Challenges in real-time wireless Cyber-Physical Systems

George K. Karagiannidis, IEEE Fellow

Wireless Communications & Information Processing Group (WCIP)

Electrical & Computer Engineering Dept.

Aristotle University of Thessaloniki, Greece

E-mail: geokarag@auth.gr

URL: http://geokarag.webpages.auth.gr/

Outline

- Cyber-Physical Systems (CPS)
- Differences between CPS and IoT
- Real Time CPS (RT-CPS)
- The big challenge of RT-CPS: Ultra Reliable Low-Latency Communications (URLLC)
- KPIs and research challenges of RT-CPS
- Requirements of next generation RT-CPS

What are Cyber-Physical Systems (CPS)?

"Cyber-Physical Systems (CPS) are physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context"

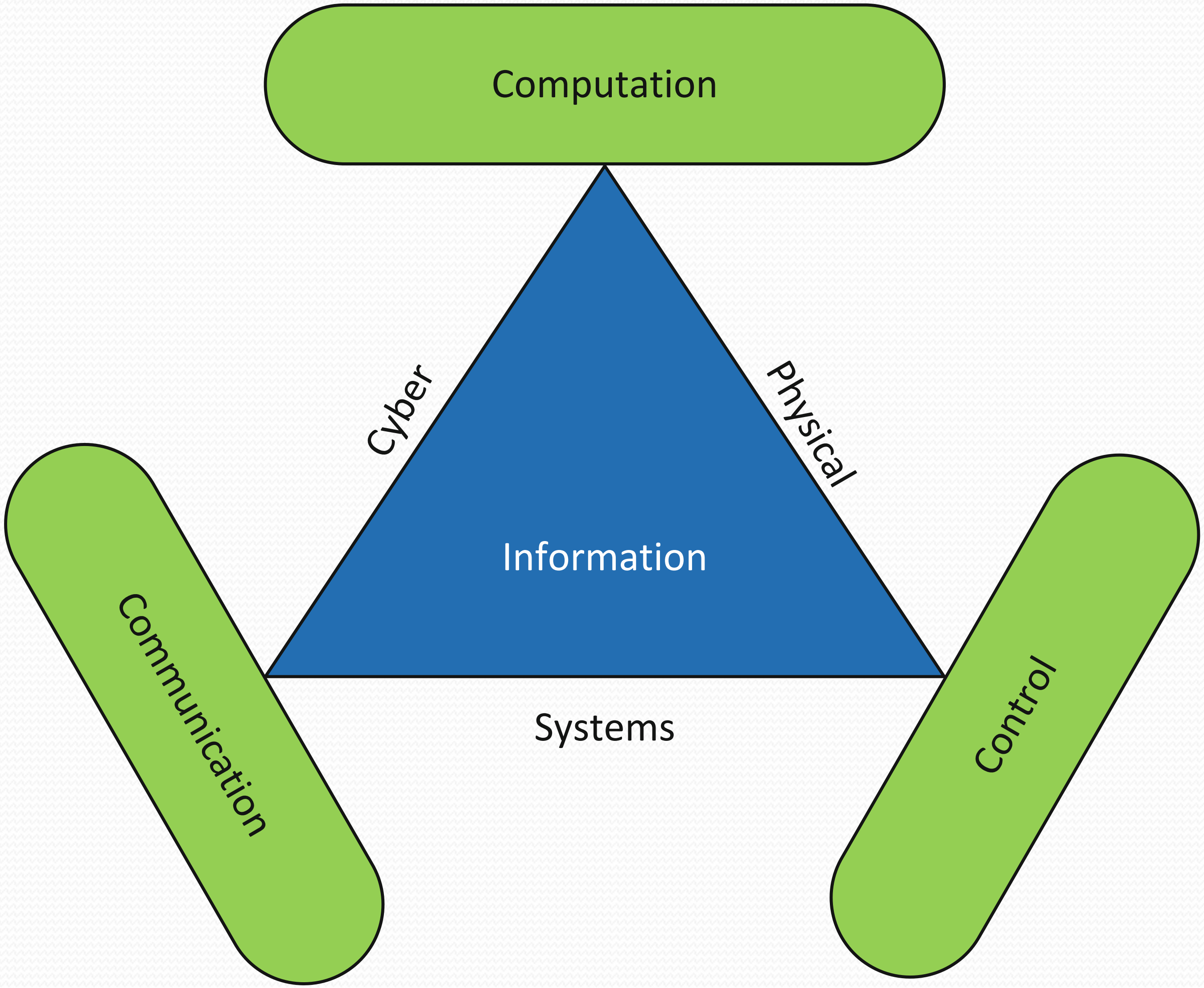
NSF, Cyber Physical Systems – Nsf10515, NSF, 2010,

URL https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.htm

Applications: robotics, distributed monitoring, process control, power-grid management

Tian Y-C Levy DC. *Handbook of Real-Time Computing*. Singapore: Springer Singapore : Imprint: Springer; 2020. doi:10.1007/978-981-4585-87-3

Cyber-Physical Systems (CPS)?



