(one6G)

Taking communications
to the next level

6G ARCHITECTURAL FOUNDATIONS AND AI-NATIVE SOLUTIONS FOR FUTURE CONNECTED ROBOTICS

WHITE PAPER

March 2026

eu ROBOTICS

eu ROBOTICS
TOPIC GROUPS

one6g.org

Executive Summary

The joint euRobotics and one6G whitepaper (Volume 2) examines how emerging 6G technologies reshape the architectural foundations of future robotic and automation systems: A four-plane 6G architecture for robotics—Robotic Service, Intelligent Service, Network Service, Data Governance—that maps directly to robotic functional blocks (sensing, perception, learning and self-learning, cognition and action). It frames 6G as a unifying substrate that provides sensing, communication, computing, and intelligence as composable services to heterogeneous robots operating across diverse environments, including industrial, medical, logistics, public-safety, defence, education, smart cities, smart home, and space domains. Building on prior work on connected robotics and 6G, the document introduces a 6G system architecture with four-plane —Robotic, Intelligent and Network Service, and Data Governance planes—tightly aligned with the robotic functional blocks. This alignment enables closed-loop behaviour in which robots explicitly express task intents, while the network acts as a digital cognitive fabric that adapts to those intents in real time.

A central contribution is the decomposition of 6G empowering robotics into interoperable layers and functions that can be instantiated across robots, edge, and cloud. At the infrastructure layer, 6G integrates ultra-reliable low latency communication, AI-native, Integrated Sensing and Communication, advanced positioning, and edge computing to support deterministic control loops and network-assisted perception. At the intelligence plane, such functions and paradigms as AI-native orchestration, semantic and goal-oriented communication, federated learning, and agent-based control form a programmable "brain" that coordinates (fleets of) robots and human operators. The Data Governance plane closes the loop by enforcing privacy and trust, security and resilience, and regulatory compliance while managing the lifecycle of data and models that underpin autonomy. Together, these elements provide an architectural toolkit that stakeholders—robotics vendors, operators, equipment suppliers, integrators, cloud, AI providers, regulators, and end users—can reuse across domains instead of building bespoke solutions.

The whitepaper analyses several representative use cases drawn from different sectors: Dynamic Safety Zones (DSZ) and fleet management in smart manufacturing; cyber-physical remote driving of mobile robots & energy efficiency via Knowledge Aggregation in smart cities; and endovascular remote robotics for stroke treatment and rehabilitation in healthcare. Each use case is decomposed into functional components (e.g., human pose and intent sensing, DSZ computation, digital-twin synchronisation, multimodal teleoperation) and mapped to concrete 6G capabilities and KPIs such as control-loop latency, system availability, spatial accuracy, semantic efficiency, throughput, and human-centric metrics like operator trust and workload. The use-case analysis highlights both the transformative potential of 6G and the identify gaps in current communications technologies, including the lack of certified wireless safety loops, limited support for integrated sensing and communication, data exposure APIs, and immature profiles for medical-grade tele-surgery.

Looking towards 2030 and beyond, the whitepaper outlines a technology and research roadmap where early 6G trials and 5G-Advanced platforms evolve into AI-native multi-site deployments. These agent-driven networks view robots as integral participants. Key directions include performance-driven co-design for robotics and networks, safety-coherent ultra-reliable and low latency, and integrated sensing and communication mechanisms, semantic communication for robotic tasks, federated learning within data governance, and cross-domain standardisation for interfaces and certification. By defining a unified architecture and key performance requirements, it aims to guide organisations in planning, building, and regulating 6G-enabled robotics and automation.

Table of Contents

1. Introduction: Context, Motivation, and Research Focus

1.1. Role of 6G technologies in future robotics and automation

6G technologies serve as a unifying substrate that connects robots, humans, Digital Twins (DTs), and cloud/edge intelligence into a cohesive cyber-physical continuum. With capabilities such as ultra-reliable low-latency communication, Intelligent Sensing and Communication (ISAC), high-precision positioning, and AI-native control, robots can share perception, coordinate actions, and offload computations while ensuring safety-critical operations. This transforms the network from a mere transport layer into an active participant in robotic perception, cognition, and control—offering functionalities like network-as-a-sensor, network-as-an-actuator, and intent-driven orchestration.

For automation ecosystems, this shift unlocks new system-of-systems designs in which fleets of heterogeneous robots, fixed automation assets and legacy equipment are orchestrated as a single, programmable resource. Production cells, warehouses, or construction sites can be mainly reconfigured in software by re-binding tasks, slices, and edge functions, reducing engineering effort and downtime. At the same time, 6G's support for privacy-preserving learning and end-to-end security mechanisms is essential to preserve trust when robots operate across organisational boundaries and public space.

1.2. Research Gaps and Challenges

Connected robotics spans several core domains, including collaborative industrial cells and flexible production lines in warehouses, hospitals and ports, inspection and maintenance of critical infrastructure, field and agricultural robotics, as well as service and assistive robots in public and domestic spaces. In each domain, robots increasingly operate in proximity to humans, other robots and legacy automation assets, forming distributed systems whose overall behaviour depends on both local control and networked coordination. Industrial and logistics scenarios demand highly deterministic control-loop latencies, robust operation in Radio Frequency (RF)-challenging indoor environments and close integration with safety regulations and certification processes. Field inspection and agricultural use cases emphasise wide-area coverage, resilience to link intermittency and the ability to fuse network-derived sensing with on-board perception. At the same time, service and assistive robots foreground privacy, trustworthiness and intuitive interaction with non-expert users.

Across all scenarios, common patterns emerge: fleets of heterogeneous robots must share perception, coordinate plans, and be supervised remotely, often across site boundaries and administrative domains. These patterns motivate the architectural and technology choices discussed in the following sections, where 6G capabilities such as network-as-a-sensor, AI-native control, and continuum computing are assembled into reusable building blocks for connected-robotics solutions.

In this whitepaper, we build on the key insights from previous works, particularly focusing on euRobotics' Position Paper on Connected Robotics [1] and the one6G WI216 Whitepaper [2] and continue exploring advancements in robotics and 6G technology while identifying crucial research gaps that warrant further exploration.

The euRobotics Connected Robotics Position Paper describes the evolution and significance of connected robotics in Europe, highlighting how advanced communication technologies are becoming intrinsic to robotic systems rather than external add-ons. It stresses the need for interdisciplinary collaboration across robotics, AI, and telecommunications to build robust, interoperable solutions and to sustain European leadership in this domain.

In parallel, the one6G 6G Robotics whitepapers analyse how 6G capabilities such as Hyper Reliable Low Latency Communication (HRLLC), Integrated Sensing and Communication (ISAC), and AI-native networking can enhance robotic systems, with particular emphasis on Dynamic Safety Zone (DSZ) and safety-critical human–robot collaboration. These works underscore that future architectures must support seamless, task-oriented connectivity for autonomous systems, enabling efficient data sharing, distributed processing, and scalable orchestration across robots, edge, and cloud.

Despite these advances, important research and standardisation gaps remain. Open challenges include integrating 6G technologies into existing robotic platforms and middleware; defining standardised communication and exposure profiles for robotics use cases; and embedding ethical, safety, and regulatory requirements into AI-native, slice-based architectures from the outset. Application specific studies are also needed to understand how connected robotics can address sector specific constraints in manufacturing, logistics, healthcare, soft robotics, and search and rescue. By addressing these gaps—including evolving regulation-abiding approaches—we can drive the development of innovative, ethical, and effective robotic solutions that align with Europe's evolving technological and regulatory landscape.

While cyber-physical security is not the focus of this whitepaper, it is recognised as a critical component alongside safety—two interrelated pillars of trustworthy robotics. Addressing cyber-physical threats and vulnerabilities through logical zoning, trusted conduits, and policy-driven isolation within the architecture is essential for safe deployment of connected robotics systems and services, including integrated robotics and Cyber-Physical Systems (CPS) such as smart cities. The EU Machinery Regulation and related frameworks already reference security requirements, making this both a technical and regulatory imperative that may require updates, new regulations, or harmonised standards for future robotics deployments.

2. 6G Enabling Technologies with Architectural Foundations for Robotics

The transition to 6G represents a fundamental paradigm shift for connected robotics, moving beyond simple data transmission to creating a unified, intelligent neural fabric where the network itself becomes a sensor and processor to seamlessly integrate communication, computation and sensing capabilities. The Connected Robotics Topic Group (CRTG), as outlined in the CRTG position paper [1] "6G Enabling Technologies: Architectural Foundations for Robotics", defines five core pillars spanning network evolution, AI integration, control systems, DTs, and cyber-physical interaction. Figure 1 illustrates: (i) Network-as-a-Sensor/Actuator transforming wireless infrastructure into pervasive environmental sensors via radio reflection analysis and precise actuator control; (ii) Reliable and deterministic communication delivering wide area Service Level Agreements (SLAs) for control loops; (iii) AI-Native Solutions including Federated Learning (FL) computational offloading with split inference; (iv) Multi-Robot Control Systems leveraging with 6G-exposed discovery, and criticality-aware slicing for fleet coordination; (v) near real-Time Digital Twins (DT) providing high-fidelity replicas for anomaly detection, predictive maintenance, and KPI trade-off simulation; and (vi) CPS fusing ISAC perception, Extended Reality (XR) interfaces, and semantic communication to enable immersive Augmented Reality (AR) workspaces. These pillars provide a unified framework mapping robotics requirement onto 6G capabilities, enabling stakeholders to co-design networks and robots meeting industrial, medical, logistics, and public-safety KPIs while closing gaps in current technologies.

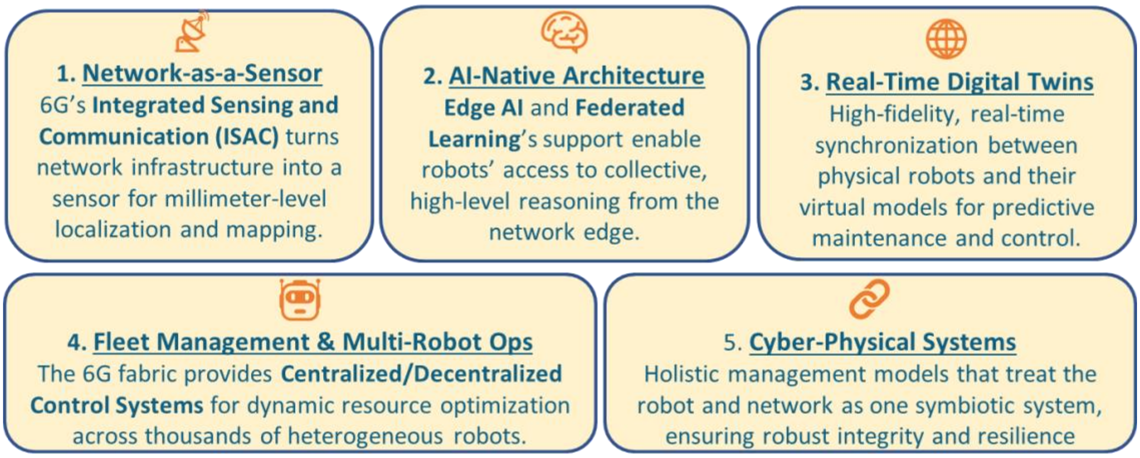

Figure 1. Connected Robotics technology pillars [1]

2.1. Integrated Sensing and Communication Technologies

ISAC in 6G allows the communication signals to be used for spatial awareness as well, enabling robots to "see" and map their environment through radio waves just like the classical radar technology without relying solely on optical cameras or LiDAR [3]. Simultaneous wireless communication and environmental sensing is considered one of the cornerstones in the evolution towards 6G. Such a technology will allow robots to simultaneously communicate and sense their surroundings, improving perception and localisation accuracy. ISAC's real-time operation fuses communication and environmental data, sup-porting high-precision spatial mapping and robust robot navigation—particularly in Global Navigation Satellite Systems (GNSS) -denied or cluttered settings. By combining communication and sensing in a unified framework, ISAC lowers infrastructural costs and spectrum usage while enhancing network intelligence. Practical applications include autonomous robotic exploration of unknown terrains in search-and-rescue operations and logistic automation, where robots dynamically adapt routes and tasks based on real-time environmental insights derived from ISAC streams.

2.1.1. Network-as-a-Sensor and Network-as-an-Actuator

6G is set to revolutionise wireless infrastructure by transforming it into a pervasive sensory system that extends robotic perception beyond their onboard sensors. This paradigm—known as Network-as-a-Sensor [3]—leverages the ability of base stations, access points, and distributed antennas to detect and map environmental features by analysing reflected and scattered radio signals. By converting communication nodes into wide-area environmental sensors, the 6G network supports high-resolution spatial awareness without requiring dedicated robotic sensors in every location. Complementing this, the Network-as-an-Actuator concept enables the wireless system to influence the physical world by controlling devices and shaping environmental responses, effectively acting as an actuator layer. Together, these capabilities al-low robotics systems to access real-time, large-scale situational awareness that is critical in scenarios like disaster recovery, smart manufacturing floors, and dynamic safety zoning. In disaster zones, where direct sensing may be impaired, the network's sensing capability enables infrastructure damage assessment and human presence detection. In smart factories, these network sensors facilitate precise coordination among collaborative robotic agents and safe human-robot coexistence.

2.1.2. High-Reliability Communication for Real-Time Robotic Control

At the core of robotic control lies the necessity for reliable and deterministic communication with latencies at level of milliseconds. 6G communications are designed to meet these stringent requirements, supporting real-time closed-loop control of robotic actuators vital for precision manipulation, tele-operation, and autonomous fleet navigation. This ultra-determinism ensures minimal control delays, enabling robots to respond instantly to control commands and environmental changes, thereby increasing safety and operation accuracy. The resulting highly deterministic communication loops enable scalability to dense robotic deployments without compromising reliability or control responsiveness, essential for automated warehouses, medical robotics, and autonomous vehicle platoons.

To bridge the gap between the stochastic nature of wireless channels and the rigid determinism required by these applications, 6G transitions from reactive error correction to predictive reliability, enabled by the synergistic use of AI-Native architectures and ISAC. By utilising ISAC to spatially map the environment and AI to foresee channel blockages or interference before they occur, the network can proactively adjust resources via Cell-Free Massive Multiple-Input Multiple-Output (MIMO) and Multi-Link Operation (MLO). This ensures that the 'tail latency'—the rare but catastrophic packet delays that cause robot failure—is virtually eliminated, guaranteeing stable performance even in cluttered, metallic industrial environments.

This newfound trust in the air interface precipitates a fundamental evolution in robotic design toward 'cloud-native' or 'thin-client' architectures. With the ability to extend Time-Sensitive Networking (TSN) standards over the wireless link, manufacturers can confidently offload computationally intensive control loops and Simultaneous Localisation and Mapping (SLAM) processes to the network Edge without fear of desynchronisation. This capability reduces the onboard power and processing requirements of individual units, leading to lighter, more agile, and lower-cost robotic fleets that rely on the network not merely for data transport, but as a real-time, deterministic extension of their own nervous system.

2.2. AI-Native Solutions for Autonomous Robotics

In 6G networks, AI is conceived not as an auxiliary function but as a native architectural component, integrated across all network layers. This integration enables the network to autonomously manage its configuration, perform rapid deployment of new services, and conduct continuous self-diagnosis. By embedding AI-driven control within the 6G framework, the network gains the ability to dynamically adapt to changing operational conditions, optimise resource allocation, and ensure consistent Quality of Service (QoS) for latency-sensitive and mission-critical applications such as robotics.

The AI-native nature of 6G also transforms how intelligence is deployed and executed. The architecture supports rapid instantiation and migration of AI models within the network, drastically reducing the time required for deploying intelligent functions at the edge or in the core. This ease of AI deployment directly benefits robotic systems, which traditionally face severe limitations in onboard processing power due to hardware constraints inherent to mobile and embedded platforms. By offloading computationally intensive AI processes to network-integrated intelligence—particularly at the edge—robots can operate with enhanced perception, planning, and control capabilities while maintaining ultra-low latency performance.

To fully exploit these AI-native capabilities, robotic systems must establish a structured and semantically rich interaction with the network, through which they can dynamically express their communication and computation needs. Depending on the operational phase, a robot may request different connectivity parameters, such as ultra-low latency for control loops or high data rates for perception, as well as on-demand computational resources at the edge and the deployment of specific AI models from a network-accessible model repository. In 6G, this interaction is enabled through intent-based interfaces that allow robots to communicate high-level, human-readable objectives rather than low-level configuration details. These intents are interpreted by AI-driven network management and orchestration functions, which translate them into concrete actions across communication and computing resources. Over time, robotic systems can learn to effectively formulate and adapt their intent expressions, evolving a shared “network language" that enhances efficiency and autonomy. Extending this concept further, future 6G systems are expected to support direct intent-based interactions between robot-resident AI agents and network-resident AI agents, enabling tight integration of the two agentic systems and allowing collaborative decision-making across robotic control and network intelligence domains.

Two architectural features are key to understanding how AI integration in 6G enables advanced robotics. Firstly, Federated Learning (FL) across networks allows distributed robotic agents to collaboratively train models without sharing raw data, preserving privacy and enabling global learning from local experiences. This mechanism not only accelerates adaptation to dynamic environments but also supports the emergence of agentic networks, where each robot or network node acts as a semi-autonomous entity capable of negotiation, coordination, and self-optimisation.

Secondly, the abstraction of computation through edge servers enables the delegation of high-level reasoning and AI inference to the network infrastructure itself. Edge computing nodes, strategically located close to the robotic endpoints, provide the necessary processing and storage capacity to execute complex AI workloads—such as real-time vision processing, semantic mapping, and motion prediction—without compromising response time. Together, FL and edge-based intelligence form the cornerstone of a hyper-distributed and programmable AI architecture that extends the cognitive capabilities of robotics far beyond their physical limitations, enabling adaptive, scalable, and efficient autonomous systems in the 6G era. We provide more details on these two enablers in the next two subsections.

2.2.1. Federated Learning for Robotic Systems and Agentic AI Enablement

It is important that fleets of robots can share partial/full models and polices while respecting data protection,per anonymisation-by-design and privacy mandates. In a 6G setting, FL rounds are orchestrated at the edge so that robots contribute gradients or parameters—optionally protected via secure aggregation and differential privacy—while the network schedules training and aggregation according to radio and compute conditions. Robotics-focused FL frameworks (e.g., Robot Operating System (ROS2)–based pipelines) show that navigation or perception policies can be collaboratively trained across heterogeneous agents without centralising sensor logs, improving generalisation under non-IID data (non-independent and identically distributed) – each robot sees different environments/tasks/sensors) and reducing training variance in multi-agent tasks [4]. Complementary studies showcase personalised FL strategies and continual learning mechanisms that mitigate catastrophic forgetting and handle intermittent connectivity—conditions typical for mobile robots—thereby making cross-site adaptation practical in real deployments [5], [6].

This privacy-preserving substrate dovetails with emerging Large Language Model (LLM) and audio-enhanced autonomy. Language-guided navigation and manipulation policies can be fine-tuned per site and then aggregated via FL, allowing robots to exploit language priors for planning in cluttered or dynamic spaces while keeping videos on-device. Similarly, federated audio classification for ambient scene understanding (e.g., sound event detection) lets robots adapt to local noise profiles by sharing only model updates, not waveforms. In both cases, FL provides an anonymised, iterative learning loop that accelerates domain adaptation for high-variance tasks—navigation, mapping, and auditory perception—where single-site data are insufficient.

Moreover, 6G moves toward to agentic networks, where autonomous AI agents run in-network (RAN/core/edge) with their own goals, memory, and tools, and can be dynamically assigned to specific robots or sub-fleets. Operators instantiate agents—e.g., a coverage-optimisation agent, a safety-auditor agent, or a policy-distillation agent—bind them to slices and attach them ad hoc to endpoints to steer QoS, compute offloading, semantic compression, and even FL scheduling. Recent architectural proposals describe agent discovery, negotiation, and collaboration within 6G cores and Radio Access Network (RAN), enabling goal-driven, programmable control loops where network-resident agents coordinate with on-robot agents to co-optimise connectivity, inference pipelines, and learning cadence [7], [8], [9]. In this view, FL supplies the privacy-preserving learning substrate, while agentic network functions provide operational governance: matching models to tasks, steering dataflows, and allocating compute/communication resources at runtime.

Coordinated FL tightly coupled with robot mobility and data collection is critical for real-world deployments, where sensing, movement, and learning are inherently interdependent. In applications such as environmental monitoring, warehouse automation, smart agriculture, disaster response, etc., robots must decide *where to move, what to sense, and when to learn* under energy, latency, and connectivity constraints. Coordinating FL with motion planning and task allocation allows robots to actively explore informative regions, balance sensing coverage across the fleet, and adapt data collection strategies to the current learning objectives. This closed-loop interaction between learning and control not only accelerates model convergence but also improves robustness in dynamic and partially observable environments, enabling scalable, privacy-preserving intelligence that evolves continuously as robots operate in the field [10].
In mission and safety-critical robotics systems, the choice of the FL aggregation model is a fundamental design decision rather than a mere implementation detail. Conventional schemes such as Federated Stochastic Gradient Descent (FedSGD) and Federated Averaging (FedAvg), originally developed for mobile or cloud-centric settings, often struggle to satisfy the stringent latency, energy, and reliability requirements of robotic platforms operating over wireless links. More advanced approaches, including heterogeneity-aware methods like Federated Proximal (FedProx), operator-splitting techniques, adaptive optimisers (e.g. FedAdam and FedYogi), and low-complexity ensemble-based models, highlight the growing need for innovation beyond traditional aggregation paradigms. Such resource-aware and flexible aggregation strategies are essential to enable real-time, scalable, and dependable FL across collaborative robotic fleets [11].

Beyond collaborative training with local inference discussed this far, FL also applies when robots observe different modalities of the same scene through heterogeneous sensors. Termed Vertical Federated Learning (VFL) [12], this approach allows each robot to encode its local observation with a local encoder and exchange compact intermediate features (embeddings) at decision time, enabling joint inference without transmitting raw sensor streams thus inherently preserving privacy. In typical deployments, decisions are executed by a master robot (termed server) that aggregates peer robots embeddings; however, the same scheme generalises to symmetric setups in which any or all robots can act as leader when needed. This design improves decision accuracy by fusing multi-view, multi-sensor observations at inference time, which yields a more complete representation than single-view pipelines. In addition, VFL can prove more communication-efficient than centralised raw-data fusion-based decision-making approaches, as traffic scales with the embedding dimensionality and request rate (i.e. the master's decision rate), rather than with the bitrate of the robots' sensors (e.g. raw camera or LiDAR feeds) [13]. Furthermore, bandwidth can be further reduced by filtering information in time so that only the most informative features are transmitted. In this case, VFL can exploit temporal coherence; as

consecutive scenes often change little, robots can cache recent embeddings and transmit only their deltas or low rank/sparse updates, maintaining accuracy while meeting bandwidth and latency budgets. This mirrors sparse-communication techniques in standard FL and keeps inference responsive under tight bandwidth constraints. Finally, VFL enables robust autonomy; even when embeddings from peer robots are delayed or unavailable, VFL inference can prove resilient to their absence [14], [15]. In the worst case, the master robot can rely solely on its local model estimate, ensuring that decision-making continues without interruption.
In practice, FL rounds should be scheduled around radio/compute availability: (i) use link-aware orchestration to pick aggregation windows when multi-link or Non-Terrestrial Networks (NTN) fallback provides required reliability; (ii) employ heterogeneity-aware aggregation (FedProx/FedAdam variants) to handle diverse robot compute and sensing stacks; (iii) integrate FL with motion planning so robots actively collect data from informative states (exploration for model improvement); and (iv) expose simple ROS2 middleware hooks for gradient/embedding exchange, with optional secure aggregation and differential privacy. VFL is particularly useful when robots observe different modalities of the same scene — exchange compact embeddings rather than raw streams to meet bandwidth and latency budgets. These patterns reduce tail latency impact and preserve privacy while keeping model update cadence aligned with operational constraints.
Gradient-based learning is the foundational mathematical tool in robot learning. It is the method by which a robot calculates exactly how to change its behaviour to reduce error by avoiding random movements and following optimised and precise behaviour. Specifically, the gradient points in the direction of the steepest ascent of a performance function, and by taking the negative gradient (gradient descent), a robot iteratively updates its control parameters to minimise errors or maximise rewards.

