Cyber-physical systems

ME 2150 HACPS

What Are Cyber-Physical Systems?

- ▶ **Definition**: Integrations of computational and physical components designed to interact with and control the physical world.
- **▶** Core Components:
 - Embedded software
 - Sensors and actuators
 - Communication networks
- Examples:
 - Smart thermostats
 - Autonomous vehicles
 - Power grids
 - Medical devices
 - Industrial automation

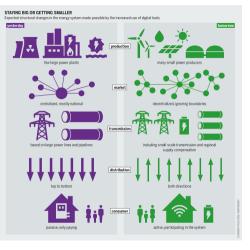


Figure 1: Smart Grid (source: Wikipedia)

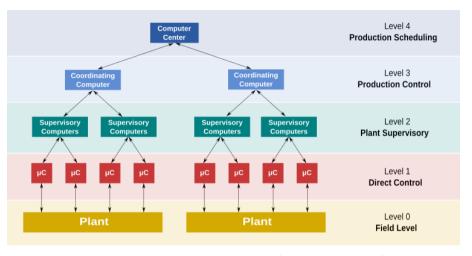


Figure 2: Industrial control system (source: Wikipedia)



Figure 3: Infusion pump (source: Wikipedia)



Figure 4: Programmable logic controllers (source: Wikipedia)

Key Characteristics of CPS

- ► Tight integration of:
 - Computation
 - Communication
 - Control
- ► Features:
 - ► Real-time data collection and processing
 - Feedback loops for adaptation and optimization
 - Precision and responsiveness
- ► Applications:
 - Stabilizing aircraft
 - Robotic manufacturing
 - Patient monitoring in healthcare

Benefits and Challenges

- ► Benefits:
 - Enhanced efficiency and automation
 - Safer infrastructure
 - Optimized energy use
 - Innovations in healthcare
- ► Challenges:
 - Dependability and fault tolerance
 - Cybersecurity risks
 - Ethical and regulatory concerns

Examples of CPS Failures

Year
1980s
1991
1996
1999
2003
2009—2010
2010
2018

Ariane 5: Dead code with no protection against integer overflow caused improper exception handling, which halted the INS.

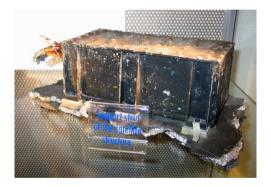


Figure 5: Ariane 5 fragment (source: Wikipedia)

Mars Climate Orbiter: There was mismatch between units: SI units by NASA and US customary units by Lockheed Martin

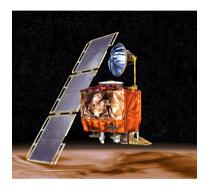


Figure 6: Mars climage orbiter (source:) Wikipedia

Failures in a CPS can occur at various levels and involve both computational and physical components.

1. Software Failures

- ▶ Bugs and Logic Errors: Flaws in code causing incorrect system behavior.
- Concurrency Issues: Errors from improper handling of parallel processes (e.g., race conditions).
- Inadequate Testing: Lack of stress testing or real-world scenario validation.
- ▶ Legacy Code Issues: Reuse of outdated or unsuitable software without adaptation.
- Algorithmic Errors: Inaccurate computations or decisions based on incorrect algorithms.

2. Hardware Failures

- ► Sensor Malfunctions: Faulty or degraded sensors providing incorrect data.
- Actuator Failures: Actuators unable to perform physical actions correctly.
- ▶ Communication Failures: Loss or corruption of signals between components.
- ▶ Power Supply Issues: Interruptions or inconsistencies in power sources.
- Wear and Tear: Physical degradation over time in mechanical or electronic components.

3. Integration Failures

- System-Level Incompatibility: Mismatch between hardware, software, or network protocols.
- Interdisciplinary Misalignment: Miscommunication between teams in software, hardware, and system integration.
- Model Inaccuracy: Computational models not accurately reflecting physical processes.
- ▶ Interference: Crosstalk or unintended interactions between interconnected systems.

4. Real-Time Performance Failures

- ▶ Timing Issues: Delayed responses failing to meet real-time requirements.
- Resource Starvation: Insufficient computational or memory resources during critical tasks.
- Clock Synchronization Failures: Lack of alignment in timing between components.

