Digital Twins:

A survey on enabling technologies, challenges, trends and future prospects,

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Agenda

- Overview
- Motivation
- How DT works?
- Potentials and trends
- Enabling tech
- Use Cases
- Case Studies
- Research Challenges

Introduction

- **Digital Twin:** it replicates the physical systems in the digital world. It provides a mechanism for real-time simulation, testing, analysis, and hazards prevention, offering a better understanding of physical systems and enabling optimization
- **Core tech:** it became a practical solution for various industries, leveraging ML, AI, data integration, VR/AR, sensing technologies, cloud storage, data visualization and uRLLC

Major Role

- **Replicate physical elements** e.g. machinery, sensors, and even human operations in the digital space
- **Allow real-time synchronization** between the physical and digital systems through seamless data transfer and enabling both to operate
- **Optimize processes** by allowing data-driven insights, predictive analytics, and real-time adjustments in physical systems

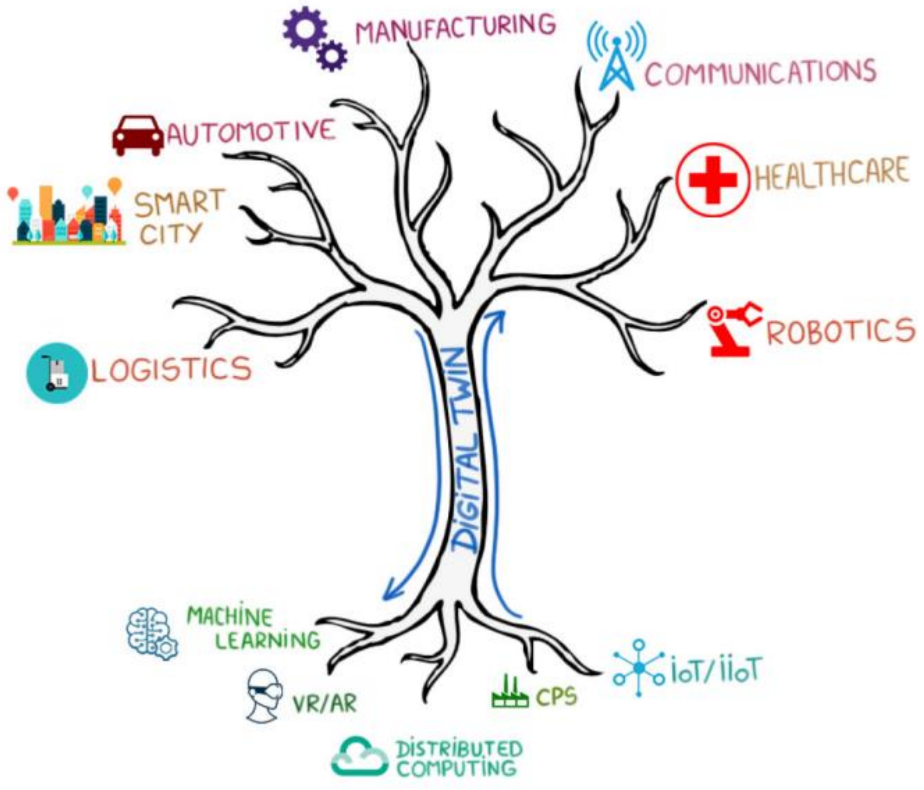

Fig. 1. The Digital Twin's central role in the Industry 4.0 era.

