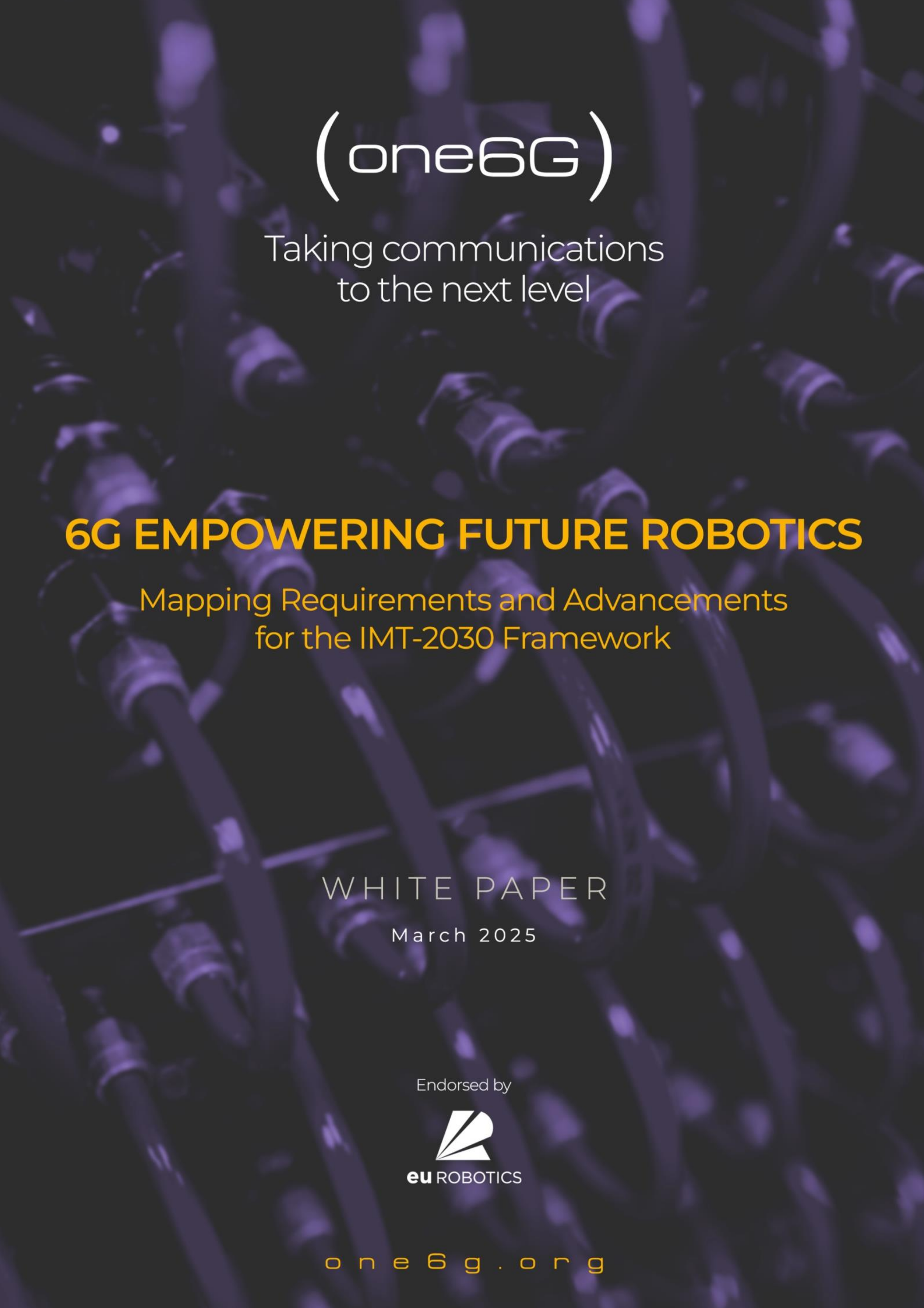

(one6G)

Taking communications
to the next level

6G EMPOWERING FUTURE ROBOTICS

Mapping Requirements and Advancements for the IMT-2030 Framework

WHITE PAPER

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Scope

The one6G Association acknowledges the increasing demand for robotic applications across various sectors, including logistics, manufacturing and delivery, telerehabilitation and telesurgery, and smart cities (including social robots for elderly care). It advocates for the integration of wireless sensing, communication, and computational capabilities within robotic systems to enhance reliability, operational efficiency, and physical capability while minimizing complexity and costs. The vision is for the future 6G communication system to empower these robotic applications, with the mobile communication industry actively seeking to understand the specific system requirements necessary for this integration.

Key domains explored in previous one6G whitepaper [1] detailed various use cases for robotics, including precision agriculture, healthcare (specifically remote surgeries and AI diagnostics), industrial robotics with seamless IoT integration in smart factories, logistics and transport within integrated smart city systems, assisted living, space exploration, construction, inspection and maintenance, automation and navigation, autonomous mining operations, and operations in harsh environments (including nuclear and recycling) and categorized them by the interactions between robots, humans, and controllers.

Another white paper [2] introduced a methodology to define the requirements for 6G robotic applications across dimensions such as wireless sensing, communication, and AI/ML support. This methodology outlines use cases in terms of phases and atomic functions, establishing baseline system requirements that can enhance the future 6G system's ability to provide cost-effective network services for these applications. For each domain, we outline specific vertical demands related to connectivity, sensing, and positioning services provided by 6G networks. For example, in the domain of aerial robotics, we examine how 6G networks can support long-distance operations at low altitudes, provide accurate positioning to enhance GNSS-based systems, and offer edge computing resources to enable high-demand AI algorithms for real-time, and safety-critical functionalities.

This white paper aims to explore the foundational understanding of the robotic application demands placed on 6G technologies to map the robotic requirements to the innovations expected from International Mobile Telecommunications 2030 (IMT-2030). To this end, the whitepaper will explore related sensing, communication, actuation, and control requirements of robotic applications as well as the integration with physical hardware. It will identify 6G enhanced and new features and enabling technologies that can support these requirements by focusing on the following key areas:

- **New/enhanced features from 6G:** We will investigate the new or enhanced features introduced by 6G that are critical for advancing the robotics industry. We outline the expected functionalities of robotic applications, detailing their communication and sensing needs for application domains such as agriculture, healthcare, social and industrial robotics.
- **Enabling technologies:** We will identify the essential elements required to meet stringent robotic requirements while exploring the reciprocal benefits that robotic technologies can bring to 6G network performance.
- **Architecture impacts:** We will examine how the architecture of 6G will support the seamless integration of sensing, computation, and control within mobile communication networks.
- **Trust, ethical and sustainability considerations:** We will examine the implications of AI models and techniques related to the processing of multimodal information gathered by robotic sensors, with a focus on privacy, ethical concerns, and sustainability issues as overarching IMT-2030 features.

- **Multidisciplinary research and standardisation:** Finally, we will outline the pathway for 6G research outputs to inform standardisation efforts, discussing the challenges of achieving harmonised and interoperable standards.

Through this structured approach, the white paper will provide a comprehensive analysis that guides the development of the 6G communication system tailored for robotic applications while considering the influence of use case parameters on service requirements and correlating findings with existing studies.

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1. Overview

The critical role of 6G Technologies in advancing essential robotics functionalities encourages foundational research and innovations at this early stage of 6G technology definition and standardisation. Essential functionalities underscore the importance of intelligence and context awareness, which enable capabilities like robot coexistence, collaboration, interaction, and safe navigation. These functionalities encompass both macro-level operations—such as manoeuvring, localization, and collision avoidance—and micro-level tasks, including grasping, manipulation, and picking and placing. To this end, in this work, we investigate IMT-2030 capabilities that align with the functionalities of autonomous agents, focusing on perception, sensing, and actuation. The integration of multimodal and multi-source data collection and fusion, coupled with advanced interfacing, computing, and sensing technologies, is vital for the deployment of autonomous robots—whether they appear in small numbers or in a swarm, or whether they are rigid or soft in their structure.

Moreover, this framework incorporates sub-tasks such as motion primitives, dynamic trade-offs based on real-time sensing data, and decisions regarding computation offloading and network-assisted processing for model inference. It also emphasizes the need for reliable availability, safety, trust, accountability, resilience, and energy efficiency in robotic operations. This comprehensive approach highlights the intricate interplay of technologies and methodologies driving advancements in the overall field of robotics.

Recent advancements in robotics have significantly transformed various sectors, underscoring the necessity of exploring their integration with 6G technologies. Innovations in soft robotics, swarm robotics, sensing technologies, and intelligent actuation systems have enhanced the capabilities of robots, enabling them to operate in complex and dynamic environments. These advancements are particularly relevant in critical applications such as healthcare, logistics, and environmental monitoring, where precision, adaptability, and real-time responsiveness are paramount.

In healthcare, for instance, soft robots can assist in surgeries and rehabilitation, where their ability to perform safe manoeuvres in a compliant manner is crucial. The low-latency communication and high reliability offered by 6G enable these robots to respond instantaneously to changes in patient conditions, significantly improving outcomes. In logistics, soft robots can navigate tight spaces and handle fragile items efficiently, leveraging advanced sensing capabilities to optimize their paths, avoid obstacles, and adapt to a wide range of complex objects.

Furthermore, in remote inspection and repair scenarios, soft robots equipped with sophisticated sensors can be teleoperated to assess and maintain equipment in hazardous environments, such as nuclear power plants. The combination of real-time feedback and ultra-reliable communication ensures that operators can control these robots safely from a distance. Similarly, in environmental monitoring, soft robots deployed in sensitive ecosystems can gather critical data on air and soil quality, facilitating research and conservation efforts while minimizing human risk.

The potential of 6G features—such as hyper-reliable low-latency communication (HRLLC), advanced sensing technologies, and edge computing—aligns closely with the requirements of these robotic applications. By mapping robotic advancements with 6G capabilities, we unlock new possibilities for enhanced collaboration, autonomy, and efficiency in robotic systems, paving the way for innovative applications across a multitude of fields. This exploration emphasizes the necessity of adapting robotic functionalities to leverage the full spectrum of 6G advancements, ensuring that future technologies meet the evolving demands of users and industries alike.

In summary, the intersection of robotics and 6G technology presents a promising frontier for enhancing human-robot interactions and advancing the capabilities of autonomous systems. As we progress in both fields, the potential to develop more intelligent, flexible, and responsive robotic solutions becomes increasingly attainable, addressing critical societal challenges and transforming various industries, including precision agriculture, healthcare, industrial robotics, and logistics. This whitepaper delineates the transformative potential of 6G in enhancing robotic functionalities, emphasizing essential features for smart industrial applications, such as swarm robotics and autonomous operations. It identifies key technology enablers like networked sensing, AI-native intelligence, and integrated positioning, while outlining the functional requirements and architectural impacts necessary for advancing robotics applications. Furthermore, it advocates for collaborative development efforts among stakeholders and standard development organizations to establish harmonized and interoperable standards for effective 6G and robotics integration.

2. Robotics High-level Functionality Blocks and Emerging Concepts

The high-level functionality blocks that underpin robotics use cases include sensing and perception, cognition and reasoning, planning and execution, as well as self-learning. In this context, emerging concepts such as soft robotics, swarm robotics, and shared control—particularly in the contexts of exoskeletons and dual user shared tasks (DUST)—need to be explored. Additionally, advancements in design, materials, sensors, actuators, and interfacing need to be addressed, while examining the various levels of autonomy necessary for the effective implementation of robotic systems.

