Digital Twins in Aircraft
Merging Cyber-Physical System and Human Decision-Making

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Funded by the European Union
NextGenerationEU

CPS Digital Twin for Predictive Maintenance

- From Time-Based Maintenance to **Predictive Maintenance (PdM):**
  - **Improve safety:**
    - Predict potential failures before they occur
  - **Cost mitigation:**
    - In 2022, **77$ billion** was spent for aircraft maintenance

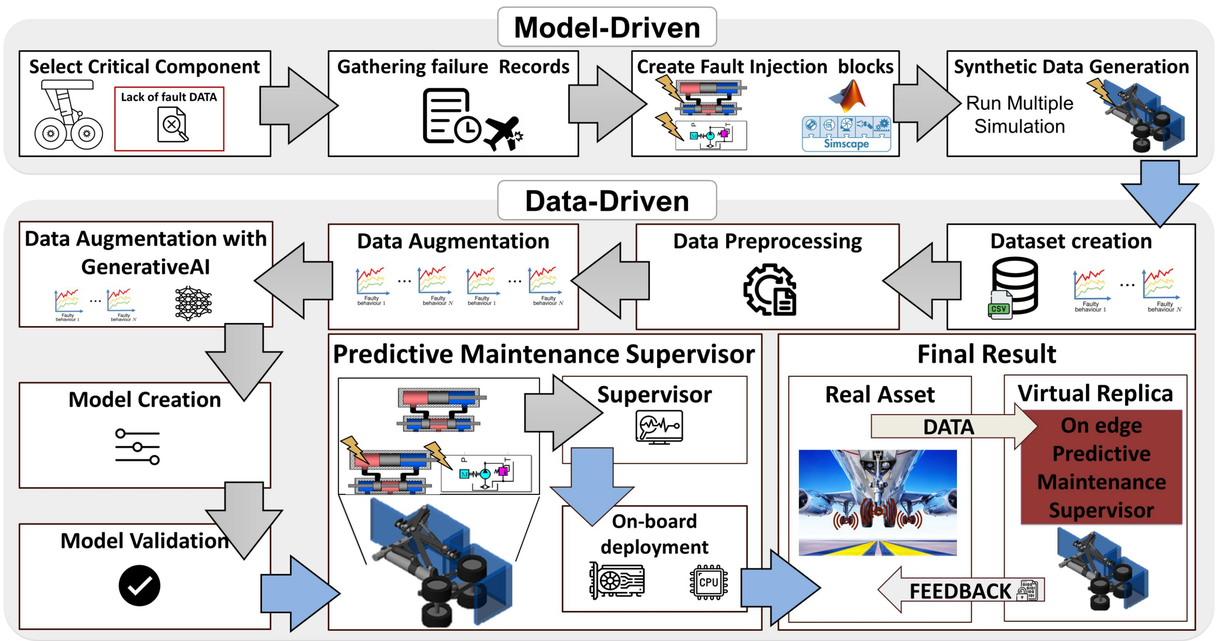
- **Challenges** for **PdM**:
  - **Complexity** and **Explainability**: Models must be accurate and interpretable for stakeholders
  - **Data Availability**: Scarcity of publicly available datasets to train and validate predictive models
  - Limited computational power
  - **Safety Risks**: Ensuring the reliability of predictions