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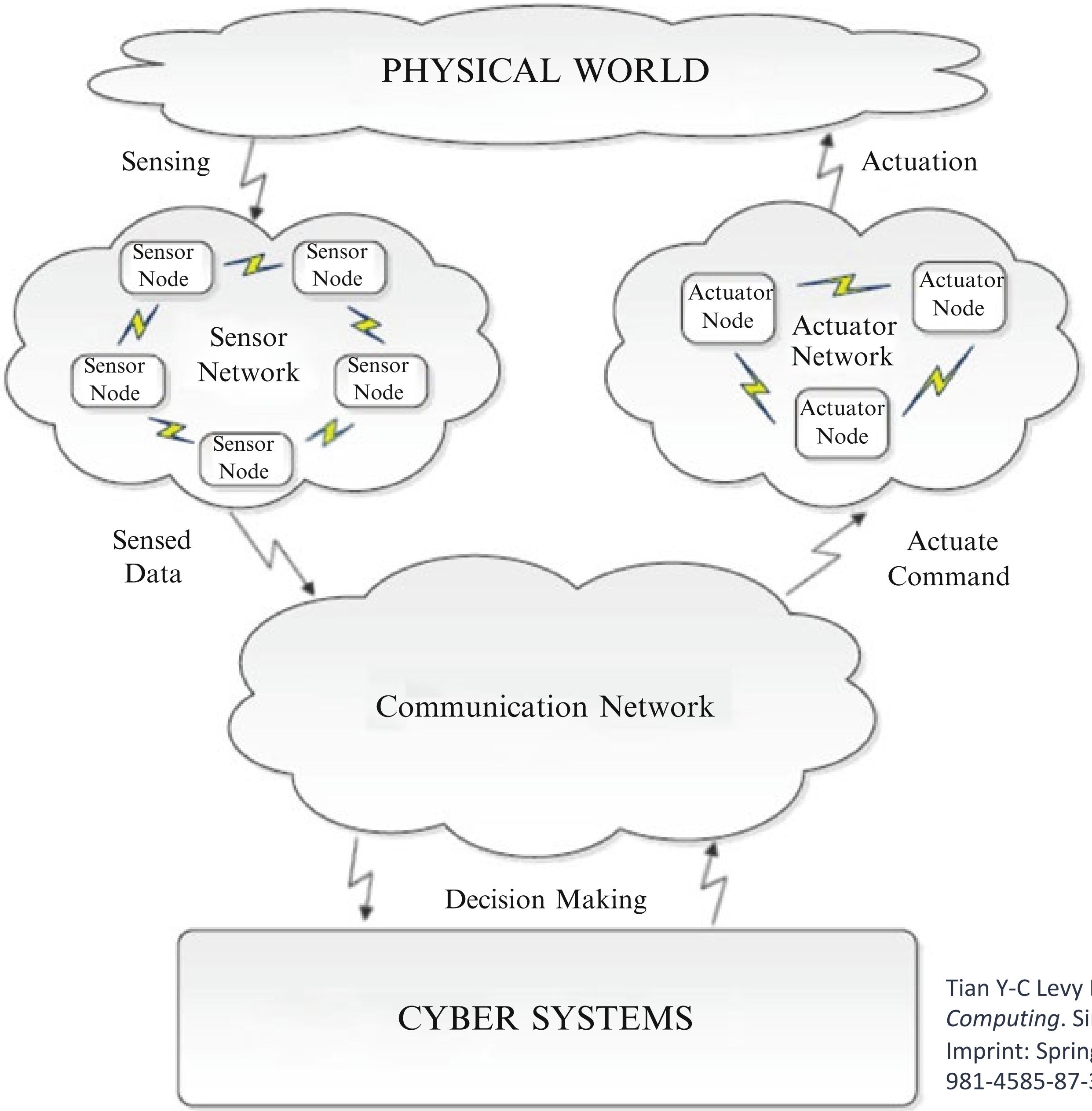
Components of CPS