2.1. High-level functionality blocks

2.1.1. Sensing and Perception

There is a need for context awareness and intelligent use of the associated date in robotics. Perception refers to a system that equips robots with the ability to observe, understand, and make decisions regarding their environment. It involves processing sensory data and applying artificial intelligence (AI) and machine learning (ML) techniques to interpret and analyze the surroundings.

Robotic perception is essential for various robotic applications where sensory data and AI/ML play a crucial role. It enables tasks such as the detection of objects, including humans, environment representation, and activity recognition. By learning from sensory inputs, robots can react and make decisions based on acquired models. Perception involves creating a shared environmental model for decision-making and control processes by processing data from external and internal sensors, or radio-based techniques. The data can be managed by uploading sensor data for fusion locally or in the cloud, enabling interchangeability and collaboration among robotic systems. Additionally, downloading fused data or perception maps enhances context awareness and information sharing among robots.

2.1.2. Cognition and reasoning

Sensing and perception are complemented by intelligent analysis to facilitate action. Cognition in robotics involves cognitive reasoning and inference concerning the real-world environment where robots operate. It is essential for various robotic applications that rely on environment perception for effective action and control. Cognitive reasoning allows robots to analyze and understand information from different perspectives, enabling logical structuring of data to support decision-making processes. Cognitive control aims to create a cognitive model representing the robot, its environment, and interactions, enhancing the robot's ability to execute tasks efficiently and make informed decisions based on cognitive reasoning from the perception layer.

2.1.3. Planning, execution and actuation

Actuation and Control in robotics encompasses the execution of control algorithms to generate commands for actuating and calibrating robotic structures based on perception inputs. It involves functions like motion control, force control, and impedance control to achieve specific control objectives. Robotic control mechanisms, adaptive control, fuzzy control, and Artificial Neural Network-based systems, can be executed as software applications on the robot, at the edge, or in the cloud, depending on the robot type and user requirements. This is also the case for higher-level schemes, like Flexible Manufacturing Systems or Fleet Management Systems.

2.1.4. Self-Learning

Self-learning is the process by which a robot autonomously enhances its performance without explicit external guidance. This capability involves utilizing various techniques, such as unsupervised learning, to identify patterns in data and improve algorithms based on its own experiences. For instance, a robot might optimize its movements through trial and error, becoming increasingly efficient over time without reliance on pre-programmed instructions.

Unlike traditional learning methods that often require direct instruction or supervision, self-learning emphasizes the robot's ability to adapt and evolve independently. This autonomy allows robots to refine their skills through perceptual learning [2]-[4], which focuses on extracting relevant information from sensory input via repeated exposure and practice.

By integrating these learning mechanisms, robots establish a powerful paradigm that combines human demonstration with real-time feedback, enabling them to acquire new skills and adapt their performance in dynamic environments. This autonomous learning aspect empowers robots to operate effectively in unpredictable situations, ultimately enhancing their overall functionality and adaptability.

Figure 1 gives an example of the relation and interaction between the functional building blocks of sensing, perception, cognition, actuation, and self-learning described in this section.

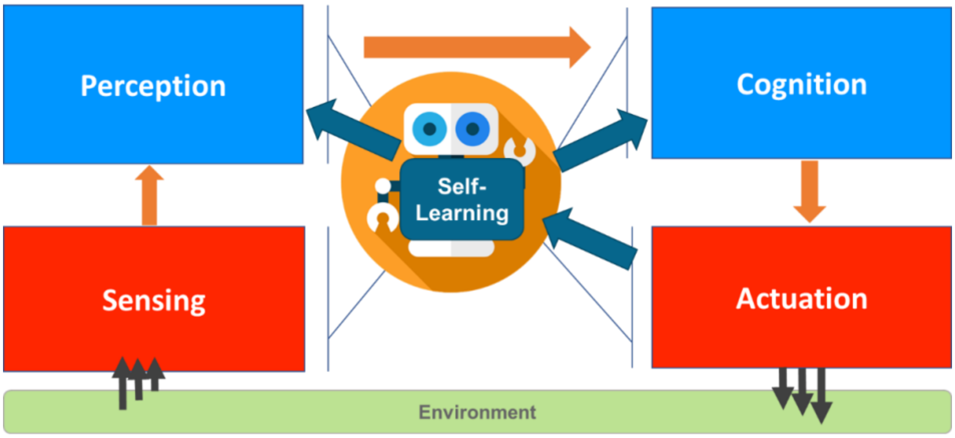


Figure 1: Robotics fundamental and high-level functionality block

2.2. Robotics Emerging Concepts

A number of emerging technologies in robotics are further highlighted below, focusing on three key areas: **soft robotics**, which emphasizes the development of flexible robots that can mimic biological movements and adapt to complex environments; **multi-robots systems and swarm robotics**, which utilizes decentralized coordination among multiple robotic agents to enhance collaborative efficiency; and **shared control**, which improves user-robot interactions by enabling users to maintain agency while benefiting from adaptive robotic assistance. These innovations showcase advancements in materials, communication technologies, and control frameworks, paving the way for more intelligent and responsive robotic systems across various applications.

2.2.1. Soft Robotics

Soft robotics is an innovative field that focuses on creating robots from flexible materials, allowing them to mimic the movements and adaptability of biological organisms. Unlike traditional rigid-component robots, soft robots utilize materials such as silicone rubber, fabrics and polyethylene sheets, which enable them to perform delicate tasks and navigate complex environments more effectively. The key feature of soft robots includes their inherent flexibility, adaptability, and safety, which are discussed as follows:

- **Actuator Flexibility and Adaptability:** Soft robots, thanks to their inherent flexibility, can adapt to various shapes and environments without extensive reconfiguration. This makes them ideal for tasks requiring gentle handling of fragile items, like those found in logistics, warehousing and AgriFood operations, as well as dynamic and unpredictable situations where traditional rigid robots struggle. To achieve this flexibility, soft robots utilize actuators made from new materials and designs, such as dielectric elastomers, shape memory alloys, and pneumatic actuators, which enable controlled movement and force generation while maintaining flexibility.

- **Soft Environment-Interaction Mechanisms:** Robots equipped with adaptive e*nvironment-interaction* mechanisms can adapt to their surroundings exploiting the soft nature of the integrated interaction mechanism. This capability ensures stability and safety during operations, particularly in unstructured and unpredictable environments. Such mechanisms are essential for applications like aerial drones or robots designed for search and rescue missions [5].

- **Resilience Enhancements:** Engineers have developed innovative solutions to improve the resilience of soft robots. For example, new pneumatic actuation techniques enable these robots to autonomously manage internal pressure and isolate damaged components, allowing them to continue functioning even after sustaining damage in places. This resilience is vital for applications where robots operate in hazardous environments or where delicate objects are being handled [6].

- **Safety in Human-Robot Interaction:** The compliant nature of soft robots minimizes the risk of injury during interactions with humans. Their inherent flexibility and ability to absorb impact make them safer collaborators in shared workspaces, promoting a more harmonious human-robot coexistence. Examples include collaborative robots in industrial environments and soft prosthetics [7].

- **Sensors and Perception:** Soft robots make use of advanced sensors, including integrated tactile and force sensors, as well as external sensors such as vision systems, to perceive their environment and interact with objects safely and effectively. For the internal sensors, recent breakthroughs in the field led to novel, miniaturized solutions allowing integration into the robot's structure without disturbing the robot's flexibility. The integrated sensors allow for precise monitoring of the robot's movements and interactions, enabling them to detect contact forces and navigate complex environments. Recent advancements in this area are pushing the boundaries of perception and autonomy in soft robotics [8].

- **Power and Control:** Efficient power sources and control systems are essential for soft robots to operate autonomously. Wireless power transfer, miniaturized batteries, and advanced control algorithms are being developed to address these needs.

- **Integrated Sensing and Actuation:** Soft sensitive actuators can be designed using silicone 3D printing techniques that embed sensors within the actuator material itself. This monolithic design minimizes mechanical stress on individual components while allowing for seamless communication between sensing and actuation functions [9].

2.2.2. Multi-Robot Systems and Swarm Robotics

Certain key applications, like logistics or search and rescue, can benefit from multiple robots cooperating to complete the mission. Multi-Robot Systems (MRS) rely on the robots being able to share information, adapt to each other's actions, and make decisions that benefit the collective goal rather than individual objectives. Swarm robotics involves the coordination of multiple robotic agents that communicate and collaborate, in most cases, through decentralized control systems. This approach is particularly applicable in scenarios such as autonomous vehicles and environmental monitoring, where collective action can enhance efficiency and effectiveness. The principles of swarm robotics are inspired by social insects like ants or bees, which work together to achieve common goals. This field emphasizes local sensing and communication capabilities among robots, allowing them to operate without centralized control.

Collective behaviour emerges from interactions between robots and their environment, relying heavily on local communication for coordination and task completion [10], meaning that direct device-to-device communications should be available even in the complete absence of infrastructure. There are various communication strategies within swarm robotics, such as the creation of terrestrial or flying ad hoc networks, novel paradigms including non-directional goal-based communication and methods for robots to share information about their states and actions. These models enhance cooperation and efficiency in tasks like foraging [11]. Additionally, methods for exchanging information regarding states and actions enhance cooperation, enabling effective task execution. The integration of robotic and communication systems is, therefore, crucial for applications such as rescue operations. A co-design approach becomes essential for optimizing performance in these environments. Key insights include:

- **Robotic Design and Integration:** An efficient use of communications in MRS requires a natural integration within the robot architecture. For example, when utilizing tools like the Robot Operating System (ROS), it is important to consider the differences between ROS1 and ROS2. While ROS1 offers wider support, ROS2 provides better integration for multiple robots, simplifying the overall system architecture. Thus, features like Collaborative Simultaneous Localization and Mapping (C-SLAM) algorithms with data shared from different robots can be implemented [12]. The feasibility of sharing data among several robots can also benefit multimodal datasets, a scarce resource in many application areas.
- **Network Configuration Challenges:** Setting up networks for robotic systems in dynamic environments involves careful planning for factors such as network coverage, network mobility support, Quality of Service (QoS), and cybersecurity. Stand-alone networks introduce additional variables, as network elements can move, impacting performance and requiring a flexible design approach that often involves self-configuration mechanisms, robots acting as network relays, and alternative security mechanisms such as neighbor trust assessment mechanisms.
- **Communication Capabilities:** Availability of low-latency, high bandwidth communication systems can significantly simplify the overall architecture of AMRs, eliminating the need for concurrent communication systems and their extensive network tuning.
- **New Applications:** Advanced communication systems can enable new applications, such as remote Simultaneous Localization and Mapping (SLAM), remote inference of AI-based algorithms that require large processing time, and edge-cloud management of robot fleets using public mobile networks. The integration of robotic and communication systems can significantly enhance operational capabilities in various scenarios.
- **Network Optimization:** Adaptive exploration and modifications to network slicing configurations are necessary to optimize resources for robotic systems. The flexibility of mobile networks such as can provide additional resources through enhanced configurations. Moreover, the usage of Network Exposure functionalities can be an enabler in robotic applications that can benefit from the acknowledgement of the network status to offload different processes to edge and cloud.
- **Low-power IoT robot platforms:** The integration of low-power communications in 6G can provide new challenges mainly in supplying energy to low-scale robots. Most of them bio-inspired devices that integrate swarm coordination and can benefit from the harvesting capabilities of 6G networks [12].