Challenges

- **Data security** integration of digital and physical systems requires robust cyber security measures to protect sensitive information
- **Complexity** implementing DTs for complex systems, especially system-of-systems, requires sophisticated integration and management capabilities
- **Interoperability** various industries and sectors use varying standards, protocols and technologies, creating hurdles for interoperable solutions

Evolution

- **DT concept** in a presentation by Micheal Grieves, under topic “Conceptual ideal for product lifecycle management” represented an idea of monitor and manage the life cycle of a product through a virtual replica which became a formation of DT to transform industry
- **Early architecture of DT** proposed and named tripartite architecture based on
  - **Real space** presented physical object or system
  - **Virtual space** digital counter, or virtual replica of the physical object
  - **The link** a communication medium facilitating the connection and real-time synchronization between the real and virtual spaces

Accelerating impact

- **Covid 19** crisis has pushed digital transformation into overdrive. While Industry 4.0 was well underway, however, pandemic had accelerated the pace of digital transformation across industries
- **Global Impact** real time interactive applications access forecast aligns with the overall trend of increased information availability, accessibility and opportunities for innovation and development

Apollo 13 Incident

- **The birth of DT concept** the Apollo 13 mission in 1970 became an early and pivotal example of a real-time system simulation. An unexpected explosion aboard the spacecraft endangering the lives of the astronauts. In response spacecraft simulators that mirrored the physical conditions of the real spacecraft. Allowing engineers to simulate various failure scenarios and devise optimal solutions to bring the astronauts safely home

Definition

- **DT** often referred to as Self-X constructs, are fundamental to understanding a true Digital Twin
  - **Self-Adapting** ensuring operational excellence in real time by auto adjusting its virtual model to change in the real world condition
  - **Self-Regulating** ensuring the system operates with in safe limits, changes made by the DT in response to environmental conditions must not exceed the physical system's capabilities
  - **Self-Monitoring** keep track of relevant parameters and conditions to ensure real-time awareness
  - **Self-Diagnosing** DT assesses its own performance and health, identifying when it is unable to maintain optimal operation, and taking corrective actions if necessary

Industry adoption

- **Market growth** has not been very impressive due to significant hurdle for business as return on investment. Academic research has positioned the DT as a transformative technology, the real-world adoption remain slower
- **IBM** is one of the top providers of DT solutions, prepared case studies show promising returns from sectors of manufacturing and smart buildings includes ASTRI (validated software packages before deployment on physical systems which reduced cost by 30% and expediting deployment by 40%), UC San Francisco implemented DT at Mission Bay Hospital that helped reduce diagnosis and repair time of the building pipes
- **Ansys** a major player in DT space and a leading engineering simulation software providing a bridge among product development and operations, Mecuris a company specialized in custom prostheses and orthotics, Jet Towers it models modular wireless towers reducing installation and design time by 80%
- **General Electric** its DT solutions help optimize the performance of power plants by monitoring and predicting operational behavior, delivering significant financial benefits
- **Spirent optimizing 5G networks with DT** uses cases for DT in 5G includes V2X testing and virtual drive testing and private 5G networks for smart factories

ML

- **Central role** ML use enables the DT to perform tasks like optimization, predictive modeling, anomaly detection to improve performance, prevent failures and enhance decision making
- **Applications** optimize operational parameters such as energy consumption, production yield, or even predicting fire scenarios, predict future behaviors of a physical asset based on historical data, integrate ML with physics based models to improve transparency and performance when predicting asset behavior and security like remote surgery services from Dos attacks
- **Challenges** data requirements where DL techniques require large amounts of training data, which might not always be readily available, again ML/DL models are often considered lack transparency in decision making process which is unlikely in critical apps like fault detection, data generalization DT data must resemble real-world data provided by ML

Cloud, fog, edge computing in DT

- **Distributed computing need** complex systems requires computational demands of DT to do real-time sync between physical and virtual worlds,
  - **Cloud computing** to provide heavy computational power required for tasks like complex simulations, big data analysis and hosting virtual counter parts of physical assets, acts as a central data repository and host virtual twins of equipment to enable predictive maintenance, healthcare remote services and collaborative decision making to patient’s health
  - **Fog and edge computing** to avoid overloading cloud resources and reduce latency, both are often employed to process data closer to the source

