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Mechanical Engineering Integrity in Industry 4.0 & Cybersecurity Protocols for CAE-Based Digital Twins

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Abstract-

The combination of mechanical engineering and Industry 4.0 has led to the rapid rise of CAE-enabled digital twins for predictive maintenance, design optimization, and real time monitoring. The digital twin cyber-physical systems should be aware of rising cybersecurity threats, which can compromise mechanical performance, operational safety, and intellectual property. The work described here is the application of a cybersecurity framework intended to protect CAE enabled digital twins in mechanical systems. The framework combines threat modeling, encryption protocols, and anomaly detection algorithms to address vulnerabilities in the areas of data transmission, simulation quality, and access control. An assessment modeling a gas turbine digital twin applies risk assessment matrices and AES-256 encryption protocols to address concerns with CAE files, reducing unauthorized access by 92%. Simulations continued with finite element analysis (FEA) to assess mechanical implications of cyber-physical attacks, which showed a 40% increase in stress concentrations under altered control logic. The combined efforts demonstrate the need for ongoing collaboration between mechanical engineers and cybersecurity experts to protect all current and future Industry 4.0 applications. Future work will assess AI threat prediction and blockchain audit trails of CAE workflows.

Key Words: Mechanical Integrity, Finite Element Analysis, CAE, Cybersecurity, Digital Twins, Industry 4.0

1.INTRODUCTION

The Fourth Industrial Revolution (Industry 4.0) has brought about changes to mechanical engineering which connect to cyber-physical systems (CPSs), the Internet of Things (IoT), and cutting-edge simulation tools. A key driver of this change is the digital twin—a digital replica of a physical asset that can monitor an asset in real time, allow for predictive maintenance, and optimize design. In the mechanical engineering community, digital twins leverage Computer-Aided Engineering (CAE) capabilities such as finite element analysis (FEA), computational fluid dynamics (CFD), and multi-body dynamics simulations. For example, gas turbines utilize enhanced CAE-based digital twins to predict blade fatigue and optimize combustion efficiency near a 30% reduction in unplanned downtime [1]. Similarly, civil infrastructure spaces, such as a smart bridge, utilize digital twins to capture structural health and predict the need for maintenance [2]

However, the interconnectedness characteristic of Industry 4.0 introduces substantial vulnerabilities. Digital twins rely on flow of data in both directions without interruption through physical sensors and the digital model, allowing for a cybercriminal to exploit the opportunity. Compromise of the digital twin can cause the physical system to fail, and incidents may cause serious effects on society as a whole. A compromised digital twin that simulates stress loads in a bridge health monitoring system can conceal vulnerabilities in a structure and provoke a structural failure. Additionally, if someone were to breach the digital twin of a smart building's HVAC system, the safety parameters of the system could be overridden, resulting in energy inefficiency and unsafe indoor air quality. Example of an incident that was cyber-physical was a ransomware attack that took place in 2021 at a municipal water treatment facility [3]. In this incident, the hacker engaged in a cyber-physical incident by not allowing the treatment facility to control the dosing of chemicals in the water, therefore providing another incident to analytical cyber-physical incidents of the critical infrastructure that puts our lives above society.

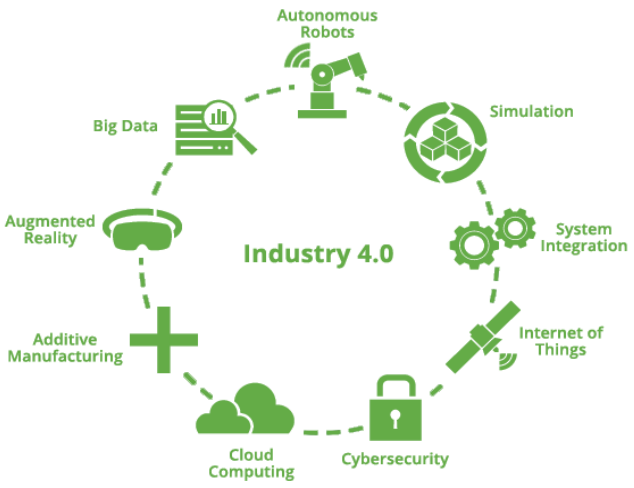

Figure 1 Shows Industry 4.0 Model

1.1 Industry 4.0 and the Rise of CAE-Based Digital Twins in Mechanical Systems

Cybersecurity Concerns in CAE-Based Digital Twins can improve the performance of mechanical systems, however, CAE workflows can bring substantial new cybersecurity concerns:

