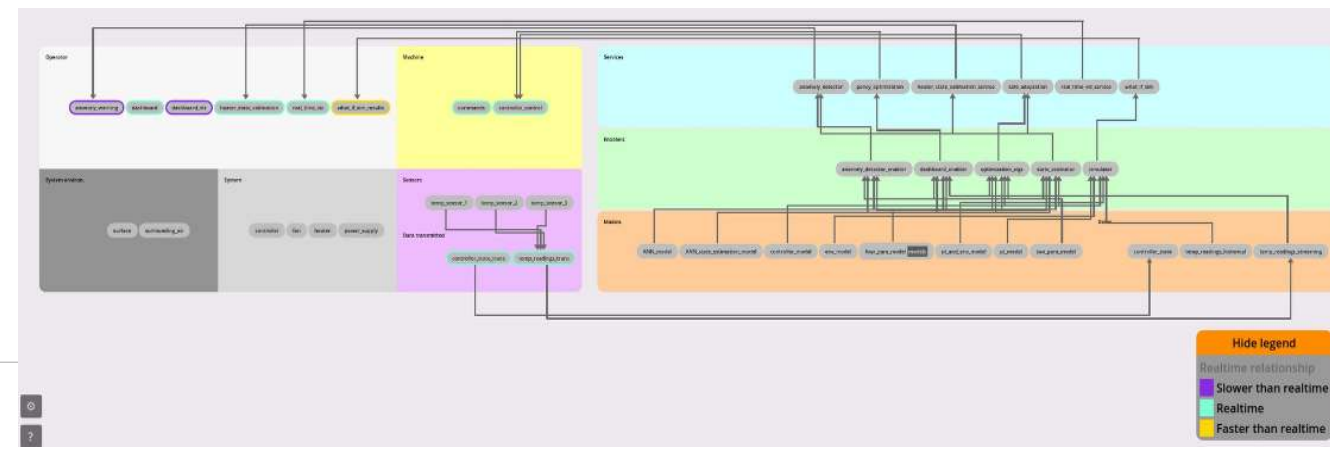
- Validation on further case studies

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	<ul style="list-style-type: none"> - 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



- Model/ontology-based production of visualisations/reports



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.



POLYTECHNIQUE
MONTRÉAL
TECHNOLOGICAL
UNIVERSITY

Conclusion

Oakes 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

- Observability of DTs
- DT engineering using LLMs



Globalink Research Intern



Angelica Portocarrero

Universidad Autónoma de Occidente, Colombia

- DT engineering using LLMs

Conclusion

Takeaways:

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

Thank you!