In robotics, "learning" is framed as an optimisation problem. The robot has a loss function which is a mathematical score of how badly it is performing (e.g., distance from a target, amount of energy wasted, or number of collisions). The gradient is a vector that points in the direction of the steepest increase in error. Therefore, to learn, the robot updates its parameters by moving in the opposite direction. In this way robots learn complex tasks (like walking or grasping) in a reasonable amount of time.

As robots become increasingly distributed, mobile, and intelligent, their ability to learn from data in real time and adapt to dynamic environments hinges on the underlying communication infrastructure. Distributed gradient-based learning methods are foundational to modern robotics, enabling robots to collaboratively train models, share knowledge, and coordinate actions. However, these capabilities remain constrained by the limitations of current wireless networks, particularly in terms of latency, bandwidth, device density, and integration with edge computing and sensing.

Distributed gradient-based learning algorithms, rely on frequent communication of model updates among robots and/or edge/cloud servers. High latencies, especially for mobile nodes and in multi-hop scenarios can severely slow down convergence, increase staleness of updates, and degrade model accuracy particularly in time-sensitive robotic applications like swarm coordination, real-time control, and adaptive navigation.

Ultra-low latency directly accelerates distributed gradient descent learning. In particular it reduces synchronisation delays by enabling more frequent and timely aggregation of gradients thus reducing staleness and improving convergence speed. Robots can adapt their models on-the-fly in response to new data or environmental changes, critical for dynamic tasks. Sub-millisecond latency allows integration of learning with control loops, enabling closed-loop adaptation in robotics [16], [17]. Empirical studies show that reducing communication latency from tens of milliseconds to sub-millisecond can yield up to 5x improvements in training time and convergence rates for distributed learning algorithms.

6G targets end-to-end latencies as low as 0.1 ms. This is achieved through several techniques and mechanisms: a) direct, geographically-aware peering which minimises unnecessary network hops thus reducing round-trip times, b) strategic placement of UPFs at the edge allowing robots to access services directly, bypassing core network delays, c) near-real-time Radio Access Network (RAN) Intelligent Controllers (RICs) that consolidate session and mobility management at the edge, enabling faster decision-making, d) dedicated, low-latency slices which ensure that learning-related traffic receives prioritised, guaranteed resources and e) by integrating sensing and communication, 6G enables immediate environmental awareness and feedback, further reducing the perception-action loop latency [18], [19].

Bandwidth and throughput are another important factor to be considered, since robotic systems generate and consume vast amounts of data, including high-resolution sensor streams, video and multimodal environmental information. Distributed learning workflows require frequent exchange of model parameters, gradients, and sometimes raw or compressed data for collaborative training and validation. In legacy networking technologies, bandwidth constraints can limit the frequency and size of model updates, especially in dense deployments or when multiple robots share the same channel. 6G leverages THz and mmWave bands to deliver high peak data rates [20]. High-throughput links support real-time sharing of sensor data, environmental maps, and semantic information, enhancing the quality and diversity of training data and the overall performance of the robotic systems.

Frequent exchange of gradients or model parameters can overwhelm network resources, especially as model sizes and the number of devices grow. Communication delays and bandwidth limitations can slow convergence and increase energy consumption. 6G promises to overcome these major obstacles in the connected robot world by ensuring milli second level delays and bandwidth offerings in the order of Gbps.

2.2.2. Edge AI and World-Models: Predictive Control and Offloading

Recent advances in world model-based control introduce a new class of robotic intelligence wherein robots learn an internal, compact representation of the environment and its dynamics, enabling them to simulate future trajectories, evaluate candidate actions, and anticipate hazards before they materialise [21]. A world model typically consists of a learned latent dynamics model, a representation model, and a planner or policy head; together, these elements allow robots to operate with imagination-based foresight, improving sample efficiency, long horizon planning, and robustness to partial observability. In the context of 6G empowered robotics, world models become significantly more capable: the network provides real time exteroceptive updates through ISAC and distributed sensing, while edge hosted inference allows heavy predictive rollouts and large-scale latent space planning to be executed close to the robot with deterministic latency. 6G's AI native orchestration further coordinates the placement of world model components—representation learning on robot, predictive simulation at the edge, and cross robot latent state fusion in the Intelligent Service Plane—creating a continuum where the robot's internal model is constantly refined by network assisted perception, FL, and Digital Twin synchronisation. In safety critical settings, the combination of world model prediction and HRLLC enables proactive behaviour, such as forecasting human–robot collisions in DSZ or predicting network and environmental perturbations during remote driving. Thus, world model-based control emerges as an essential paradigm for next generation autonomy, tightly aligned with 6G's architectural vision of distributed intelligence, semantic communication, and closed-loop cognition.

In 6G systems, computational offloading enables robots to shift heavy AI workloads from resource-constrained embedded platforms to proximate edge servers, thereby reducing end-to-end latency and unlocking more capable perception and planning models. Beyond raw speedups from stronger processors, split inference partitions a neural network between the device and the edge, with early layers executing on the robot while deeper layers running at the edge; transmission and computation then overlap, shortening wall-clock time to decision for tasks such as semantic perception, global mapping, and language-guided planning. Recent studies quantify these gains for multi-view analytics and multi-device co-inference, showing latency and bandwidth reductions versus device-only or cloud-only baselines when models are partitioned and collaboratively executed at the edge [22], [23].

These capabilities align with Open RAN (O-RAN) disaggregation, which separates radio functions (Radio Unit / Distributed Unit / Control Unit) and introduces the RAN Intelligent Controller (RIC) as a programmable control plane with xApps (near-real-time) and rApps (non–real-time). Locating portions of the inference pipeline—and their schedulers—within the near-RT RIC places AI close to the access network on low-jitter infrastructure, enabling per-slice QoS enforcement for robotic fleets. Complementing this, intelligent user-plane designs provide native support for AI applications—specifically In-Network Computing (INC)–assisted Split-AI—so that selected neural layers execute within the user plane while others remain on the robot or at the edge, further compressing decision time and easing bandwidth pressure [24]. Contemporary RIC placement and orchestration frameworks, together with end-to-end edge-AI service provisioning for O-RAN, show how latency-sensitive components, xApps/rApps, and Split-AI partitions can be dynamically deployed and scaled across the cloud–edge continuum to meet stringent robotic control-loop deadlines [25]. In parallel, task-oriented communication methods explicitly co-design feature encoding and the wireless link for edge inference, improving accuracy–latency trade-offs under realistic bandwidth constraints—an effect that complements Split-AI for robot swarms offloading to the edge.

2.3. 6G capabilities for Multi-Robot Operations and Fleet Management

Fleet management is a cornerstone of scalable robotics because it is, at its heart, a large, coupled optimisation problem. The objective is to assign tasks, route robots, and schedule charging and maintenance in ways that minimise travel time, congestion, and idle capacity while meeting service-level constraints. Better optimisation directly improves economic viability: with more efficient coordination, fewer mobile robots are needed to complete the same workload, capital expenditure is reduced, and utilisation rises. It also yields energy efficiency by shortening paths, smoothing acceleration profiles, and avoiding redundant motion—an effect that compounds at fleet scale. Although commonly associated with warehouse intralogistics, the same optimisation pressures appear in last-mile delivery (e.g., dynamic dispatch and curb side coordination) and construction (e.g., staged material movement and site-aware task sequencing), where tasks, maps, and constraints evolve rapidly and must be reconciled across heterogeneous robot types.

Two complementary fleet-management paradigms address these challenges. In centralised control, a global planner (often at the edge or in the cloud) maintains system-wide state—maps, queues, resource availability—and computes task assignments and trajectories for all robots; this enables globally optimal or near-optimal decisions, consistent policy enforcement, and simpler safety guarantees, at the cost of higher dependency on connectivity and potential bottlenecks. In decentralised control, robots negotiate among themselves—using local communication, auctions, consensus, or market-based methods—to dis-tribute tasks and deconflict motion; this improves robustness and scalability in dynamic or partially connected environments but may sacrifice some global optimality. Modern 6G-enabled architectures increasingly adopt hybrid strategies that fluidly combine both modes: centralised planning for long-horizon allocation and fairness, with decentralised execution for fast, local reactions and resilience to network variability. 6G can support both types of fleet management through different capabilities.

2.3.1. 6G Communications for centralised robot fleet management

Suitable local communication setup is pivotal for multi-robot operations: robots must exchange data reliably among themselves and with fleet planners to coordinate tasks, avoid conflicts, and meet timing constraints. In practice, the ROS2 ecosystem has converged on Data Distribution Service (DDS)-based pub/sub as the default communication substrate, with multiple ROS Middleware (RMW) implementations (e.g., Fast DDS, Cyclone DDS—ROS2-compatible data distribution services—and Zenoh—a lightweight pub/sub protocol) offering distinct latency, reachability, and discovery behaviours under mesh and heterogeneous links. Recent evaluations on multi-robot topologies highlight how middleware choice and QoS tuning materially affect delay, reliability, and Central Processing Unit (CPU) overhead—reinforcing that protocol selection is a first-order design decision for fleet-scale systems [26]. However, interconnecting robots across different networks and administrative domains introduces complications (discovery across subnets, Network Address Translation (NAT) traversal, firewalling, multicast limitations). Surveys and adoption studies point to configuration complexity in DDS discovery as a recurring barrier, especially when fleets span Wi-Fi/ethernet/5G segments (even LoRa [27]) or must bridge to edge/cloud services [28], [29]. A 6G-oriented control plane can mitigate this by exposing DDS service-discovery primitives as network services (e.g., discovery relays, rendezvous points) and by Network Address Translation (NAT) breakout policies that allow robots to register, locate peers, and publish/subscribe across slices—so that a fleet planner hosted at the edge or in the cloud can coordinate robots without brittle per-site tunnelling.

Robotic fleets operate routinely in human-populated environments, which imposes strict functional-safety requirements. Contemporary standards mandate that mobile platforms perform on-board detection of nearby persons and trigger immediate safe-stop behaviours, ensuring that local perception and reaction remain effective even under communication impairment. The latest revision of the industrial robot safety baseline, ISO 10218-1:2025, codifies design and risk-reduction principles that underpin these local safety loops and the verification of protective measures [30]. This safety-first posture creates a structural tension with centralised fleet control: moving decision-making off the robot—e.g., to an edge-hosted planner—can jeopardise the hazard analysis if a single wireless link becomes a point of failure or adds jitter to protective actions.

Industry experience further shows a persistent scepticism toward wireless in safety-critical control, often comparing it unfavourably with cabled fieldbuses (e.g., PROFIsafe over PROFINET) on determinism, interference resilience, and diagnosability. Recent discussions and studies on functional safety over deterministic wireless explicitly note that promised generic wireless infrastructures must still demonstrate end-to-end safety integrity and predictable timing in brownfield deployments, reflecting ongoing caution among Operational Technology (OT) stakeholders [31],[32]. Consequently, any 6G architecture supporting centralised or hybrid fleet management must preserve local safety functions on the robot while delivering industrial-grade communication assurances to overcome these adoption barriers.

Meeting these expectations requires redundancy, prioritisation, and continuous adaptation in the radio and core. Beyond the default “stop on loss of link,” 6G systems should combine multi-connectivity with packet duplication to raise delivery probability under mobility and interference, as validated by recent evaluations that show Packet Data Convergence Protocol (PDCP)-level duplication across independent links can substantially reduce outage and latency tails in dynamic scenarios [33]. In parallel, criticality-aware slicing must enforce pre-emptive scheduling and hard resource reservations so that safety-critical telemetry and control messages pre-empt noncritical traffic under congestion, a capability emphasised in emerging 6G roadmaps and slicing research [34], [35]. Practically, this entails (i) configuring parallel paths (dual cells) with selective PDCP duplication; (ii) carving guaranteed radio resources (e.g., mini-slots) and admission rules for certified message classes from robots and safety sensors; and (iii) continuous slice re-optimisation from the control plane, tuning scheduler weights, Hybrid Automatic Repeat reQuest (HARQ) budgets, and pre-emption thresholds to keep ultra-low latency and loss within bounds as the environment and load evolve.

Adaptive resource optimisation should be safety-coherent: network policies and slice SLAs ought to be traceable to the risk assessment (per ISO 10218-1) and validated against worst-case transients (handover, blockage, interference bursts). Coupling on-robot “local stop” fallbacks with network-side redundancy and prioritisation enables centralised or hybrid orchestration without eroding the safety envelope. This integrated approach—local protective autonomy plus resilient, priority-aware 6G connectivity—supports the economic and energy gains of fleet-level optimisation while preserving human safety as a non-negotiable constraint.

While computational offloading mitigates processing constraints, it does not address the fundamental inefficiency of transporting raw sensory data from robots to the network. Modern robotic perception pipelines rely on high-resolution, high frame-rate sensors such as stereo RGB cameras and 3D LiDARs, generating data streams that can easily reach multiple gigabits per second and rapidly saturate even advanced 6G uplink capacities. To enable ultra-low-latency and highly reliable operation under these conditions, semantic representations of sensory information must be exchanged instead of compressed raw signals, with semantics explicitly aligned to the downstream AI tasks executed at the 6G edge. A growing body of work [36], [37] proposes semantic communication frameworks that jointly optimise sensing, communication, and inference, including deep learning-based joint source-channel coding, task-aware feature transmission, latent-space compression, and generative or diffusion-based reconstruction techniques that infer perceptually or task-relevant details at the receiver. For high-end robotic vision, semantic communication methods that transmit structured scene representations, such as object-level descriptors, geometric primitives, or task-conditioned latent embeddings, offer a promising path to achieving deterministic latency, graceful degradation, and robust performance in multi-robot cooperative environments.

2.3.2. 6G Communications for decentralised robot fleet management

Decentralised management requires from suitable robot-to-robot exchange of sensor and scheduling data. Therefore, device-to-device (D2D) communication for decentralised coordination is essential. Current cellular technology supports D2D through sidelink communications which allows to transmit data between two end devices, without the direct interaction of a base station. While 5G sidelink introduced foundational support, its deployment and configuration remain complex for robotics, and simplified, robotics-friendly D2D is needed to lower integration cost and enable market adoption in existing modems. Evidence from industrial swarm scenarios shows that NR sidelink with context-aware beam selection can meet stringent swarm requirements (e.g., ~10 ms latency, four-nines reliability) and scales better in high-density settings—directly benefiting bio-inspired coordination patterns (flocking, task auctions) where robots negotiate locally without a central broker [38], [39]. Beyond factories, Unmanned Aerial Vehicles (UAV) swarms can extend coverage in emergencies, acting as airborne relays to preserve local communication and enable service discovery for ground robots operating in disconnected or congested cells; analytical models demonstrate how such UAV-assisted links sustain connectivity and throughput for disaster recovery communications. Together, these directions argue for a dual track: (i) streamline DDS-based discovery and routing from the 6G control plane to make cross-domain ROS2 communication routine, and (ii) strengthen D2D/sidelink as a first-class path for decentralised, resilient multi-robot coordination.

Interaction among autonomous robots and the human-robot collaboration will require efficient and resilient communication and coordination in near real-time. This involves intelligent agents to understand the needs dynamically and coordinate sub-tasks, resources, and actions among robots in a system. Furthermore, semantic communication provides meaningful content from which the goal-oriented data relevant to desired outcome can be extracted and transmitted, thereby increasing efficiency and reducing latency. This enabling combination is in harmony with the expected evolution of autonomous operations driven natively by digital intelligence that is increasingly contextual and dynamically adaptive. There is a growing interest including body of research to support this powerful integration of communication, computing, control and sensing in multi-robot systems, as autonomous and intelligent AI agents are leveraged within an intent-based interpretive context. Moreover, the notion of extracting features has a wide range of usage scenarios such as Digital Twin reconstruction.

Semantic communication represents a shift from raw bit transmission to context- and meaning-aware information exchange. By intelligently compressing and transmitting only task-relevant data, semantic communication conserves bandwidth, reduces retransmissions, and accelerates decision cycles. This paradigm enhances multi-robot coordination efficiency, reduces communication overload during collaborative missions, and improves reliability under constrained channel conditions, directly impacting mission success in fields like automated inspection or precision agriculture.

2.4. Real-Time Monitoring, Simulation and Digital Twins for High-Fidelity Synchronisation

Digital Twins are virtual replicas of physical systems. They are typically constructed using simulators and/or models which are configured or trained using sensors and monitors which collect telemetry or other data from the physical system. Once it exists, the Digital Twin can be used as a proxy for the real system and support, detection of anomalies, diagnosis and root causing of these anomalies, what-if scenarios and optimisation of the system. Today they are applied to many domains, including physical infrastructure (e.g. bridges and buildings), aircraft, and utility networks; in this context, we focus specifically on their use for robotic systems.

2.4.1. Continuous Monitoring and Proactive Maintenance Through Digital Twins

When Digital Twins of physical robotic systems are continuously synchronised in real time or near-real time, they can enable predictive maintenance, virtual testing, and “what-if” scenario simulations for those systems. Achieving very low latency synchronisation between the physical system and the Digital Twin can be very challenging. The 6G enablers are key factors in realising the low latency synchronisation. Leveraging 6G’s ISAC capabilities provides a valuable observation of the environment in which the robot fleet operates, complementing more traditional sensors and telemetry data from the robots. The ultra-reliable, low-latency communication, means that the Digital Twins can receive the sensor and telemetry data almost instantaneously, increasing fidelity and lowering latency.

This combination of richer sensing data and data delivered with greater reliability and near instantaneously unleashes operators and autonomous algorithms to deliver many use cases including detecting anomalies, predicting system degradations, and optimising missions. Application examples range from monitoring critical factory robots to disaster-response units, where infrastructure status can be assessed virtually before physical deployment. The Digital Twin becomes a more potent dynamic decision support and validation tool, reducing downtime, improving safety, and accelerating iterative design in complex, networked robotic ecosystems.

If the value of a Digital Twin for a single robot is clear, its value multiplies for fleets of robots. Once a digital replica of the whole system is created including the robots and the environment, sensor data enable real-time monitoring of the robots’ behaviour and operational states. Through the Digital Twin, system operators and AI-controlled systems can observe the robots’ positions, trajectories, task executions, interactions of robots with each other and with the environment without the direct physical access. For autonomous robots implemented in remote or large-scale environments where conventional servicing is challenging and dangerous, this non-contact monitoring [40], [41], [42], [43], [44] is crucial. Even in situations when physical access is restricted, digital twins enable operators to obtain a thorough situational knowledge, make well-informed judgements, and act quickly when needed by offering a permanent, current virtual representation. Along with just visualisation and monitoring, digital twins also enable dynamic maintenance and fault detection and management by continuously analysing the deviations between the expected and observed behaviour, along with cross-correlation of anomalies between robots. Instead of depending on regular examinations which may create delays and scalability limitations. the digital twin allows early detection of anomalies, performance degradation or potential failures. In highly interconnected robotic ecosystems envisioned for 6G, such continuous and automated monitoring becomes essential to maintain system reliability and safety, reducing downtime and enabling timely corrective actions.

2.4.2. Advanced Simulation for Robotic System Validation and Optimisation

Digital Twin offers a complete platform for sophisticated simulation and predictive analysis, which makes it feasible to assess behaviour settings, navigation algorithms, and control techniques without compromising the actual robot. Digital Twins can predict future states, determine possible decision outcomes, and carry out complex what-if assessments by incorporating AI algorithms, such as Machine Learning (ML) models and LLMs. Furthermore, the twin can continuously integrate real-time sensor data, environmental feedback, and robot activities into the simulation using closed-loop modelling. In addition to validating autonomous behaviour in a variety of scenarios, this iterative method facilitates the optimisation of operational and decision-making processes prior to its deployment. Predictive simulations, for example, can assess various navigation routes, foresee crashes, or identify task performance measures that save time and energy.

When paired with real-time sensor data and edge computing resources, these AI-enhanced simulations enable adaptive, near-real-time decision-making. In addition to typical predictive models, LLMs can help with work planning, scenario reasoning, and anomaly explanation. To preserve the integrity of the closed-loop Digital Twin, 6G-enabled ultra-low-latency connection makes sure that the robot or control system receives simulation results and AI forecasts promptly. This combination of simulation, prediction, and real-time monitoring enables fleet-level optimisation, fault anticipation, and continuous learning, resulting in a strong framework for deploying autonomous robotic systems that are safe, efficient, and capable of operating in dynamic and complex settings.

Beyond mirroring current state, Digital Twins serve as high fidelity simulation environments where new behaviours, control policies, semantic communication strategies, or DSZ logics can be validated under realistic network and environmental conditions. 6G enabled twins can incorporate time synchronised network emulation—varying latency, jitter, and link failures—so that co-design of robotics and communication stacks becomes possible. This is particularly important for validating AI native and split computing approaches, where parts of the perception or control pipeline run in the network. By exercising these control loops at scale in the twin, designers can explore KPI trade-offs (e.g., safety vs. throughput vs. energy), verify that ISAC function is dimensioned correctly, and derive configuration templates that can be deployed into live 6G systems with reduced risk. Transcending their application for testing of control systems, the ability for Digital Twins of robotic systems to respond realistically to stimulus and control means that they have a crucial role to play in training the control systems themselves. By exercising the what-if analysis capability of the Digital Twin, AI can be allowed to explore the system in a wide range of nominal and pathological modes in ways that can never be possible in the physical counterpart. ML strategies such as reinforcement learning are powerful but they learn by breaking things and explore many strategies that range from sub-optimal to catastrophic before they converge to winning strategies. The Digital Twin is the perfect environment in which to learn, make mistakes and finally master the art of delivering optimal outcomes.

2.5. Cyber-Physical Systems for Immersive Human-Robot Interaction

CPS integrate computation, communication, and physical processes, enabling robots as part of the CPS to interact with their environment. Coupled with AR and Virtual Reality (VR) over-lays, powered by 6G's high-bandwidth, ultra-low latency links, CPS enable human operators to visualise real-time robot status, environmental data, and control interfaces directly in their physical workspace. This fusion boost situational awareness, facilitates remote teleoperation, and enhances collaborative robotics in smart factories, logistics hubs, and telemedicine settings by offering contextual, immersive feedback through holographic data visualisation and intuitive controls.

CPS in robotics integrate sensing, computation, communication, and actuation into unified control loops that span physical robots, Digital Twins, and human operators. When augmented by 6G's high-bandwidth, low-latency connectivity, precise localisation, and AI-native orchestration, these systems enable immersive human–robot interaction through spatially anchored Augmented/Mixed Reality (AR/MR) overlays. Operators see live robot states, DSZ, predicted trajectories, and shared environmental models superimposed on their physical workspace, creating intuitive collaboration where gestures, gaze, and haptic cues guide robots while maintaining safety and context awareness across smart factories, logistics, hospitals, and field operations.

2.5.1. Perception-Driven Situational Awareness

Perception-driven Situational Awareness in immersive human-robot CPS depends on continuously fusing heterogeneous signals (robot sensing, human intent, environment state) into a coherent, queryable "world model." Building on the themes above, situation awareness can be strengthened by translating engineering artefacts—system models, resilience requirements in natural language, and linked data—into structured inputs for LLMs and deep surrogates (e.g., Graph Neural Networks (GNNs)). This enables AI-assisted reasoning over dependencies, behaviours, and failure/attack propagation, rather than treating perception as raw sensor processing alone [45].

CPS leverage high-fidelity perception from ISAC, multi-modal robot sensors (LiDAR, cameras, force/torque), and network-assisted localisation to construct shared digital representations of the workspace. These feed immersive XR interfaces where AR overlays—robot joint states, DSZ boundaries, collision risks, task cues—coexist with the physical scene in real time. By fusing ego-motion data with network-derived environmental insights, CPS close the loop between physical interaction (human gestures → robot response → visual/haptic feedback), boosting operator trust and enabling natural, safety-aware collaboration even in cluttered or remote environments.