IoT/IIoT

- **Virtual representation** accuracy is required when collecting a real-time data from physical assets in DT environment which is combination of physical and digital world. Use cases are smart sensors (RFID tags, wearables provide cheap and reliable data streams that feed into the DT), smart cities (hazard prediction and remote safety management), industrial app (continuously monitoring health of equipment)
  - **Challenges** communication protocols like MQTT, CoAP, OPC-UA and 5G uRLLC needs to be harmonized with in DT systems to ensure seamless data transmission and real-time synch between the physical and virtual twins, data privacy and security for remote healthcare and industrial operations includes federated learning and block chain technology

Cyber-Physical systems

- **Ubiquitous and intelligent systems** CPS can refer to a holistic convergence of real-world equipment (sensors, actuators, human operators) with virtual intelligent control mechanisms to ensure resilience and adaptability of the system to changes and failure e.g. manufacturing execution systems (MES) and SOA

VR/AR

- **VR** provides a virtual representation of the physical systems useful for remote surgeries where doctors can control robotic arms and monitor real-time feedback from the patients virtual twin, training simulations for industrial equipment to allow operators to interact with virtual models of machines before working on real systems
- **AR** enhancing real-time monitoring and dynamic interaction with physical assets e.g. workers can see real time data from a machine or system just by pointing their device at it, thereby reducing the need for physical interaction

Infrastructure

Propositions various models have been proposed recently to deal with various infrastructure's performance evaluations e.g.

- Thyssenkrupp and Microsoft (improve performance of high rise elevator system by predicting elevator usage and optimizing travel time by AI),
- Ruohomaki (DT plaform for the city of Helsinki to enhance city management, integrating 3D city models with IoT sensors for real-time monitoring of urban systems),
- Akelos (developed a holistic DT framework for offshore structures using parallel cloud computations to make real-time, risk based decisions),
- General Electric (a framework for power plants integrating data across various domain e.g. thermal, mechanical, electrical etc) to optimize safety

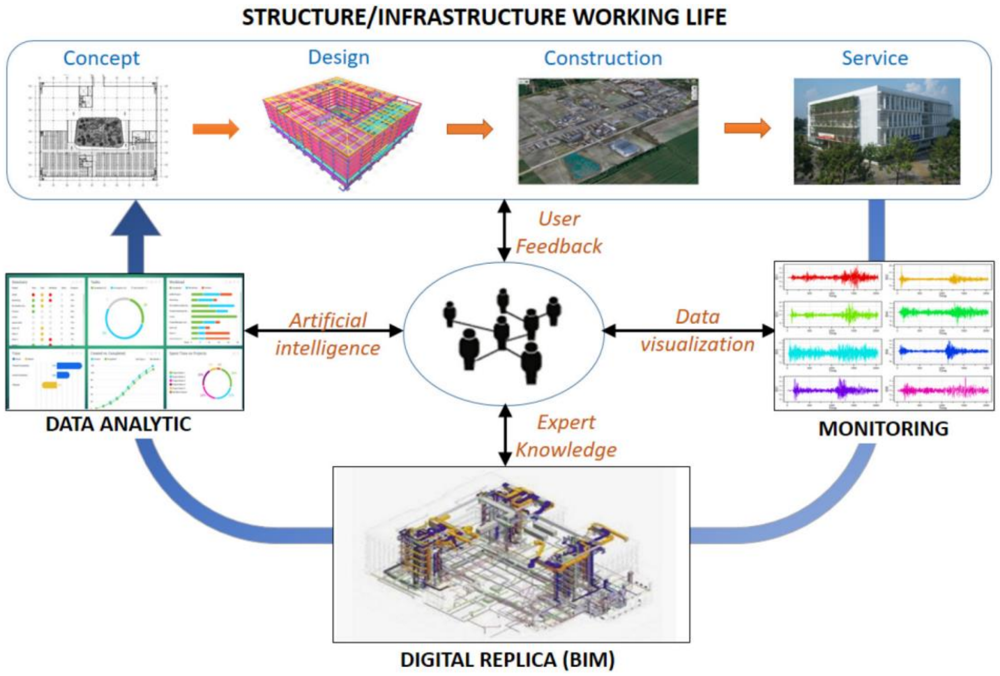

Fig. 7. Digital Twin in infrastructure.