- **Co-Design:** A collaborative design process that considers the interplay between robotic and communication systems is essential for developing effective multi-robot solutions. This co-design approach allows for the optimization of the overall system to meet the unique requirements and constraints of challenging environments.

2.2.3. Human-Robot Collaboration

An important emerging technology is the interaction and collaboration between humans and robots with shared control in robotic systems. By integrating advanced communication technologies and real-time data from various sensors, shared control frameworks aim to maintain user agency while enhancing safety and responsiveness. The focus is on developing adaptive systems that can effectively respond to user intentions and environmental changes, thereby optimizing the user experience in assistive and mobility applications.

Shared Control of Exoskeletons

Exoskeletons are an example of shared human-robot control frameworks, allowing users to maintain agency while benefiting from robotic assistance, enhancing user experience and safety. Effective communication between users and exoskeletons allows adaptive responses to user intentions and environmental changes, leveraging features such as ultra-reliable low-latency communication (URLLC) from B5G. Additionally, integrating real-time data from various sensors creates a responsive shared control system that dynamically adjusts assistance based on user feedback and contextual understanding [14]-[16]. Improving user intent recognition and environmental perception using novel vision-based approaches enhances wearable robots' performance [16]. Specifically, the integration of additional sensing can benefit shared control of exoskeletons such as:

- Incorporation of diverse sensors (e.g., force sensors, IMUs, EMG, accelerometers, gyroscopes) to gather real-time data, improving responsiveness and adaptability of exoskeletons.
- Enhanced feedback mechanisms allow for better user awareness and control over their movements, supporting smart environments characterized by high-capacity communications.
- Focus on developing intelligent systems that leverage environmental data for improved decision-making in mobility assistance, aligning with 6G features like edge computing for low-latency processing.
- Integration of multiple sensing modalities to create a holistic system for movement enhancement, ensuring interoperability and scalability in assistive technologies.

There is a need to explore new communication protocols and algorithms that enable seamless interaction between users and robotic systems, taking advantage of advancements in 6G technology. The implementation of machine learning (ML) models, such as reinforcement learning can further improve shared control by enabling predictive adaptation to user behavior and environmental conditions. Additionally, ongoing research should focus on achieving a balance between autonomy and user control in assistive technologies, ensuring that future mobility solutions are designed with a user-centric approach.

Dual User Shared Task

The concept of Dual User Shared Task (DUST) refers to collaborative scenarios where two users work together with a robotic system to achieve a common goal. This approach emphasizes the importance of effective communication and coordination between users and robotic assistance, allowing for a more integrated and user-centered experience. Key aspects of DUST are as follows:

- **Shared Agency:** DUST frameworks facilitate shared control, where both users actively participate in decision-making and task execution. This balance between autonomy and collaboration enhances user engagement and satisfaction.
- **Adaptive Interaction:** The system is designed to adapt to the preferences and intentions of both users. By leveraging advanced communication technologies, such as ultra-reliable low-latency communication (URLLC), the robotic system can respond in real-time to the users' actions and feedback.
- **Enhanced Communication:** Effective communication is crucial in DUST scenarios. Users must be able to convey their intentions and observations to the robotic system and to each other, ensuring synchronized efforts in task execution. This requires robust communication protocols that support clarity and responsiveness.
- **Multi-Modal Sensing:** DUST systems often incorporate various sensors to gather comprehensive data about the environment and the users. This includes force sensors, motion trackers, and biometric sensors that provide critical information for improving the system's responsiveness and adaptability.
- **Contextual Awareness:** The success of DUST relies heavily on the system's ability to understand the context of the shared task. By integrating contextual data—such as user movements, environmental conditions, and task parameters—the robotic system can optimize its assistance, enhancing both performance and safety.

Incorporating DUST principles into robotic systems, such as exoskeletons, allows for improved collaboration between human users and robots. This approach is particularly relevant in applications like rehabilitation, assistive technologies, and industrial automation, where tasks often require joint effort and coordination. The Dual User Shared Task framework represents a significant step toward creating more intuitive and effective human-robot collaborations. By focusing on shared agency, adaptive interaction, and contextual awareness, DUST can enhance the overall user experience and improve the outcomes of robotic assistance, paving the way for innovative applications in various fields.

3. From IMT-2020 (5G) to IMT-2030 (6G)

While current robotics connectivity protocols such as PROFInet, EtherCat and Ethernet provide robust wired connectivity for industrial and automated environments, they face limitations in flexibility and mobility. Wireless options like Wireless Ethernet and Time-Sensitive Networking (TSN) aim to address these issues but still struggle with providing consistent low latency and reliability across large areas or in complex environments. Deterministic Networking (DetNet) enhances the predictability of data flows, but its implementation in wireless scenarios remains challenging.

These shortcomings highlight the need for more advanced connectivity solutions, particularly in scenarios requiring:

- Seamless mobility across large areas
- Ultra-reliable and/or low-latency communication for critical applications
- Massive connectivity for swarms of robots or IoT devices
- Enhanced radio sensing and positioning capabilities

The evolution of mobile communication systems from International Mobile Telecommunications 2020 (IMT-2020 aka 5G) to IMT-2030 (aka 6G) [18],[19] is envisioned to be transformative, particularly for advanced robotic applications. While 5G introduced significant improvements in terms of throughput, latency, and reliability, early market deployments and research findings have highlighted specific challenges that need to be addressed to fully realize next-generation services. These include supporting extremely high device density, ensuring consistent quality of service across diverse environments, and seamlessly integrating cutting-edge technologies such as AI, edge computing, and ubiquitous sensing [20]-[23].

6G is expected to address these challenges by broadening the scope of what mobile communication networks can deliver, both in technical performance and in the range of services offered. Beyond simply increasing data rates or lowering latency, 6G will incorporate tight integration of sensing, computing, and communication to enable new levels of intelligence and autonomy. This is especially relevant for robotic ecosystems, where simultaneous perception, real-time decision-making, and collaboration among large numbers of robots (and other devices) become critical [24]-[26].

IMT-2030 proposes a comprehensive set of fifteen capabilities, which include nine research targets that build upon the IMT-2020 framework. These targets focus on critical aspects such as peak data rates (projected at 50, 100, or 200 Gbps), user-experienced data rates (300 or 500 Mbps), spectrum efficiency improvements of 1.5x to 3x compared to IMT-2020, and one-way latency of 0.1 to 1 ms. Additionally, six broader capabilities are identified, addressing coverage, sensing, AI integration, sustainability, interoperability, and positioning, although these are currently described mostly in qualitative terms. It is important to note that the proposed values may not be achievable simultaneously across different usage scenarios. Figure 2 presents a summary of the IMT-2030 capabilities.

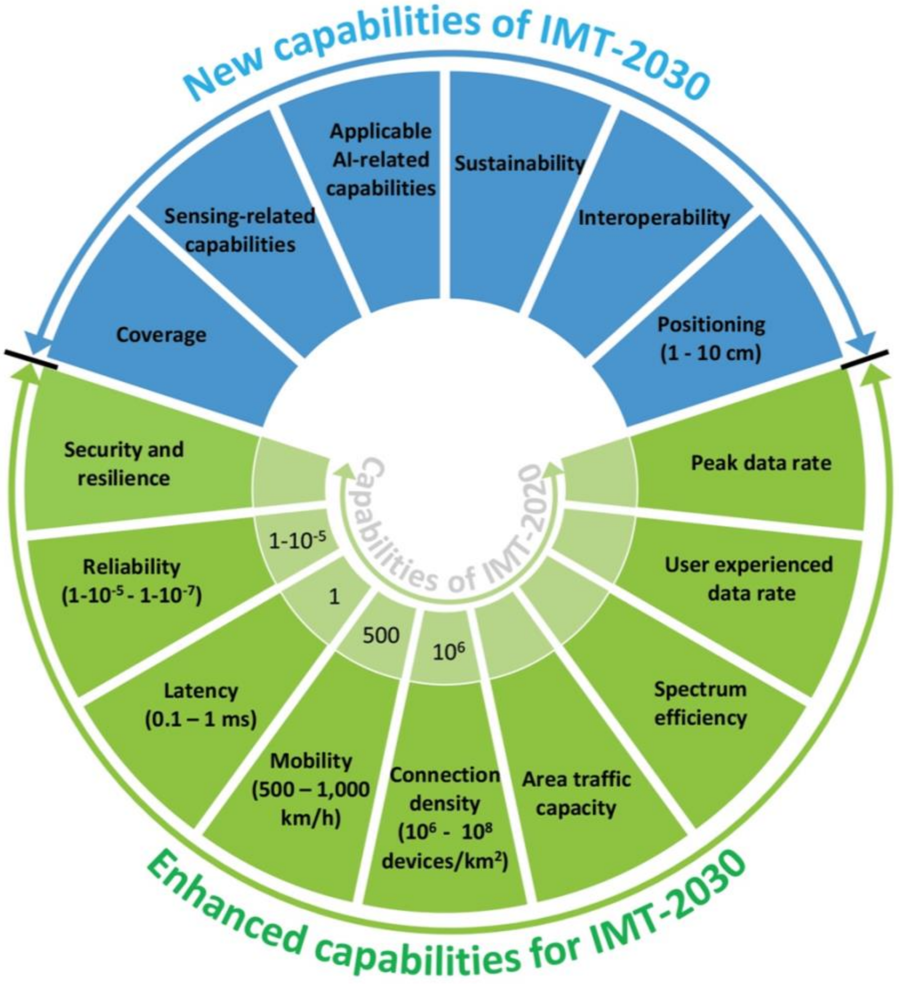
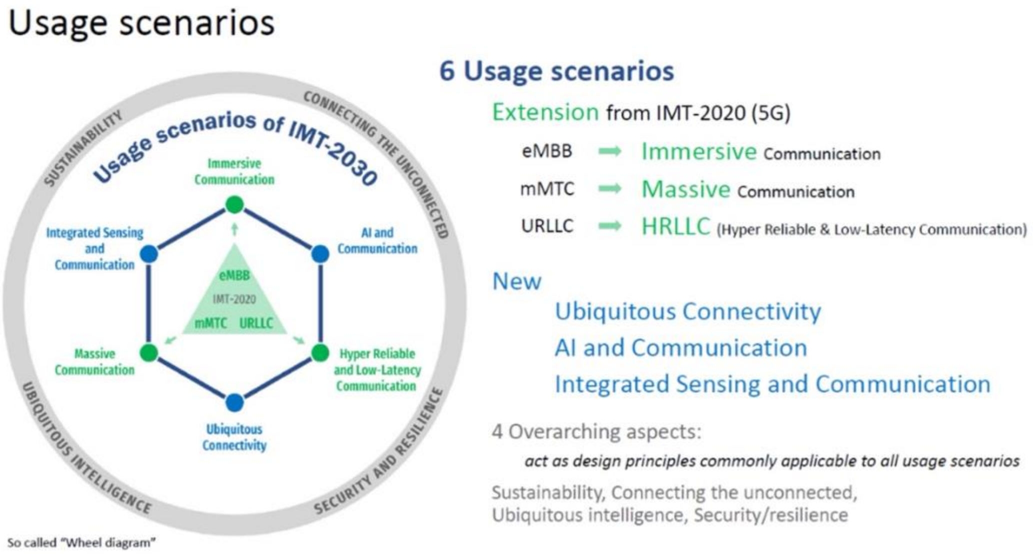


Figure 2: Enhanced and new capabilities of IMT-2030 [18]

The IMT-2030 framework emphasizes the ongoing development of mobile networks in relation to existing IMT systems, suggesting that requirements can be met by enhancing these systems, integrating new technologies, and developing novel radio interface technologies. In the context of robotics, these advancements can support the deployment of more efficient and reliable robotic systems, enabling applications such as autonomous and intelligent robots' cooperation in manufacturing or disaster scenarios.