2.5.2. Semantic Communication for Efficient Context Sharing

Semantic compression and context-aware communication aim to exchange meaning (task state, intent, risk, constraints) instead of high-volume raw data—vital for immersive Human Robot Interaction (HRI) where latency and bandwidth shape experience and safety. Using the approach above, CPS engineering models can be converted into AI-ready representations that define what context matters, how components relate, and which resilience metrics must be preserved. These structured inputs let LLMs + GNNs compress and prioritise shared context (e.g., "operator intent + safety envelope + predicted downtime") while GNN-style message passing captures how semantics should propagate differently across node/edge types (sensor links vs. control links vs. service dependencies).

AR empowering CPS anchor semantic encoders/decoders and goal-oriented, context-aware communication, where only task-relevant scene abstractions (human poses, object locations, safety constraints) are exchanged between robots, edge intelligence, and 6G functions rather than raw sensor streams. This reduces bandwidth while preserving information needed for distributed DSZ computation, multi-robot coordination, and holographic workspace synchronisation across stakeholders. For efficient context sharing in robotics use cases, one main challenge is ensuring semantic consistency (e.g. latent space alignment) across distributed agents with heterogeneous models, ideally without joint training and with reasonably sized decoders. The semantic-oriented compression, while allowing reduced bandwidth, should still maintain a level of information adapted to the goal of a given task. 6G features—centimetre-level localisation, dynamic QoS adaptation, exposure APIs—ensure these shared representations remain consistent with physical reality under mobility and load variations, positioning CPS/AR as a core architectural pattern for trustworthy, scalable human–robot systems [46].

In summary, the integration of 6G technologies into robotics presents significant opportunities to address existing challenges across various domains. The pillars of connected robotics, as outlined in Table 1, highlight how innovations such as Network-as-a-Sensor and AI-native architectures can enhance environmental perception and adaptiveness. These elements form a unified architectural framework that empowers robotics and bridges critical gaps through enhanced 6G capabilities.

Table 1. Connected Robotics Pillars: Bridging Robotics Gaps with 6G Capabilities

Connected Robotics Pillars	Challenges	Enabling Technologies in 6G Robotic Architecture
6G ISAC	Scalable and reliable environmental perception beyond onboard sensors, or GNSS-denied environments.	Network-as-a-Sensor/Actuator and distributed radio sensing extend, cooperative radio sensing, network-based localisation and mapping beyond line of sight.
AI-Native Architecture	Constrained onboard processing limitations and static AI pipelines that cannot adapt to dynamic missions.	AI-native 6G architectures with intent-based control enable network-integrated AI execution.
Real-Time DT	Restricts predictive maintenance and safe virtual validation.	Real-time DT synchronised via 6G for continuous monitoring and simulation.
Fleet Management & Multi-Robot Control	Scaling safe, efficient, and reliable control to large, heterogeneous robot fleets.	Deterministic low latency, criticality-aware slicing, and hybrid centralised–decentralised control architectures ensure reliable fleet coordination.
CPS	Human–robot collaboration suffers from limited situational awareness and non-immersive interaction mechanisms.	CPS combined with AR/VR over 6G, and high-precision localisation enable immersive and trustworthy human–robot interaction.

3. Unified Architectural Frameworks for 6G-Empowering Robotics

The architectural frameworks for integrating 6G technologies into robotics and other verticals are informed by a convergence of evolving industry standards, ambitious research agendas, and emerging reference models. These frameworks must address the need for a unified, programmable, and AI-native system architecture that aligns both with the specific requirements of robotic systems and the broad vision of intelligent, resilient, and context-aware networks. In this context, 6G is not just a faster connectivity layer but also provides sensing, communication, compute, and intelligence as-a-service to robotic systems [47].

A unifying view is to align the four-plane 6G architecture—data plane, intelligent plane, sensing plane, and service plane—with the layered robotic stack (perception, cognition, action, and self-learning). This alignment enables closed-loop behaviour where robots and networks adapt: robots inform the network about task and context, while the network dynamically configures resources, sensing, and AI functions to sustain safe and efficient operation [48]. This mapping of IMT-2030 KPIs to robotic functional blocks, along with the proposed multi-plane integration of robotic, intelligent, and network service planes, enables closed-loop behaviour where robots express task/context intents and networks dynamically configure resources, sensing, and AI functions to sustain safe operation [49].

3.1. Integration of 6G architecture into the layered robotic systems

A key paradigm for 6G empowering robotics architecture is the decomposition into interoperable component —ranging from physical sensing/actuation up through cognition, decision-making, and self-learning. The 6G infrastructure acts as both a digital nervous system and a cognitive amplifier, enabling robots to leverage networked ISAC capabilities, edge-cloud intelligence, and real-time semantic communication for advanced perception, task planning, and coordinated action. The enabling technologies introduced in Section 2—network-as-a-sensor/actuator, ultra-reliable communication, ISAC, AI-native control, FL, computational offloading, semantic communication, DT, and immersive XR—must ultimately materialise as coherent architectural patterns that practitioners can implement. This section introduces a unified framework in which 6G planes and robotic system layers are explicitly mapped to each other providing a common reference for the use cases and KPIs in Section 4. The architecture can be presented as a *four-plane* unified system of 6G networks and robotics. This system provides a modular integration of sensing, perception, cognition and planning, and actuation and execution across four planes of the robotic, intelligent, data-governance, network-service, and robotic-service planes, each comprising a number of functional layers, which then can be instantiated in diverse applications from industrial automation to remote healthcare. The architectural planes define a set of interfaces that connect robotic applications, network intelligence, and data infrastructure, enabling end-to-end self-learning and task-oriented communication.

Intelligent Service Plane: The Intelligent Service Plane forms the cognitive core of the framework and primarily supports the cognition, reasoning, and planning layer. It hosts distributed AI agent and lifecycle-management functions that process multimodal sensor data and semantic representations coming from robots and the network, enabling advanced decision-making and context-aware coordination. Integrating cognitive communication and computing, this plane operates intelligent user-plane functions, semantic communication engines, and generative models that jointly select and adapt traffic, optimise task-oriented encoders/decoders, and derive policies for multi-robot cooperation and predictive control. Through distributed AI agents embedded in the core, RAN, and edge, self-learning capabilities can be realised, continuously optimising slices, QoS profiles, and semantic encoders for robotic workloads.

Through distributed AI agents embedded in core, RAN, and edge, self-learning capabilities can be realised, continuously optimising slices, QoS profiles, and semantic encoders for robotic workloads while interfacing with governed data and policy constraints from the Data Governance Plane.

Network Service Plane: The Network Service Plane is the foundational layer that provides critical sensing, positioning, communication, and compute-offload capabilities to the upper planes. It encompasses the 3rd Generation Partnership Project (3GPP) user and control planes, as well as a dedicated sensing plane for exchanging environment and positioning information that is distinct from the classical user plane but tightly integrated with it. ISAC is a core feature of this plane, enabling the network not only to carry traffic but also to perceive the environment and support network-as-a-sensor/actuator functionality for robotics use cases (further discussions in Section 4). In addition, the plane supports semantic data representation and in-network processing, exposing services such as task-oriented slices, HRLLC bearers, localisation, time synchronisation, and compute placement to the Robotic Vertical and Intelligent Service planes.

Data Governance Plane: The development and deployment of intelligent robotic systems generate vast amounts of sensor, log, and model-update data that must be managed across their full lifecycle. The Data Governance Plane oversees data collection, storage/public memory, processing, and model provisioning, ensuring integrity, lineage, and reliable exposure of models and AI tools back to the Intelligent Service and Robotics Vertical planes. It implements Policy & Assurance functions for privacy, security, and regulatory compliance, including access control, anonymisation, retention, and audit trails for training and adaptation loops. This plane therefore anchors ethical and accountable operation: all data-driven decisions made by robotic or network-resident agents can be traced to governed datasets and models subject to explicit policy rules, supporting certification and cross-organisational deployments which are further discussed in subsection 3.2.

Intent-based Interfaces Across Planes: Figure 2 illustrates how the three functional layers—Sensing & Perception, Cognition/Reasoning/Planning, and Control & Execution—are realised across the planes through a set of well-defined existing and emerging bidirectional interfaces. These interfaces can be grouped into:

- **Intent-based interface between the Robotics Vertical Plane and the Intelligent/Network Service planes:** At this interface, robotic applications provide task descriptors, semantic intent, and safety constraints (for example, human–robot separation margins, braking-delay limits, or critical perception zones) and receive optimised semantic encoders, control policies, and service configurations. This bidirectional exchange supports human–machine interaction by propagating mission-critical needs, while returning policies and models refined through fleet-level learning and digital-twin simulation.

- **Data-governance interface between all planes and the Data Governance Plane:** The Data Governance interface mediates access to curated datasets, model artefacts, and feedback signals required for self-learning, while enforcing privacy, trust, and regulatory constraints. Robotic and network-resident agents request data, publish logs, and submit updated models through governed APIs, enabling continual learning processes that remain auditable as models evolve and are redeployed. Policy & Assurance functions apply ethics, sustainability, privacy, security, and safety requirements as cross-cutting constraints on these exchanges.
- **Service interface between the Network Service Plane and other planes:** The interface between the Network Service Plane and the Robotics Vertical / Intelligent Service planes orchestrates sensing, positioning, computation, and communications as task-oriented services. Through this interface, AI agents can configure and refine slices, semantic physical/MAC-layer behaviour, and ISAC parameters to keep sensing fidelity, localisation accuracy, compute placement, and connectivity aligned with task objectives and safety envelopes. Closed-loop feedback from robots and DT enables continuous re-optimisation of these services under changing traffic, mobility, and environmental conditions.

Across all interfaces, network-service handlers such as sensing-fusion functions, communication controllers, and computation-offload managers provide reusable primitives that can be composed per application. Embedding AI agents in the Intelligent Service Plane and leveraging governed data access plus Policy & Assurance in the Data Governance Plane add adaptive reasoning, self-learning, and compliance to these handlers, while cross-plane security mechanisms ensure trusted operation. Overall, the architecture unifies robotic control and network intelligence delivering (Figure 2 real-time perception, cognition, and actuation for next-generation autonomous systems (Figure 2).

- **Robotic Service Plane:** This plane serves as the integration role for robotic applications and directly hosts the sensing & perception, cognition, and control functions realised through the Infrastructure, Middleware, and Application layers in Figure 2. Through the intent-based interface, robotic applications expose task descriptions, mission goals, and safety envelopes, and receive back optimised communication, compute, and AI services without binding to specific network or data implementations. It exposes services for enhanced perception, collaborative actions, fleet management, DT, AR/VR based teleoperations and human–robot interaction.
- Robotic systems are organised along an orthogonal stack of layers—Infrastructure, Middleware, and Application—that map onto the 6G planes described above. This stack clarifies how robotic software components consume 6G capabilities through the intent-based interface instead of directly binding to low-level network functions.
- **Infrastructure Layer:** This layer encompasses the robotics and networking hardware and underlying infrastructure that jointly support the 6G system and robotic platforms. It includes RAN, core network, edge and cloud resources, as well as on-site compute, sensing, localisation units, and robot controllers, corresponding to the 6G Network Service Plane and the “robotics system hardware” blocks in the figures. The Infrastructure Layer is a horizontal substrate layer that includes (not "belongs to") the 6G Network Service Plane's physical/virtual resources. These network capabilities are exposed as services to the Robotic Service Plane above via intent-based interfaces, but their ownership/control remains with the Network Service Plane. It provides the physical and virtual substrates on top of which connectivity, ISAC functions, and edge computing are deployed for higher-level robotic and AI services.

- **Robotic Middleware layer:** Positioned between the 6G Robotic Service-Enabling Plane and the robotics software stack, this layer offers data-centric communication and coordination across robots, edge, and cloud. In many industrial robot applications ROS2 is the most common operating system for robotic in other domains. ROS2 in combination with DDS as a middleware protocol standard. In many domains, ROS2 combined with DDS (and increasingly Zenoh as a more scalable and flexible alternative optimised for wireless, including non-IP transports) provides real-time, high-performance communication between devices, and can be bound to 6G services exposed through the Network Service and Intelligent Service planes.
- **Robotic Application layer:** This layer corresponds to the robotics software and interfaced with Robotics Service-Enable Plane and intent-based interface that builds on middleware and network services to realise robotic services, autonomy, and adaptive behaviours. It hosts functions such as fleet management, safety-zone controllers, DT, and human–robot interaction interfaces, which consume middleware topics and 6G APIs to deliver end-to-end autonomous behaviour across heterogeneous robots and sites.

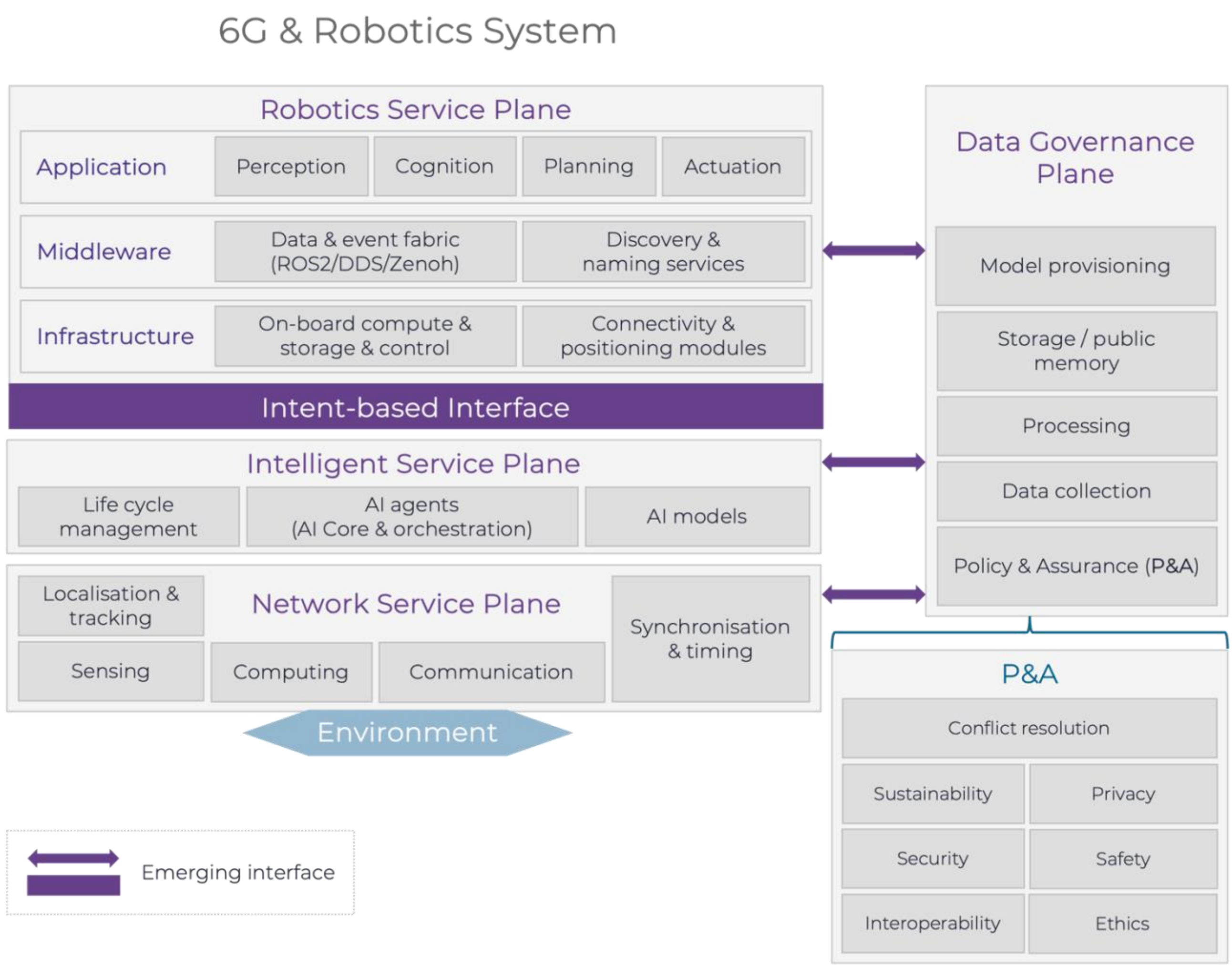

Figure 2. High-Level Architecture

3.2. Policy and Assurance

Responsible and resilient autonomy in robotics is underpinned by safety, cybersecurity, privacy, ethics, sustainability, and reliability/availability, which we treat as first-class Policy & Assurance (P&A) feature in Figure 2. The Data Governance Plane hosts P&A functions that define policies for these properties, monitor compliance, and propagate constraints into the Robotics Vertical Plane, the Intelligent Service Plane, and the Network Service Plane via both the data-governance APIs and the intent-based interface.

To cope with heterogeneous fleets and intent-driven orchestration, the architecture introduces an explicit Policy Arbitration & Conflict Resolution function within the Data Governance Plane. This function performs intent validation and policy conflict resolution whenever high-level intents or configuration changes are issued. It detects and negotiates conflicts between, for example, safety-critical perception (which may demand increased sensing and data sharing), privacy and data-minimisation requirements, sustainability constraints, or mission-driven performance targets. When conflicts arise, it supports dynamic prioritisation, runtime conflict detection and mitigation, and fleet-level policy consistency and overrides, ensuring that agreed trade-offs are enforced coherently across robots, AI agents, and network services. Furthermore, interoperability feature ensures multi-vendor fleet deployment across diverse robotic systems via standardised intents and service exposure—critical for all use cases requiring heterogeneous coordination.

As robots become deeply embedded in critical domains—healthcare, manufacturing, mining, logistics, smart cities, and domestic environments—the combined stack of AI, integrated sensing, cloud/edge computing, and continuous connectivity significantly expands the potential attack surface. Vulnerabilities may appear at sensors and actuators (spoofing, tampering, poisoning), middleware and controllers (malicious reconfiguration or model manipulation), communication and cloud infrastructure (eavesdropping, lateral movement, denial of service), and human–machine interfaces (social engineering, misleading feedback). Compromises at any of these layers can lead to loss of privacy and data integrity, production outages, legal and financial damage, and—most critically—safety hazards in human–robot interaction and remote or autonomous operations.

Addressing these risks requires end-to-end architectural and implementation principles that treat safety, cybersecurity, privacy, sustainability, and ethics as fundamental design constraints. This includes security and dependability by design (identity, attestation, policy enforcement over the full lifecycle), continuous behavioural monitoring and assurance (where network and robotic AI agents detect anomalous behaviour, enforce safe fall-back modes, and support post-incident forensics), and integration of governance controls (constraints on autonomy levels, human-in-the-loop controls, data-usage policies) directly into the orchestration logic of the 6G planes and the robotics vertical plane.

Taken together, network-as-a-sensor and network-as-an-actuator, ultra-reliable communication, ISAC, AI-native control, FL, computational offloading, semantic communication and digital-twin support define a coherent toolbox for connected robotics in the 6G era. The architectural frameworks in the next section show how these enablers can be combined into layered, programmable systems that align 6G planes with robotic perception, cognition, action and self-learning, while the subsequent use-case chapters demonstrate how these patterns materialise in concrete deployments and KPI definitions.

4. Case Studies and Architectural Validation

This section applies the unified, AI-native 6G architecture by anchoring it to concrete robotic use cases and evidence-driven validation. Each case study is mapped to the layered model—Infrastructure, Network Service, Robotic Middleware, and Application—to show how advances in wireless (ISAC-enabled RAN, O-RAN/RIC programmability, edge/cloud continuum, semantic communication) become deployable capabilities for robots' perception, cognition, action, and self-learning. The focus is dual: (i) demonstrate tangible performance and economic value (fewer robots to do more work, lower energy per task through optimised motion and offloading) in domains such as warehouse logistics, last-mile delivery, construction robotics, and emergency response; and (ii) verify that these gains are achieved without compromising safety or trust, aligning with ongoing standardisation on interoperability, exposure APIs, and safety-by-design.

By structuring the section this way, each case demonstrates a line of sight from programmable network intent to robotic outcomes: how a slice policy or an in-network agent changes task allocation and path planning; how split inference and semantic exchange compress perception-to-action loops; how edge placement and service discovery govern fleet scalability across heterogeneous networks. The result is a set of reusable architectural patterns—centralised, decentralised, and hybrid—that validate the framework's claims and provide a blueprint for industrial adoption in 6G empowering robotics.

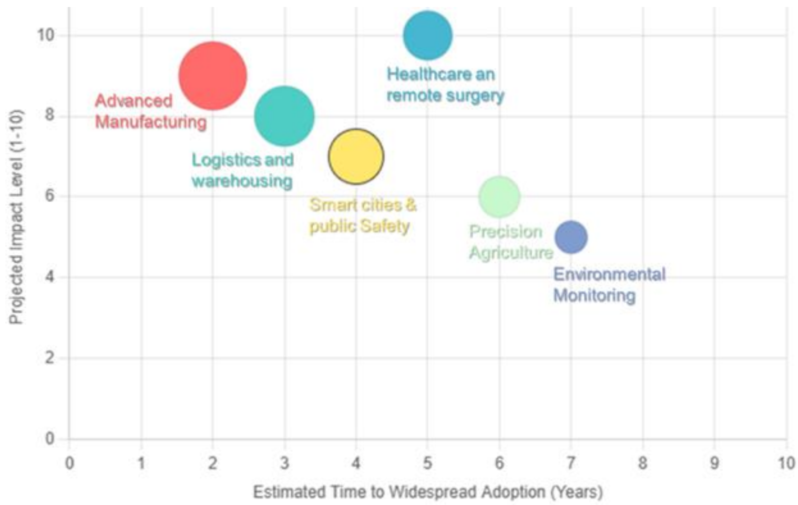

Figure 3. Future-Forward Applications of Connected Robotics

4.1. Potential Case Studies KPIs and long-term transformation

To quantify the impact of 6G-enabled robotics and automation systems, the use case defines a KPI set at the level of atomic functions and end-to-end behaviour, rather than only at the aggregate system level. Representative KPIs include:

- **Technical/HRI KPIs:** control-loop latency from human movement to robot response; spatial accuracy of human pose and zone estimation; rate of near-misses and incidents; minimum separation distances in operation.
- **Operational KPIs:** throughput per cell or area; robot and human utilisation; time and cost to reconfigure zones when layouts or product mixes change.
- **Ecosystem KPIs:** time-to-certify or re-certify after modifications; interoperability across vendors and networks; effort to port safety policies between sites.

We first focus on the technical KPIs for human-to-robot and robot-to-robot interactions in this whitepaper.

Use Case 1) Dynamic Safety Zone in Smart Manufacturing

The Dynamic Safety Zone (DSZ) concept targets Human Robot Collaboration (HRC) where fixed or mobile robots share space with human operators. Current safety planners are static—lacking real-time adaptability since safety actions rely solely on AGV's local perception without global updates [50]. Human Recognition Services enhance HRC perception (Human Machine Interfaces (HMIs) delivers outputs to operator interfaces; HRI encompasses the broader collaboration discipline)—continuously tracking workers feeds DSZ safety logic + task coordination. Core capabilities:

- Multi-modal sensing (vision, depth, force, wearables) for pose estimation, gesture recognition, intent inference
- Multi-camera networks with geometric calibration for occlusion-robust perception
- Semantic outputs (pose/gaze/gestures/activity labels) to controllers/HMIs

DSZ maintains per-operator safety zones that dynamically expand, shrink, or reshape as a function of distance, relative speed, and predicted human motion. When a human worker approaches a robot workspace or planned trajectory, DSZ evaluates collision risk and triggers graded responses, including speed reduction, path re-planning, safe stop, and task re-negotiation. Functionally, DSZ is instantiated across Infrastructure: (i) an ISAC-enabled RAN supporting human pose sensing beyond onboard sensors; (ii) HRLLC and deterministic transport enabling time-critical DSZ loops; (iii) AI-native orchestration to prioritise safety-relevant flows and adapt function placement (robot vs edge vs cloud); and (iv) exposure APIs for DSZ telemetry integration. By contrast, current deployments typically combine wired fieldbuses for local safety with best-effort WLAN/private 4G/5G for telemetry, which does not guarantee deterministic DSZ updates and does not natively integrate network-assisted perception.

