

Advanced Product and Systems Design Engineering in the Era of Autonomous Robotics and the Internet of Robotic Things (IoRT)

Klonis Christos¹, Dr Klonis Apostolos²

Department of Product and Systems Design Engineering, University of Western Macedonia, Kila, 50150,
Kozani - Greece¹

Department of Computer, Informatics and Telecommunications Engineering, International Hellenic University,
end of Magnisias Str, 62124, Serres - Greece²

Abstract

The rapid convergence of Cyber-Physical Systems (CPS), distributed sensor networks, and edge-native artificial intelligence has transformed modern technology from isolated mechanical devices into complex, interconnected ecosystems. At the heart of this transformation lies **Product and Systems Design Engineering (PSDE)**, a multidisciplinary discipline that bridges mechatronic engineering, human-centered design, software architecture, and systems engineering. This paper presents an extended theoretical and methodological framework for PSDE tailored specifically to **Autonomous Robotics** and the **Internet of Things (IoT)**—collectively conceptualized as the **Internet of Robotic Things (IoRT)**.

We systematically examine the multi-layered lifecycle of IoRT development, addressing critical trade-offs between dynamic mechanical optimization, deterministic edge-computing, wireless network latency, cyber-physical security, and human-robot interaction (HRI). Furthermore, we detail the implementation of Model-Based Systems Engineering (MBSE) and hardware-in-the-loop (HIL) simulation paradigms as mechanisms for risk mitigation and cost reduction. The paper concludes by outlining future design directions under the Industry 5.0 paradigm, highlighting the role of generative design, bio-inspired robotics, and circular lifecycle economics.

Keywords: Product and Systems Design Engineering (PSDE), Autonomous Robotics, Internet of Things (IoT), Internet of Robotic Things (IoRT), Model-Based Systems Engineering (MBSE), Human-Robot Interaction (HRI), Cyber-Physical Systems (CPS), Edge AI.

Date of Submission: 09-10-2026

Date of acceptance: 20-10-2026

I. Introduction and Background

The industrial and consumer technology landscapes are undergoing a fundamental paradigm shift. Traditional engineering methodologies, historically structured around siloed domains (mechanical, electrical, embedded software), are increasingly unequipped to handle the systemic complexity of modern connected devices. A modern robotic platform or IoT node is no longer a static physical entity; it is a dynamically interacting node within a wider, heterogeneous digital ecosystem.

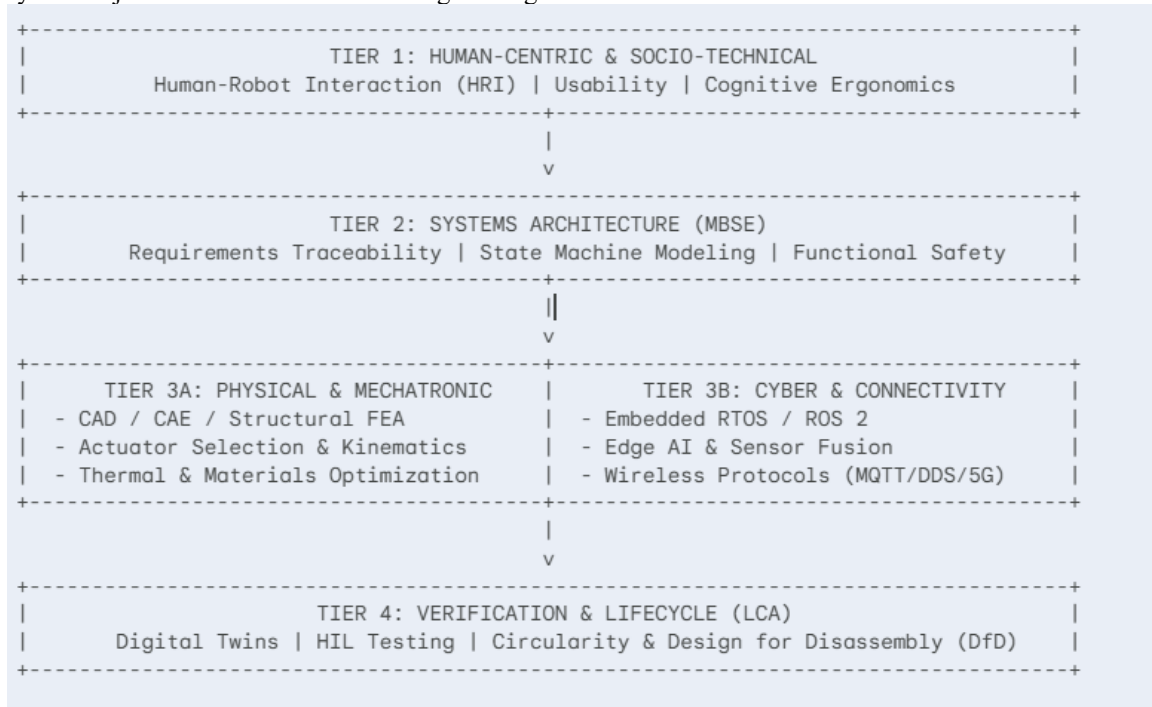
This evolution is best exemplified by the emergence of the **Internet of Robotic Things (IoRT)**, a concept that merges the physical agency and spatial awareness of autonomous robotics with the connectivity, analytical power, and distributed sensing of the Internet of Things. Designing an IoRT system requires the simultaneous orchestration of:

1. **Physical Mechanics & Kinematics:** Lightweight structural enclosures, high-torque density actuators, and passive compliance.
2. **Embedded Electronics & Sensing:** Multimodal sensor fusion (LiDAR, cameras, IMUs, ultrasonic sensors) with severe power and thermal constraints.
3. **Cyber-Physical Infrastructure:** Real-time deterministic communication protocols, edge analytics, cloud telemetry, and over-the-air (OTA) updates.
4. **Human-Centric Interfaces:** Cognitive ergonomics, physical safety guarantees, intuitive interaction, and ethical design principles.

Product and Systems Design Engineering (PSDE) provides the necessary cross-disciplinary framework to harmonize these competing requirements. Rather than treating design as an aesthetic post-processing step or systems engineering as a purely administrative task, PSDE embeds holistic design thinking into every stage of technical development.

II. Integrated Methodological Architecture

The PSDE framework for IoRT operates as an integrated multi-tier architecture, ensuring that macro-level system objectives inform micro-level engineering choices.



2.1 Systems Architecture via Model-Based Systems Engineering (MBSE)

To prevent integration failures, PSDE leverages Model-Based Systems Engineering (MBSE) using standardized languages such as SysML or Capella. MBSE replaces document-centric development with a single source of truth—a unified digital model linking system requirements directly to mechanical, electrical, and software sub-components.

Through MBSE, design engineers can model operational state machines, define system boundary conditions, and verify functional safety compliance (e.g., ISO 13849 / ISO 10218 for robotic safety) prior to physical fabrication.

2.2 Mechatronic and Structural Co-Design

Robotic platforms operating in unstructured environments demand structural integrity while adhering to strict mass and payload budgets. PSDE employs advanced computational engineering techniques:

- **Generative Design & Topology Optimization:** Algorithmically redistributing structural material to minimize mass while preserving stiffness under maximum dynamic torque loads.
- **Multi-Physics Simulation (CAD/CAE):** Simultaneous evaluation of mechanical stress, vibration modes, and thermal dissipation generated by high-density brushless DC (BLDC) motors and onboard compute boards.

2.3 The Cyber-Physical Layer: Edge AI and Deterministic Connectivity

In IoRT architectures, data processing must be carefully allocated across a multi-tier compute hierarchy:

- **Micro-Level (Sensor / Motor Controllers):** Ultra-low-latency, deterministic execution (microseconds) using Field Oriented Control (FOC) and Real-Time Operating Systems (FreeRTOS / Zephyr).
- **Edge-Level (Onboard Compute):** Medium-latency execution (milliseconds) running Robot Operating System 2 (ROS 2) on edge AI accelerators (e.g., NVIDIA Jetson / NPU platforms) for SLAM (Simultaneous Localization and Mapping), perception, and obstacle avoidance.
- **Cloud-Level (Distributed Infrastructure):** High-latency, macro-level operations (seconds to hours) utilizing telemetry protocols (MQTT, Data Distribution Service - DDS) for fleet management, global mapping, and deep learning model training.

III. Critical Technical Challenges and PSDE Solutions

Designing IoRT systems requires navigating severe engineering trade-offs. Table 1 summarizes the primary engineering bottlenecks and the corresponding systemic solutions offered by PSDE.

Table 1: Technical Trade-Off Matrix in IoRT Product System Design

Engineering Constraint	Conflicting Requirement	PSDE Integrated Solution
Power Budget & Autonomy	High-performance compute required for real-time spatial AI	Hybrid power management; dynamic frequency scaling; duty-cycled sensing; integration of lightweight carbon-fiber composite chassis to reduce motor load.
Real-Time Safety vs. Cloud Latency	Cloud-based decision making exposes actuators to variable network jitter	Dual-loop control architecture: safety-critical emergency braking and local collision avoidance executing deterministically at the edge; global route planning offloaded to cloud/fog servers.
Cyber-Physical Security	Wireless IoT connectivity creates physical attack vectors (actuator hijacking)	Hardware Root of Trust (TPM/HSM chips); encrypted DDS/TLS communication buses; secure Over-The-Air (OTA) firmware signing; fail-safe mechanical lockouts.
Human Ergonomics vs. Structural Rigidity	Hard physical enclosures necessary for industrial durability cause safety risks to humans	Compliant actuation (Series Elastic Actuators - SEAs); soft-robotic overmolding; vision-based speed and separation monitoring (SSM) algorithms.