Figure 3 illustrates the spectrum of usage scenarios enabled by IMT-2030, alongside these overarching design principles. It highlights how sustainability, inclusive connectivity, ubiquitous intelligence, and security/resilience intertwine to form the foundation of future robotics. A holistic approach (integrating technical innovation with ethical, environmental, and societal imperatives) ensures that 6G networks and robotic applications jointly advance global well-being, productivity, and trust.



6 Usage scenarios

Extension from IMT-2020 (5G)

eMBB ➡ Immersive Communication
mMTC ➡ Massive Communication
URLLC ➡ HRLLC (Hyper Reliable & Low-Latency Communication)

New

Ubiquitous Connectivity
AI and Communication
Integrated Sensing and Communication

4 Overarching aspects:

act as design principles commonly applicable to all usage scenarios

Sustainability, Connecting the unconnected,
Ubiquitous intelligence, Security/resilience

Figure 3: Usage scenarios and overarching aspects of IMT-2030 [18]

3.1. Impact of Advancements from 5G to 6G Features on Robotics Applications

The transition from 5G to 6G involves more than incremental enhancements in throughput, latency, and reliability. It includes a significant rethinking of underlying network architecture, protocols, and service models to support use cases that demand real-time intelligence, contextual adaptability, and seamless integration of communication with sensing and computing. In 5G, three distinct service pillars (enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC)) provided a framework for different application domains. As we move to 6G, each of these pillars is extended to meet more stringent performance requirements and integrate additional functionalities, paving the way for immersive communication, massive communication, and hyper-reliable low-latency communication (HRLLC)[27]-[31].

From a technical standpoint, 6G is expected to achieve higher peak data rates (potentially in the terabit-per-second range), near-zero latency (on the order of microseconds for certain mission-critical tasks), and enhanced spectral efficiency potentially through the addition of new frequency bands (e.g., higher mid-band and higher mmWave) and advanced antenna technologies. Moreover, 6G research emphasizes integrating artificial intelligence at every layer of the network, from radio resource management to application-level quality of service. This AI-driven approach ensures that communications are both context-aware and adaptive, addressing demands from diverse and highly dynamic robotic applications. Collectively, these advancements lay the groundwork for continuous connectivity and real-time intelligence, features increasingly essential for robotic systems operating in multi-robot, multi-sensor, and multi-domain environments [27],[32]-[35].

3.1.1. eMBB to Immersive Communication for Multi-Sensory Interaction

In the context of 5G, enhanced Mobile Broadband (eMBB) primarily focused on delivering higher peak data rates, increased network capacity, and improved end-user experiences for bandwidth-intensive applications. Typical use cases included high-definition video streaming, real-time gaming, and large data downloads or uploads all of which benefited significantly from 5G's reduced latency and enhanced throughput compared to previous generations [36].

As we move toward IMT-2030 (6G), eMBB capabilities are expected to evolve into a broader paradigm often referred to as Immersive Communication. This evolution entails a shift from mere content delivery toward multi-sensory, interactive, and adaptive experiences, as needed. The goal is to support richer and more contextually aware applications that extend beyond entertainment and into domains such as healthcare, education, and advanced robotics [37],[38]. The transition to multi-sensory interaction can advance the future of robotics from multiple aspects including:

Advanced Requirements & Design Considerations

- **Ultra-Low Multimodal Synchronisation and Realtime Feedback Loop:** Immersive communication puts a premium on latency. The network must handle high volumes of multimodal data and deliver them in near real-time. Any delays can break the sense of presence and compromise safety in applications like remote surgery or tele-operated robotic arms [38].
- **Adaptive QoS:** To maintain high-quality interactive experiences, 6G networks may rely on AI-driven adaptive streaming and dynamic resource allocation, prioritizing data flows for immersive tasks under congested conditions or when network capacity fluctuates [48],[49].
- **Energy Efficiency Challenge:** Supporting such data-heavy, interactive experiences can increase energy consumption. Therefore, energy efficiency in both network infrastructure and end-user devices remain a crucial design target [28].

Key Technology Enablers

- **Network Infrastructure Upgrades:** The delivery of immersive content requires broader frequency bandwidths (e.g., cmWave, mmWave or sub-THz), more dense network deployments, and advanced antenna technologies such as massive MIMO [50]-[52].
- **Computing and Edge Architectures:** Real-time rendering of 3D environments and low-latency haptic control loops will often offload computational tasks to edge clouds, which must be tightly integrated with the radio network [53].

Impact of Future Robotics

- **Immersive Telepresence and Extended Reality and Media (XRM) services:** Immersive communication capabilities will allow human operators to experience remote robotic environments almost as though they were physically present. This can be transformative in search-and-rescue missions, disaster relief, industrial maintenance, where on-site human presence is either risky or impractical [45] and as a solution to assist autonomous robots in critical situations on demand. 6G networks will be equipped to handle not only high-resolution 2D video but also 3D holographic displays, virtual reality, augmented reality (AR), and mixed reality (MR) systems that demand real-time, large-scale data rendering [39]-[41].
- **Human-Robot Interaction:** By integrating real-time visual, auditory, and haptic feedback, robots can more seamlessly interact with human operators or technicians. This is crucial in settings such as smart manufacturing or healthcare, where precise coordination between human skills and robotic precision is vital [45]-[47].
- **Haptic Feedback and Tactile Internet:** Beyond sight and sound, immersive communication envisions touch-based feedback loops, where users can feel remote objects or surfaces via

robotic and sensor-based mechanisms, enabling applications like remote rehabilitation or skill training with near-realistic physical feedback [42]-[44].

- **Vertical Industry Integration:** Sectors such as telemedicine, logistics, retail, and education will increasingly adopt immersive applications to streamline operations, training, and user engagement [37].
- **Rich New User Experiences & context-aware applications:** The leap to immersive communication promises not just incremental improvements, but fundamentally new types of experiences and services. For robotics, this means more intuitive, hands-on, and context-rich interactions between humans and automated systems, thereby accelerating the deployment and acceptance of robotic solutions in daily life [20].

In summary, by transforming eMBB into Immersive Communication, 6G networks will deliver real-time, high-fidelity, and truly interactive experiences that fundamentally reshape how humans and robots collaborate, learn, and perform tasks across a multitude of sectors. This evolution is a key milestone in fulfilling the vision of IMT-2030, wherein seamless human-robot synergy becomes a practical reality [20].

3.1.2. mMTC to Massive Comm. to Scale Beyond Basic IoT Connectivity

The usage scenario on Massive Communication too has a great deal of impact on robotics, such as supporting high sensor/machine density and lightweight and secure devices with reduced power consumption as in multi-robot systems and swarm robotics. Scaling beyond basic IoT connectivity leading to massive communication can advance the future of robotics from multiple aspects including:

Advanced Requirements & Design Considerations

- **Exponential Device Growth:** The number of IoT devices (including both stationary sensors and mobile robots) is expected to grow exponentially in 6G, making efficient resource utilization and interference management crucial [26].
- **Diverse Traffic Profiles:** Traditional mMTC focused on sporadic, low-throughput sensor data. However, advanced robotics can generate heterogeneous traffic, ranging from real-time control signals to periodic high-bandwidth data streams (e.g., sensor feeds) [26].Each robot is equipped with hundreds of sensors of different types linked with onboard and external data processes and digital twins.
- **Network Self-Organization and Distributed Intelligence:** In massive fleets of autonomous robots, local and global coordination targeting at dynamically optimizing network performance even without human intervention. 6G networks will integrate AI-driven algorithms for efficient scheduling and load balancing, ensuring that each device receives the necessary resources based on real-time conditions [57],[58],[63].
- **High-Density Connectivity:** Moving beyond low-rate applications, 6G's Massive Communication targets an environment where hundreds or thousands of robots may operate concurrently. Each is equipped with huge number of sensors and all requiring robust wireless links. Consequently, support of higher bandwidth for as consequence of Massive Connectivity including novel robotics requirements [26].
- **Ultra-High Device Density:** It is expected that network congestion will increase due to millions of robots, sensors/actuators, and IoT devices operating in the same environment, constituting simultaneous communication as an important challenge [35].

- **Security and Privacy:** With thousands of interconnected robotic devices, potential vulnerabilities increase. Ensuring secure communication and data privacy becomes more complex, requiring robust authentication, encryption, and network segmentation [56].
- **Regulatory and Ethical Concerns:** Massive-scale deployment of robotic systems raises ethical concerns, including data privacy, and AI decision-making biases. Regulations and ethical AI frameworks will be essential for ensuring trustworthy and responsible robotic operations related to AI-driven automation, and data handling policies [87].

Key Technology Enablers

- **Intelligent Energy-Efficient Algorithms:** Robotic systems consume significantly more power than passive IoT devices, requiring efficient energy management for continuous operation. Energy-efficient AI algorithms and smart/adaptive power management would be essential to optimize robotic power consumption [28].
- **Spectrum Management and Optimization:** Achieving highly dense connectivity requires advanced spectrum-sharing techniques, dynamic allocation, and novel waveforms that minimize interference [63].
- **Adaptive Protocols:** Traditional IoT protocols might not scale well under high traffic loads or dynamic topologies typical of robotics fleets. As a result, 6G research focuses on protocols that adapt to real-time constraints, device capabilities, and network conditions [26].

Impact on Future Robotics

- **Swarm Robotics:** Large-scale swarm operations (such as drone fleets for disaster management or autonomous guided vehicles in warehouses) demand consistent communication among numerous agents. Massive Communication ensures that all robots can share situational data (e.g., positions, sensor readings) without overloading the network [56],[59].
- **Collaborative Sensing and Actuation:** In scenarios where, multiple robots work collectively (e.g., infrastructure inspection or environmental monitoring), high-density connectivity supports the aggregation of vast sensor data. This enables coordinated decision-making and the fusion of insights from multiple viewpoints [56],[60].
- **Edge Intelligence for Real-Time Control:** With massive connectivity, robots can offload computation or pull AI inferences from edge servers dynamically. This approach reduces onboard processing requirements and enhances real-time responsiveness across a large fleet of devices [56],[61],[62].
- **Increased Autonomy and Efficiency:** By providing a reliable backbone for data-intensive collaborations, massive communication allows robots to make group decisions with minimal human intervention. This paves the way for more autonomous and efficient operations in settings like automated factories, ports, and large-scale agricultural fields [56].
- **Global Reach and Scalability:** Leveraging non-terrestrial networks (e.g., satellites, high-altitude platform stations) alongside terrestrial infrastructure can extend coverage to remote areas, enabling large robotic deployments for terrestrial and maritime farming, resource extraction, environmental reclamation, and disaster response where traditional connectivity is sparse [56].

In summary, massive Machine Type Communication in 5G set the stage for large-scale IoT ecosystems but did not fully address the requirements for complex, data-intensive robotic use cases. In 6G, Massive Communication fills this gap by not only scaling up the number of connected devices but also ensuring adaptive, high-throughput, and reliable data exchange among distributed fleets of robots. This capability will be a cornerstone for advancing automation, enhancing operational intelligence, and supporting innovative applications across countless industries.