Predictive Maintenance (PdM)

Key concepts emphasizing its potential to optimize costs, time, and resources in industry through accurate predictions of machine failures. PdM systems increasingly rely on ML and DL techniques to predict machine failures. It includes concepts as

- Data acquisition data collection from machines or sensors,
- Data analysis and state detection identifying the condition of the machine,
- Health assessment and prognosis estimating remaining useful life and identifying potential failures,
- Maintenance actions and alerts triggering maintenance operations when necessary

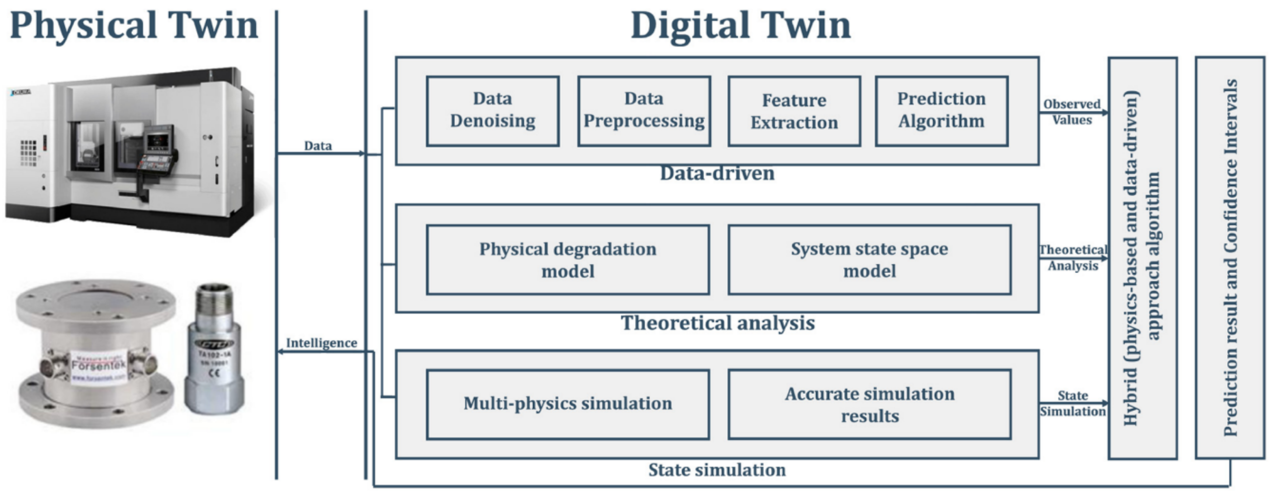

Fig. 10. DT-based PdM scheme using hybrid modeling.

Tea Industry in India

This DT tech is focused on identification and prediction of machine anomalies during the tea-bag production process

- <u>Operational challenges</u> face by company due to human errors, equipment breakdown, down time events
- <u>Identified anomalies</u> included tread knot anomaly, outer envelop print misalignment, missing filter bag in the envelop, tag paper print misalignment, missing outer envelope paper, faulty filter paper tube, filter paper slicing issues