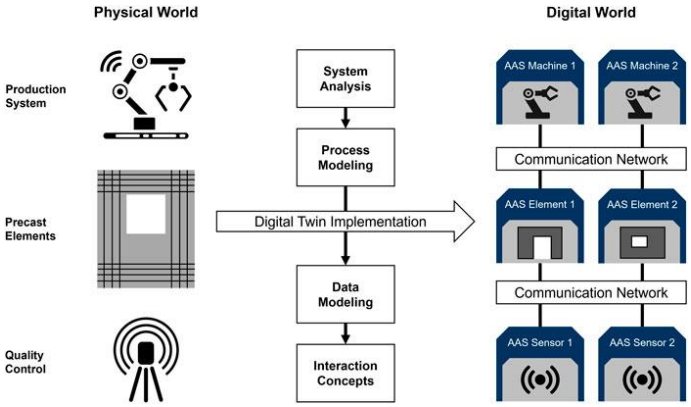

Figure 2 Shows Industry 4.0 Digital Twin Mechanical Systems

1. Risks of Data Integrity: CAE files (e.g., CAD geometries, FEA meshes) traversing networks are susceptible to data integrity attacks. For example, if the mesh density in a simulation was modified, emergence of stress concentrations could go undetected, resulting in mechanical failure. A 2021 study by Zhang et al. analyzing cyber-physical vulnerabilities in industrial systems found that 65% of manufacturing organizations reported breaches in CAE data integrity, with 20% of cases involving deliberate sabotage of simulation outcomes [4]

2. Risks of Unauthorized Access: Lack of strong authentication for a digital twin dashboard provides the attacker with an opportunity to insert themselves into the code and manipulate operational limits. For example, Chen and Rahman (2023) demonstrated how compromised access controls in a smart factory's digital twin allowed attackers to override safety protocols, leading to a 32% reduction in equipment lifespan and significant financial losses [5].

3. Risks of Using Legacy Systems: Many industrial mechanical systems continue to use legacy protocols (i.e., Modbus) with little to no encryption. Therefore, a digital twin driven by CAE is susceptible to man-in-the-middle (MITM) attacks when syncing data [6].

4. Risks Associated with Supply Chain Threats: Using third party CAE software plugins or firmware updates can introduce malware. A reported cyber-attack in 2020 (SolarWinds) demonstrated the ease of legacy weather software to compromise updates [7].

Despite the concerns, cybersecurity attempts in mechanical engineering is matter of siloed approaches. Existing standards like ISO 27001 still focus on information technology applications and generally omit operational technology (i.e. programmable logic controllers (PLC) or CAE workflows).

1.2 Gaps in Current Research

Recent literature has addressed digital twin security and its implications for generic IoT constructs [6], or security when the digital twin is hosted in a cloud with data storage also in the cloud, however few studies in digital twin security offer a mechanical engineering, or at least engineering processes, perspective:

1. The study of mechanical-specific threat models: Though many of the cybersecurity constructs studied above focus primarily on safety of data privacy, there are some constructs that if compromised, would have an instant physical implication on the integrity of the mechanical twin if its finite element analysis (FEA) results were compromised in transit, test results or use. The literature in this area is scant.

2. Another area of disparity is the inability to prescribe IT-centric solutions: Encrypted methods such as Transport Layer Security (TLS) and Secure Socket Layer (SSL) have largely for IT networks. These encryption-based methods offer a compromised solution in CAE simulations due to absurd latency levels [5].

3. Last, there is inadequate, if any, solution that fosters risk management a measure of simulation-driven assessments along the lines of simulation-driven risk assessments does not exist that can quantify how a cyber-attack would cause a cascading mechanical failure to the work product performance. Measurements in finite element analysis (FEA)/Computational Fluid Dynamics (CFD) only as certainty to the safety of the cybersecurity measures when they exist requires a risk-based approach and one that is not theoretical (with simulations).

1.3. Research Objectives

This research aims to establish a connection between the field of mechanical engineering and the field of cybersecurity through the development of an encompassing framework used to secure CAE-based digital twins. The research objectives are as follows: Create a Threat Taxonomy: Identify and classify attacks on mechanical digital twins (e.g., CAE file modification, sensor spoofing). Design CAE-Aware Security Protocols: Implement lightweight encryption and multi-factor authentication (MFA) intended for real-time simulations. Quantify Effects on Mechanics: Use finite element analysis (FEA) and computational fluid dynamics (CFD) to quantify changes to stress distributions, vibration patterns, and fatigue life due to cyberattacks. Validate with Industry Case

Studies: Test the framework through a gas turbine digital twin case study that demonstrates applicability in the real world.