3.1.3. URLLC to HRLLC Transition

In 5G, URLLC was introduced to meet critical performance requirements in applications where even milliseconds of delay or slight packet loss could lead to significant risks. Targeting sectors such as industrial automation, autonomous driving, and remote healthcare, URLLC sought to achieve latencies of around 1 ms and reliability as high as 99.999%. Despite these advances, future 6G use cases demand an even more stringent performance envelope that addresses increasingly complex real-time interactions in robotics and other mission-critical domains. This next evolutionary step is referred to as Hyper Reliable & Low-Latency Communication (HRLLC) [29]-[65]. Elevating reliability and providing latency guarantees can advance the future of robotics from multiple aspects including:

Advanced Requirements & Design Considerations

- **Reliability Further Approaching 100%:** While URLLC aimed for “five-nines” reliability, HRLLC aspires to push these boundaries closer to zero packet loss (7-9 nines reliability [29]); ensuring that every critical control message or sensor reading reaches its destination in time-sensitive scenarios [29].
- **Latency Below 1 milliseconds (ms):** To accommodate ultra-fast feedback loops for robotic control, latencies may need to drop below 0.5 ms in certain high-stakes applications, such as collaborative surgical robots, robotic tasks relying on tactile communications or swarm drones in dynamic environments [29],[66].
- **Hardware and Protocol Optimization:** Achieving sub-millisecond latencies requires optimizing physical-layer waveforms, scheduling algorithms, and processing hardware. Each layer of the network stack must be streamlined to minimize delays [29],[66].
- **Security in Critical Environments:** As reliability increases, so must security. Any successful cyberattack on a hyper-reliable network could have magnified effects, particularly if it targets safety-critical robots or infrastructure [66].

Key Technological Enablers

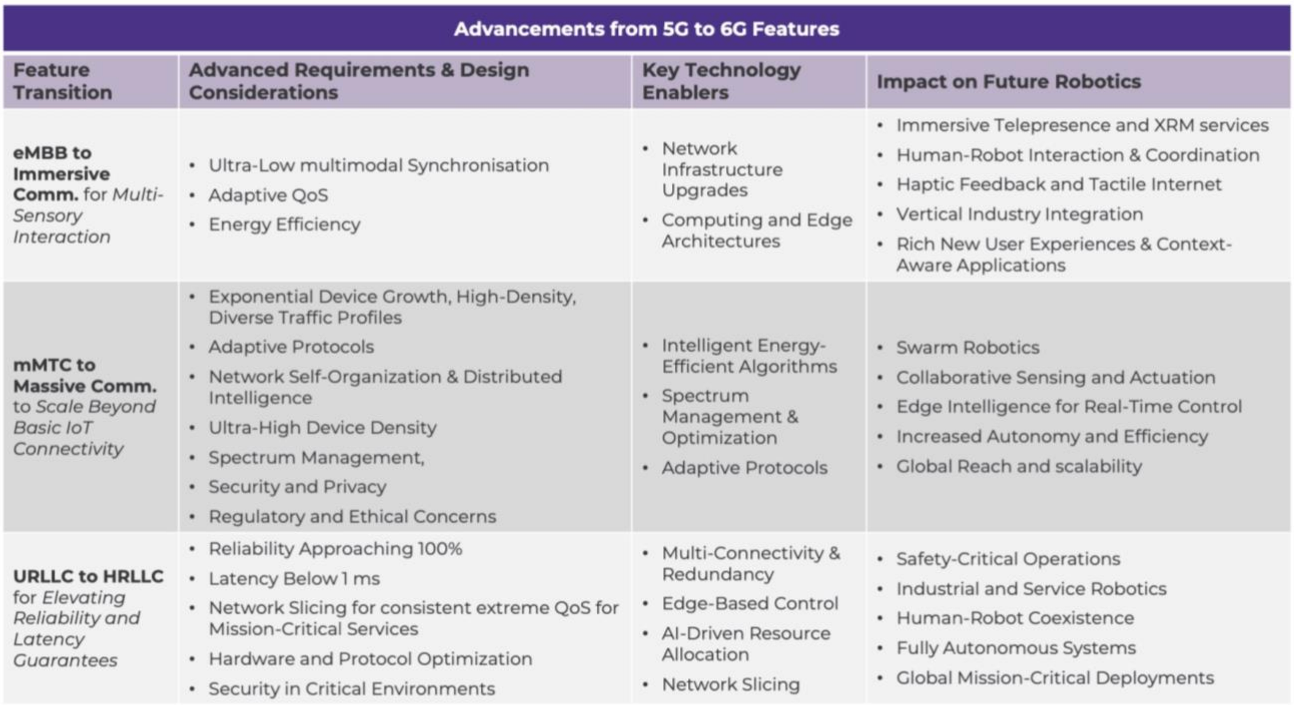
- **Multi-Connectivity and Redundancy:** By connecting to multiple cells or frequency bands simultaneously, robots can maintain active backup links that automatically handle failover if one connection degrades [66].
- **Edge-Based Control:** Placing control logic and data processing at the edge, closer to robotic devices, removes delays associated with backhaul links. This localized intelligence allows for millisecond or sub-millisecond round-trip times in command and control loops [68].
- **AI-Driven Resource Allocation:** Advanced machine learning algorithms can predict traffic spikes, user mobility, and interference patterns, proactively reallocating network resources to guarantee minimal latency and high reliability [66].
- **Network Slicing for Mission-Critical Services:** Even under HRLLC, not all traffic can receive the same extreme quality of service. Network slicing ensures that mission-critical robotic applications have reserved resources, isolating them from non-critical data flows [66], [69],[70].

Impact on Future Robotics

- **Safety-Critical Operations:** Robots working in human-centric environments (be it in hospitals, on factory floors, or in search-and-rescue missions) depend on instantaneous data exchange to avoid collisions, perform precise maneuvers, or respond to unforeseen obstacles. Any delay or packet drop could jeopardize human safety or mission success [67].
- **Industrial and Service Robotics:** In precision manufacturing, robotic arms and conveyor systems must operate in near-perfect synchronization. HRLLC ensures real-time command execution, reducing errors and downtime while increasing overall productivity [66].
- **Human-Robot Coexistence:** With HRLLC, robots can interact more safely and fluidly alongside humans, sharing tasks and cooperating without fear of communication-induced delays that could cause accidents [71].
- **Fully Autonomous Systems:** The near-absolute reliability and extremely low latency of HRLLC enable deployments where large-scale robot fleets make split-second, collective decisions in scenarios as diverse as drone traffic management, autonomous supply chain operations, or telemedicine in rural areas [66],[71].
- **Global Mission-Critical Deployments:** By leveraging satellite constellations and advanced terrestrial networks, HRLLC can be extended to remote locations, guaranteeing fail-safe operations for emergency response robots or environmental monitoring systems, regardless of geography [66],[71].

The transformative advancements from 5G to 6G have significant implications for and impacts on robotics, as summarized in Table 1.

Table 1: Advancements from 5G to 6G features and impact on robotics ecosystem



Advancements from 5G to 6G Features			
Feature Transition	**Advanced Requirements & Design Considerations**	**Key Technology Enablers**	**Impact on Future Robotics**
eMBB to Immersive Comm. for *Multi-Sensory Interaction*	• Ultra-Low multimodal Synchronisation • Adaptive QoS • Energy Efficiency	• Network Infrastructure Upgrades • Computing and Edge Architectures	• Immersive Telepresence and XRM services • Human-Robot Interaction & Coordination • Haptic Feedback and Tactile Internet • Vertical Industry Integration • Rich New User Experiences & Context-Aware Applications
mMTC to Massive Comm. to *Scale Beyond Basic IoT Connectivity*	• Exponential Device Growth, High-Density, Diverse Traffic Profiles • Adaptive Protocols • Network Self-Organization & Distributed Intelligence • Ultra-High Device Density • Spectrum Management, • Security and Privacy • Regulatory and Ethical Concerns	• Intelligent Energy-Efficient Algorithms • Spectrum Management & Optimization • Adaptive Protocols	• Swarm Robotics • Collaborative Sensing and Actuation • Edge Intelligence for Real-Time Control • Increased Autonomy and Efficiency • Global Reach and scalability
URLLC to HRLLC for *Elevating Reliability and Latency Guarantees*	• Reliability Approaching 100% • Latency Below 1 ms • Network Slicing for consistent extreme QoS for Mission-Critical Services • Hardware and Protocol Optimization • Security in Critical Environments	• Multi-Connectivity & Redundancy • Edge-Based Control • AI-Driven Resource Allocation • Network Slicing	• Safety-Critical Operations • Industrial and Service Robotics • Human-Robot Coexistence • Fully Autonomous Systems • Global Mission-Critical Deployments

3.2. New 6G capabilities' Impact on Future of Robotics Applications

Ubiquitous connectivity in 6G aims to deliver seamless, high-quality network coverage across a wide range of geographies and environments, spanning densely populated urban centers, remote rural regions, underground facilities, and even maritime or aerial domains. This evolution builds on 5G's significant improvements in throughput and coverage but extends its scope to ensure *always-on* connectivity in scenarios where infrastructure may be sparse or dynamic. For robotic applications, maintaining robust communication links is essential for real-time control, data exchange, and safe operation, especially when robots are deployed in hard-to-reach or hostile environments [73]-[75].

3.2.1. Ubiquitous Connectivity and Expanding Coverage Beyond 5G

Serving robotic systems deployed anywhere in the world, even in areas previously considered unreachable. This will ensure that robots can operate in remote construction sites, open-ocean wind farms, or disaster-stricken regions without losing connectivity [76].

Advanced Requirements & Design Considerations

- **Efficient Spectrum Allocation:** Supporting global, uninterrupted service requires efficient spectrum usage. Competition for bandwidth (from both terrestrial and non-terrestrial sources) demands robust interference mitigation and dynamic spectrum sharing [85].
- **Energy Consumption:** Providing consistent coverage across vast areas can be energy-intensive. As the density of connected nodes increases, networks must implement energy-saving mechanisms (such as sleep modes or intelligent power scaling) to maintain sustainability [86].
- **Security and Privacy:** A broader coverage footprint expands the potential attack surface. Robust encryption, secure authentication, and intrusion detection become even more critical to protect mission-critical robotic operations from cyber threats [87].

Key Technological Enablers

- **Adaptive Radio Access Technologies:** 6G protocols can dynamically switch between available Terrestrial and Non-Terrestrial Networks (NTNs) such as satellite, cellular, or ad hoc to maintain optimal signal quality and minimize handover disruptions [80],[81].
- **AI-Assisted Beamforming:** Intelligent beam steering and interference management help extend coverage to areas with challenging terrain or high mobility. This approach is crucial in industrial scenarios, where robots move among metal structures that cause signal reflections [82],[82].
- **Edge Computing for Reduced Backhaul:** Localized processing at the network edge ensures real-time analytics, reducing latency and dependence on distant cloud servers. This is particularly beneficial for remote outposts or sea-based robotic platforms [84].
- **Mesh Networking and Multi-Hop Links:** Localized mesh networks enable robotic teams to maintain communication even if the core network is unavailable. In disaster response, for instance, a group of drones can form a multi-hop relay to extend the operational radius of rescue robots on the ground [77].