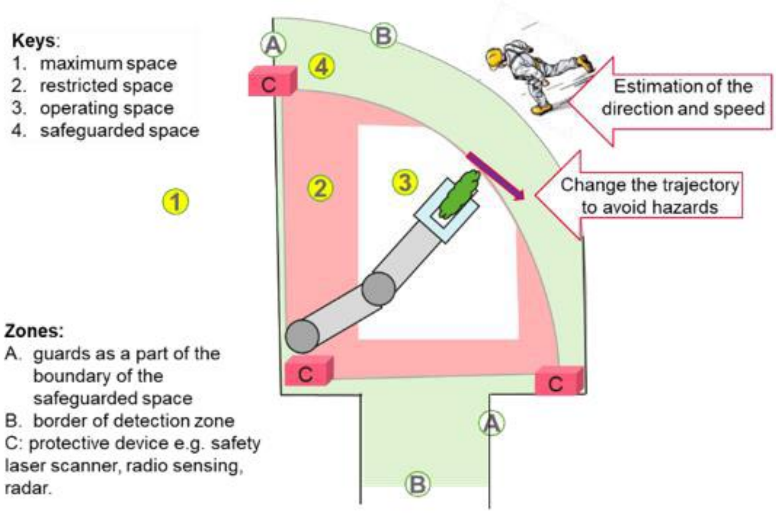

Figure 4. A safeguarded space, guards and end-effector device [50]

The DSZ use case is primarily constrained by the closed-loop delay and determinism from human state estimation to robot actuation, as well as by the reliability and availability of safety-critical processing and communications. In addition, DSZ performance depends on the spatial accuracy of human pose/workspace representations and on operational safety and productivity indicators (e.g., near-misses and throughput).

- At system level, this plane-explicit integration enables: (i) progressive replacement of physical fencing with dynamically computed, certifiable soft zones; (ii) portability of DSZ safety policies and KPI templates across facilities via standardised exposure and intent interfaces; and (iii) coupling of safety telemetry to operational optimisation loops, allowing throughput, utilisation, and energy objectives to be co-optimised under explicit safety and governance constraints. Core Components Mapped to Four-Plane 6G Architecture (Section 3) can be listed as following:

- **Robotic Service Plane:** Hosts Infrastructure (AGV hardware, proximity sensors, PLCs), Middleware (ROS2/DDS/Zenoh for real-time coordination), and Application layers (DSZ application logic for zone generation, graded interventions, HMI feedback, fleet management integration); exposes safety envelopes (separation margins, protected zones, braking-delay limits) and DSZ state/KPIs as machine-readable intents via intent-based interfaces.

- **Intelligent Service Plane**: Cognitive core with distributed AI agents (core/RAN/edge) processing multimodal data (ISAC, vision, depth, wearables) for human pose/intent estimation, shared semantic map maintenance, collision-risk prediction, and policy adaptation; continuously optimises DSZ parameters (zone geometries, semantic encoders, compute partitioning); supports fleet-level learning of safety policies across sites via FL interfacing governed data/P&A.

- **Network Service Plane:** Foundational sensing/positioning/comms/compute via 3GPP user/control/sensing planes; ISAC-native RAN extends perception beyond onboard sensors (cm-level 3D human pose); HRLLC-grade, deadline-bounded transport for time-critical DSZ loops; controllable compute placement (robot/edge/cloud) aligned with timing constraints; exposure APIs integrate DSZ telemetry; network becomes active sensor/actuator substrate.

- **Data Governance Plane:** Manages human-centric sensing/safety evidence lifecycle (pose traces, near-miss logs, model updates); Policy & Assurance (P&A) enforces privacy/security/safety with policy-controlled access, retention, lineage, auditability; policy arbitration resolves conflicts (increased sensing for safety vs. data minimisation/sustainability/productivity); enables portability of DSZ policies/KPIs across facilities.

- **Intent-based Interfaces Across Planes**: Robotic intents (safety envelopes, task constraints) flow to Intelligent/Network planes for optimised services (semantic encoders, HRLLC slices, ISAC parameters); data-governance APIs mediate governed access; service interfaces orchestrate perception/comms/compute; P&A propagates cross-cutting constraints for interoperability/zero-trust across deployments.

The DSZ use case is constrained by closed-loop delay/determinism from human state estimation to robot actuation, reliability/availability of safety-critical processing/comms, spatial accuracy of human pose/workspace representations, and operational safety/productivity indicators (near-misses, throughput).

Use Case 2) Cyber-Physical Remote Driving

The "Cyber-Physical Remote Driving" use case concerns immersive remote control of physical vehicles via Digital-Twin (DT)-based interfaces over hyper-distributed IoT–Edge–Cloud platforms. The functional objective is to enable an operator to perceive and act remotely, using an immersive cockpit integrating XR and haptic feedback, in hazardous or operationally complex outdoor environments. This serves as a proof-of-concept for convergence of the Human, Digital, and Physical worlds as envisioned for future 6G networks [51].

In contrast to legacy remote-control approaches based on best-effort video feeds and manual inputs, the proposed approach maintains a synchronised DT in which physical actions and digital simulation states are continuously aligned. This is supported by a computing continuum spanning the vehicle, network edge, and cloud. Validation is conducted on testbeds deployed at Universitat Politècnica de València and Technology Innovation Institute (TII).

Core components and functional interactions [52] are mapped across the architecture shown in Figure 5, includes infrastructure, network services, robotic middleware, and application layers to deliver resilient, low-latency robotic control with Digital Twin alignment. The infrastructure layer ensures continuity through handover-aware operation, multi-connectivity, and precise synchronisation. Network services are orchestrated by AI-driven mechanisms that prioritise and adapt resources for safety-critical and high-bandwidth flows. The robotic middleware maintains deterministic control loops, enforces safety, and interfaces with DT components, while the application layer leverages edge offloading to enhance perception, predictive rendering, and latency compensation for responsive, context-aware operation.

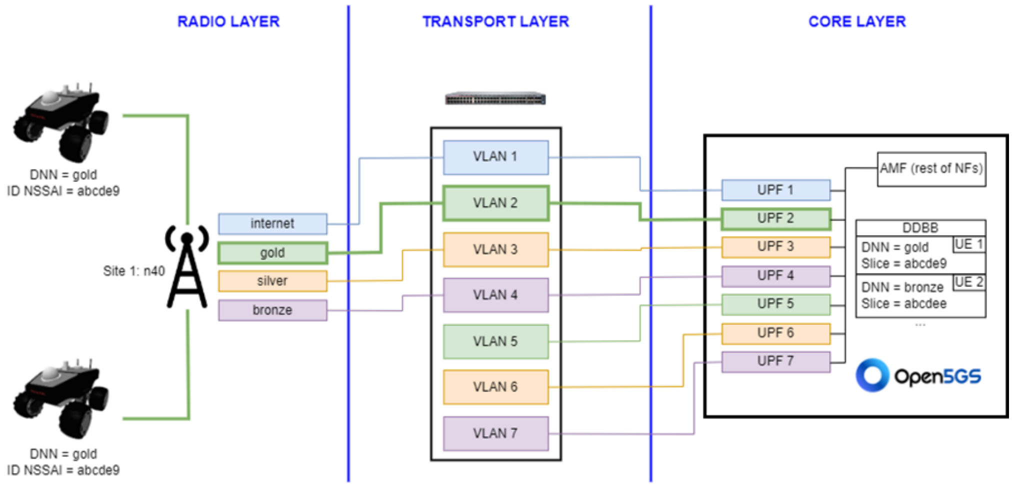

Figure 5. Slicing architecture of the UPV testbed. Radio resources are prioritised in specific slices (e.g., gold over silver and bronze), which are routed over different VLANs and served by different UPFs.

Experimental validation [53] highlights that the limiting factors for cyber-physical remote driving are not only transport latency but end-to-end "motion-to-photon" delay, worst-case one-way delay bounds (e.g., the 99th-percentile latency) and jitter under mobility, and the ability to sustain high-throughput, multi-stream media/DT traffic while protecting safety-critical command/telemetry. The measurements also indicate that video processing (encoding/decoding/buffering) is a dominant contributor to offloading latency, motivating co-optimisation of networking, edge processing, and actuation.

This use case indicates a shift from "remote driving over connectivity" to "cyber-physical driving over a programmable networked system", impacting the four-plane architecture in Section 3.

- **Robotic Service Plane**: Remote driving is redefined as a DT-mediated robotic service composed of atomic functions (telemetry ingestion, DT state alignment, safety envelope enforcement, cockpit interaction primitives). These functions become composable and portable across deployments, enabling domain-specific applications to specify service intents (control protection, perception fidelity, DT synchrony) independently of vendor-specific implementations.
- **Intelligent Service Plane**: The DT-based control loop becomes prediction-driven and context-adaptive. Orchestration integrates time-series forecasting (e.g., AutoRegressive Integrated Moving Average (ARIMA)) and closed-loop optimisation to continuously adapt compute placement (vehicle/edge/cloud), codec settings, buffering policies, and service-class parameters so that end-to-end perceptual stability is maintained under varying load and radio conditions. Latency compensation and predictive rendering become first-order control functions rather than auxiliary UI features.
- **Network Service Plane**: The network evolves from a throughput/latency substrate into a multi-service control fabric that guarantees differentiated behaviour across concurrent streams (control/safety, low-latency perception, high-fidelity DT/media). Deterministic prioritisation, admission/pre-emption, and mobility-aware session continuity become safety-critical primitives. The measured dominance of video processing delay implies that transport KPIs alone are insufficient; network services must jointly optimise transport, edge processing, and buffering to bound "motion-to-photon" delay and p99 one-way delay/jitter, especially at high vehicle speeds [53].

- **Data Governance Plane**: Sustained handling of high-rate telemetry, multi-stream video, and DT state requires policy-controlled storage, access, and auditability across the IoT–Edge–Cloud continuum. The expanded attack surface motivates cross-layer security controls and privacy-preserving learning (e.g., FL) without violating stringent timing constraints. The observed variability of "command-to-execution" latency (up to 350 ms) further suggests that safety assurance must incorporate not only network metrics but also mechanical/electrical actuation delays, enabling holistic certification evidence that spans sensing, networking, computation, and actuation.

Collectively, these transformations operationalise the 6G-era view in which vehicles become cyber-physical peripherals of a hyper-distributed computing continuum, interoperable through exposure APIs and governed through plane-consistent assurance mechanisms.

Use Case 3) Search and Rescue Robotics

Search and Rescue Robotics (SAR) in 6G can be framed as a use case where multi-robot teams, human responders, and the network co-operate to clear debris and evacuate victims in infrastructure-challenged disaster areas (e.g., post-earthquake urban environments), using 3GPP sensing for precise grasping and advanced 6G connectivity for coordination.
In the SAR scenario, two or more robots cooperate with professional responders to clear rubble blocking access to a building after an event such as an earthquake, in a realistic outdoor environment with constrained access (e.g., tunnels, uneven terrain) and partially destroyed communication infrastructure. SAR robotic systems are required to:

- **Perceive and locate victims under harsh conditions** (dust, smoke, occlusions) using multimodal sensing (3GPP RF sensing, RGB-D, LiDAR, BLE, environmental sensors).
- **Map and plan with representations of victims, debris, and obstacles**; computationally heavy algorithms may be executed via remote processing under low-latency and high-reliability communications.
- **Precisely localise and grasp irregular rubble**, leveraging 3GPP sensing for macro-object characterisation and micro-level grasp-point localisation with mm-level accuracy in the pre-grasp phase.
- **Coordinate cooperative manipulation** (e.g., two Autonomous Mobile Robots (AMRs), two humanoids, or mixed teams lifting a slab) under tight latency/reliability constraints, with continuous radio-sensing-based updates as arms approach grasp points.
- **Interact with human teams via 5G/6G-connected edge devices** (e.g., smartphones integrated into ROS) for mission requests (casualty extraction, equipment delivery, path clearing).
- **Operate safely near responders and victims,** where semantic perception supported by URLLC enables safe human–robot interaction in frontline tasks.

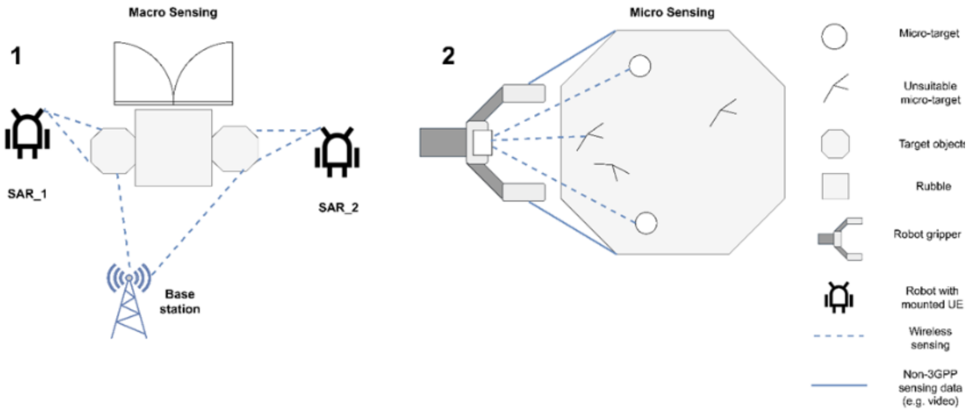

Figure 6. Precise Localisation of Robot Grasping [54]

A representative functional interaction is as follows: a SAR coordinator requests exploration of a collapsed building via the mobile operator; a surviving base station plus portable 5G/6G assets form a local cell and configure mono-/bi-/multi-static sensing between base station(s) and robot UEs; macro-sensing detects victims and infers rubble geometry/material and candidate micro-targets; action and motion planning is executed onboard, remotely, or jointly; robots then perform micro-sensing and pre-grasp, followed by cooperative lifting; network slices provide low-latency, high-reliability transport for safety-critical streams and edge-hosted functions such as SLAM and mission-level coordination.

The SAR use case is dominated by the need to restore dependable connectivity in damaged infrastructure while sustaining deterministic, safety-critical coordination across heterogeneous robots and human responders. Key KPIs therefore include extreme reliability/availability for control and coordination streams, high connection density for multi-agent operation, high-accuracy positioning and sensing (including RF-assisted grasping), and bounded latency/jitter to support cooperative manipulation and safe human proximity.

6G-enabled SAR robotics can evolve from bespoke, site-specific integrations toward a reusable Internet of Cooperative Agents [55], in which robots, sensors, and networks form standards-aligned systems-of-systems with guaranteed QoS, integrated sensing, and native Digital Twin support. In terms of the Section 3 architecture, SAR drives plane-specific transformations:

- **Robotic Service Plane**: SAR missions are decomposed into reusable, composable robotic services (exploration, victim localisation, mapping/SLAM, debris manipulation, cooperative lifting, logistics delivery) by robot-to-robot interactions, KPIs via intent-based interfaces enabling agile mission reconfiguration of multipurpose robots under common service abstractions.
- **Intelligent Service Plane**: Multi-agent cognition becomes network-assisted and context-adaptive, integrating macro-/micro-sensing, semantic scene understanding, and coordinated planning. This supports predictive coordination for cooperative manipulation and safer interaction with responders, while enabling continuous adaptation as the environment evolves.
- **Network Service Plane**: The network transitions from best-effort coverage to an active coordination substrate providing deployable, mission-critical slices with deterministic low-latency and high-reliability transport, as well as integrated sensing services. Such capabilities

are required to sustain coordination in partially destroyed infrastructure and to host edge functions (e.g., SLAM and mission-level coordination) closer to the operational area.

- **Data Governance Plane**: SAR requires governed sharing of sensitive operational data (victim indicators, responder locations, semantic maps, sensing-derived evidence) across temporary, multi-stakeholder deployments. Policy-controlled access, auditability, and security controls become prerequisites for inter-agency cooperation without compromising safety or timeliness. Policy & Assurance (P&A) enforces policy-controlled interoperability via standardised exposure) enabling inter-agency cooperation.
- **Intent-based Interfaces Across Planes**: Robotic intents (mission goals, safety constraints) flow to Intelligent/Network planes for optimised services (semantic encoders, slices); data-governance APIs mediate access to governed datasets; service interfaces orchestrate sensing/comms/compute for coordination; P&A propagates constraints ensuring heterogeneous agents' interoperability.

5G URLLC supports basic coordination but lacks RF-assisted, mm-accurate grasping and centimetre-level positioning, coupled with networked Digital Twins of robots, environment, and communication assets, which enable autonomous debris handling and casualty evacuation, reducing responder exposure and improving mission success in complex, infrastructure-denied scenarios. Multimodal sensing (3GPP RF sensing, RGB-D, LiDAR, BLE, environmental sensors) combined with semantic perception can materially improve situational awareness for both humans and robots in dynamic, unstructured environments.

Use Case 4) Energy Efficiency in Connected Robots via Knowledge Aggregation

Energy efficiency in connected robotic systems constitutes a defining constraint for scalable autonomy in 6G. This use case frames energy efficiency as an emergent property of knowledge aggregation, whereby robots, edge infrastructure, and AI-native networks cooperate to minimise sensing, computation, communication, and actuation energy while preserving collective intelligence. Instead of exchanging raw data streams or repeating local learning, connected robots exploit shared, structured knowledge (e.g., model blocks, semantic abstractions) to reduce redundant operations and extend operational lifetime [56], [57].

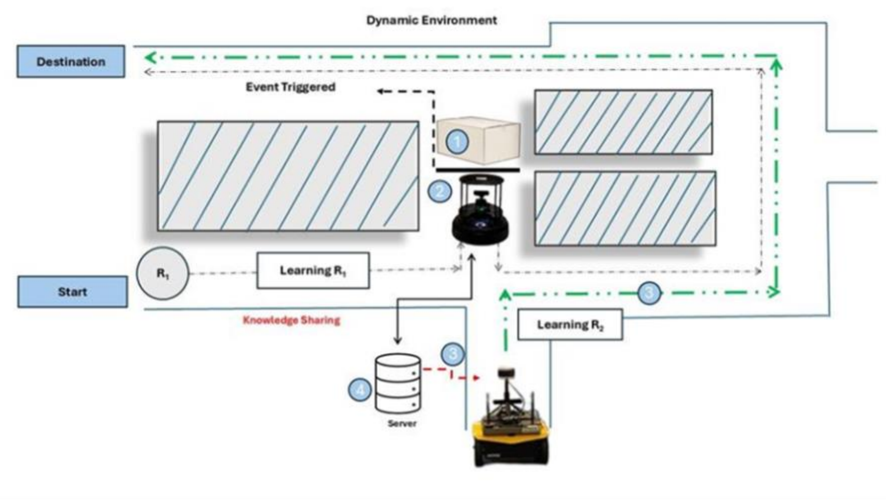

Figure 7. Knowledge aggregation for connected robot in dynamic environment showing robot (2) observing obstacle (1) and sharing update of environment to robot (3) via edge computing server (4)

In this use case, heterogeneous connected robots (e.g., UAVs, autonomous ground vehicles, and mobile robotic platforms) operate collaboratively in energy-constrained environments such as urban mobility, large-scale inspection, disaster response, and distributed industrial automation. Functional requirements include:

- **Knowledge-centric exchange**: actionable knowledge (learned model blocks, semantic representations, temporal abstractions, causal relations) is exchanged instead of raw sensor streams, reducing communication energy.
- **Edge-assisted federated and multi-task learning**: robots benefit from collective experience without repeated full-model training or centralised data aggregation [58].
- **Temporal and hierarchical clustering**: learning and communication are restricted to contextually similar robots, avoiding unnecessary global updates [57].
- **One-shot inference and model reuse**: newly deployed or resource-constrained robots acquire capabilities rapidly without extensive sensing or training.
- **Causal knowledge aggregation**: repeated exploration, replanning, and trial-and-error behaviours are reduced, lowering sensing, computation, and motion energy [59].
- **Energy-aware edge services**: knowledge-update frequency, inference placement (robot vs edge), and aggregation scope are dynamically adapted to power constraints and task urgency [56], [60].

A typical interaction proceeds as follows: robots perform local perception and inference, selectively upload compact knowledge updates to an edge node, and the edge aggregates, clusters, and refines the knowledge before redistributing it only to relevant robots. This closed-loop process accelerates convergence, reduces sensing cycles, and enables energy-efficient task execution without continuous high-rate data transmission. 6G-enabled knowledge aggregation implies a shift from platform-centric optimisation to system-level energy intelligence, in which energy is managed jointly across robots, edge, and network rather than locally per device [58]. Over time, robotic ecosystems may evolve into sustainable, knowledge-centric systems-of-systems where total energy consumption is minimised while autonomy, robustness, and scalability are maximised [56], [60]. Within the proposed architecture, the transformation is plane-explicit:

- **Robotic Service Plane**: knowledge aggregation is exposed as reusable robotic services (knowledge publication/subscription, model-block exchange, reusable capability bundles) that reduce redundant sensing/training and enable rapid capability to transfer across heterogeneous robots.
- **Intelligent Service Plane**: Cognitive core with distributed AI agents (core/RAN/edge) implementing federated/clustered/causal aggregation policies as optimisation functions; selecting what knowledge to share, when to share it, and which robots benefit, thereby reducing exploration and replanning costs under energy budgets using multi-task learning governed data/P&A constraints
- **Network Service Plane**: the network evolves toward energy-aware service provisioning, co-optimising HRLLC scheduling, inference placement, and resource allocation so that communication and computation energy are minimised while task urgency and safety constraints are maintained.
- **Data Governance Plane**: knowledge sharing across deployments requires governed handling of model updates and semantic/causal representations, including provenance, access control, and assurance mechanisms that prevent leakage or misuse without imposing prohibitive overheads.
- **Intent-based Interfaces Across Planes:** Robotic intents (energy budgets, knowledge needs) flow to Intelligent/Network planes for optimised services (clustered aggregation, energy-aware HRLLC/slices); data-governance APIs mediate governed model access; service interfaces orchestrate comms/compute for minimal-energy operation; P&A propagates constraints ensuring interoperability/zero-trust across deployments.

By embedding intelligence into the 6G fabric, experience can be shared across deployments without proportional increases in energy cost, enabling long-duration missions and large-scale deployments under strict power constraints. Federated, clustered, and causal knowledge aggregation supports continuous adaptation and robustness, positioning 6G as an enabler of environmentally sustainable, scalable, and resilient connected robotic systems.
This use case emphasises energy-centric KPIs that are not adequately captured by connectivity-only optimisation: energy per inference, energy per model update, and energy per successful task/mission, alongside energy-aware scheduling and adaptive edge placement that reduce both transmission and onboard compute energy. In contrast, current systems often rely on centralised learning, repetitive training, and persistent data exchange, increasing total energy consumption and limiting autonomy duration [58].

Use Case 5) Fleet management of heterogeneous connected robots in construction

Automation in construction is increasingly treated as a strategic necessity in Europe because housing demand is rising while supply remains constrained, with persistent productivity gaps contributing to a structural housing shortage [61]. In parallel, the construction ecosystem faces sustained labour and skills shortages; the European Commission reports that 25–30% of companies identify lack of workers as a key limitation to output [62]. In this context, a heterogeneous robotic fleet is considered for the construction of a multi-storey building to improve productivity, reduce safety risks, and stabilise project timelines.