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Differences between CPS and IoT

- Cyber-Physical Systems (CPS)
  - ✓ Integration of Physical and Computational Processes
  - ✓ Complexity and Scale
  - ✓ Precision and Reliability
  - ✓ Emphasis on Control and Feedback
- Internet of things (IoT)
  - ✓ Network of Physical Devices
  - ✓ Focus on Connectivity and Communication
  - ✓ Consumer and Commercial Applications
  - ✓ Data Collection and Analysis
  - ✓ Examples: Smart thermostats, fitness trackers, connected refrigerators

Real-time systems

Real-time systems are systems designed to respond to input within a guaranteed time frame, often measured in milliseconds or microseconds. The key characteristic of a real-time system is its predictability and reliability in timing constraints.

- Hard Real-Time Systems
- Soft Real-Time Systems

Real time CPS (RT-CPS)

CPS and RT-CPS share the fundamental characteristic of integrating computational elements with physical processes. However, the key difference lies in the emphasis on timing constraints and predictability in RT-CPS

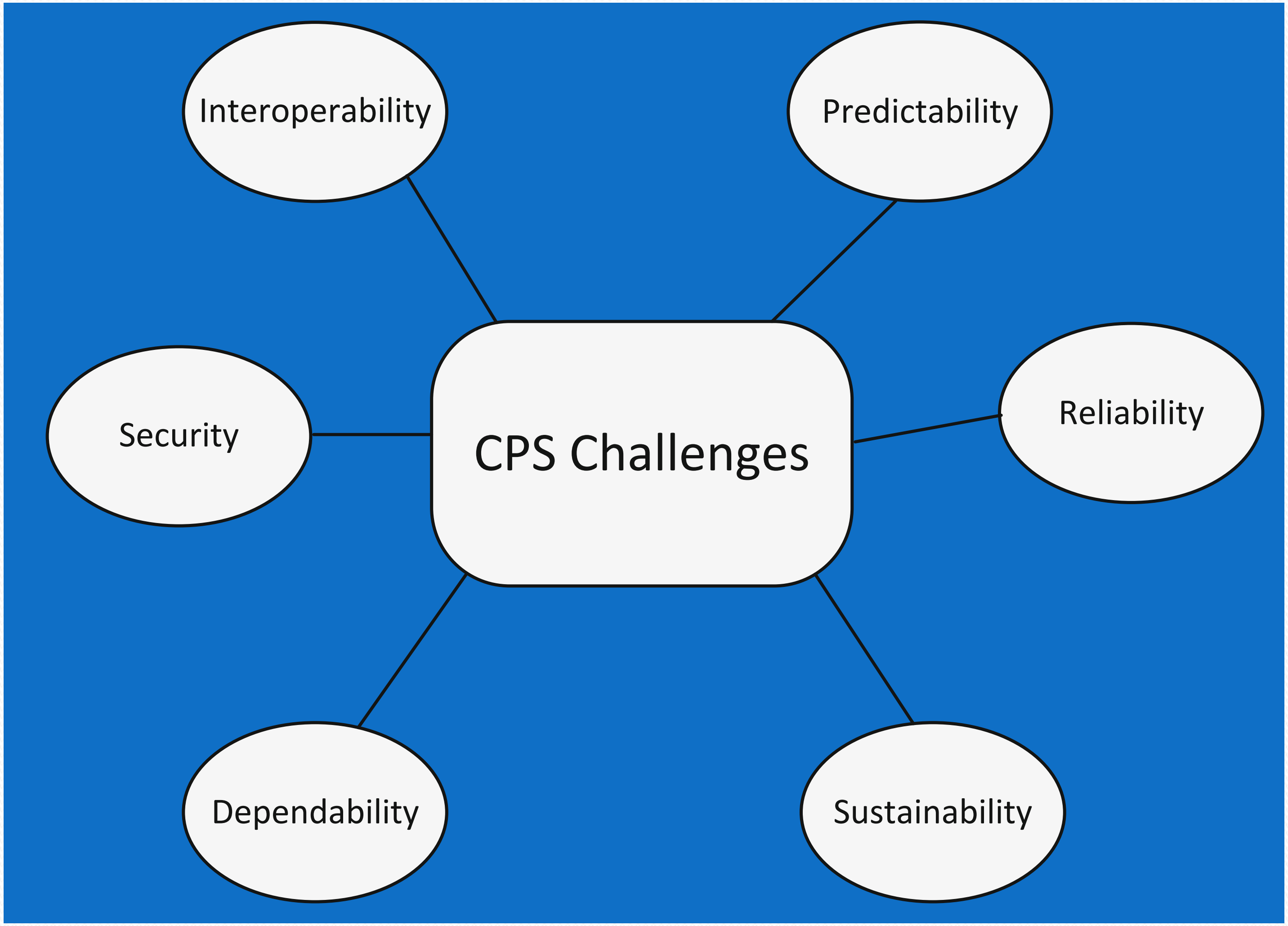
- Timing Constraints
- Predictability and Reliability
- Applications
- System design and complexity