Impact on Future Robotics

- **Continuous Mission-Critical Operations:** Robots performing search-and-rescue, precision agriculture, or long-range inspection require uninterrupted data exchange for navigation and control. Ubiquitous connectivity ensures high reliability and responsiveness, enabling them to function autonomously far from traditional infrastructure [78].
- **Scalability in Large Deployments:** Whether it is a fleet of autonomous delivery vehicles spanning an entire city or underwater drones monitoring marine ecosystems, the ability to connect every robotic unit (regardless of location) facilitates large-scale coordination and efficient resource use [79].
- **Global Coordination and Management:** With near-ubiquitous connectivity, organizations can monitor and control robotic fleets deployed on multiple continents in near real-time. This capability is transformative for logistics, environmental conservation, and emergency response [88].
- **Cross-Sectoral Synergies:** From healthcare services in remote villages to autonomous mining in unpopulated areas, extended coverage underpins new business models, accelerates digital inclusion, and enhances overall societal resilience [88].
- **Autonomy in Extreme Environments:** Whether at high altitudes, polar regions, or undersea locations, robots can rely on stable communication links for navigation updates, sensor data sharing, or teleoperation guidance extending the frontier of human and robotic exploration [90].

In summary, Ubiquitous Connectivity is a cornerstone of 6G that aims to ensure robust, low-latency coverage for robotics and other advanced use cases, regardless of environmental constraints. By integrating terrestrial, satellite, and edge computing resources, 6G networks will expand operational boundaries and unlock novel applications (from large-scale drone fleets in remote areas to on-demand robotic services in underserved communities) catalyzing a more connected and autonomous future.

3.2.2. AI and Communication in Network Operations

Integrating artificial intelligence (AI) into every layer of the network architecture is one of the defining features of 6G. While 5G introduced initial concepts of AI-driven network optimization, 6G envisions a more profound synergy where AI algorithms orchestrate resource allocation, predict network conditions, and even adapt waveforms in real-time. For robotics, AI-enhanced communication unlocks new possibilities enabling machines to collaborate more intelligently, offload computationally intensive tasks to the edge or cloud, and benefit from proactive network services that cater to their operational contexts [91].

Advanced Requirements and Design Considerations

- **Data Privacy and Security:** As robots and edge servers exchange large volumes of potentially sensitive data, robust privacy-preserving techniques, and secure transmission protocols become indispensable [100].
- **AI Explainability:** In safety-critical robotic applications, understanding how AI-driven decisions are made (i.e., model interpretability) is important for compliance and user trust, especially if an error leads to physical harm or system disruption [101].

- **Computational Overhead:** Running sophisticated AI models at edge nodes demands high-performance hardware and energy management. Balancing scalability with cost and power consumption remains a key challenge [99].

Key Technological Enablers

- **Edge and Fog Computing:** By processing data near its source, edge or fog nodes can offer low-latency inference for robot decision-making. This drastically cuts response times compared to cloud-based AI solutions that rely on distant data centers [92].
- **Federated Learning and Collaborative AI:** Multiple robots can collectively train shared models without sending raw data to a central server, preserving bandwidth and maintaining data privacy. This approach is especially relevant in situations where local data (such as factory layouts or patient information) must remain confidential [92],[97].
- **Semantic Communication:** Instead of transmitting raw sensor data, AI-based encoders can extract essential “meaning” (semantics) to reduce payload sizes and improve efficiency. Robots receive the critical insights needed for decision-making while minimizing network overhead [98].
- **Adaptive Resource Allocation:** Machine learning (ML) models can predict traffic loads, user movement, and channel conditions, adjusting bandwidth and transmission power dynamically. Robots thus should receive a consistent QoS for critical control messages or sensor data, even under changing network conditions [92].
- **Predictive Network Maintenance:** AI-based anomaly detection can anticipate failures or congestion in the network. This proactive approach should ensure minimal downtime for robotic operations, crucial in time-sensitive environments like factories or healthcare facilities [93],[94].

Impact on Future Robotics

- **Distributed Intelligence:** Robots can offload tasks such as high-level path planning, complex vision processing, or multi-robot coordination to AI modules running on edge servers. This reduces on-board power and processing requirements while allowing for more sophisticated functionalities [95].
- **Context-Aware Interaction:** AI-driven communication enables robots to understand the user’s context (such as location, intent, or resource availability) and tailor their responses or actions. This paves the way for seamless human-robot collaboration in shared workspaces or in dynamic public environments [96].
- **Adaptive Multirobot Cooperation:** In warehouses, fleets of robots can synchronize tasks, maximizing throughput and safety using AI-generated schedules that consider real-time inventory levels, worker locations, and incoming orders [102]. The level of human involvement, or collaboration, depends on the specific application, level of autonomy, and operational context.
- **Collaborative Robots (Cobots) Symbiosis:** With context-aware, low-latency communication and advanced AI, robots can interact more naturally with humans, providing intuitive user interfaces, gesture recognition, and predictive assistance in settings like hospitals, retail outlets, or homes [103],[104].
- **Continuous Learning and Evolution:** AI-driven networks can collect performance metrics from robots, update models automatically, and disseminate improvements back to the entire

fleet. This closed feedback loop accelerates innovation and ensures that robotic systems operate at peak efficiency [105],[106] .

In summary, AI and Communication converge in 6G to create a network that is not only faster and more reliable but also contextually adaptive and capable of real-time collaboration. By offering distributed intelligence and predictive resource allocation, AI-enhanced communication elevates robotic applications, empowering them to handle complex tasks, interact safely with humans, and adapt to evolving operational conditions with minimal intervention.

3.2.3. ISAC and Unifying Wireless Signals for Dual Purposes

A distinguishing feature of 6G is the convergence of sensing and communication functionalities within a unified framework, often referred to as Integrated Sensing and Communication (ISAC). While earlier mobile networks have primarily focused on data transport, 6G envisions leveraging communication signals for simultaneous environmental sensing, reconstruction, localization, object detection and even object imaging. For robotic systems, this synergy unlocks powerful capabilities such as enhanced navigation, real-time mapping, and situational awareness without relying solely on onboard sensors [107]-[109].

Advanced Requirements and Design Considerations

- **Privacy and Ethical Concerns:** Using communication signals for sensing can inadvertently gather sensitive data (e.g., tracking individuals or identifying assets). Regulatory and ethical frameworks must be established to address privacy implications [107]-[111].
- **Interference Management:** Sensing operations share the same spectrum used for data transmission. Striking a balance between sensing fidelity and communication throughput calls for sophisticated interference cancellation and resource allocation schemes [114],[115].
- **Computational Overhead:** Real-time signal analysis for sensing tasks can be computationally intensive, requiring edge computing solutions and efficient AI models to keep latency low [116].

Key Technological Enablers

- **Environmental Scanning and Reconstruction:** Radio waves used for communication can also capture reflections from surroundings, enabling radar-like sensing for obstacle detection, material classification, or motion tracking [107]-[110].
- **Precise Localization:** By analyzing signal propagation delays, angles of arrival, or Frequency doppler shifts, ISAC systems can determine the position of robots (or other objects) with centimeter-level accuracy, even in indoor or GNSS-denied (Global Navigation Satellite System denied) environments [107]-[111]. ISAC enables localization of any kind of objects even it is not equipped with a radio node.
- **Imaging:** ISAC enables the mobile radio system to perform imaging even of hidden objects. Materials have different reflection coefficients in different frequency bands of the entire mobile radio spectrum. Radio waves are absorbed or even propagated through the material to the objects behind of wall or inside of paper boxes [112].
- **Advanced Waveforms and Antenna Arrays:** Techniques such as massive MIMO (Multiple Input Multiple Output) and beamforming allow 6G networks to direct energy precisely, enhancing both sensing resolution, accuracy and communication efficiency [113].

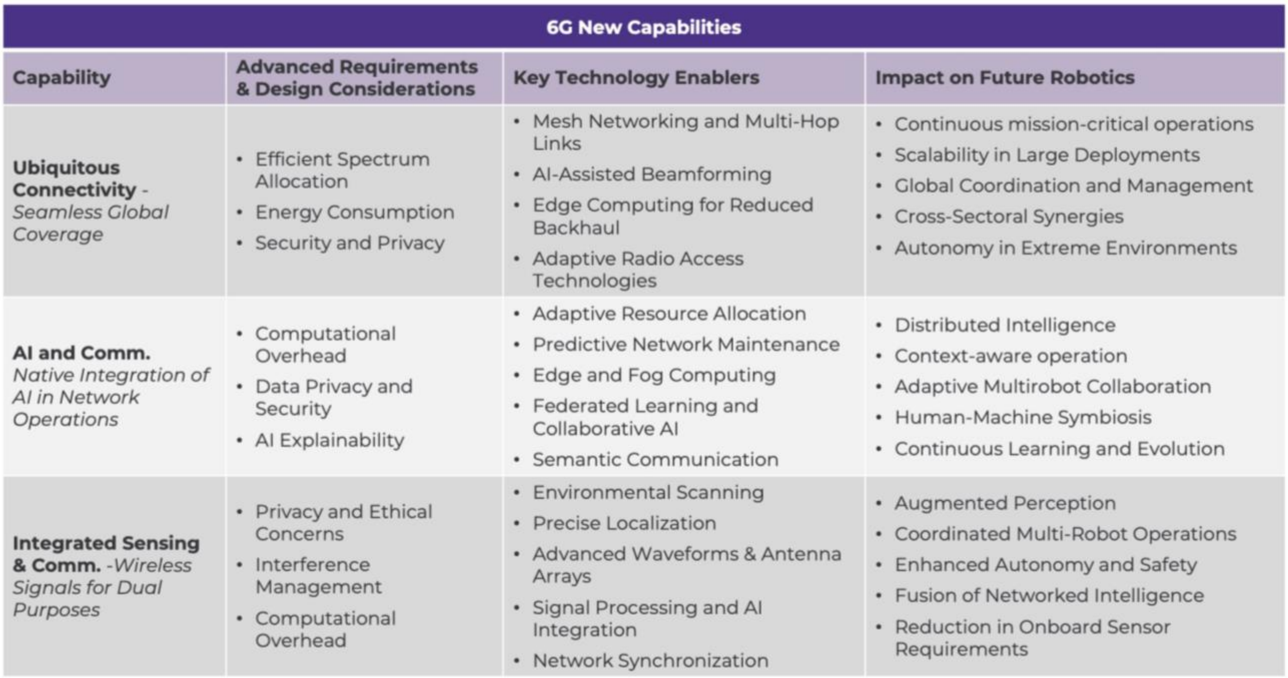
- **Signal Processing and AI Integration:** AI-driven algorithms can analyze reflected signals to detect objects, classify objects and obstacles, or predict motion trajectories. These insights can be relayed back to robots instantly for adaptive path planning [107]-[111].
- **Network Synchronization:** Reliable time and frequency synchronization across base stations and edge nodes ensures that sensing data remains coherent, enabling collaborative sensing and precise localization in multi-robot deployments [107]-[111].
- **Network and Device assisted ISAC:** ISAC can be applied at 6G base stations as well as on 6G devices. Sensing performed by 6G base stations enables network centric sensing in a kind of “bird view” of the area covered. It is using OFDM signals in downlink to illuminate the scene while device-based sensing utilizes the radio signals transmitted by the 6G user equipment e.g. via antennas mounted on the robot. Combining both, multiple base station and/or multiple devices forms a multi-static-sensing network.