Construction sites feature non-structured and dynamically changing environments (temporary obstacles, material stacks, evolving geometry, changing access paths, scaffolding, and intermittent GNSS). This makes navigation, situational awareness, and task execution inherently non-stationary, requiring frequent replanning and robust localisation.
To address these constraints, a hybrid fleet-management architecture is defined, combining decentralised and centralised coordination:

- **Level 1 — Field teams with decentralised coordination (D2D):** Field robots (quadrupeds, cable-driven parallel robots, UAVs, and cranes instrumented and interfaced through robotics frameworks such as ROS2) are organised into small teams assigned to spatially separated work zones (e.g., different floors). Within each team, communications are implemented device-to-device (D2D) to support local collaboration and resilience under coverage variation. Team-level coordination follows the principle of stigmergy, i.e., an indirect coordination mechanism in which agents self-organise by reacting to traces left in a shared medium rather than relying on explicit central commands [63]. In construction robotics, the "shared medium" is operationalised as locally shared digital traces (e.g., task markers, hazard annotations, local map deltas, progress tags) that are created/updated by robots and consumed by peers to trigger subsequent actions (e.g., re-routing around a newly marked obstruction, prioritising a newly marked subtask).
- **Level 2 — Site edge management over an in-situ network:** A server attached to the on-site network performs global fusion and optimisation. Robots periodically upload sensing-derived updates; the edge server generates and maintains site-wide maps (supporting localisation and navigation despite environmental change) and produces construction progress analytics. These analytics are aligned with the Building Information Model (BIM) so that planned-versus-as-built deviations can be detected and used to re-issue tasks. Based on the updated global state, the server performs task allocation and path planning at team level (and, where needed, robot level), rebalancing robots across teams/floors and updating mission objectives.

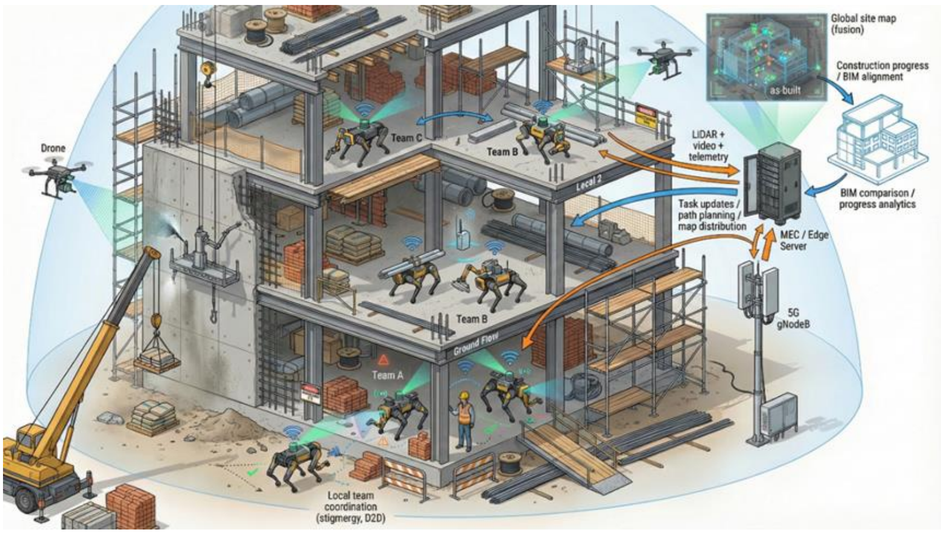

Figure 8. Overview of the construction scenario

Connectivity requirements can be estimated for a three-level construction site organised into three teams (ground floor plus two upper floors) comprising 13 heterogeneous robots in total (quadrupeds, a humanoid, two façade cable-driven parallel robots, two cranes, and two drones). Each platform can be assumed to carry standard navigation sensing: a 3D LiDAR (on the order of ~300k points/s with intensity), a forward RGB camera at 1080p/30 fps (compressed), and low-rate proprioceptive telemetry (IMU/odometry/joint and health signals). The per-robot uplink may be derived from these sensing streams and can be aggregated across the fleet, including a modest margin for protocol overhead and traffic peaks. Core Components Mapped to Four-Plane 6G Architecture can be mapped as followings

- **Robotic Service Plane**: Hosts Infrastructure (robot hardware: LiDAR/RGB/IMU/actuators), Middleware (ROS2/DDS/Zenoh for D2D stigmergy traces), and Application layers (composable work packages: surveying, inspection, material transport, façade operations, lifting support); exposes intents (team tasks, safety constraints, environmental change) and KPIs via intent-based interfaces for agile reconfiguration/heterogeneous teaming.
- **Intelligent Service Plane:** Cognitive core with distributed AI agents (core/RAN/edge) performing multi-robot fusion for site-wide maps/construction-state estimation, BIM-aligned analytics, task allocation, conflict-aware path planning, inter-team rebalancing; context-adaptive reasoning handles non-stationary environments; fleet-level learning via FL interfacing governed data/P&A.
- **Network Service Plane:** Two-tier control fabric via 3GPP user/control/sensing planes; deterministic D2D/sidelink for intra-team coordination/safety; slice-based services for uplink-heavy mapping updates, low-latency edge feedback, mission reconfiguration; ISAC enhances mapping through dust/occlusion/shadowing; 6G improves multipath resilience, tighter jitter for manipulation.
- **Data Governance Plane:** BIM-linked progress models/site maps as governed assets across stakeholders (contractors, vendors, safety officers); Policy & Assurance (P&A) enforces provenance, access control, retention, auditability for certifiable decisions (re-tasking, safety zoning, compliance); policy arbitration balances operational needs vs. privacy; interoperability via standardised exposure.
- **Intent-based Interfaces Across Planes:** Robotic intents (work packages, dynamic constraints) flow to Intelligent/Network planes for optimised services (D2D slices, edge compute, ISAC mapping); data-governance APIs mediate BIM/map access; service interfaces orchestrate sensing/comms/compute; P&A propagates constraints ensuring interoperability/zero-trust across multi-vendor deployments.

5G URLLC supports D2D coordination but lacks hyper-reliability for safety-critical lifting, cm-level ISAC through occlusion, self-healing against RF shadowing; 6G provides deterministic sidelink/HRLLC, AI-native orchestration, resilient slices for programmable construction ecosystems. This use case motivates a hybrid paradigm—local, decentralised coordination within field teams and centralised optimisation at the site edge—aligned with the proposed plane-based architecture. It targets construction automation as a response to constrained housing supply and persistent labour shortages reported by the European Commission.
Overall, the long-term effect is a transition from ad-hoc site robotics to a programmable, plane-consistent construction ecosystem in which heterogeneous robots can be deployed, reconfigured, and assured at scale while accommodating continuous environmental change.

Use Case 6) Stroke Care Robotics: Acute Intervention and Chronic Rehabilitation

Stroke is the second leading cause of death across the world, annually killing approximately 6 million people and the third leading cause of disability. In England, Wales and Northern Ireland, 85,000 people are hospitalised with stroke each year [64]. Projections indicate that by 2035, the annual cost of stroke in the UK could rise to £75 billion, nearly tripling the 2015 value [65]. In parallel, stroke survivors face a critical six-month subacute window in which high intensity, repetitive rehabilitation (20–30 hours per week) is required to leverage neuroplasticity, yet staffing and infrastructure constraints mean that only a fraction of this "dose" is delivered in practice. Term disability, with approximately 6 million deaths worldwide per year and substantial economic burden projected for the UK alone by 2035. Mechanical thrombectomy (MT) is an evidence backed, highly effective treatment for ischaemic stroke but is currently limited by a small number of endovascular capable centres, sparse 24/7 coverage, and long door-to-door transfer times, which disproportionately affect patients in remote regions.
This use case therefore frames stroke care as a continuum of robotic and networked interventions spanning acute, time critical MT and long-term neurorehabilitation. 6G-enabled connected robotics supports (i) teleoperated endovascular MT from regional hubs to remote hospitals and (ii) semiautonomous, network supported rehabilitation robots that extend therapists' reach from specialised centres into patients' homes, underpinned by real-time digital patient twins and XR interfaces.

Core Components Mapped to Four-Plane 6G Architecture (Section 3) are as following:

- **Robotic Service Plane:** Hosts Infrastructure (hardware substrates), Middleware (ROS2/DDS/Zenoh for data-centric coordination), and Application layers (MT cockpits, XR rehab interfaces, soft-robot surgical teleoperation/shared control, DTs, and crew management); exposes intents for perception, collaboration, teleoperation, and HRI via intent-based interfaces.
- **Intelligent Service Plane**: Cognitive core with distributed AI agents (core/RAN/edge) for reasoning/planning; processes multimodal data/semantic representations; optimises task-oriented encoders, multi-robot cooperation, predictive control; self-learns slices/QoS via FL while interfacing governed data/policies.
- **Network Service Plane**: Foundational sensing/positioning/compute/comms; 3GPP user/control/sensing planes with ISAC (network-as-sensor/actuator); HRLLC bearers, semantic processing, task-oriented slices, localisation/sync/offload exposed to upper planes for robotic workloads.
- **Data Governance Plane:** Manages data lifecycle (collection/storage/processing/provisioning); Policy & Assurance (P&A) for privacy/security/ethics/sustainability/interoperability; intent validation, policy arbitration/conflict resolution (e.g., safety vs. privacy); distributed trust (FL, ledger-inspired provenance) for heterogeneous fleets; data-governance APIs enforce compliance across planes.
- **Intent-based Interfaces Across Planes:** Robotic intents (task/safety constraints) flow to Intelligent/Network planes for optimised services; data-governance APIs mediate governed access; service interfaces orchestrate ISAC/HRLLC/compute; P&A propagates cross-cutting constraints (e.g., interoperability via standardised exposure, zero-trust auth)

UC 6.a) Endovascular remote robotics operation

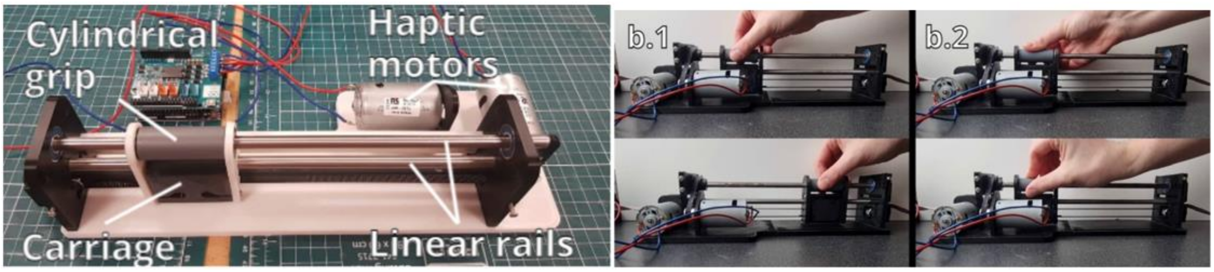

Figure 9. Left: Robotic haptic controller used for controlling interventional radiology robotics. Right: (b.1) Advancing and retracting the catheter or guidewire with the controller. (b.2) Rotating the catheter or guidewire with the controller

In the acute phase, the objective is to decouple MT eligibility from geography by allowing expert neuroradiologists to operate endovascular robots over distances of 50–100 miles or more. Tele-operated robot MT, which does not exist [66], can reduce the time gap from diagnosis to thrombectomy, which will lead to an increase in the percentage of patients treated. Today, no commercially available MT platforms provide true haptic feedback, and existing controllers (e.g. joysticks) poorly replicate the fine finger movements used for manual catheter and guidewire manipulation, while many systems require bespoke catheters and still depend on substantial onsite manual intervention.

The proposed robotic MT system introduces haptic catheter controllers that reproduce tactile cues from forces on catheters and wires, using off-the-shelf devices and extended stroke length to reduce manual assistance. The challenges -related to robotics- for building a fit-for-purpose system [67] are:

- First, no commercially available robotic platform provides haptic feedback [66] despite operators innately using tactile feedback from forces applied to catheters/wires to navigate safely through vasculature to safely deploy devices (Figure 9 left). The research community has been developing haptic feedback in robotics [66] which the team at Kings College London (KCL) has developed in the context of MT [67].

- Second, controllers such as joysticks are not similar to finger movements on "catheters/wires" [66]. A catheter/wire controller replica bridges an operator training gap and is preferred by experienced operators [67] (Figure 9 1.b).

- Third, endovascular robots typically require bespoke catheters/wires, and many adjunctive devices such as stents used in MT cannot be used [66]. KCl's applied robot uses all catheters/wires "off the shelf" [67].

- Fourth, considerable manual intervention during robotic endovascular procedures is currently required, often related to a short catheter/wire stroke length [66].

However, to overcome the unmet healthcare need of timely thrombectomy regardless of geographical location, two transformational solutions are now required to ensure safe and effective tele-operation.

Firstly, it is challenging for the responder to replicate the controller movements perfectly in real time, especially with Remote endovascular neuroradiology procedures performed over 50 or 100 miles. To mitigate risk, safer sensing and telecommunication is required in robotic MT tele-operation.

Secondly, as explained in [68], enhanced “situational awareness” through immersive technology is required for safer robotic use for remote endovascular neuroradiology operation which is acceptable to expert operator.

Current 5G slicing and scheduling 5G technologies have advanced towards these goals by incorporating stream scheduling and network slicing technologies [69], [70]. Also, the use of AI for improving quality of multi-modal data communication has been investigated in 5G settings, e.g. in demonstrating bandwidth savings and latency reductions for robotics applications [71]. The current robotic thrombectomy systems often lack sufficient haptic feedback, which is essential for assessing tissue interaction and ensuring safe navigation within sensitive neurovascular structures. Even in the presence of haptic feedback, capability of the existing medical robots is still constrained by the long sampling time. Furthermore, under conventional priority-setting mechanisms for data modes, the effective data rates of video streams are significantly reduced - even to zero- with the arrival of delay-sensitive haptic streams [72]. New 6G technologies for enhanced multimodal robotic sensing, robot-to-DT and robot-to-human communication can address the above challenges for realising remote robot MT [73].

UC 6.b) Rehabilitation Robotics for stroke recovery use case

1.2M EU strokes/year create millions with permanent disability [ESO/ESAP]. Subacute phase (6 months post-stroke) is critical neuroplasticity window requiring 20-30hr/wk high-intensity therapy—impossible with current staffing. Robotic rehabilitation combined with gamification through serious games and the use of objective data, has shown promise in improving patient outcomes and adherence [74], [75].

Existing robotic solutions face complexity, inflexibility, and poor personalisation despite aims to extend therapists' capacities [76]. Current systems fail to dynamically adapt FITT-VP parameters (Frequency, Intensity, Time, Type, Volume, Progression), operating as deterministic playback devices. Patient Digital Twins [77] achieve high-fidelity musculoskeletal simulation but critically miss physical contact dynamics (fitting errors, slippage, soft-tissue deformation) and cognitive adaptation, making them computationally expensive and requiring constant recalibration.

Figure 10. Typical scene of a rehabilitation robottR Physio-Bot in an hospital environment showing robot (end effector type) mobilising the patient, while the clinician (right side) sets the therapy parameter via handheld tablet. In the left downside the detailed GUI for the Clinici

Physio-Bots represent the most intimate human-robot interaction, mobilising subacute stroke patients' limbs for rehabilitation. Advanced systems use Learning from Demonstration (LfD) to replay clinician-recorded movements, delivering essential repetitions. However, they lack real-time adaptation to patients' physiological state, functioning as rigid playback devices.

6G transforms Physio-Bots into semi-autonomous coaches via ISAC sensing and AI-native edge processing. Edge-hosted Digital Patient Twins execute real-time musculoskeletal simulations, requiring healthcare-telco integration where robots serve as physical interfaces and networks as nervous system [77]. Lightweight XR glasses offload rendering to the network, overlaying gamified instructions for seamless hospital-to-home transitions.

Clinicians provide high-level FITT-VP intents/safety envelopes while edge AI handles micro-adjustments (trajectories, assistance levels, pause/stop). Multimodal sensing (force/torque, EMG, inertial, physiological) feeds continuous limb kinematics and patient state estimates. FL-updated Twins maintain privacy across sites. Furthermore, 1-5ms response to abnormal resistance ensures instant softening/stopping. P&A integration enforces clinical protocols (HIPAA) and resolves safety-privacy conflicts. ISAC in wearables provide contactless sub-cm pose tracking for fatigue/spasm detection. The architecture scales hospital to home using identical components over 6G, improving clinical efficiency and reducing rehabilitation costs [78].

UC 6.c) Soft robotics for Minimally Invasive Surgery

Soft robots [79], [80] built from compliant materials (silicones, textiles, elastomers) can safely interact with humans, conform to complex objects, and navigate cluttered or confined spaces. They are increasingly proposed for delicate manipulation, wearable assistance (e.g. soft exosuits) in health care [81] where rigid robots pose safety or access limitations. However, their continuous deformability and non-linear dynamics make state estimation and control difficult: dense embedded sensors are hard to integrate without compromising softness, traditional rigid-body models do not apply, and learning-based controllers are computationally demanding. For soft robots, whose bodies continuously deform, accurately determining their own shape and precise location in 3D space ("proprioception") is a significant inherent challenge [80], For tasks requiring fine motor control, precise manipulation, or coordination with other robots (e.g., cooperative carrying [1]), knowing the exact position of every deformable part is non-negotiable. If a soft robot cannot reliably self-localise or understand its spatial relationship to its environment and other agents, it cannot execute precise movements or coordinate effectively. Ultra-high accuracy positioning [82] provided by the 6G network offers a critical external reference, effectively compensating for the inherent difficulties in internal proprioceptive sensing in deformable bodies. Core components mapped to Section 3:

- Infrastructure Layer: ISAC-enabled RAN for external shape/pose/material sensing.
- Network Services Layer: HRLLC slices (0.1-10ms) + semantic compression for dense tactile streams.
- Robotic Middleware Layer: Integrates minimal onboard sensing (pressure/IMU sensors) with edge DT to enable finite element method (FEM)-based learning-driven control.
- Application Layer: Multi-robot coordination, haptic teleoperation, human-soft-robot shared control.

Figure 11. First soft robot for colo-rectal surgery in human cadaver. Credit by: STIFF-FLOP [83]

6G is expected to have latency as low as 1ms (<5 ms haptic-visual skew), few-N tactile resolution over compliant surfaces. Edge DTs (Intelligent plane) run FEM/learning models for tissue interaction prediction; HRLLC enforces surgical safety envelopes (e.g., max force, separation). P&A enables interoperability for hybrid rigid-soft fleets and tele-surgery. Long-term: from tethered prototypes to deployable neurosurgical systems with reusable controllers (FL-updated), enabling remote expert intervention in underserved regions.

4.2. Stakeholders in the robotics and telecommunications sectors

The emergence of 6G-enabled robotics use cases, ranging from ultra-reliable remote control and autonomous multi-robot coordination to mission-critical healthcare and disaster-response applications, has created a tightly coupled stakeholder ecosystem spanning i) robotics technology providers, ii) telecommunication actors, iii) network equipment vendors, iv) academic and research institutions, v) system integrators, vi) digital solution providers (cloud, edge computing, and AI platform), vii) defence agencies ,viii) space agencies, ix) venture capitals and x) vertical end users.

Each stakeholder group contributes complementary capabilities that are essential for realising the stringent latency, reliability, coverage, and intelligence requirements of next-generation robotic systems.

- **Robotics manufacturers and solution providers** represent a core stakeholder group, delivering autonomous robotics-based platforms that increasingly depend on advanced wireless connectivity. Companies such as Evasive Robotics, Ubiquity Robotics, Olive Robotics, and LionsBot develop mobile and service robots targeting logistics, inspection, cleaning, and autonomous navigation in complex environments [84], [85], [86], [87]. These platforms directly align with 6G robotics use cases such as autonomous mobility, multi-robot cooperation, and Robotics-as-a-Service (RaaS), which require seamless mobility support, high-precision positioning, and resilient connectivity. In parallel, other robotic companies such as Asensus Surgical exemplifies high-value medical robotics, where remote assistance, real-time sensing, and human-in-the-loop control impose extreme requirements on latency, determinism, and reliability are the key drivers for future 6G hyper-reliable and low-latency communication HRLLC and ISAC capabilities [88], [89].

- **Mobile network operators (MNOs)** are key enablers of robotics-over-6G by providing ubiquitous connectivity, private network deployments, and service-level guarantees. Robotics use cases such as remote teleoperation, autonomous fleets, and public-safety robotics increasingly motivate operators to adopt advanced features including network slicing, edge computing, and non-terrestrial networks NTNs to ensure service continuity and geographic reach. In this context, robotic systems act as both demanding network clients and strategic drivers for new Business-to-Business (B2B) and business-to-government (B2G) revenue models [90].

- **Network equipment vendors and technology providers** supply the radio access, core network, and enabling technological products required to meet robotic performance constraints. This includes support for cell-free massive MIMO, AI-native RAN functions, RIS-assisted propagation control, and NTN integration—capabilities that are particularly relevant for mobile robots operating in cluttered indoor environments, large industrial sites, or disaster-stricken areas [91]. Their role is critical in translating robotics-driven requirements into scalable and interoperable 6G network architectures.

- **Academic and Research Institutions** are forming alliances to support improvements in Human-machine collaborations that continue to progress beyond their limits, thanks to advancements in communication technologies such as URLLC and massive Machine Type Communication (mMTC). TU Dresden and TU Munich teamed up for the 6G-life research hub46, which brings under its umbrella many startups like Olive Robotics, Meshmerise, and Evasive Robotics. Similarly, institutions like the Open-Source Robotics Alliance (OSRA) [92] are widening their work areas with 5G/6G advancements, which shows how emerging advancements in telecommunication alter the robotic industry to new frontiers via pioneers of both the robotic and telecommunication industries.

- **System integrators and digital transformation consultancies**, exemplified by Accenture, play a pivotal orchestration role in the robotics–telecommunication convergence. Recent work by Accenture highlights the integration of robotics, AI, cloud/edge platforms, and advanced connectivity into end-to-end enterprise and public-sector solutions. Such actors map 6G robotics use cases onto operational workflows, combining robotic platforms with Open RAN-based networks, AI-driven orchestration, and vertical-specific DT. This system-level perspective is essential for scaling use cases such as smart factories, autonomous logistics, and resilient robotic operations in critical infrastructure and emergency response scenarios [93].

- **Digital solution providers (Cloud, edge computing, and AI platform providers)** support robotics use cases through distributed intelligence and low-latency processing. Edge-assisted perception, cooperative autonomy, and multi-robot coordination rely on tight integration between robotic platforms and telecom edge infrastructure, increasingly managed through AI-driven Service Management and Orchestration (SMO) frameworks consistent with Open RAN principles [94].
- **Defence Industry's** historical symbiosis between telecommunications is currently undergoing a paradigm shift driven by the emergence of 5G, Edge Computing, and URLLC. While firepower remains a core tenet of military capability, modern warfare doctrine is increasingly defined by the ability to process and disseminate information rapidly; just as logistics shaped the outcome of historical conflicts, the secure and high-speed transmission of data is now paramount. Current legacy systems often struggle to support the computational demands of AI and the Internet of Battlefield Things, whereas next-generation networks facilitate the offloading of processing burdens from autonomous units to centralised hubs. This transformation is evident in NATO's recent initiatives, such as the digitisation strategies tested during the CWIX 2025 and Joint Viking operations in Norway, and the multi-national experiments at the Ādaži Military Base in Latvia. By collaborating with technical integrators like LMT Defence, NATO members—including the Portuguese Navy—are validating unified architectures that leverage 5G for real-time asset tracking, Counter-Uncrewed Aerial System (C-UAS) operations, and immersive R simulations, thereby establishing the interoperability required for future Multi-Domain Operations [95], [96], [97].
- **Space agencies** are rapidly emerging as key stakeholders in the telecommunications domain, leveraging the convergence of space and terrestrial technologies to expand operational frontiers beyond Earth. European Space Agency (ESA) is spearheading this integration through its ARTES 4.0 program and 5G/6G Hub, which focus on mitigating critical latency issues in interplanetary robotics by validating hybrid satellite-terrestrial networks for seamless remote autonomy. Concurrently, NASA is extending these capabilities from Urban Air Mobility (UAM) applications on Earth to the lunar surface, employing initiatives like LunarLiTES and the FIGARO project to transition experimental 4G/LTE infrastructures into resilient 5G relay networks vital for the Artemis program's Deep Space interoperability [98], [99], [100], [101], [102], [103].
- **Commercial Ecosystems and Venture Dynamics:** Venture Capital (VC) firms and the startup ecosystem are executing a strategic pivot to capitalise on the convergence of telecommunications and robotics, particularly within the Industry 4.0 framework. The integration of massive mMTC and Edge Computing has catalysed a new generation of use cases. Innovators such as Botsync are advancing autonomous vehicle architectures for logistics and manufacturing, while Meshmerise is redefining network resilience to provide wider coverage. When synthesised with the capabilities of URLLC, these solutions fundamentally alter industrial standards. This shifting technological landscape has driven a

corresponding realignment in capital allocation, where increased funding accelerates the maturation of novel robotic applications and the proliferation of specialised startups.