Human Digital Twin for Decision Making

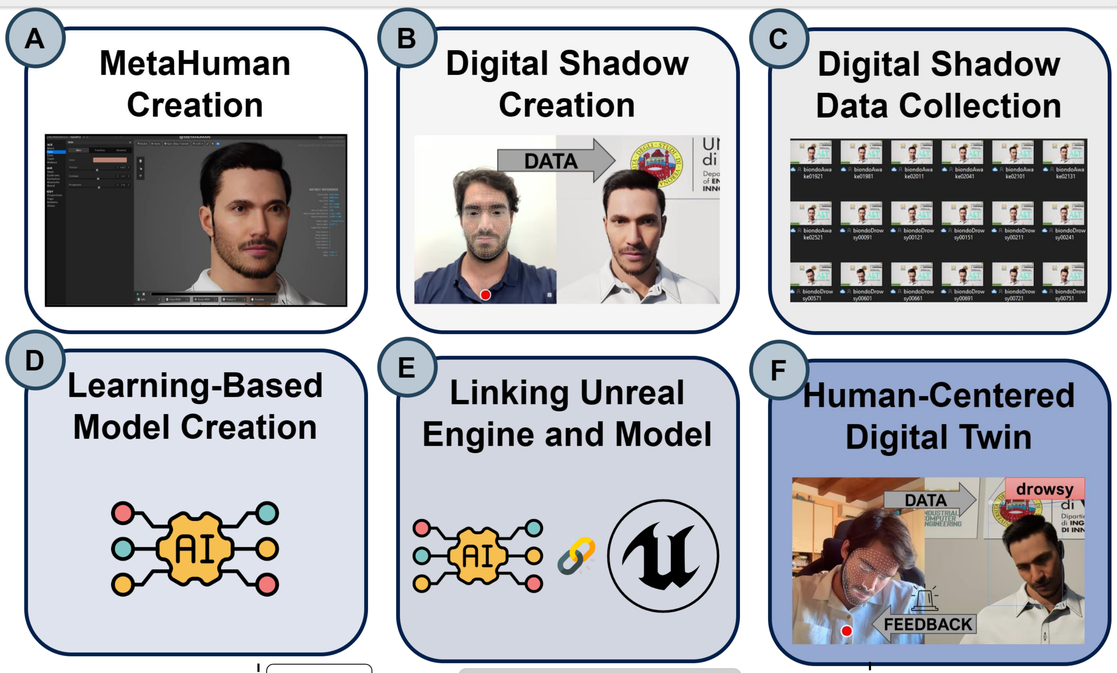
- **Human Digital Twin (DT) Benefits**:
  - Real-Time Insights: Continuously monitos human fatigue, stress, and cognitive load
  - Decision-Making Support: Assesses whether the human is in a state to make critical decisions
  - Synthetic data for Edge Cases: Generates realistics training scenarios for extreme conditions

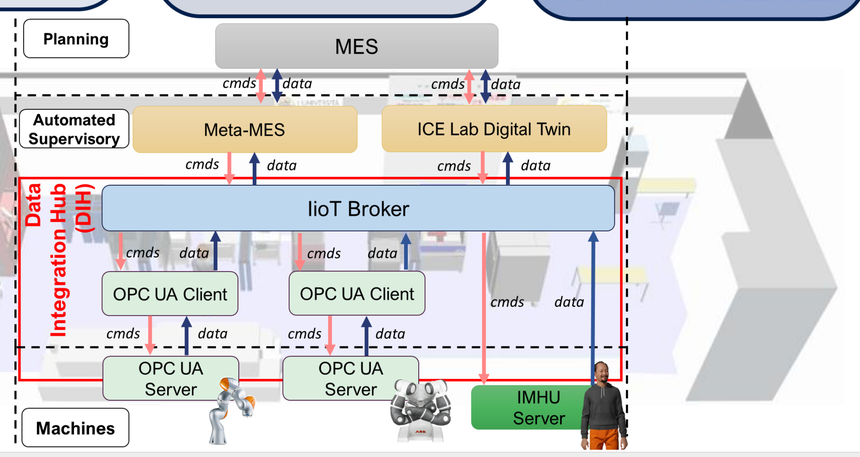
- **Challenges** for **Human Digital Twin** Development
  - **Lack** of **standardize framework for** human Digital Twin
  - Existing digital twin approaches focus on **machines**
  - **Complexity of Human Modeling**
  - Human behavior is **non-deterministic**

CPS Digital Twin Framework



Human Digital Twin Framework





Use-Case: Landing Gear System & ICE Laboratory

- **Landing Gear System**
  - Essential Aircraft Component
  - Safe takeoffs, taxiing and landings
  - Accounts for 20% of the airframe's maintenance

- **ICE Laboratory**
  - Fully-fledged production line
  - Service Oriented Architecture
  - Heterogeneous Environment
  - Digital Twin Infrastructure for Industry 4.0

References

1) F. Biondani, et al. “**Fault Injection for Synthetic Data Generation in Aircraft: A Simulation-Based Approach**” IEEE 22nd International Conference on Industrial Informatics (INDIN)
2) F.Biondani, et al. "**The Future of Aircraft Maintenance: Goals and Challenges of Digital Twins for In-flight Operations**" 2024 : CPS Summer School
3) F. Biondani, et al. “**Human-Centered Digital Twin in Industry 5.0**", 2025 Design, Automation and Test in Europe Conference (DATE)
4) F.Biondani, et al. "**IMHU: A Service-Oriented Framework for Human Digital Twins in the Industrial Metaverse**" 2025 : IEEE TRANSACTIONS ON SERVICES COMPUTING

Take Home Message

A Design Methodology for Cyber-Physical System and Human-Centered Digital Twins