Impact on Future Robotics

- **Augmented Perception and Environmental Awareness:** Network-assisted sensing will serve as an additional source of environmental data for robots since ISAC complements onboard cameras and LiDAR systems, improving the detection of transparent, reflective, or occluded objects. Thus, robots operating in complex environments (like crowded warehouses or urban streets) benefit from a richer perception layer [107]-[111].
- **Coordinated Multi-Robot Operations:** ISAC allows robots to share real-time environmental data, enabling better coordination and collaborative decision-making, e.g. for navigation and trajectory plan, collaboration and safe co-existence, etc. Shared sensing data can be fused across robotic fleets, creating a collective map of the environment. This is critical for swarm robotics, where distributed teams coordinate tasks like large-scale search and rescue or industrial inspections [111].
- **Enhanced Autonomy and Safety:** Robots can navigate unfamiliar or dynamic environments with reduced risk of collisions, thanks to near-instantaneous awareness of obstacles and potential hazards gleaned from ISAC data [67],[107]-[110].
- **Fusion of Networked Intelligence:** Multiple robots can collectively build high-resolution maps, share them over 6G connections, and constantly refine situational awareness. This fosters cooperation in scenarios like warehouse automation, construction, or public safety [56][59][79].
- **Reduction in Onboard Sensor Requirements:** By leveraging ISAC signals from the network, robots may rely less on costly or bulky sensors, lowering hardware costs and power consumption while still achieving high levels of autonomy [107]-[111]. Furthermore, any robot will be equipped with radio antennas that can be re-used for radio sensing purposes in the different frequency bands defined by ITU for radio communication.

In summary, ISAC transforms the network from a mere data conduit into a sensor-rich platform capable of offering precise and real-time environmental information. By merging these functions, 6G empowers robots with heightened awareness and the ability to collaborate intelligently, laying a foundation for highly autonomous operations across diverse application domains. The new capabilities of 6G technology have significant implications for and impacts on robotics, as summarized in Table 2.

Table 2: 6G new capabilities and their impact on robotics ecosystem



6G New Capabilities			
Capability	**Advanced Requirements & Design Considerations**	**Key Technology Enablers**	**Impact on Future Robotics**
Ubiquitous Connectivity - *Seamless Global Coverage*	• Efficient Spectrum Allocation • Energy Consumption • Security and Privacy	• Mesh Networking and Multi-Hop Links • AI-Assisted Beamforming • Edge Computing for Reduced Backhaul • Adaptive Radio Access Technologies	• Continuous mission-critical operations • Scalability in Large Deployments • Global Coordination and Management • Cross-Sectoral Synergies • Autonomy in Extreme Environments
AI and Comm. *Native Integration of AI in Network Operations*	• Computational Overhead • Data Privacy and Security • AI Explainability	• Adaptive Resource Allocation • Predictive Network Maintenance • Edge and Fog Computing • Federated Learning and Collaborative AI • Semantic Communication	• Distributed Intelligence • Context-aware operation • Adaptive Multirobot Collaboration • Human-Machine Symbiosis • Continuous Learning and Evolution
Integrated Sensing & Comm. -*Wireless Signals for Dual Purposes*	• Privacy and Ethical Concerns • Interference Management • Computational Overhead	• Environmental Scanning • Precise Localization • Advanced Waveforms & Antenna Arrays • Signal Processing and AI Integration • Network Synchronization	• Augmented Perception • Coordinated Multi-Robot Operations • Enhanced Autonomy and Safety • Fusion of Networked Intelligence • Reduction in Onboard Sensor Requirements

3.3. 6G Overarching Aspects

As IMT-2030 (6G) expands communication capabilities to meet the sophisticated demands of next-generation robotics, several overarching design principles ensure that these technological advancements align with broader societal, environmental, and ethical considerations. These guiding principles provide a holistic framework for developing networks and robotic solutions that are not only high-performing but also sustainable, inclusive, and secure [117].

Sustainability

- **Eco-Friendly Practices:** The deployment of 6G networks and robotic systems must minimize carbon footprints through energy-efficient hardware, renewable energy integration, and intelligent power management [118].
- **Lifecycle Considerations:** From manufacturing to end-of-life, designing robots and network components with reusability and recyclability in mind helps reduce waste and environmental impact [118].
- **Resource Optimization:** AI-driven algorithms can dynamically adjust transmission power and network resources, ensuring minimal energy consumption while maintaining performance [119].

Connecting the Unconnected

- **Expanded Access:** One of 6G's core objectives is to bridge the digital divide by extending coverage to underserved or remote areas, enabling robotics solutions for agriculture, healthcare, and education in places previously lacking reliable connectivity [120].

- **Inclusivity and Cost-Effectiveness:** Lower-cost hardware, shared infrastructure models, and simplified network architectures help ensure that small businesses and local communities can adopt robotic technologies without prohibitive upfront costs [121].
- **Community Empowerment:** By providing robust connectivity, local innovators and entrepreneurs can develop or adapt robotic applications to address region-specific challenges ranging from crop monitoring to medical diagnostics [122].

Ubiquitous Intelligence

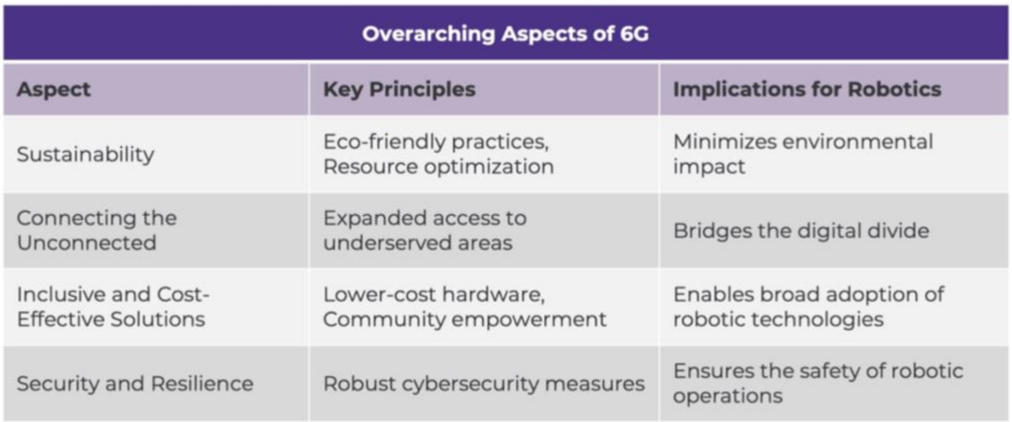
- **AI-Driven Autonomy:** 6G natively integrates machine learning at every layer, from radio resource management to application orchestration, enabling robots to operate autonomously with context-aware decision-making [123]-[125].
- **Distributed Learning:** Edge computing and federated learning models allow robots and network nodes to collaboratively refine AI algorithms, improving functionality while preserving privacy and reducing backhaul traffic [84],[126]-[130].
- **Adaptive, Self-Optimizing Systems:** Continuous monitoring and predictive analytics help preempt performance bottlenecks or failures, ensuring robots and the network adapt in real-time to shifting operational demands [131],[132].

Security and Resilience

- **Robust Cybersecurity:** As robots handle increasingly critical tasks, from manufacturing lines to healthcare services, encryption, secure authentication, and intrusion/ anomaly detection become paramount to prevent malicious interference and other aberrations [87].
- **Network and System Redundancy:** Multi-connectivity and edge-based failover strategies protect against single points of failure, ensuring that mission-critical robotic applications remain operable even during localized outages [87],[133].
- **Privacy Preservation:** Data gathered by robots (often from sensitive environments) must be processed and shared responsibly. Mechanisms such as secure enclaves, differential privacy, and role-based access can help uphold user trust and regulatory compliance [87].

The overarching aspects of 6G technology have significant implications for and impacts on robotics, as summarized in Table 3.

Table 3: 6G overarching aspects and their implications to robotics ecosystem



Overarching Aspects of 6G		
Aspect	**Key Principles**	**Implications for Robotics**
Sustainability	Eco-friendly practices, Resource optimization	Minimizes environmental impact
Connecting the Unconnected	Expanded access to underserved areas	Bridges the digital divide
Inclusive and Cost-Effective Solutions	Lower-cost hardware, Community empowerment	Enables broad adoption of robotic technologies
Security and Resilience	Robust cybersecurity measures	Ensures the safety of robotic operations

4. When 6G Meets Robotics

Expected to roll out around 2030, 6G will bring unprecedented advancements in speed, latency, and connectivity, enabling robots to operate with enhanced precision, autonomy, and efficiency. Technology enablers are further explored below in their capacity empowering robotics with a view to map them with the IMT-2030 new and enhanced capabilities (Section 3) to map with the robotic functional blocks (Section 2.1). We will further present a high-level architecture highlighting the capabilities of communication networks' role in supporting robotics applications, especially in perception, cognition, and actuation domains. Understanding these impacts is essential for optimizing network performance for robotics.

4.1. Integrated Sensing and Communication for Robotics Applications

Since robotic operations require high-resolution sensing, precise actuation, and ultra-reliable communication for minimal sensing error and seamless interactions with close-to-zero latency, there is a need to provide innovative integrated sensing and communication solutions [134]. The current ISAC landscape faces several challenges such as cost-effectiveness, effective waveform design, channel modelling, etc., which have started to be addressed in the latest research works [135],[136], and are expected to mature for use-cases such as in smart healthcare, public safety, industrial IoT and robotics-based applications.

Besides the evident issues of security and privacy, sensing/mapping accuracy and communication reliability are equally important aspects while utilizing ISAC for robotics to accurately perceive their environments and interactions, especially reliability becomes more crucial in applications where robots operate in close proximity to humans. Based on latest updates of 3GPP Rel. 19, ISAC can be utilized to further robotics-oriented applications such as in public safety and disaster management scenarios (such as with integration of non-terrestrial networks and use of dual function ISAC signalling for object detection and setup communication links in the disaster affected region), smart healthcare where ISAC-based robotics can be utilized for gesture recognition, fall detection and prevention, motion monitoring, etc., and in vehicular networking scenarios such as driverless cars where centimetre level accuracy is required for high-resolution localization and positioning [137]. In 2025 5G-ACIA has published a white paper about ISAC for connected industries and automation [200]. To this end, ISAC-robotics can be utilized to achieve centimetre or even mm-level accuracy for localization, object detection and tracking and imaging depending on the used frequency band and signal bandwidth.

ISAC, in conjunction with 6G capabilities, is intended to use shared communication channels, that are susceptible to eavesdropping and cyberattacks. Thus, the ISAC-assisted robotics poses challenges for implementing robust encryption and authentication mechanisms which are expected to be addressed comprehensively as we progress towards making 6G a reality, and explore merger of different technologies such ISAC and robotics enabling various 6G applications and use-cases as mentioned above.

4.2. Connected Perception in Robotics

The integration of connected robots into the Cooperative, Connected, and Automated Mobility (CCAM) ecosystem represents a significant advancement in the field of autonomous systems. This paper explores the development of connected perception, a critical capability that enhances a robot's understanding of its environment through effective communication with vehicles and other agents. By facilitating the exchange of information regarding detected objects, connected perception serves as the foundation for improving situational awareness and safety in complex urban traffic scenarios.