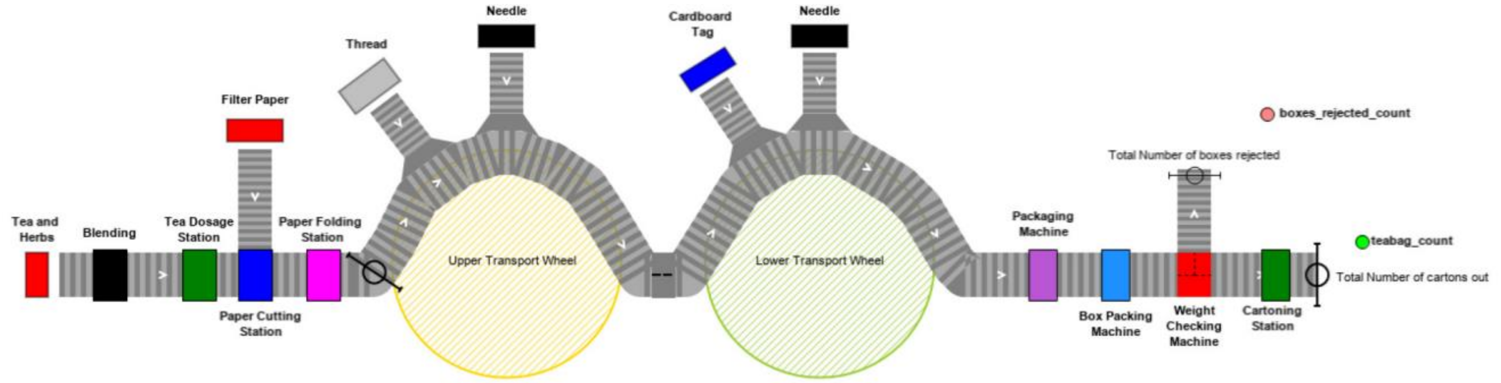

Fig. 11. Conveyor Belt Snapshot of a Tea Manufacturing Plant.

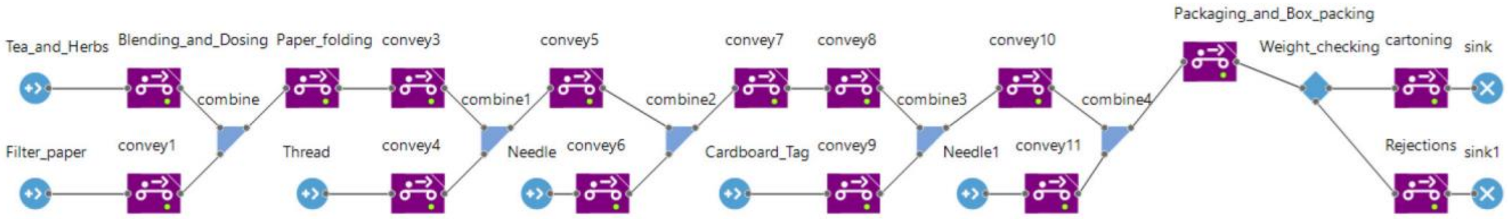

Fig. 12. Steps in the Process of Tea Manufacturing.

cDTSHM Framework

A DT based system developed at the London DT Research Centre for SHM with a primary focus on bridges. Its technology includes ML, DL, cloud computing and sensor data integration for real-time SHM. It uses web application for visual understanding and results computations. It tech stack is based on python, pytorch, aws and sensors. Its case studies are Toy Model of the Sydney Harbour Bridge, Simplified Laboratory Model of a Stayed-Cable Bridge, Real Data from the Z24 Bridge, Application to the Nam O Railway Bridge.