- Communication and Network Failures
 - Latency: Delays in data transmission impacting real-time decision-making.
 - ▶ Data Loss: Missing information due to packet drops or communication errors.
 - ▶ Signal Jamming: Intentional or unintentional disruption of wireless signals.
 - ▶ Bandwidth Limitations: Insufficient capacity for data-intensive operations.
- 6. Cybersecurity Failures
 - ► Hacking and Intrusion: Unauthorized access to system components.
 - ▶ Malware and Viruses: Malicious software disrupting operations (e.g., Stuxnet).
 - ▶ Data Breaches: Compromise of sensitive or critical data.
 - ▶ Denial of Service (DoS) Attacks: Overloading the system with excessive requests.

7. Environmental and Physical Failures

- External Environmental Factors:
- Extreme temperatures
- Vibration or shock
- Electromagnetic interference (EMI)
- ► Natural disasters (e.g., floods, earthquakes)
- Physical Damage:
- Accidental impacts
- Tampering or vandalism

8. Human Factors

- Design Errors: Poorly planned interfaces, workflows, or system architecture.
- Operational Errors: Mistakes made by users or operators during interaction with the system.
- Mismanagement: Insufficient oversight, training, or maintenance.

- 9. Systemic Failures
 - ► Cascading Failures: A single fault triggering failures in interconnected systems.
 - ▶ Feedback Loop Errors: Faulty feedback causing instability or incorrect adjustments.
 - Control Loop Failures: Inability of control systems to stabilize or maintain desired states.
- 10. Regulatory and Ethical Failures
 - Non-Compliance: Failure to adhere to safety, quality, or industry standards.
 - Ethical Concerns: Neglect of user safety, privacy, or fairness in system design.

Lessons from CPS Failures

- 1. Software Failures: Use formal verification and rigorous testing to prevent bugs and logic errors.
- 2. Hardware Failures: Implement redundancy and regular maintenance for reliability.
- 3. Integration Failures: Conduct thorough system-level testing and ensure interdisciplinary collaboration.
- 4. Human Factors: Design user-friendly systems and provide comprehensive operator training.
- 5. Communication Failures: Build robust, fail-safe communication protocols.

Lessons from CPS Failures cont'd

- 6. Cybersecurity Failures: Integrate strong security measures and regularly update systems.
- 7. Real-Time Performance Failures: Ensure adequate resources and precise timing for real-time operations.
- 8. Environmental Failures: Design systems to withstand environmental extremes and physical shocks.
- 9. Systemic Failures: Prevent cascading effects with robust, fault-tolerant designs.
- 10. Regulatory Failures: Adhere to industry standards and incorporate ethical considerations.

High-Assurance systems are designed with rigorous reliability, safety, and security for critical tasks in scenarios with high consequences.

- 1. Safety: The system must operate without causing harm to people or the environment under all conditions.
- 2. Security: Strong measures must protect the system against unauthorized access, tampering, and cyber threats.
- 3. Reliability: The system must consistently perform its intended functions as designed.
- 4. Robustness: The system should gracefully handle unexpected inputs, errors, or adverse conditions.
- 5. Fail-Safe Design: In the event of a critical failure, the system must default to a safe and stable state.

High-Assurance systems are designed with rigorous reliability, safety, and security for critical tasks in scenarios with high consequences.

- Real-Time Responsiveness: The system must meet strict timing requirements for tasks in real-world scenarios.
- 7. Fault Tolerance: The system must maintain functionality even when components fail or degrade.
- 8. Formal Verification: Mathematical models should validate that the system operates correctly and adheres to its specifications.
- 9. Comprehensive Testing: Rigorous testing must address edge cases, stress conditions, and real-world scenarios.
- 10. Standards Compliance: The system must adhere to applicable industry standards and certifications to ensure safety and quality.

Procedure for Ensuring High-Assurance

- 1. Define Requirements and Constraints
 - Document functional, safety, and security requirements.
 - Specify constraints and identify failure modes.
- 2. Risk Analysis and Hazard Assessment
 - Use methods like FMEA, HAZOP, or STPA.
 - Prioritize high-risk scenarios.
- 3. Formal Design and Architecture
 - Modular, fault-tolerant designs with redundancy.
 - Develop system models for verification.
- 4 Formal Verification
- Use mathematical proofs for correctness.
- 5. Comprehensive Testing
 - - Include unit, integration, and real-world scenario testing.

Procedure for Ensuring High-Assurance cont'

- 6. Implement Standards and Best Practices
- Adhere to industry standards 7. Cross-Disciplinary Collaboration
- Involve experts across relevant fields.
- 8. Documentation and Traceability Maintain detailed records and ensure traceability.

Reassess and safely decommission systems.

- Continuous Monitoring and Feedback
 - Implement real-time monitoring and update systems as needed.
- 10. Lifecycle Assurance