IV. Human-Robot Interaction (HRI) and Usability

A cornerstone of Product and Systems Design Engineering is its uncompromising focus on the human user. As autonomous mobile robots (AMRs) and collaborative robots (cobots) move into shared human spaces (hospitals, warehouses, homes), **Human-Robot Interaction (HRI)** becomes a primary determinant of system success.

4.1 Physical Ergonomics and Safety

Physical safety is achieved through a combination of passive and active design mechanisms:

- **Passive Safety:** Rounded chassis geometry, lightweight foam/elastomer outer shells, and torque-limiting joint designs.
- **Active Safety:** Multi-layered optical and acoustic sensing (3D LiDAR, Time-of-Flight cameras, ultrasonic sensors) mapped directly to real-time safety controllers that override autonomous navigation when human proximity thresholds are breached.

4.2 Cognitive and Intuitive Interfaces

To reduce operator cognitive fatigue, PSDE integrates multi-modal feedback systems:

- **Visual Status Indication:** Directional light-array indicators (LED matrices/diffused light-guides) that communicate the robot's intent (e.g., turning, stopping, error state) intuitively to surrounding personnel.
- **Graphical User Interfaces (GUI) & Augmented Reality (AR):** Simplified touch-screen digital twins and AR overlays allowing non-expert operators to program spatial waypoints without writing code.

V. Verification, Digital Twins, and Life Cycle Assessment (LCA)

5.1 Digital Twin and Hardware-in-the-Loop (HIL) Simulation

To accelerate time-to-market and lower physical iteration costs, PSDE relies heavily on **Digital Twins**—real-time virtual representations of the physical robot and its operating environment. Utilizing advanced simulation platforms (such as Gazebo, NVIDIA Isaac Sim, or Webots), design engineers validate:

- Sensor perception pipelines under adverse environmental conditions (lighting shifts, rain, sensor noise).
- Kinematic control loop stability during sudden load transfers.
- Network degradation and packet-loss resilience over cellular/Wi-Fi networks.

5.2 Environmental Sustainability and Circularity

Aligned with global directives for sustainable industrial production, PSDE embeds **Life Cycle Assessment (LCA)** methodologies from the concept phase:

- **Design for Disassembly (DfD):** Modular mechanical architecture utilizing standardized fasteners rather than permanent adhesives, enabling fast component replacement, repair, and end-of-life recycling.

- **Material Circularity:** Selection of bio-composites, recyclable aluminum alloys, and halogen-free printed circuit board (PCB) substrates.

VI. Industry 5.0 and Future Horizons

As the industrial domain transitions from Industry 4.0 (focused primarily on automation and data exchange) to **Industry 5.0** (focused on human-centricity, resilience, and sustainability), the mandate of Product and Systems Design Engineering becomes even more prominent.

Future developments in PSDE for IoRT will be shaped by three major technological frontiers:

1. **Generative AI in System Architecture:** Leveraging machine learning algorithms to co-optimize hardware topologies, wiring harness routing, and embedded firmware code simultaneously.
2. **Soft and Bio-Inspired Robotics:** Transitioning from rigid metal linkages to compliant, bio-inspired materials that offer superior adaptability and inherent safety in unstructured human environments.
3. **Autonomous Swarm Systems:** Scaling systems design methodologies from single-robot platforms to decentralized multi-robot swarms capable of collaborative problem solving in search-and-rescue, agriculture, and logistics.

VII. Conclusion

Product and Systems Design Engineering is not merely an engineering sub-discipline; it is an indispensable paradigm for navigating the immense systemic complexity of modern technology. By synthesizing mechatronic precision, Internet of Things connectivity, edge computing, Model-Based Systems Engineering, and human-centered design, PSDE enables the creation of intelligent, autonomous, and safe robotic systems. As technology becomes increasingly embedded in human society, the holistic approach of PSDE will remain at the forefront of sustainable and human-centric innovation.

References

- [1]. Estefan, J. A. (2008). *Survey of model-based systems engineering (MBSE) methodologies*. INCOSE MBSE Focus Group, 25(8), 1-12.
- [2]. Ray, P. P. (2016). Internet of Robotic Things: Concept, technologies, and challenges. *IEEE Access*, 4, 9489-9500. <https://doi.org/10.1109/ACCESS.2016.2647747>
- [3]. Sethi, P., & Sarangi, S. R. (2017). Internet of Things: Architectures, protocols, and applications. *Journal of Electrical and Computer Engineering*, 2017, Article 9324035. <https://doi.org/10.1155/2017/9324035>
- [4]. Simões, W. C., de Souza, A. D., & Filho, G. P. (2020). Internet of Robotic Things: Current technologies, applications, and challenges. *International Journal of Advanced Robotic Systems*, 17(2), 1-22. <https://doi.org/10.1177/1729881420911000>