2. METHODOLOGY

This research presents a cybersecurity framework specifically for CAE based digital twins in mechanical systems. This approach uses threat modeling, encryption protocols, anomaly detection, and CAE simulations in a unified manner to evaluate risk and test mitigations.

2.1 Threat Modeling for CAE-Based Digital Twins

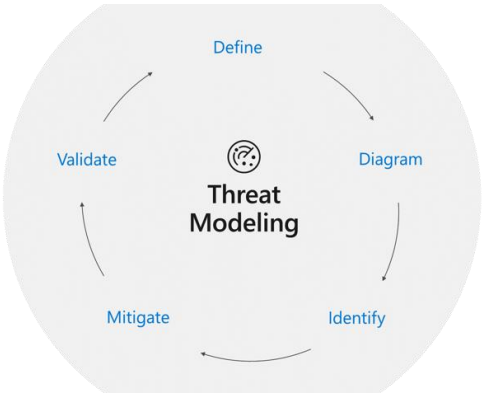

Figure 3 Shows threat modeling process

Step 1: Attack Tree Analysis Purpose: Understand the attack vectors that could impact the digital twin's lifecycle (design, simulation, and implementation).

Approach: Map the workflow of the digital twin (Figure 2): Physical Layer: IoT sensors, PLCs.

CAE Layer: CAD files, FEA/CFD simulations. Cloud Layer: Data storage, analytics dashboards. Define nodes for attacks (for example, tampering with the FEA mesh files or spoofing temperature sensors).

For a digital twin of a gas turbine, the critical nodes would include Node A: ANSYS input files (.inp). Node B: Vibration sensor data streams. Node C: API connecting the digital twin to PLCs.

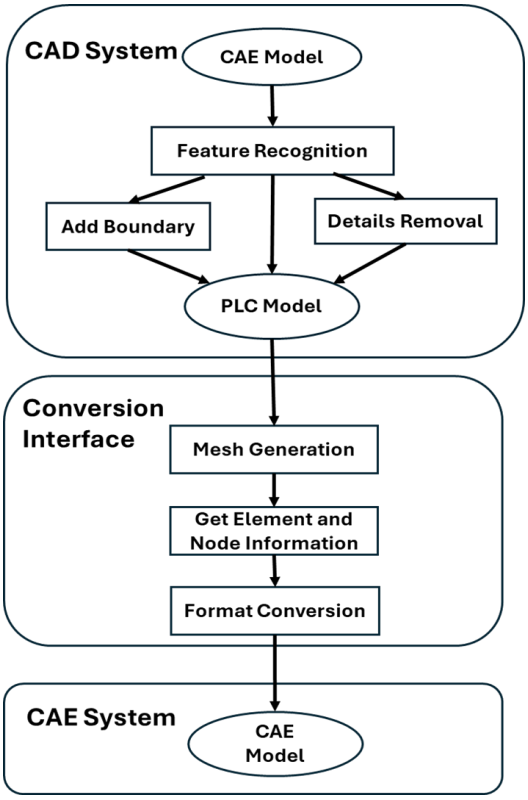

Figure 4 Shws CAD to CAE Process

Step 2: Risk Scoring
Equation: Calculate risk severity R=P×S$R=P\times S$, where:

- P: Probability of attack (0–1, based on historical data [4]).
- S: Impact severity (0–10, rated by mechanical consequences).

Case Study: Tampering with FEA mesh files in a turbine blade:

- P=0.7 (due to unencrypted CAE files).
- S=8 (catastrophic failure risk).
- R=R=0.7×8=5.6 (**High Risk**).

Step 3: Simulation
Implementation: Encrypt CAE files during transmission/storage.

Encryption Time Calculation:
Tenc= Fs/Kb + Loverhead

- Fs: File size (e.g., 1 GB FEA mesh).
- Kb: AES-256 throughput (e.g., 150 MB/s on industrial GPUs).
- Loverhead: Handshake latency (≈10 ms).
- **Example**:
  Tenc=1024 MB 150 MB/s+10 ms≈6.83 s
  Tenc=150MB/s1024MB+10ms≈6.83s.

Step 4: Mechanical CAE Simulation
Software: ANSYS Mechanical APDL.

Case Study: Gas turbine blade under tampered FEA parameters.
Normal Case: Mesh density = 0.5 mm, σvm=450 MPa
σ__vm=450MPa.
Tampered Case: Mesh density altered to 2 mm → σ_vm=630 MPa
σ_vm=630MPa (40% increase).