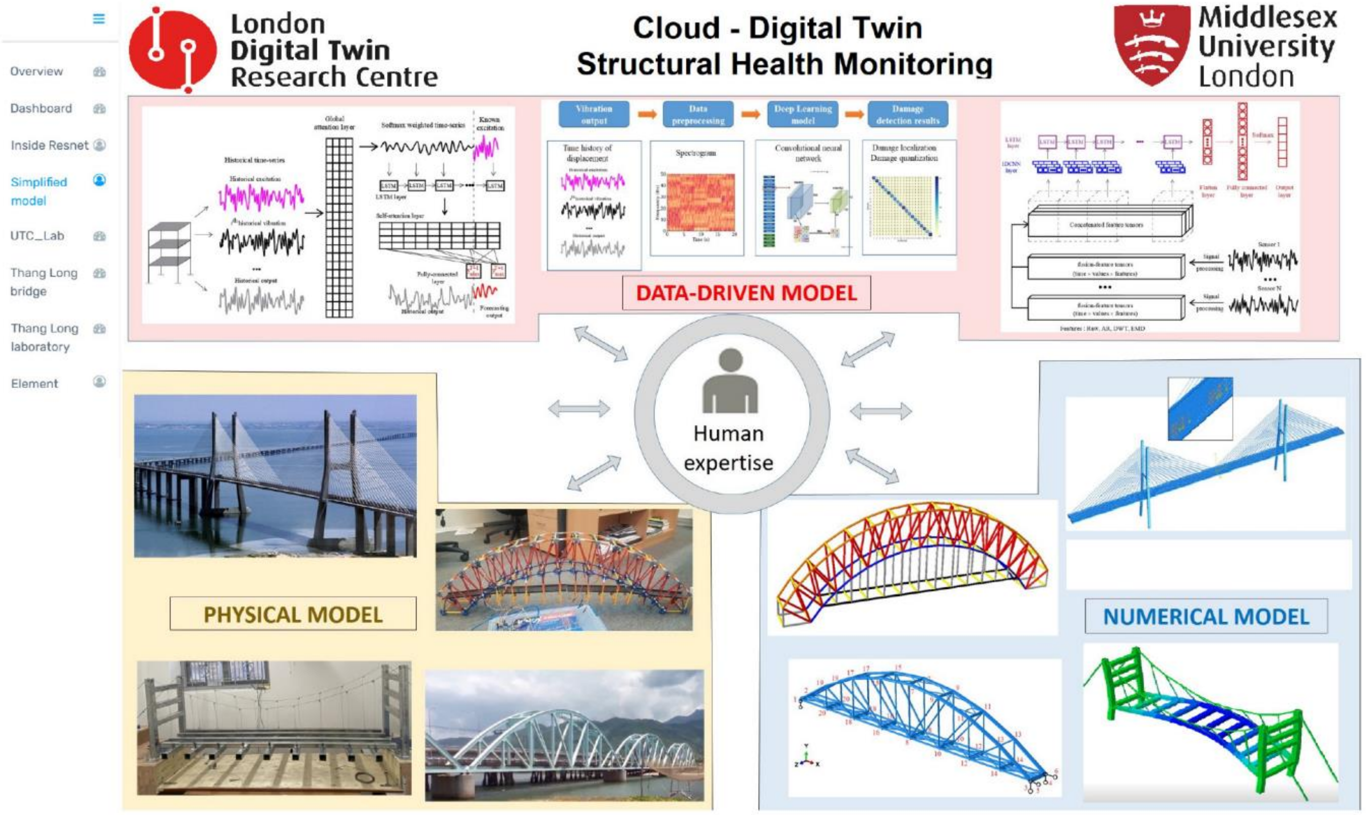

Fig. 14. Cloud Digital Twin Structural Health Monitoring Web application.

Future Directions

- **Return on Investment** reluctance of business to adopt DT is a significant challenge in their widespread implementation, primarily due to perceived high development costs and the difficulty in quantifying their ROI
- **Socio-Technical DT (STDT)** is characterized by the interplay of heterogeneous networked agents both human and machines to integrate human behavior, social systems and machine operations. Such systems involve joint optimization and evolution of technical and social systems
- **Fidelity and real-time synch** based on specific app needs because they are costly e.g. traffic management simple DT that store and process basic data includes traffic light coordinates and density, can deliver effective results. While, complex and sensitive apps like remote surgery, real-time mirroring becomes crucial to ensure safe and accurate outcomes
- **Need for standardization** to models or interfaces could streamline the process of building, deploying and integrating DTs across different domains e.g. ISO/IEC SC41, NIST, Digital Twin Consortium, Microsoft's Digital Twin Definition Language (DTDL)
- **Security in DT** a key feature of a Digital Twin is its ability to communicate in real-time with the physical twin, exchanging data to create a dynamic representation of the physical asset. This communication link is crucial for the functioning of the DT but also poses a potential vulnerability for **data theft, corruption**, or **malicious attacks**.