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bentleyoakes.com

Student Report Example

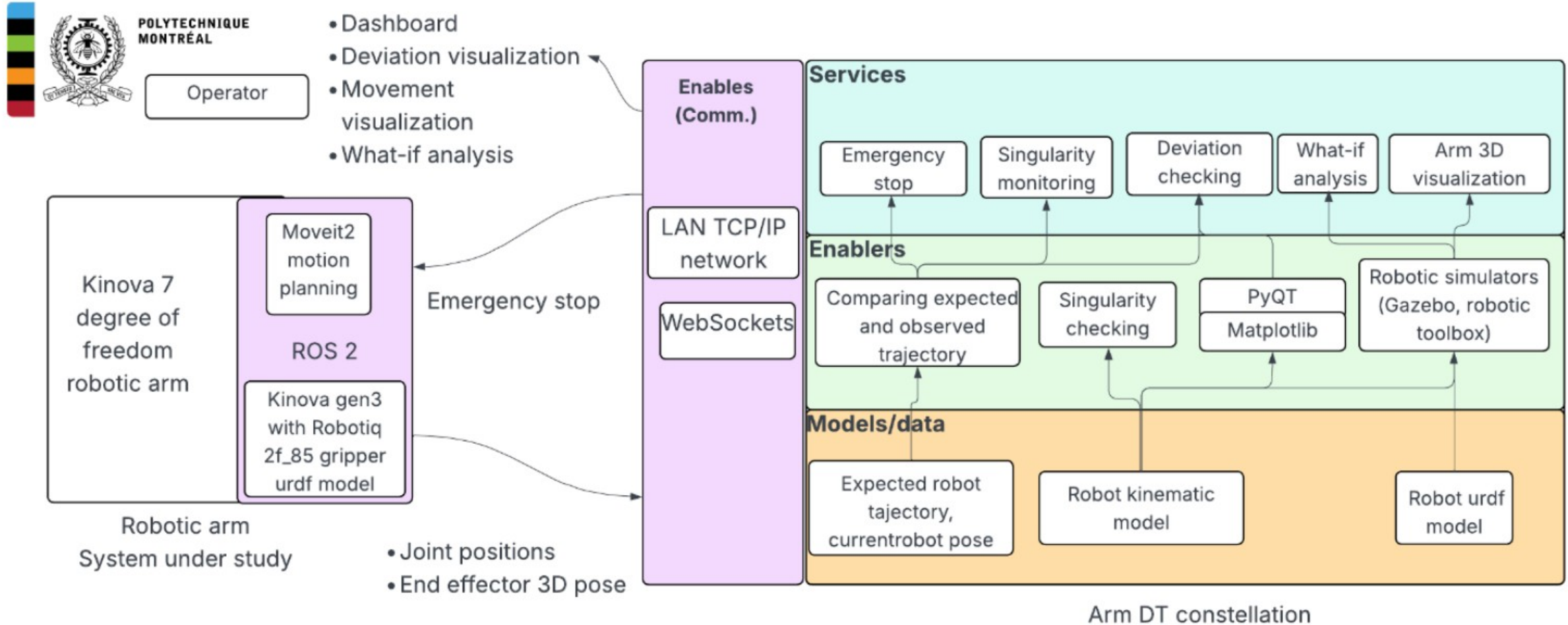


Figure 10: Digital twin constellation

Student Report Example

Proposed DT characteristics:

DT Characteristic	Description	
MC1: System-under-Study	Describes the SUS, i.e., the PT, of the system of interest.	The PT is a 7-Dof Kinova 3 robotic arm programmed to perform a pick and place task. It is controlled by a computer running ROS2. The PT is accessible through a Wi-Fi router to external devices.
MC2: Physical acting components	Mechanisms the DT can use to act on the PT.	Emergency stop service implemented in ROS 2 allow the DT to communicate to the PT to stop any movement of the robot.
MC3: Physical sensing components	Mechanisms the PT can use to transfer data to the DT.	<p>Joint position sensor: this data is provided by the robot controller as sampled from sensors located in the physical joints at 1kHz +.</p> <p>Expected Joint position: this data is provided by the robot controller.</p>

Robotti Example

Table 7. Brief description of the Desktop Robotti DT case study with our proposed DT description framework.

Merged Characteristic	Desktop Robotti case study
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 <i>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.</i>
MC13: Twinning Process and Digital Twin Evolution	The DT was engineered based on an existing prototype of a large-scale agricultural robot (Robotti ⁷⁰) with a subsequent engineering approach. The evolution presents five milestones: the setup of the parallel operation, enhancement with fault-injection, time discrepancy detection (between real and simulated/DT time), runtime model-swapping, collision zone detection for a
MC10: Digital Twin Models and Data	There are a kinematic model of the robot, specifically a bicycle model with the virtual wheels placed at the center of the front and rear axles, and an actuation model for the DC motors expressed as a first-order system. The data of interest are related to robot positioning and velocity.
MC11: Tooling and Enablers	RabbitMQ and the Robot Operating System (ROS) ⁶⁷ for communication and interfacing. Maestro and RMQFMU to run the co-simulation scenarios. The Model Swap and Fault Injection plugins to run the DT services related to fault injection ⁶⁸ and runtime model swapping ⁶⁹ . RViz for visualization.

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.