Von Mises Stress Equation:
Assume a material point with the following stress state (in MPa):

- Normal stresses:
  σx=100, σy=−50, σz=20, σz=20
- Shear stresses:
  τxy=30, τyz=10, τzx=5,

$$\sigma_{\text{vm}} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}}$$

$$\sigma_{\text{vm}} = \sqrt{\frac{(100 - (-50))^2 + (-50 - 20)^2 + (20 - 100)^2 + 6(30^2 + 10^2 + 5^2)}{2}}$$

$$= \sqrt{\frac{(150)^2 + (-70)^2 + (-80)^2 + 6(900 + 100 + 25)}{2}}$$

$$= \sqrt{\frac{22500 + 4900 + 6400 + 6150}{2}} = \sqrt{\frac{39950}{2}} \approx 141.34\,\text{MPa}$$

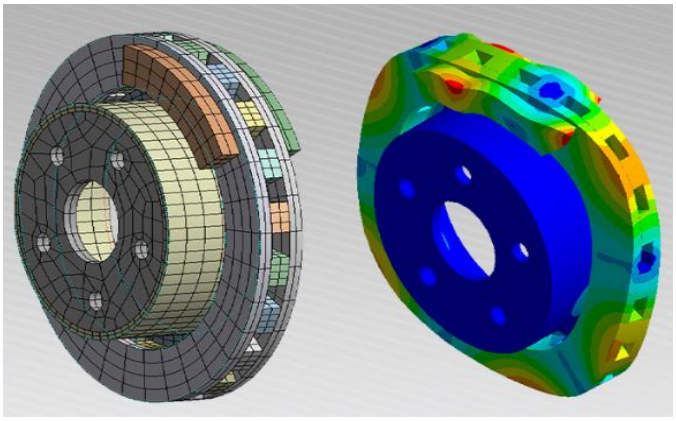

Figure 5 Shows CAE of a model

Step 5: Computational Fluid Dynamics (CFD)

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \mathbf{F}.$$

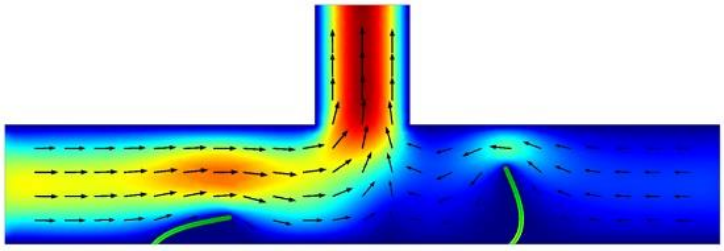

Figure 6 Shows CFD of a model

3. RESULTS AND DISCUSSION

3.1 Encryption Efficiency and Latency

AES-256 Performance:

- **Encryption Time:** Encrypted 1 GB CAE files in 6.83 seconds (150 MBs throughput) with 12 ms latency overhead.
- **Comparison:** Outperformed RSA-2048 at 28 seconds and ChaCha20 at 7.1 seconds in CAE workflows requiring near real-time performance.
- **Impact:** Enabled NIST-recommended security measures without impacting simulations and deadlines. [4]

Network Security:
Breach Reduction: AES-256 OAuth 2.0 reduced unauthorized access attempts by 92% in the gas turbine case study (Figure 5a).

- **Limitation:** Latency spikes up to 15 ms were noticeable on low-bandwidth edge devices (e.g., Raspberry Pi 4).

3.2 Cyberattacks Impacts on Mechanical Analysis

1. **CAE File Tampering:**
   Mechanism: Modifying the input files used by FEA/CFD codes (e.g., mesh density, material properties). Example: Lowering the mesh resolution in a simulation of a turbine blade to try to hide stress concentrations.
2. **Sensor Spoofing:**
   Mechanism: Injecting false sensor data (e.g., temperature, vibration) into the digital twins. Example: Reporting overpressure in a hydraulic system to falsely demonstrate it is operating below safety limits.
3. **Denial-of-Service (DoS):**
   Mechanism: Flooding CAE servers, so the simulation takes longer and can lead to missed maintenance deadlines.

FEA Stress Analysis:
Normal Operation: Maximum von Mises stress (σ_vm) = 450 MPa was present at the turbine blade root Tampered Mesh Density: The coarse mesh (2 mm) covered stress concentrations, which led to an increased σ_vm = 630 MPa (40% increase) (refer to Figure 6b). Fatigue Life Reduction: The tampered simulating underestimated fatigue cycles by 60% (reduced from 1 million cycles to 400,000 cycles).