- **End users and vertical stakeholders**, including healthcare providers, industrial operators, logistics companies, and public safety agencies, ultimately define the performance and reliability requirements of robotics-over-6G systems. For example, surgical robotics prioritises deterministic latency, robustness and dependability, while service and cleaning robots emphasise scalability, cost efficiency, and energy-aware operation. Disaster-response and public-safety robotics further stress network resilience, rapid deployment, and autonomous reconfiguration, reinforcing the need for elastic and self-organising 6G architectures [104].

Last but not least, standardisation bodies, regulators, and public funding agencies shape the long-term viability of the ecosystem by defining interoperability frameworks, spectrum policies, and safety regulations. Organisations such as 3GPP, ETSI, and the O-RAN Alliance increasingly incorporate robotics-driven requirements into their visions for 6G, ensuring that future networks can natively support autonomous and cooperative robotic systems [105]. Together, these stakeholders form a multi-layered value chain in which robotics platforms, telecommunication networks, and AI-driven orchestration co-evolve. The convergence of their roles is fundamental to realising scalable, resilient, and economically sustainable 6G robotics use cases across industrial, medical, and public domains.

4.3. Cross-Use-Case KPIs, 6G Capabilities, and Gaps

The stakeholders outlined in Section 4.2 provide the technological, economic and regulatory levers needed to close the gaps identified in each use case; Table 2 links their roles to the required KPIs and 6G capabilities.

The analysed use cases span industrial DSZ safety control, human-recognition services for HRC, cyber-physical remote driving of mobile robots, and endovascular remote robotics. Each combines stringent technical KPIs (latency, reliability, accuracy, throughput) with domain-specific safety and efficiency targets that cannot be fully met by current fieldbuses, Wi-Fi, or even today's 5G deployments. These gaps directly map onto the interests of key stakeholders: robotics vendors and vertical users articulate the KPIs; operators and equipment vendors must provide HRLLC, ISAC, edge AI and exposure APIs; system integrators and digital solution providers are responsible for composing these capabilities into end-to-end solutions that satisfy regulators and certification bodies.

Table 2. Key KPIs, 6G capabilities, gaps and stakeholder focus per use case

Use Case	Key KPIs	6G Capabilities	Current Gaps (Wi-Fi/4G-5G)	Stakeholder Focus
DSZ (Manufacturing)	HRI safety latency (<1ms); Cm-level pose accuracy; 99.99999% availability	ISAC 3D human sensing; AI risk prediction + P&A	No certified wireless safety; Best-effort latency (5-10ms); 10-20cm positioning limits	Operators: Safety-rated slices; Regulators: Wireless certification
SAR (Search & Rescue)	<1ms manipulation loops, high reliability, <10cm 3D positioning	ISAC victim/mm-grasping Self-healing slices	Disaster coverage failure 1-10m positioning 10^{-5} reliability limits	Public safety: Resilient networks, Emergency: Rapid deployment
Energy Efficiency	Energy/task (1pJ/bit) Model update cadence, Inference convergence	AI-native offload, Semantic/Gbps comms, Energy-aware orchestration	No joint comms-energy opt, Centralised training, Gbps bandwidth	Industry: Sustainability KPIs, Operators: Energy slices
Construction Fleet	D2D coordination jitter, BIM map sync accuracy	Deterministic sidelink, ISAC through occlusion, Edge BIM fusion	RF shadowing vulnerability, No stigmergy D2D, Wired fallback dependency	Construction: Multi-vendor interop, Real estate: Labour productivity
Stroke Care Robotics	≤1ms haptic E2E <5ms multi-modal sync; mm catheter tracking	Multimodal HRLLC bearers; mm-shape sensing; Edge DT + policy arbitration	No haptic guarantees; 15-50ms E2E robotic latency; cm-level positioning	Healthcare: Clinical certification, Medtech slices

Together, these KPIs provide a quantitative framework for stakeholders to compare use cases, prioritise 6G features and identify where existing wired, Wi-Fi and 4G/5G technologies fall short, reinforcing the need for coordinated innovation among robotics vendors, operators, network suppliers, integrators and regulators.

5. Challenges, Considerations, and Market Viability

As we explore the implications of 6G technologies for robotics, it is crucial to address the technical and regulatory challenges that accompany their implementation. Building on the insights and advancements highlighted in the earlier sections, we can better understand the obstacles that must be overcome to realise the full potential of connected robotics in a 6G environment.

5.1. Technical and regulatory challenges in implementing 6G for robotics

5.1.1 Safe Robots and Human Robot Interaction

Existing safety standards are optimised for conventional industrial and personal-care robots rather than networked, 6G-enabled systems operating in unstructured environments. Key references include DIN EN ISO 10218-1 on safety requirements for industrial robots and robot systems, and ISO 13482 on safety requirements for personal care robots, which address hazards in controlled industrial or domestic settings with assumptions of local control and restricted workspaces.

Illustrative gaps appear in complex locomotion scenarios involving close human–robot interaction, such as legged robot assistants supporting elderly users or wheelchair guidance in public spaces as shown in Figure 12.. While instability and fall protection are recognised challenges for legged robots, the risks associated with robots physically supporting humans remain underspecified. Current standards do not fully address how robots should prioritise fall direction, contact avoidance, or residual motion control—for instance, when guiding a wheelchair on sloped pavement. These gaps directly link to Section 4 robotics use case KPIs listed in Table 2, necessitating extensions to ISO 10218-2 quasi-static and transient contact limits for network-assisted fall recovery and predictive stability via 6G ISAC and Digital Twins.

Targeted evolution of safety standards must therefore integrate network-centric functions such as cloud robotics, cooperative sensing, and remote supervision, with a focus on end-to-end system behaviour across distributed 6G infrastructure.

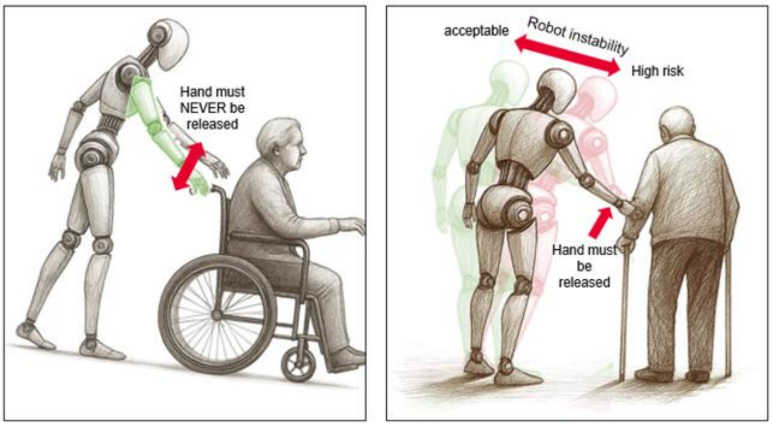

Figure 12. *Robot guides wheelchair or elderly*

5.1.2 Regulatory & Spectrum Considerations for NTN-Assisted Robotics

6G's integration with NTN offers unique coverage and resilience advantages for wide-area robotic operations, but it also poses regulatory and spectrum coordination challenges that must be addressed early in system design. Practical deployments (e.g., LEO-enabled telemetry or NTN-backed fleet coordination) require harmonised licensing for downlink/uplink bands, cross-border coordination, and a clear interference-mitigation strategy when NTN coexists with terrestrial ISAC functions. Operators and robotics integrators should adopt a regulatory-by-design approach: map required spectrum profiles for each use case (control loop, high-rate perception, ISAC sensing), identify national regulatory differences affecting NTN gateway placement and handover, and specify fallback modes under constrained spectrum or cross-domain interference. Key elements of a regulatory checklist include assigned frequency and licensing model, allowed Effective Isotropic Radiated Power (EIRP) and antenna masks, gateway latency bounds for control loops, cross-jurisdictional spectrum coordination plan, and required exposure APIs for operator/regulator audits. Where public spectrum is constrained, private network + NTN hybrid models and dynamic spectrum access (with geolocation Data Bases and assured coexistence) provide pragmatic alternatives. Including regulatory KPIs alongside technical KPIs (time to licence, % of sites compliant, escalation latency) converts abstract legal constraints into engineering requirements that can be tested and certified.

5.2. Standardisation considerations for interoperability and harmonisation

Looking back to 5G, where many new features and capabilities were included in the final standard. The experiences with 5G and the adoption of vertical business requirements show that closer cooperation between end users and communication network standardisation is required. The standardisation becomes more complex, the product more expensive, and the return on investment more questionable for the end-user. Business considerations should be considered before standardising complex solutions. The central aspect must also focus on the simplest possible configuration for new features.

Ensuring seamless interoperability between robotic systems and the underlying 6G infrastructure requires harmonised standards across key technology areas, including sensing, AI, communication protocols, security, and orchestration. The global 3GPP is at the heart of this effort. 3GPP, in Releases 20 and 21, is developing foundational Study Items and Work Items for 6G, including architectural support for integrated positioning, sensing, and AI-native network control [106]. Cross- Standards Development Organisation (SDO) coordination between ETSI ISG ENI, 3GPP SA1/SA2, one6G, and robotics-oriented standards and alliances to ensure that AI-native, slice-based architectures remain implementable and verifiable in safety-critical robotic deployments:

- Within 3GPP, both SA1 (service requirements) and SA2 (architecture) collaboratively define essential capabilities for AI-agent-based, vertical-aware architectures. SA1 focuses on refining use cases and requirements for time-sensitive and cyber-physical applications, including positioning, sensing, and AI-native support relevant to robotics. Meanwhile, SA2 specifies the integration of AI functions, sensing capabilities, and slice management into a cloud-native 6G core, building on concepts such as service-based architectures, network exposure functions, and CAPIFs. The emerging 3GPP CAPIF [107] aims to provide a unified exposure of network and service capabilities, compatible with various devices and vertical domains, including robotics, manufacturing, and healthcare.
- SA2 is also dedicated Work Tasks (WT) to developing a 6G system architecture that enables AI-native, agent-based networking. Current initiatives encompass machine learning (ML) integration and distributed intelligence, as outlined in [108]. Work Tasks such as WT#3 ("support of AI in 6GS") and WT#4 ("integration of sensing and communication over 3GPP access") are part of the latest SA2 6G Study scope, approved in SP-251634 at SA#110 (Dec. 2025). Furthermore, the 3GPP SA1/SA2 planning [109] outlines harmonisation strategies for immersive communications, DT, and cyber-physical integration, as reflected in ongoing Study Items that focus on positioning, sensing, and semantic information exchange within robotics.
- After having identified several robotics-related use cases and their associated requirements in ETSI GR ISC 001 [110], ETSI ISG ISAC is currently starting Phase 2 work on topics such as enhanced system and RAN 6G architecture for ISAC (including integration of computing and support of AI), AI/ML and data handling for sensing purposes (including data fusion/compression and semantic knowledge), security, privacy, demonstrability and adoption of ISAC technologies.
- ETSI GR ENI 051 document titled “Experiential Networked Intelligence (ENI): Study on AI Agents based Next-generation Network Slicing” is a pivotal reference for robotics developments. This document introduces the concept of AI agents as first-class entities responsible for managing slice lifecycles and implementing closed-loop control mechanisms. By incorporating feedback loops within an AI-native architecture, these agents can observe contextual changes, infer decisions, and act on various network functions and slices. For the robotics sector, the implications are significant:
    - Robotics-Aware Slices: AI agents can continuously adapt slice parameters—such as latency, bandwidth, reliability, and priority—based on real-time factors like robot workload, motion, and safety constraints. This adaptability enhances the overall performance and safety of robotic operations.

- **Hierarchical Agent Structures**: The architecture allows for the creation of hierarchies of AI agents that align with the intelligent plane of the 6G framework. Local agents can focus on optimising cell-level KPIs, while higher-level agents are tasked with coordinating fleets or overseeing operations across multiple sites. This tiered approach enables a more efficient allocation of resources and improved coordination among different robotic systems.

- The emerging IEEE P1955[123] and IEEE P1918.1[124] standard projects are positioning 6G as a transformative enabler for **robotics and tactile internet applications**, integrating AI-native networking, real-time sensing, and vertical-aware orchestration. These efforts reflect a shift from connectivity-centric thinking to **capability-centric frameworks**, where AI agents, service-aware slices, and real-time semantic intelligence are core components.

- Industry whitepapers, including those from one6G and 5GPPP, emphasise the need for open interfaces, network service orchestration, dynamic resource slicing, and continuum orchestration to address the demands of distributed, intelligent robotic ecosystems. Concurrently, platforms like the one6G Association and initiatives under the 5G-PPP and NGMN Alliance are creating methodology papers and requirements specifications for joint robotic use cases, which serve to inform and complement current 3GPP technical studies.

To effectively leverage the potential of 6G technologies in robotics, it is vital that telecom-centric efforts seamlessly interoperate with existing robotics middleware and software ecosystems. This integration is crucial for achieving optimal data exchange, orchestration, and telemetry within robotic systems. Notable frameworks - —ROS2, DDS, OPC UA (industrial automation), MQTT (lightweight messaging), and Zenoh (pub/sub protocol)— have emerged as de facto standards in this domain. Each framework comes with its own set of assumptions regarding reliability, timing, and addressing, which must be understood to ensure compatibility and performance.

In this context, organisations like the Open Standard Robotics Association (OSRA) and other robotics standard bodies are actively exploring hybrid communication methods that incorporate both IP and non-IP protocols. They are also developing safety-related profiles and reference architectures that align more closely with the capabilities of 6G networks, moving beyond the traditional view of the network as a black box. This shift is essential for creating a more intelligent and responsive robotic ecosystem. The 6G-empowering robotics architecture must therefore embed mechanisms for behavioural assurance, cybersecurity, and ethical compliance across all layers—from strong identity, attestation, and lifecycle policy enforcement for devices, services, AI models, and data flows, to human-in-the-loop checkpoints, explainability, and override capabilities at the application level. Standardisation efforts in ETSI, CEN/CENELEC (EU standards), IEC/ISO (global), and IEEE on ethical AI, safety, and trust for autonomous and AI-enabled systems, together with regulatory frameworks such as the EU AI Act, provide the process backbone for these P&A functions. Candidate harmonised standards under development (e.g. for AI risk management, data governance, transparency, robustness and cybersecurity) should be treated as core design constraints and explicitly mapped to the P&A and Policy Arbitration blocks in the architecture. CEN/CENELEC is currently developing candidate harmonised standards offering presumption of conformity with AI Act requirements in terms of AI risk management, dependability, data governance, transparency, human oversight, accuracy, robustness, and cybersecurity. Integration of ethical and governance controls (e.g. constraints on autonomy levels, human-in-the-loop checkpoints, data-usage policies) into the orchestration logic of the 6G planes and the robotics vertical plane, including in remote operation scenarios where physical access is limited. Given the context sensitivity of ethical properties, emerging global standards (see ISO/IEC/IEEE 24748-7000:2022) provide foundational ethical assurance processes for the 6G empowering robotic implementation of autonomous intelligent systems in the defined operational scenarios.

Table 3. Key SDOs and robotics alignments

SDO	Focus	Robotics Relevance
3GPP SA2	AI-native core, ISAC	Slice management for fleets
ETSI ENI	AI agents (GR ENI 051)	Intent-based control
ETSI ISAC	Sensing + AI data fusion	mm-pose for DSZ/SAR
IEEE P1955	6G robotics framework	e2e PCA model robotics
OSRA	ROS2-6G profiles	Middleware interoperability

5.3. Ethical and Societal Considerations for Architectural Design

The ethical assurance of complex technological artefacts requires careful and systematic consideration of operational and system requirements, architecture, various life-cycle phases, operational scenarios, and the communities that will interact with the system. This is compounded when AI technologies are embedded with a potential for autonomous operation. Global standards provide systems frameworks for addressing various facets of social responsibility and impact [111]. The first global standard that addressed AI ethics is IEEE 7000 [112], "Standard model process for addressing ethical concerns in System Design". The standard is primarily aimed at Autonomous Intelligent Systems (AI based products and systems). It advocates a five-stage process for the responsible design of AI-based systems comprising:

- Articulation of the concept and context of operation,
- Stakeholder exploration of the idea of ethical values,
- Articulation of the ethical requirement for incorporation into system architecture and design,
- Ethical risk-based design,
- Management of transparency throughout the architecture and design processes.
- Whilst the IEEE 7000 five architecture and design processes are globally applicable to any AI-driven solutions, specific ethics standards and guides for the robotic applications, which recommend a risk-based approach to ethical assurance [113], and inherent ethical design have also emerged lately.

Latest developments in the context of technology ethics have gravitated towards assessment and certification against a specific core ethical concern such as privacy, accountability and bias. The IEEE CertifAIEd [114] developed over a period of six years at the IEEE Standards Association provides SMART criteria suites to assess and certify AI and robotic systems for ethical properties, namely, transparency, bias, accountability, privacy, fairness and ethical governance. The assessment process is preceded by an Ethics Profiling stage that determines the ethical centre of gravity for the AI system application as a collective and systematic basis for the selection and implementation of the appropriate criteria suite.

The latest Management System standard for AI [115] also sets an enterprise-level approach to the responsible design, development and deployment that addresses leadership, planning, support, operation and performance evaluation/improvement aspects pertinent to any AI system, including robotic deployment.

Overall, ethical concerns should be proactively identified and incorporated into architecture and design processes, and 6G empowering robotics is no exception to this precautionary principle.

From 6G perspective, cybersecurity constitutes a foundational pillar of an ethical 6G framework [116]. The pervasive connectivity of 6G, combined with extensive edge computing, large-scale deployments of IoT devices and robots, and deep integration of AI, significantly expands the network attack surface. Accordingly, there is a shift toward security-by-design [117] and security-by-default principles, supported by zero-trust architectures [118], quantum-resistant cryptography [119], AI-driven threat detection, and privacy-preserving FL. In the context of 6G, cybersecurity is not merely a technical requirement but a societal responsibility, as failures may directly compromise critical infrastructure, public safety, and trust.

The protection of privacy emerges as a critical ethical challenge in 6G networks due to the unprecedented volume, granularity, and sensitivity of the data. Advanced applications such as biosensing, DT, immersive communications, and autonomous systems blur the boundary between physical and digital identities. Traditional safeguards, such as consent and anonymisation [120], may prove insufficient in 6G environments, as linked or de-identified datasets can still enable re-identification. Consequently, the ethical framework prioritises privacy-by-design, supported by secure multi-party computation, synthetic data generation, FL, and blockchain-based mechanisms for data governance, integrity, and ownership.

Another key requirement is consumer protection to ensure that the benefits of 6G do not come at the expense of user rights and welfare. The rapid pace of technological innovation in 6G risks outstripping existing consumer protection regimes, exposing users to harms such as opaque data practices, unfair pricing, inadequate remedies for data breaches, and exploitative contractual terms. Transparency, effective grievance redressal mechanisms, and transparent accountability of service providers to safeguard digital rights within increasingly complex 6G ecosystems [121].

Competition and market fairness represent a crucial ethical dimension of 6G. The convergence of telecommunications with AI, robotics, cloud computing, and data-driven platforms may give rise to market concentration, abuse of dominance, and challenges related to standard-essential patents and access to critical infrastructure. Therefore, the ethical framework calls for proactive oversight, of competition, support for open and interoperable standards, and regulatory coordination to prevent monopolistic outcomes while preserving incentives for innovation and investment.

Overall, establishing a trusted 6G ecosystem is essential for widespread adoption and long-term societal benefit. Trust must be embedded both technically and institutionally, encompassing secure network communication, transparency in system design and operation, accountability for failures, and responsible management of cross-border data flows. Given the global nature of 6G, achieving these objectives requires international cooperation, shared principles, and interoperable standards to sustain a secure, open, and trusted digital environment [122].

Table 4. Ethical and Societal Considerations for Architectural Design

Aspect	Ethics	Security	Privacy	Systematic Safety
Core focus	Confidence in autonomous robotic behaviour under uncertainty	Protection against cyber and cyber-physical threats	freedom from intrusion into the private life or affairs of an individual	Absence of catastrophic consequences for humans, the environment, or assets.
Key Concern	Alignment with human values; Fairness; Accountability; Explainability; Bias; Responsible autonomy	Confidentiality Integrity Availability	Constant Data Minimisation Purpose Limitation User Control	Probability of Catastrophic Failure; Failure Severity; Human Exposure Duration and Controllability of Unsafe States; Acceptable Risk Level

5.4. Cost-Benefit Analysis, Business Models, and Roadmap

Business models for 6G robotics are not well investigated in the case of service robots used in public domains. Since the nature of mobile radio is to provide connectivity and services everywhere and mostly out of buildings different stakeholders may be involved in the end-to-end service provisioning.

Robots will be rented by end-users from MNO, used as a service from robot operators with and without MNO contracting. Finally, the end-user is also buying it and booking additional services like communication, computing, AI model delivery from MNO or other partners.

Robot operator may host the AI services and models by themselves or take advantage of pre-trained models regarding environmental perception from the MNO.

Sensing service capabilities of MNO might be used because the MNO has a perfect model of the environment where the robot is or is going to act. Agents hosted by robot operators may coordinate the robot task planning and coordinate the additional sensing and computation resources with the corresponding agent in the Mobile Network. Long-term contracts or even micro contracting could become efficient to ensure the reliable coordination of all the resources.

Business models for public-domain service robotics remain underexplored, involving MNOs, operators, and end-users. Robots-as-a-Service (RaaS) via MNO slicing charges €/robot-hour for HRLLC/ISAC; micro-contracting covers on-demand sensing/AI (e.g. environmental models from MNO data). Robot operators leverage MNO-hosted agents for task planning, with long-term SLAs ensuring reliability. MNOs gain scale supporting 100s–1000s of robots as trusted partners for connectivity/models (Figure 13). Cost-benefits accrue via reduced onboard compute resource (edge offload), fleet-scale FL, and certifiable safety zones (Table 5), - aligning with the 2026–2030 technology roadmap.

Table 5. Technology Roadmap (2026-2030)

Phase	Focus Use Cases (Sec. 4)	Key 6G Milestones
Near	DSZ, HRC	5G-Advanced pilots, Rel-20 AI trials
Mid	Remote driving, SR	Multi-site agents, NTN integration
Long	Endovascular, soft rehab	Semantic comms, world models

Figure 13 illustrates a simplified 6G-enabled business ecosystem for connected robotics. End-users lease or purchase robots; specialised robot operators provide Robots-as-a-Service (RaaS) and mission planning; a 6G-enabled MNO hub delivers connectivity, ISAC-based sensing, AI models, and compute offload; and integrators or hyperscalers supply hardware and cloud/edge resources. Short-term micro-contracts (service contracts) specify services such as €/robot-hour connectivity, sensing, or AI inference, allowing resources to be allocated and billed per mission or per fleet.