All RT-CPS are a type of CPS, but not all CPS are real-time. The distinction lies in the critical emphasis on real-time response and predictability in RT-CPS

RT-CPS: Characteristics

- ✓ Safe, efficient and reliable
- ✓ Hierarchical, distributed control systems with "self-features"
- ✓ Require the strict deadlines in performing real-time activities
- ✓ They are time sensitive

RT-CPS challenges



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The big challenge of RT-CPS: Ultra Reliable Low-Latency Communications (URLLC)

The most formidable challenge of RT-CPS in 5G and beyond 5G era is to achieve URLLC for mission-critical applications including autonomous vehicles, industry automation, and tele-robotic surgery, i.e. the roundtrip delay of 1 millisecond and less than 1 out of a million in packet loss.

In addition to the latency and reliability requirements, some other Key Performance Indicators (KPIs) should also be taken into account, including Spectrum Efficiency (SE), throughput, Energy Efficiency (EE), Age of Information (AoI), jitter of latency, round-trip delay, network availability, and security

What is Latency in a comm network?

Latency in a communication network refers to the time it takes for a data packet to travel from its source to its destination. This delay is typically measured in milliseconds and is influenced by various factors

- Propagation delay
- Transmission delay
- Processing delay
- Queuing delay

Latency is a critical factor in network performance, affecting user experience in activities like online gaming, video conferencing, and real-time data applications. Lower latency indicates a more responsive and faster network

What is the Age of Information (AoI)

The AoI in a wireless network is defined as the time that has elapsed since the data packet, currently being used at the destination (e.g., a receiver or a server), was generated at the source. Essentially, it measures the "freshness" of the information

- Importance
- Calculation
- Impact of Network Performance
- Optimization
- Different from Latency
- Applications

In wireless networking, the AoI is a vital metric that helps maintain the relevance and timeliness of the data being used for decision-making processes, directly impacting the efficiency and effectiveness of the communication system.

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KPIs and research challenges for RT-CPS

Indoor large-scale scenarios		
Applications	**KPIs**	**Research Challenges**
Factory automation	SE, EE, and AoI	Scalability and network congestions
VR/AR applications	SE and throughput	Processing/transmission 3D videos
Indoor wide-area scenarios		
Applications	**KPIs**	**Research Challenges**
Tele-surgery	Round-trip delay, throughput, and jitter	Propagation delay and high data rate
eHealth monitoring	EE and network availability	Propagation delay and localization

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She, C., Duong, T.Q., Khosravirad, S.R., Popovski, P., Bennis, M. and Quek, T.Q.S. (2023). URLLC : Faster, Higher, Stronger, and Together . In Ultra-Reliable and Low-Latency Communications (URLLC) Theory and Practice

KPIs and research challenges for RT-CPS

Outdoor large-scale scenarios		
Applications	**KPIs**	**Research Challenges**
Vehicle safety	AoI, SE, security, and network availability	High mobility and scalability
Outdoor wide-area scenarios		
Applications	**KPIs**	**Research Challenges**
Smart grid	SE	Propagation delay and scalability
Tele-robotic control	SE, security, network availability, and jitter	Propagation delay and high data rate
UAV control	EE, security, network availability, and AoI	Propagation delay and high mobility

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Requirements of next generation RT-CPS

- Faster Responses
  - factory automation and autonomous vehicles,
  - UAVs

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Requirements of next generation RT-CPS

- Higher Throughput and Density
  - ✓ VR/AR
  - ✓ Autonomous vehicles and mission-critical IoT devices

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Requirements of next generation RT-CPS

- Stronger Connectivity and Security
  - ✓ Multi-connectivity
  - ✓ Suffer from different kinds of attacks

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Requirements of next generation RT-CPS

- Human Intelligence Together with Artificial Intelligence
  - ✓ Cross-layer Design
  - ✓ Deep Learning
  - ✓ Integrating Knowledge into Learning Algorithms
  - ✓ Fine-tuning in Real-world Systems

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Thank you very much!

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