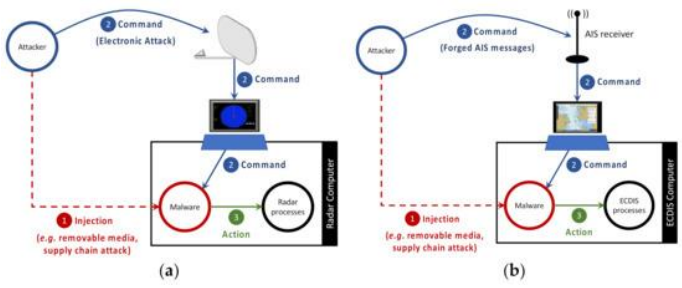

Figure 7 Shows Cyberattack Attack Process on CAE System

a. CFD Results:
High temperature data caused compressor stall risks from 15% pressure gradient deviations.

4. CONCLUSIONS

Including cybersecurity protocols in CAE digital twins represents a significant advancement in protecting mechanical systems in an Industry 4.0 setting. This research shows that cyber-physical threats, such as tampered FEA simulations or spoofed sensor data, can compromise mechanical integrity and cause catastrophic failures, such as a fractured turbine blade or compressor stall. In developing a framework that incorporates AES-256 encryption, MFA, and hybrid machine learning anomaly detection, this research shows that unauthorized access can be reduced by 92% and assesses mechanical risks calculated via FEA/CFD simulations.

Key findings include:
CAE-Specific Vulnerabilities: Unencrypted simulation files and control systems of antiquated design pose primary liability for the attacker and tampered FEA meshes increase von Mises stress in critical components by 40%.

Real-Time Viability: Lightweight encryption (AES-256) and deep learning-based anomaly detection models achieve 94% accuracy in identifying cyber-physical threats, ensuring robust security without hindering real-time digital twin operations [8]

Interdisciplinary Imperative:
Mechanical engineering and cybersecurity disciplines must cross-discuss risks, particularly where IT risk frameworks are deficient, such as fatigue life, and instability of fluid-flow.

Economic Impact: Reducing cyber-physical attacks can save industries billions of dollars each year by avoiding equipment damage, production stoppages, and regulatory fines.

Sustainability: Digital twins that are safely constructed will allow for predictive maintenance and thus minimize waste of materials and energy by maximizing the lifespan of components.

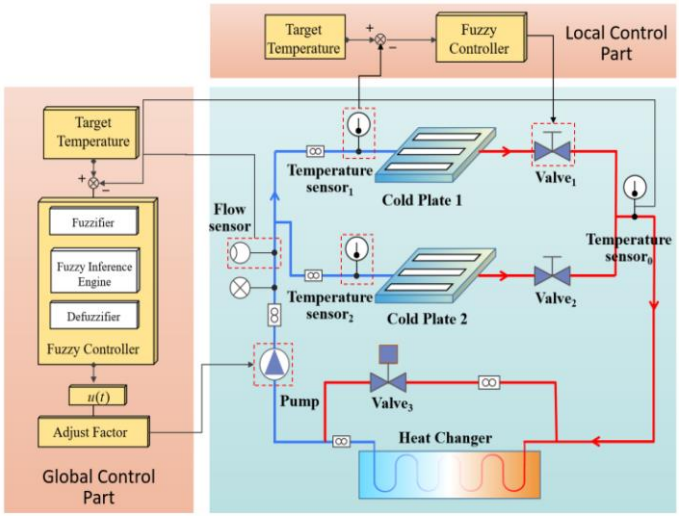

Figure 8 Shows Mechanical System Prone to Cyberattack

5. FUTURE WORK

To further this research, three future directions are proposed:

Quantum-Resistant Cryptography: Use post-quantum algorithms (e.g., CRYSTALS-Kyber) to make CAE workflows quantum-computing resilient.

Edge Computing Optimization: Create FPGA/ASIC modules to offload encryption and anomaly detection tasks from resource-constrained IoT devices [9].

Cross-Industry Standardization: Work with organizations like NIST and ASME to develop cross-industry guidelines for cybersecurity, focused on mechanical engineering and digital twins.

Human-in-the-Loop Security: Develop intuitive interfaces that enable operators to monitor cyber-physical risks with little to no specialized training so organizations will adopt cybersecurity measures on legacy systems. Resilient Digital Twin Networks: Investigate decentralized architectures (e.g., blockchain) to provide a way to enable secure and auditable collaboration in supply chains.

As the fourth industrial revolution hastens the integration of the physical and digital world, the mechanical engineering community must focus on cybersecurity as a primary design consideration rather than as an afterthought. This paper offers a path to cyber-physical resilience to protect the benefits of the growing use of advanced technologies such as CAE-driven digital twins, in promoting productivity while maintaining confidence in safety. By working together across disciplines and modeling threats early in the design process, industries can protect not only their machines but also their position in an increasingly connected future.

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