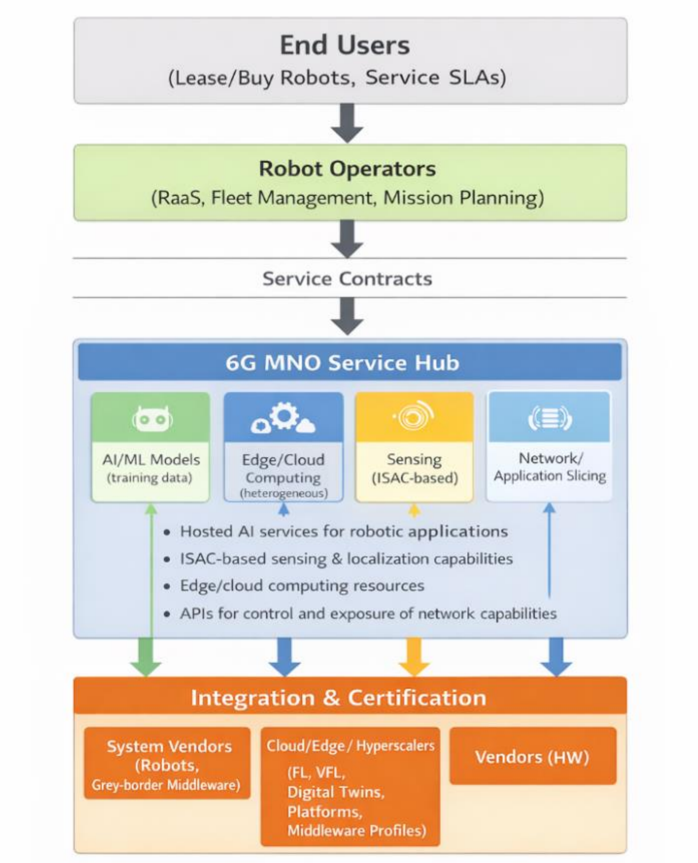

Figure 13. Business Model for 6G Robotics as a Service

The architecture diagram illustrates a comprehensive ecosystem for robotic services within a 6G framework. At the top, End Users interact with Robot Operators for leasing or purchasing robots, underpinned by service contracts. The 6G MNO Service Hub acts as a central node, integrating ISAC-based sensing, network slicing, and hosting AI agents for computational tasks. This hub facilitates data and model services for both edge and cloud computing. Additionally, the architecture includes elements for Integration & Certification, highlighting the roles of system vendors and cloud/hyperscaler platforms, underscoring the collaborative nature of robotics, hardware vendors, and middleware solutions in achieving a cohesive robotic ecosystem.

6. Conclusion, Roadmap, and Future Research Directions

The convergence of 6G and robotics is reshaping how sensing, communication, computation, and intelligence are organised across CPS. The whitepaper has proposed a unified architectural framework that aligns a four-plane 6G system (Robotic Vertical, Intelligent Service, Data Governance, Network Service) with layered robotic stacks (infrastructure, middleware, application; perception, cognition, action, self-learning). This alignment enables closed-loop behaviour in which robots continuously expose task and safety intents, while the network acts as a digital cognitive amplifier, supplying reliable connectivity, ISAC-based perception, distributed AI, and governed data services as composable capabilities. Across the detailed use cases—DSZ, human-recognition for HRC, cyber-physical remote driving, and endovascular remote robotics—the same pattern recurs: mission-critical KPIs (control-loop latency, availability, spatial accuracy, semantic efficiency, operator trust) require co-designed robotic-communication architectures rather than independent silos.

The key architectural contribution lies in decomposing 6G-empowering robotics into atomic functions and service handlers (e.g., human pose and intent sensing, environment modelling, DSZ computation, policy enforcement, orchestration and exposure) that can be instantiated flexibly across robots, edge, and cloud. This componentised view enables systematic mapping of functions to 6G capabilities—HRLLC, ISAC, semantic and goal-oriented communication, edge AI, FL, and Network-as-Code interfaces—while exposing clear interfaces to robotic middleware (ROS2, DDS/Zenoh, OPC UA, MQTT) and vertical applications. It also provides a common vocabulary for stakeholders: robotics vendors can specify required behaviours in terms of KPIs and atomic functions; operators and equipment vendors can implement matching slices, sensing services, and edge platforms; integrators and digital-solution providers can compose these into end-to-end blueprints; regulators and standardisation bodies can reference them in safety, interoperability, and certification frameworks. The cross-use-case KPI analysis further shows that a small, recurring set of metrics—control-loop latency and jitter, system uptime, spatial and semantic accuracy, and human-centric indicators—suffices to characterise performance requirements across industrial, medical, logistics, defence, and public-safety domains.

Looking ahead to 2026–2030+, the technology roadmap for 6G-enabled robotics can be divided into three overlapping phases. In the near term (2026–2027), the focus will be on maturing 5G-Advanced and early 6G trial platforms to support pilot deployments of DSZ, remote driving, and human-recognition services in controlled environments such as testbeds, lighthouse factories, hospital labs, and living labs. In this phase, the priority is to harden HRLLC and edge computing for robotics, integrate ROS-centric middleware with network exposure interfaces, and develop reference implementations of the four-plane architecture and its atomic functions. Quantitative KPI measurement and benchmarking across multiple sites will be essential to inform standardisation and business cases, including the first domain-specific profiles for tele-operation and XR-enhanced control.

In the mid-term (2028–2029), attention will shift to large-scale multi-site deployments, cross-domain interoperability, and increasing autonomy of in-network AI agents. Networks will progressively evolve into computing continua where AI-native management spans RAN, core, and edge, and where FL and agent-based orchestration are routinely used to update perception, control, and safety models across fleets and sites. DSZ-like capabilities will begin to be treated as reusable, certifiable services that can be ported across factories, logistics hubs, and hospitals; exposure frameworks such as NaC/CAPIF-like APIs will become more uniform, enabling vertical developers to control slices, ISAC, and edge AI through software abstractions rather than per-operator integrations. Early instances of NTN-assisted robotics and RIS-enhanced coverage for outdoor fleets and search-and-rescue robots are expected to appear in this timeframe.

In the longer term (2030 and beyond), 6G's native features—advanced ISAC, cell-free and ultra-dense RANs, NTN integration, and pervasive intelligent surfaces—will support robotics systems that treat the network as an integral extension of their bodies and minds. In this horizon, world-model-based control—where robots learn latent dynamics models to simulate future outcomes and evaluate actions proactively—will become a foundational capability, with 6G providing the continual sensory updates, edge-hosted predictive rollouts, and distributed learning substrate needed to sustain accurate, real-time internal world representations. Robots will increasingly offload not only perception and planning but also parts of their self-learning processes to network-resident agents operating over governed data spaces. Semantic and goal-oriented communication will become the default for multi-robot coordination and human-in-the-loop control, significantly reducing bandwidth demands while improving determinism and robustness. At the ecosystem level, the stakeholder relationships described earlier will mature into shared reference architectures and certification schemes, enabling plug-and-play interoperability between robots, networks, and AI services across vendors and verticals. Future research should therefore prioritise: formalising KPI-driven co-design methodologies; developing safety-coherent HRLLC and ISAC mechanisms; exploring agentic and FL frameworks tailored to robotics; designing semantic communication protocols aligned with robotic tasks; and establishing regulatory, ethical, and governance models that keep human safety, trust, and societal benefit at the centre of 6G-empowering robotics.

Acknowledgements & Endorsements

This whitepaper includes the outcome of one6G (6G empowering robotics) and euRobotics (Connected robotics Topic Group) discussions.

Developed by the TG Connected Robotics, this paper reflects the specialised knowledge of its contributors. It is intended as a contribution to the ongoing work within euRobotics and should be understood as expressing the views of the TG, not necessarily those of the organisation as a whole.

This whitepaper is endorsed by leadership members and participants of the IEEE SA 6G Empowering Robotics Working Group (IEEE P1955) (https://sagroups.ieee.org/1955/) and the IEEE Robotics and Automation Society Standards Committee (RAS SC). This endorsement solely represents the views of the IEEE P1955 Working Group and the IEEE RAS SC and does not necessarily reflect the position of either IEEE or the IEEE Standards Association.

The following people and entities participated in the development of this publication.

Editors & Leaders:

Mona Ghassemian, Javan Erfanian, Kaspar Althoefer

Technical Reviewers:

- Section 1: Ranga Rao Venkatesha Prasad (TUDelft)
- Section 2: George T. Karetsos (University of Thessaly)
- Section 3: Toktam Mahmoodi (KCL)
- Section 4: Jesús Fernández Lozano (UMA)
- Section 5: Ranga Rao Venkatesha Prasad (TUDelft)

Entities - Country - Contributor(s)

1. Atlas University (Turkey): Kaveh Ahmadi
2. Huawei (Germany, UK): Joseph Eichinger, Mona Ghassemian
3. ITI (Spain): Andrés Meseguer Valenzuela
4. Kontor 46 s.a.s. (Italy): Paolo Barattini
5. King's College London (KCL) (UK): Mohammad S. Bahaei, Thomas Booth
6. Mitsubishi Electric R&D Centre Europe (France): Arnaud Bouttier, Cristina Ciochina, Mohamad Mestoukirdi
7. Polytechnic Institute of Castelo Branco (Portugal): Paulo Goncalves

8. Queen Mary University of London (UK): Kaspar Althoefer
9. Technology Innovation Institute (TII) (UAE): Enrico Natalizio, Jennifer Simonjan
10. TurkCell (Turkey): Mehmet Basaran, Fatih Cogen, Yakup Emre Ozsahin
11. UC3M (Spain): Alberto Jardón Huete
12. University of Glasgow (UK): Lina Mohjazi, Olaoluwa Popoola
13. University of Malaga (UMA) (Spain): Jesús Fernández Lozano
14. University Novi Sad (UNS) (Serbia): Dejan Vukobratovic
15. University Padova (Italy): Stefano Ghidoni
16. University Politechnic Valencia (UPV) (Spain): Francisco Blanes Noguera, Raul Lozano
17. Uni Napier (UK): Berk Canberk
18. Veezhen (Canada): Javan Erfanian
19. VegaSystems (UK): Ali Hessami
20. Viavi Solutions (UK): Chris Murphy

Abbreviations

3GPP	3rd Generation Partnership Project
6G	Sixth generation of the mobile communications technology
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMR	Autonomous Mobile Robots
API	Application Programming Interface
AR	Augmented Reality
ARIMA	AutoRegressive Integrated Moving Average
B2B	Business-to-Business
BIM	Building Information Model
CRTG	Connected Robotics Topic Group
CPS	Cyber-Physical Systems
D2D	Device to Device
DDS	Data Distribution Service
DSZ	Dynamic Safety Zones
DT	Digital Twin
ENI	Experiential Networked Intelligence
FedProx	Federated Proximal
FL	Federated Learning
GNN	Graph Neural Network
HMI	Human-Machine Interface
HRI	Human Robot Interaction
HRLLC	Hyper Reliable and Low-Latency Communication
IEEE	Institute of Electrical and Electronics Engineers
ISAC	Integrated Sensing and Communication
KPI	Key Performance Indicator
LLM	Large Language Model
MEC	Multi-Access Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMTC	massive Machine Type Communication

MT	Mechanical Thrombectomy
NTN	Non-Terrestrial Networks
O-RAN	Open RAN
OSRA	Open-Source Robotics Alliance
P&A	Policy & Assurance
PDCP	Packet Data Convergence Protocol
QoS	Quality of Service
RaaS	Robotics-as-a-Service
RAN	Radio Access Network
RF	Radio Frequency
RIC	RAN Intelligent Controller
ROS	Robot Operating System
SAR	Search and Rescue Robotics
SDO	Standardisation Development Organisation
SLAM	Simultaneous Localisation and Mapping
SMO	Service Management and 0rchestration
UAM	Urban Air Mobility
UAV	Uncrewed Aerial Vehicles
UGV	Uncrewed Ground Vehicles
URLLC	Ultra-reliable and low-latency communication
VFL	Vertical Federated Learning
WG	Working Group
WLAN	Wireless Local Area Network
WT	Work Task
XR	Extended Reality

References

[1] euRobotics Connected Robotics Topic Group Coordinators, "Connected Robotics: Evolution and Significance for Europe," euRobotics, Oct. 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://eu-robotics.net/wp-content/uploads/Connected-Robotics_-postition-paper-16-10-2025.pdf

[2] K. Althoefer, M. Ghassemian, J. Erfanian, and et. al., "6G Empowering Future Robotics: Mapping Requirements and Advancements for the IMT-2030 Framework," one6G Association, White Paper, Mar. 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://one6g.org/download/5439/

[3] Nokia Bell Labs, "Network as a sensor," 6G Technologies (Nokia Bell Labs). Accessed: Feb. 07, 2026. [Online]. Available: https://www.nokia.com/bell-labs/research/6g-networks/6g-technologies/network-as-a-sensor/

[4] G. M. Gutierrez, J. A. Rincon, and V. Julian, "Federated Learning for Collaborative Robotics: A ROS 2-Based Approach," Electronics, vol. 14, no. 7, p. 1323, 2025, doi: 10.3390/electronics14071323.

[5] H. Xu, Z. Fan, and X. Liu, "Application of personalized federated learning methods to environmental sound classification: A comparative study," Eng. Appl. Artif. Intell., vol. 135, p. 108760, Sep. 2024, doi: 10.1016/j.engappai.2024.108760.

[6] A. Akhtarshenas et al., "Federated learning: A cutting-edge survey of the latest advancements and applications," Comput Commun, vol. 228, no. C, Dec. 2024, doi: 10.1016/j.comcom.2024.107964.

[7] X. Li, W. Shi, H. Zhang, C. Peng, S. Wu, and W. Tong, "The Agentic-AI Core: An AI-Empowered, Mission-Oriented Core Network for Next-Generation Mobile Telecommunications," Engineering, vol. 56, pp. 104–119, Jan. 2026, doi: 10.1016/j.eng.2025.06.027.

[8] Y. Xiao, G. Shi, and P. Zhang, "Towards Agentic AI Networking in 6G: A Generative Foundation Model-as-Agent Approach." 2025. [Online]. Available: https://arxiv.org/abs/2503.15764

[9] M. Elkael et al., "AgentRAN: An Agentic AI Architecture for Autonomous Control of Open 6G Networks." 2026. [Online]. Available: https://arxiv.org/abs/2508.17778

[10] M. Abualhayja'a, M. Alquraan, K. A. Alblaihed, A. Kaushik, D. Nguyen, and L. Mohjazi, "Federated Learning-Empowered RIS-Assisted UAV Networks for IoT Data Collection and Optimisation," in 2025 IEEE 36th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2025, pp. 1–6. doi: 10.1109/PIMRC62392.2025.11274723.

[11] M. Al-Quraan et al., "Edge-Native Intelligence for 6G Communications Driven by Federated Learning: A Survey of Trends and Challenges," IEEE Trans. Emerg. Top. Comput. Intell., vol. 7, no. 3, pp. 957–979, Jun. 2023, doi: 10.1109/TETCI.2023.3251404.

[12] P. Kairouz and H. B. McMahan, "Advances and Open Problems in Federated Learning," Found. Trends Mach. Learn., vol. 14, no. 1–2, pp. 1–210, Jun. 2021, doi: 10.1561/2200000083.

[13] Y. Liu et al., "Vertical Federated Learning: Concepts, Advances, and Challenges," IEEE Trans. Knowl. Data Eng., vol. 36, no. 7, pp. 3615–3634, Jul. 2024, doi: 10.1109/TKDE.2024.3352628.

[14] P. Valdeira, S. Wang, and Y. Chi, "Vertical Federated Learning with Missing Features During Training and Inference," 2024, arXiv. doi: 10.48550/ARXIV.2410.22564.

[15] M. Mestoukirdi and M. Khanfouci, "Reliable Vertical Federated Learning in 5G Core Network Architecture," 2025, arXiv. doi: 10.48550/ARXIV.2505.15244.

[16] S. Zheng, Z. Huang, and J. T. Kwok, "Communication-Efficient Distributed Blockwise Momentum SGD with Error-Feedback," 2019, arXiv. doi: 10.48550/ARXIV.1905.10936.

[17] X. Fang et al., "Sensing-Communication-Computing-Control Closed-Loop Optimization for 6G Digital Twin-Empowered Robotic Systems," IEEE J. Sel. Areas Commun., vol. 43, no. 10, pp. 3330–3346, Oct. 2025, doi: 10.1109/JSAC.2025.3574601.

[18] R. Botez, D. Zinca, and V. Dobrota, "Redefining 6G Network Slicing: AI-Driven Solutions for Future Use Cases," Electronics, vol. 14, no. 2, p. 368, Jan. 2025, doi: 10.3390/electronics14020368.

[19] M. U. F. Qaisar et al., "The Role of ISAC in 6G Networks: Enabling Next-Generation Wireless Systems," 2025, arXiv. doi: 10.48550/ARXIV.2510.04413.

[20] S. K. Das, R. Mudi, and Md. S. Rahman, "Federated Reinforcement Learning for 6G Wireless Networks: Fundamentals, Challenges and Future Research Trends," Oct. 31, 2023, Preprints. doi: 10.36227/techrxiv.20069051.v3.

[21] H. Lai et al., "World Model-Based Perception for Visual Legged Locomotion," in 2025 IEEE International Conference on Robotics and Automation (ICRA), Atlanta, GA, USA: IEEE, May 2025, pp. 11531–11537. doi: 10.1109/ICRA55743.2025.11128762.

[22] M. Palena, T. Cerquitelli, and C. F. Chiasserini, "Edge-device collaborative computing for multi-view classification," Comput. Netw., vol. 254, p. 110823, Dec. 2024, doi: 10.1016/j.comnet.2024.110823.

[23] C. Cai, X. Yuan, and Y.-J. A. Zhang, "Task-Oriented Communication for Multi-Device Edge Inference: A Maximal Coding Rate Reduction Approach," in ICC 2024 - IEEE International Conference on Communications, Denver, CO, USA: IEEE, Jun. 2024, pp. 5628–5633. doi: 10.1109/ICC51166.2024.10622706.

[24] S. Schwarzmann et al., "Native Support of AI Applications in 6G Mobile Networks Via an Intelligent User Plane," in 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates: IEEE, Apr. 2024, pp. 1–6. doi: 10.1109/WCNC57260.2024.10570691.

[25] G. M. Almeida et al., "RIC-O: Efficient Placement of a Disaggregated and Distributed RAN Intelligent Controller With Dynamic Clustering of Radio Nodes," IEEE J. Sel. Areas Commun., vol. 42, no. 2, pp. 446–459, Feb. 2024, doi: 10.1109/JSAC.2023.3336159.

[26] L. P. Chovet, G. M. Garcia, A. Bera, A. Richard, K. Yoshida, and M. A. Olivares-Mendez, "Performance Comparison of ROS2 Middlewares for Multi-robot Mesh Networks in Planetary Exploration," J. Intell. Robot. Syst., vol. 111, no. 1, p. 18, Jan. 2025, doi: 10.1007/s10846-024-02211-2.

[27] J. Bravo-Arrabal, R. Vázquez-Martín, J. J. Fernández-Lozano, and A. García-Cerezo, "Strengthening Multi-Robot Systems for SAR: Co-Designing Robotics and Communication Towards 6G," 2025, arXiv. doi: 10.48550/ARXIV.2504.01940.

[28] D. Portugal, R. P. Rocha, and J. P. Castilho, "Inquiring the robot operating system community on the state of adoption of the ROS 2 robotics middleware," Int. J. Intell. Robot. Appl., vol. 9, no. 2, pp. 454–479, Jun. 2025, doi: 10.1007/s41315-024-00393-4.

[29] M. L. Gambo, A. Danasabe, B. Almadani, F. Aliyu, A. Aliyu, and E. Al-Nahari, "A Systematic Literature Review of DDS Middleware in Robotic Systems," Robotics, vol. 14, no. 5, p. 63, May 2025, doi: 10.3390/robotics14050063.

[30] International Organization for Standardization, "Robotics — Safety requirements — Part 1: Industrial robots," no. ISO 10218-1:2025, Feb. 2025, Accessed: Feb. 07, 2026. [Online]. Available: https://www.iso.org/standard/73933.html

[31] Z. Pang, "Functional Safety Communication over Deterministic Wireless Networks," 29th IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA 2024, Sep. 2024, Accessed: Feb. 07, 2026. [Online]. Available: https://www.kth.se/files/view/zhibo/66fb02d9eabcdb9bf191c9f5/etfa2024-if-functional-saf.pdf

[32] ISA Security Compliance Institute, "Industrial Wireless Enabling Safety," ISA Security Compliance Institute, Technical briefing, Sep. 2024.

[33] P. Mishra, S. Kar, and K.-C. Wang, "Enhanced reliability in mobility scenarios using multi-connectivity with packet duplication for next-generation networks," EURASIP J. Wirel. Commun. Netw., vol. 2025, no. 1, p. 43, Jun. 2025, doi: 10.1186/s13638-025-02463-y.

[34] 6G-IA Vision Working Group, "European Vision for the 6G Network Ecosystem," 6G Smart Networks and Services Industry Association (6G-IA), White paper, Nov. 2024. doi: 10.5281/zenodo.13708424.

[35] Z. Sasan and S. Khorsandi, "Balancing resource utilization and slice dissatisfaction through dynamic soft slicing for 6G wireless networks," Sci. Rep., vol. 15, no. 1, p. 22987, Jul. 2025, doi: 10.1038/s41598-025-06521-9.

[36] X. Zhong et al., "Joint Source-Channel Coding System for 6G Communication: Design, Prototype and Future Directions," IEEE Access, vol. 12, pp. 17708–17724, 2024, doi: 10.1109/ACCESS.2024.3360003.

[37] P. Li et al., "Task-aware Distributed Source Coding under Dynamic Bandwidth," presented at the Advances in Neural Information Processing Systems, A. Oh, T. Naumann, A. Globerson, K. Saenko, M. Hardt, and S. Levine, Eds., Curran Associates, Inc., Dec. 2023, pp. 406–417. doi: 10.5555/3666122.3666142.

[38] C. S. Morejón García et al., "New Radio Sidelink with Beam Selection for Reliable Communication in High-Density Dynamic Swarms," in 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates: IEEE, Apr. 2024, pp. 1–6. doi: 10.1109/WCNC57260.2024.10571035.

[39] E. Casmin and E. Ever, "An analytical approach for modelling unmanned aerial vehicles and base station interaction for disaster recovery scenarios," Wirel. Netw., vol. 30, no. 5, pp. 3299–3319, Jul. 2024, doi: 10.1007/s11276-024-03734-0.

[40] H. Chen et al., "Human-in-the-Loop Robot Learning for Smart Manufacturing: A Human-Centric Perspective," IEEE Trans. Autom. Sci. Eng., vol. 22, pp. 11062–11086, 2025, doi: 10.1109/TASE.2025.3528051.

[41] M. B. Alatise and G. P. Hancke, "A Review on Challenges of Autonomous Mobile Robot and Sensor Fusion Methods," IEEE Access, vol. 8, pp. 39830–39846, 2020, doi: 10.1109/ACCESS.2020.2975643.

[42] D. T. Le, S. Sutjipto, D. D. K. Nguyen, and G. Paul, "Design, Integration, and Field Testing of a Digital Twin-Based Teleoperated Rock Scaling Robot," IEEE Trans. Field Robot., vol. 2, pp. 188–207, 2025, doi: 10.1109/TFR.2025.3547807.

[43] H. He, J. Gray, A. Cangelosi, Q. Meng, T. M. McGinnity, and J. Mehnen, “The Challenges and Opportunities of Human-Centered AI for Trustworthy Robots and Autonomous Systems,” IEEE Trans. Cogn. Dev. Syst., vol. 14, no. 4, pp. 1398–1412, Dec. 2022, doi: 10.1109/TCDS.2021.3132282.

[44] S.-H. Lee et al., “Robotic Manipulation System Design and Control for Non-Contact Remote Diagnosis in Otolaryngology: Digital Twin Approach,” IEEE Access, vol. 11, pp. 28735–28750, 2023, doi: 10.1109/ACCESS.2023.3259539.

[45] H. Chen et al., “SymBridge: A Human-in-the-Loop Cyber-Physical Interactive System for Adaptive Human-Robot Symbiosis,” in Proceedings of the SIGGRAPH Asia 2025 Conference Papers, Hong Kong Hong Kong: ACM, Dec. 2025, pp. 1–12. doi: 10.1145/3757377.3763915.

[46] Q. Zeng, Z. Wang, Y. Zhou, H. Wu, L. Yang, and K. Huang, “Knowledge-Based Ultra-Low-Latency Semantic Communications for Robotic Edge Intelligence,” IEEE Trans. Commun., vol. 73, no. 7, pp. 4925–4940, Jul. 2025, doi: 10.1109/TCOMM.2024.3511931.

[47] M. R. Shikh-Bahaei, “A 6G ecosystem for the Verticals: Considerations for e-Health and Robotics,” 3GPP (Technologies). Accessed: Feb. 07, 2026. [Online]. Available: https://www.3gpp.org/technologies/one6g-ecosystem

[48] G. Wang et al., “Robots Empowered by AI Foundation Models and the Opportunities for 6G,” HuaweiTech (Future Technologies). Accessed: Feb. 07, 2026. [Online]. Available: https://www.huawei.com/en/huaweitech/future-technologies/robots-empowered-ai-foundation-models-6g

[49] M. Ghassemian et al., “6G Empowering Future Robotics: A Vision for Next-Generation Autonomous Systems,” 2026, arXiv. doi: 10.48550/ARXIV.2602.12246.

[50] one6G Association, “one6G white paper: 6G technology overview,” one6G Association, White paper, Sep. 2025. Accessed: Feb. 08, 2026. [Online]. Available: https://one6g.org/download/6324/

[51] L. Mohjazi, B. Selim, M. Tatipamula, and M. A. Imran, “The Journey Toward 6G: A Digital and Societal Revolution in the Making,” IEEE Internet Things Mag., vol. 7, no. 2, pp. 119–128, Mar. 2024, doi: 10.1109/IOTM.001.2300119.

[52] M. Crespo-Aguado, R. Lozano, F. Hernandez-Gobertti, N. Molner, and D. Gomez-Barquero, “Flexible Hyper-Distributed IoT–Edge–Cloud Platform for Real-Time Digital Twin Applications on 6G-Intended Testbeds for Logistics and Industry,” Future Internet, vol. 16, no. 11, p. 431, Nov. 2024, doi: 10.3390/fi16110431.

[53] R. Lozano et al., “Digital Twin-Based 6G Testbed for Immersive Outdoor Robotics: Capacity and Latency Analysis of the Interaction with Real and Virtual Objects,” in 2025 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Poznan, Poland: IEEE, Jun. 2025, pp. 163–168. doi: 10.1109/EuCNC/6GSummit63408.2025.11036873.

[54] Mohammad Shikh-Bahaei et al., “6G & Robotics: Identifying Use Cases and Potential Service Requirements - Methodology and Examples,” one6G Association, White paper, Jun. 2024. Accessed: Feb. 08, 2026. [Online]. Available: https://eu-robotics.net/wp-content/uploads/one6G_WhitePaper-Robotics_Jun24_v1.2-1.pdf

[55] J. Bravo-Arrabal, M. Toscano-Moreno, J. J. Fernandez-Lozano, A. Mandow, J. A. Gomez-Ruiz, and A. García-Cerezo, “The Internet of Cooperative Agents Architecture (X-IoCA) for Robots, Hybrid Sensor Networks, and MEC Centers in Complex Environments: A Search and Rescue Case Study,” Sensors, vol. 21, no. 23, p. 7843, Nov. 2021, doi: 10.3390/s21237843.

[56] M. W. Nawaz et al., “6G edge-networks and multi-UAV knowledge fusion for urban autonomous vehicles,” Phys. Commun., vol. 67, p. 102479, Dec. 2024, doi: 10.1016/j.phycom.2024.102479.

[57] M. W. Nawaz, O. Popoola, M. A. Imran, and Q. H. Abbasi, “K-DUMBs IoRT: Knowledge Driven Unified Model Block Sharing in the Internet of Robotic Things,” in 2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring), Florence, Italy: IEEE, Jun. 2023, pp. 1–6. doi: 10.1109/VTC2023-Spring57618.2023.10200507.

[58] M. W. Nawaz, M. A. Imran, and O. Popoola, “Temporal Hierarchical Clustering for Knowledge Aggregation in Connected Vehicular Networks with Federated Multi-Task Learning,” in 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates: IEEE, Apr. 2024, pp. 1–6. doi: 10.1109/WCNC57260.2024.10570723.

[59] M. W. Nawaz, M. M. Alam, R. Swash, Q. H. Abbasi, M. A. Imran, and O. Popoola, “Enhancing intelligence in multi-agent systems with edge-assisted causal knowledge aggregation,” Npj Wirel. Technol., vol. 2, no. 1, p. 3, Jan. 2026, doi: 10.1038/s44459-025-00006-x.

[60] M. W. Nawaz et al., “Trustworthy Autonomy in 6G Robotics: Advances and Perspectives on Edge Intelligence and Federated Self-Certification,” Mar. 28, 2025, Preprints. doi: 10.36227/techrxiv.174318141.12755600/v1.

[61] European Commission, “The European Strategy for Housing Construction: a more competitive and productive construction industry,” European Commission, Strasbourg, France, Dec. 2025. Accessed: Feb. 18, 2026. [Online]. Available: https://single-market-economy.ec.europa.eu/document/download/8e22818b-71f7-4e68-921c-2c65d458c6c6_en

[62] European Commission, "Questions and Answers on the European Strategy for Housing Construction," European Commission, Questions and Answers, Dec. 2025. Accessed: Feb. 18, 2026. [Online]. Available: https://single-market-economy.ec.europa.eu/document/download/d97ad6a4-c962-44e5-883e-1ea10c51aab8_en?filename=QA+European+Strategy+for+Housing+Construction.pdf

[63] A. Boldini, M. Civitella, and M. Porfiri, "Stigmergy: From Mathematical Modelling to Control," R. Soc. Open Sci., vol. 11, no. 9, p. 240845, Sep. 2024, doi: 10.1098/rsos.240845.

[64] Healthcare Quality Improvement Partnership (HQIP), "National Quality Improvement Programmes," HQIP. Accessed: Feb. 07, 2026. [Online]. Available: https://www.hqip.org.uk/national-programmes/

[65] A. Patel, V. Berdunov, D. King, Z. Quayyum, R. Wittenberg, and M. Knapp, "Current, Future and Avoidable Costs of Stroke in the UK: Technical report," Stroke Association, Feb. 2020. Accessed: Feb. 07, 2026. [Online]. Available: https://www.stroke.org.uk/sites/default/files/economic_impact_of_stroke_report_final_feb_2020_0.pdf

[66] W. Crinnion et al., "Robotics in Neurointerventional Surgery: A Systematic Review of the Literature," J. NeuroInterventional Surg., vol. 14, no. 6, p. 539, Jun. 2022, doi: 10.1136/neurintsurg-2021-018096.

[67] B. Jackson et al., "Comparative Verification of Control Methodology for Robotic Interventional Neuroradiology Procedures," Int. J. Comput. Assist. Radiol. Surg., vol. 18, no. 11, pp. 1977–1986, Jul. 2023, doi: 10.1007/s11548-023-02991-2.

[68] one6G Association, "6G & eHealth: Use Cases & Potential Service Requirements," one6G Association, White paper, Sep. 2024. Accessed: Feb. 18, 2026. [Online]. Available: https://one6g.org/download/5016/

[69] L. Zhou, D. Wu, X. Wei, and J. Chen, "Cross-Modal Stream Scheduling for eHealth," IEEE J. Sel. Areas Commun., vol. 39, no. 2, pp. 426–437, Feb. 2021, doi: 10.1109/JSAC.2020.3021543.

[70] D. Wu and L. Zhou, "Cross-Modal Stream Transmission: Architecture, Strategy, and Technology," IEEE Wirel. Commun., vol. 31, no. 1, pp. 134–140, Feb. 2024, doi: 10.1109/MWC.013.2200293.

[71] X. Wei and L. Zhou, "AI-Enabled Cross-Modal Communications," IEEE Wirel. Commun., vol. 28, no. 4, pp. 182–189, Aug. 2021, doi: 10.1109/MWC.001.2000448.

[72] Y. Gao, S. Ni, D. Wu, and L. Zhou, "Edge-Based Cross-Modal Communications for Remote Healthcare," IEEE J. Sel. Areas Commun., vol. 40, no. 11, pp. 3139–3151, Nov. 2022, doi: 10.1109/JSAC.2022.3211539.

[73] J. Dai, L. Li, Z. Yang, H. Chen, and M. Shikh-Bahaei, "Sum Rate Maximization for Probalistic Semantic Communication via Compression Ratio Optimization," IEEE Commun. Lett., vol. 28, no. 12, pp. 2829–2833, Dec. 2024, doi: 10.1109/LCOMM.2024.3471610.

[74] J. Mehrholz, M. Pohl, T. Platz, J. Kugler, and B. Elsner, "Electromechanical and Robot-Assisted Arm Training for Improving Activities of Daily Living, Arm Function, and Arm Muscle Strength after Stroke," Cochrane Database Syst. Rev., vol. 2018, no. 9, Sep. 2018, doi: 10.1002/14651858.CD006876.pub5.

[75] V. Caso and B. Norrving, "Action Plan for Stroke in Europe 2018-2030," European Stroke Organisation. Accessed: Feb. 07, 2026. [Online]. Available: https://eso-stroke.org/action-plan-for-stroke-in-europe-2018-2030/

[76] K. Boardsworth et al., "Upper Limb Robotic Rehabilitation Following Stroke: A Systematic Review and Meta-analysis Investigating Efficacy and the Influence of Device Features and Program Parameters," J. NeuroEngineering Rehabil., vol. 22, no. 1, p. 164, Jul. 2025, doi: 10.1186/s12984-025-01662-4.

[77] Board on Mathematical Sciences and Analytics et al., Opportunities and Challenges for Digital Twins in Biomedical Research: Proceedings of a Workshop-in Brief. Washington, D.C.: National Academies Press, 2023, p. 26922. doi: 10.17226/26922.

[78] S. Marcos-Antón, R. Cano-de-la-Cuerda, I. Aranda-Reneo, A. Jardón-Huete, E. D. Oña-Simbaña, and J. Oliva-Moreno, "Cost-effectiveness Analysis of the MYO Armband® Device in Combination with Specifically Designed Video Games for Upper Limb Rehabilitation in People with Multiple Sclerosis," J. NeuroEngineering Rehabil., vol. 23, no. 1, p. 52, Nov. 2025, doi: 10.1186/s12984-025-01801-x.

[79] C. Hegde, J. Su, J. M. R. Tan, K. He, X. Chen, and S. Magdassi, "Sensing in Soft Robotics," ACS Nano, vol. 17, no. 16, pp. 15277–15307, Aug. 2023, doi: 10.1021/acsnano.3c04089.

[80] C. Suulker, A. Greenway, S. Skach, I. Farkhatdinov, S. Charles Miller, and K. Althoefer, "Let Me Give You a Hand: Enhancing Human Grasp Force With a Soft Robotic Assistive Glove," IEEE Robot. Autom. Lett., vol. 9, no. 9, pp. 7811–7818, Sep. 2024, doi: 10.1109/LRA.2024.3433202.

[81] M. Malpani and P. Jirvankar, "A Comprehensive Review Focused on the Whole Systems of the Soft Robotics, its Design Strategies and Outlook on the Future Considerations for the Soft Robots," Int. J. Pharm. Investig., vol. 15, no. 3, pp. 823–836, Apr. 2025, doi: 10.5530/ijpi.20250239.

[82] J. Li, X. Liu, H. Deng, T. Wang, G. Lu, and J. Wang, "Reconstruction of Colored Soft Deformable Objects Based on Self-Generated Template," Comput.-Aided Des., vol. 143, p. 103124, Feb. 2022, doi: 10.1016/j.cad.2021.103124.

[83] M. Yip et al., "Artificial Intelligence Meets Medical Robotics," Science, vol. 381, no. 6654, pp. 141–146, Jul. 2023, doi: 10.1126/science.adj3312.

[84] Evasive Robotics, "Multi-Robotic Technology," Accessed: Feb. 07, 2026. [Online]. Available: https://evasive-robotics.com/

[85] Ubiquity Robotics, "Ubiquity Robotics | Accelerate Your Robot Application Today." Accessed: Feb. 07, 2026. [Online]. Available: https://www.ubiquityrobotics.com/

[86] Olive Robotics, "Home - olive® ROBOTICS." Accessed: Feb. 07, 2026. [Online]. Available: https://olive-robotics.com/

[87] LionsBot, "Our Autonomous Cleaning Robots - The Technology Behind the Magic." Accessed: Feb. 07, 2026. [Online]. Available: https://www.lionsbot.com/technology/

[88] International Telecommunication Union, "Framework and Overall Objectives of the Future Development of IMT for 2030 and Beyond," no. Recommendation ITU-R M.2160-0, Nov. 2023, Accessed: Feb. 07, 2026. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2160-0-202311-I!!PDF-E.pdf

[89] K. Armstrong and S. Olson, "Understanding Sterile Field Challenges with Robotic-Assisted Surgery," Asensus Surgical US, Inc., Durham, NC, USA, White paper, Sep. 2024. Accessed: Jan. 09, 2026. [Online]. Available: https://www.asensus.com/documents/understanding-sterile-field-challenges-robotic-assisted-surgery

[90] 3rd Generation Partnership Project (3GPP), "Study on 6G Use Cases and Service Requirements; Stage 1 (Release 20)," 3GPP, Oct. 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/22_series/22.870/22870-041.zip

[91] C. Toche and D. Boswarthick, "ETSI Technology Radar," ETSI, Sophia Antipolis CEDEX, France, ETSI White Paper No. 61, Dec. 2023. Accessed: Feb. 07, 2026. [Online]. Available: https://www.etsi.org/images/files/ETSIWhitePapers/ETSI-WP-61-ETSI-Technology-Radar.pdf

[92] Open Source Robotics Alliance, "The OSRA explained: What is the Open Source Robotics Alliance and how does it work?," Open Source Robotics Alliance, Explainer, Mar. 2024. Accessed: Feb. 07, 2026. [Online]. Available: https://osralliance.org/wp-content/uploads/2024/03/OSRA-explainer.pdf

[93] Accenture, "Technology Vision 2025: AI: A Declaration of Autonomy," Accenture, 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://www.accenture.com/content/dam/accenture/final/accenture-com/document-3/Accenture-Tech-Vision-2025.pdf

[94] Inc. VMware, "Orchestrate, Automate, and Assure O-RAN with SMO: Saving Energy in the RAN, Optimizing Services with AI/ML, Deploying CNFs, and Other SMO Use Cases," VMware, Inc., Solution brief, Jul. 2023. Accessed: Feb. 07, 2026. [Online]. Available: https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/docs/vmw-telco-smo-use-cases-overview.pdf

[95] G. Targia, "5G at the Core of NATO's Digital Transformation," Forbes (Nokia Industry 4.0 BrandVoice). Accessed: Feb. 07, 2026. [Online]. Available: https://www.forbes.com/sites/nokia-industry-40/2025/10/07/5g-at-the-core-of-natos-digital-transformation/

[96] Vodafone, "Vodafone Provides 5G to World's Largest rRobotics Exercise," Vodafone Newsroom (Technology). Accessed: Feb. 07, 2026. [Online]. Available: https://www.vodafone.com/news/newsroom/technology/vodafone-provides-5g-world-largest-robotics-exercise

[97] NATO Allied Command Transformation (ACT), "NATO to Conduct 5G Experimentation in Latvia," NATO ACT (Articles). Accessed: Feb. 07, 2026. [Online]. Available: https://www.act.nato.int/article/nato-5g-experiment-latvia/

[98] J. Pao, "ESA Tests Teleoperated Robots for Deep Space Communication Delays," TechJournal.uk. Accessed: Feb. 07, 2026. [Online]. Available: https://www.techjournal.uk/p/esa-tests-teleoperated-robots-for

[99] European Space Agency, "Commercial Applications of Space-Enabled Robotics," ESA Business Applications. Accessed: Feb. 07, 2026. [Online]. Available: https://business.esa.int/funding/call-for-proposals-non-competitive/commercial-applications-space-enabled-robotics

[100] L. Mitchell, "NASA Tests 5G-Based Aviation Network to Boost Air Taxi Connectivity," NASA. Accessed: Feb. 07, 2026. [Online]. Available: https://www.nasa.gov/centers-and-facilities/armstrong/nasa-tests-5g-based-aviation-network-to-boost-air-taxi-connectivity

[101] B. Edwards, R. Wagner, M. Zemba, and W. Millard, "NASA's Interest in 3GPP Mobile Telecommunications Protocols for Near Earth Space and the Lunar Surface," presented at the 73rd International Astronautical Conference (IAC 2022), Paris, France: NASA Technical Reports Server (NTRS), Sep. 2022. Accessed: Feb. 07, 2026. [Online]. Available: https://ntrs.nasa.gov/citations/20220012346

[102] ePlaneAI, "NASA Tests 5G Network to Enhance Air Taxi Connectivity," ePlaneAI News. Accessed: Feb. 07, 2026. [Online]. Available: https://www.eplaneai.com/es/news/nasa-tests-5g-network-to-enhance-air-taxi-connectivity

[103] European Space Agency, "Space-enabled 5G to help reach remote and dangerous places," European Space Agency. Accessed: Feb. 07, 2026. [Online]. Available: https://www.esa.int/Space_in_Member_States/United_Kingdom/Space-enabled_5G_to_help_reach_remote_and_dangerous_places

[104] K. Alam et al., "A Comprehensive Tutorial and Survey of O-RAN: Exploring Slicing-Aware Architecture, Deployment Options, Use Cases, and Challenges," IEEE Commun. Surv. Tutor., vol. 28, pp. 1637–1678, 2026, doi: 10.1109/COMST.2025.3598406.

[105] S. Kerboeuf et al., "Final end-to-end system evaluation results of the overall 6G system design," Hexa-X-II project (SNS JU), Jun. 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://hexa-x-ii.eu/wp-content/uploads/2025/06/D2.6-final.pdf

[106] D. Chen Larsson, A. Grövlen, and O. Liberg, "New three-dimensional requirements set the tone for 6G as standardization gets going," The Ericsson Blog. Accessed: Feb. 07, 2026. [Online]. Available: https://www.ericsson.com/en/blog/2024/12/new-three-dimensional-requirements-set-the-tone-for-6g-as-standardization-gets-going

[107] Nokia, "6G System Architecture: Where Innovation Meets Evolution for a More Austainable and Connected World," Nokia 6G. Accessed: Feb. 07, 2026. [Online]. Available: https://www.nokia.com/6g/6g-system-architecture-where-innovation-meets-evolution-for-a-more-sustainable-and-connected-world/

[108] "WT3.1 - AI for 6G Architecture," 3GPP, TDoc (SA WG2 meeting document), Aug. 2025. Accessed: Feb. 07, 2026. [Online]. Available: https://www.3gpp.org/FTP/tsg_sa/WG2_Arch/TSGS2_170_Goteborg_2025-08/INBOX/DRAFTS/FS_6G_ARC/6G_WTs/WT%233_AI/S2-2507223r1%20-%20WT3.1%20-%20AI%20for%206G%20architecture.docx

[109] P. Jain, "3GPP SA 6G Planning and Progress Update," 3GPP, Presentation, Sep. 2024. Accessed: Feb. 07, 2026. [Online]. Available: https://www.3gpp.org/ftp/Information/presentations/Presentations_2024/03_2024_09_17_Puneet_v03.pdf

[110] ETSI, "Integrated Sensing And Communications (ISAC); Use Cases and Deployment Scenarios," ETSI, Sophia Antipolis Cedex, France, Group Report, Mar. 2025. Accessed: Feb. 13, 2026. [Online]. Available: https://www.etsi.org/deliver/etsi_gr/isc/001_099/001/01.01.01_60/gr_isc001v010101p.pdf

[111] International Organization for Standardization, "Guidance on Social Responsibility," no. ISO 26000:2010, Nov. 2010, Accessed: Feb. 07, 2026. [Online]. Available: https://www.iso.org/standard/42546.html

[112] International Organization for Standardization, International Electrotechnical Commission, and Institute of Electrical and Electronics Engineers, "Systems and Software Engineering — Life Cycle Management — Part 7000: Standard model process for addressing ethical concerns during system design," no. ISO/IEC/IEEE 24748-7000:2022, Nov. 2022, Accessed: Feb. 07, 2026. [Online]. Available: https://cdn.standards.iteh.ai/samples/84893/fa41581591e741259f69516e0adfbb34/ISO-IEC-IEEE-24748-7000-2022.pdf

[113] British Standards Institution, "Robots and Robotic Devices. Ethical Design and Application of Robots and Robotic Systems. Guide," no. BS 8611:2023, Mar. 2023, Accessed: Feb. 07, 2026. [Online]. Available: https://knowledge.bsigroup.com/products/robots-and-robotic-devices-ethical-design-and-application-of-robots-and-robotic-systems-guide

[114] IEEE Standards Association, "IEEE CertifAIEd™ - The Mark of AI ethics," IEEE Conformity Assessment Program (ICAP). Accessed: Feb. 07, 2026. [Online]. Available: https://standards.ieee.org/products-programs/icap/ieee-certifaied/

[115] International Organization for Standardization and International Electrotechnical Commission, "Information technology — Artificial intelligence — Management system," no. ISO/IEC 42001:2023, Dec. 2023, Accessed: Feb. 07, 2026. [Online]. Available: https://www.iso.org/standard/42001

[116] IEEE TechEthics, "Ethics Frameworks," IEEE TechEthics. Accessed: Feb. 07, 2026. [Online]. Available: https://techethics.ieee.org/ethics-frameworks/

[117] M. Menting, "Conceptualizing Security in a 6G World," ABI Research, White paper. Accessed: Feb. 07, 2026. [Online]. Available: https://go.abiresearch.com/hubfs/Marketing/Whitepapers/Conceptualizing%20Security%20in%20a%206G%20World/Conceptualizing%20Security%20in%20a%206G%20World.pdf

[118] D. Soldani, "6G starts to take shape with AI, open vRAN integration and ever increased security," Rakuten Symphony Blog. Accessed: Feb. 07, 2026. [Online]. Available: https://symphony.rakuten.com/blog/6g-starts-to-take-shape

[119] J. Shi, Y. Yu, Q. Yu, H. Li, and L. Wang, "Toward Data Security in 6G Networks: A Public-Key Searchable Encryption Approach," IEEE Netw., vol. 36, no. 4, pp. 166–173, Jul. 2022, doi: 10.1109/MNET.006.2100714.

[120] A. Iqubbal and K. Jugiani, "An Ethical Framework for 6G," CUTS International, Jaipur, India, Technical report, Dec. 2024. Accessed: Feb. 07, 2026. [Online]. Available: https://cuts-ccier.org/pdf/An-ethical-framework-for-6G.pdf

[121] C. Lee, "Standards Build Trust: How the International Telecommunication Union Supports Inclusive Sustainable Development," UN Chronicle. Accessed: Feb. 07, 2026. [Online]. Available: https://www.un.org/en/un-chronicle/standards-build-trust-how-international-telecommunication-union-supports-inclusive

[122] M. Ylianttila et al., "6G White paper: Research challenges for Trust, Security and Privacy," 2020, arXiv. doi: 10.48550/ARXIV.2004.11665.

[123] IEEE P1955, Standard for 6G Empowering Robotics, IEEE Standards Association, PAR approved 6 June 2024.

[124] IEEE Std 1918.1™-2024, IEEE Approved Draft Standard for Tactile Internet, IEEE, 2024.

one6G

Taking communications to the next level

Download a copy:

WHITE PAPER

March 2026

eu ROBOTICS

eu ROBOTICS TOPIC GROUPS

one6g.org