Fundamental to this discourse is the initiative presented in the Vehicle-to-Everything (V2X) V2X4Robot project, which proposes a "social robot policeman" that acts as an intermediary between automated vehicles and vulnerable road users as is described in Figure 4. This concept underscores the necessity for integrating three key enablers: formal specifications of driving manoeuvres, vehicular communications, and social human-robot interactions. These elements are essential for enabling robots to comprehend traffic situations and respond appropriately, thereby promoting safer interactions among road users.

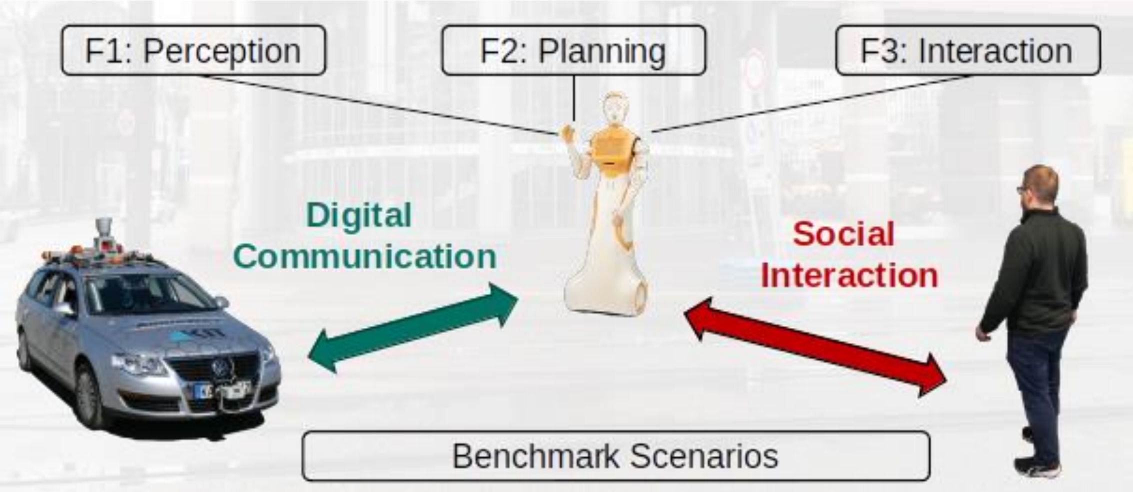


Figure 4: A social robot as a mediator of mixed traffic block

Moreover, the use of social robots for pedestrian traffic guidance, as demonstrated in the study [138] highlights the potential of utilizing immersive technologies to enhance public understanding and engagement with autonomous systems. The incorporation of point-of-view 360-degree videos in Virtual Reality allows stakeholders to visualize and interact with emerging technologies, thereby facilitating early citizen involvement and aligning expectations with the capabilities of novel systems.

As we consider the future implementation of these technologies, the emergence of 6G capabilities will play a transformative role. With ultra-reliable low-latency communication (URLLC) and high bandwidth, 6G will enable real-time data exchange among connected entities, enhancing the effectiveness of connected perception. This capability is crucial for facilitating rapid decision-making processes and ensuring that robots can adapt to dynamic environments with agility and precision.

Furthermore, the integration of advanced artificial intelligence, bolstered by 6G connectivity, will improve interaction strategies, allowing robots to utilize natural language processing for seamless communication with pedestrians. Additionally, V2X interactions will be significantly enhanced, ensuring that connected robots can communicate effectively with vehicles, infrastructure, and users in their operational environment.

The advancements brought by 6G enhance the following functionality requirements for connected perception in cobots:

- **Real-time Data Exchange:** The need for instantaneous communication between cobots and their environment to adapt to changing conditions swiftly.
- **Collaborative Decision-Making:** Enhanced mechanisms for multiple cobots to work together effectively, sharing insights and coordinating actions in real-time.

- **Adaptive Interaction:** The ability for cobots to engage with humans in a more natural and intuitive manner, utilizing immersive communication technologies to facilitate understanding.
- **Dynamic Environmental Awareness:** Continuous and integrated sensing capabilities that allow cobots to perceive their surroundings and respond to potential hazards or changes in the context.
- **Efficient Processing of Complex Data:** Leveraging AI to analyze large volumes of data transmitted through 6G networks, enabling cobots to make informed decisions based on contextual information.

In summary, the integration of 6G enhanced capabilities with new functionalities presents a transformative opportunity for connected perception in collaborative robots. By harnessing these advancements, cobots can operate more effectively within the CCAM ecosystem, ultimately leading to safer and more efficient interactions in urban environments. The future of mobility will be defined by the seamless integration of these technologies, enhancing the capabilities of autonomous systems and improving user experiences.

4.3. A 6G-Enabled Future for Soft Robotics

Soft robotics, with its inherent flexibility and adaptability, is poised to revolutionize various industries, from healthcare to manufacturing. 6G technologies, with their enhanced bandwidth, low latency, and advanced connectivity, will play a crucial role in enabling the full potential of soft robots, particularly in addressing challenges such as cabling.

Enhanced Communication Capabilities

6G technology is designed to support ultra-reliable low-latency communication, which is essential for real-time interactions among soft robots and their environments. This capability enables:

- **Inter-Robot Communication:** Soft robots can communicate with each other to coordinate tasks, share sensory data, and enhance collective intelligence, which is crucial for applications like search and rescue or environmental monitoring.
- **Intra-Robot Communication:** Within a single soft robot, 6G can facilitate communication between various sensors and actuators, allowing for more nuanced control and responsiveness to environmental changes, whilst reducing the need for cabling.

Advanced Sensing and Perception

Soft robots equipped with advanced multimodal sensors can significantly benefit from 6G's high data wireless transmission rates. These sensors enhance the robots' perception capabilities by providing real-time feedback on their surroundings, which is vital for tasks requiring precision and adaptability. The integration allows:

- **Augmented Perception Functions:** Soft robots can gather and process data from multiple sensors simultaneously, improving their ability to navigate complex environments and perform delicate tasks.
- **Machine Intelligence:** The combination of sophisticated sensors and 6G connectivity enables the development of machine learning algorithms that can process large amounts of data quickly, facilitating autonomous decision-making and enhanced operational capabilities.

Table 4 presents a mapping of the 6G enabling technologies to soft robotic functional blocks.

Table 4: Benefits of 6G enabling technologies and soft robotic functional blocks

6G Enabling Technology	Soft Robotic Functional Block	Benefits
Immersive Communication	**Sensing and Perception:** Enables high-resolution data transmission from distributed sensors embedded within the soft robot, providing detailed information about the environment and contact forces.	Improved accuracy and precision in object manipulation, obstacle avoidance, and human-robot interaction.
Hyper Reliable & Low-Latency Communication	**Control and Actuation:** Allows for real-time control of soft actuators, enabling rapid responses to changes in the environment and precise manipulation of objects.	Enhanced dexterity, responsiveness, and adaptability in dynamic environments.
Ubiquitous Connectivity	**Communication and Collaboration:** Facilitates seamless communication between multiple soft robots, enabling collaborative tasks and distributed sensing networks.	Improved efficiency, scalability, and complex task execution in challenging environments.
AI and Communication	**Learning and Adaptation:** Enables soft robots to learn from experience, adapt to new environments, and optimize their behavior for specific tasks.	Increased autonomy, intelligence, and adaptability in diverse applications.
Integrated Sensing and Communication	**Sensing and Communication Fusion:** Combines radio sensing and communication capabilities, allowing robots to use their communication channels for radio sensing purposes and vice versa.	Enhanced situational awareness, more efficient data transmission, and improved collaborative capabilities which complements onboard-sensors

4.4. Goal-Oriented Semantic Communication

This involves transmitting not just raw data, but also the meaning and context of the information. This enables robots to understand the intent and goals behind the data, leading to more intelligent and efficient operations. The field of goal-oriented semantic communication for 6G-empowered robotics is still nascent, but significant research efforts are underway. To enable robots to understand the meaning of data beyond raw bits, semantic communication requires a sophisticated approach. This involves efficiently representing semantic information for transmission, often using ontologies, knowledge graphs, or semantic networks. Crucially, context must be incorporated into the communication process, allowing robots to interpret data based on their environment and tasks. This necessitates algorithms for encoding and decoding semantic information, often leveraging AI techniques like natural language processing (NLP) or machine learning (ML) to bridge the gap between raw data and meaningful understanding. AI plays a pivotal role in this process, enabling semantic encoding and decoding, contextual understanding, and ultimately, informed decision-making based on the semantic information received. This empowers robots to become more intelligent and adaptive, leading to a new era of robotics.

6G offers crucial features for goal-oriented semantic communication, including:

- **Ultra-low Latency:** Enables real-time communication and control, vital for responsive robotics.

- **Enhanced Reliability:** The technology aims to provide ultra-reliable communication links, crucial for safety-critical applications in robotics, such as tele-medicine and autonomous driving.
- **High Bandwidth:** Allows for transmission of large amounts of data, including complex semantic information.
- **Massive Connectivity:** Supports the connection of multiple robots and sensors, facilitating collaborative tasks.
- **Advanced Sensing and Positioning:** 6G is expected to enhance the capabilities of sensors used in robotics, allowing for more accurate environmental awareness and positioning through technologies like massive MIMO and THz communications.

The envisioned *use cases* for goal-oriented semantic communication in robotics, such as industrial automation, search and rescue, healthcare, and agriculture, highlight the critical need for advanced communication capabilities like those promised by IMT-2030. These applications demand high-resolution sensing, real-time data exchange, secure and reliable communication, and precise positioning, all of which are addressed by the ultra-low latency, high bandwidth, massive connectivity, and network slicing capabilities of IMT-2030. Furthermore, the ability to transmit semantic information, enabling robots to understand the context and intent of data, is essential for intelligent decision-making in these complex and dynamic environments. Addressing the challenges of standardization, security, energy efficiency, and AI development will be crucial for realizing the full potential of this transformative technology.

Goal-oriented semantic communication, enabled by 6G technology, holds immense potential for revolutionizing robotics. By leveraging the power of AI and advanced communication capabilities, robots can become more intelligent, adaptable, and capable of performing complex tasks in diverse environments. Overcoming the *challenges of standardization*, security, and energy efficiency will be crucial for unlocking the full potential of this transformative technology.

4.5. Cognitive Communication Continuum

The Cognitive Communication Continuum (CCC) framework is deeply rooted in both foundational and contemporary research aimed at enhancing the operational capabilities of Autonomous Mobile Robots (AMRs) and Unmanned Aerial Vehicles (UAVs) in the context of emerging 6G technology. As 6G networks promise ultra-fast data transmission, enhanced reliability, and comprehensive connectivity, they will empower advanced applications that necessitate real-time data processing and intelligent decision-making.

At the core of the CCC framework is ISAC, which is vital for high-accuracy localization and situational awareness. Building upon this foundation, Demirhan and Alkhateeb [139] examined ISAC within the CCC framework, underscoring its critical role in 6G networks and autonomous systems. The framework also aligns with the Cognitive Continuum Theory introduced by Hammond [141], which explores the spectrum of cognitive processes from intuitive to analytical thinking, further illuminating how cognitive tasks influence decision-making across varied contexts.

Moreover, Nawaz *et al.* [141] emphasized the potential of quantum machine learning to enhance cognitive capabilities within 6G networks, supporting the principles of the CCC and envisioning a future for communication technologies. Murroni *et al.* [143] conducted a survey highlighting how the CCC can foster smarter urban environments through improved communication and decision-making, thereby enhancing the effectiveness of 6G applications in smart city scenarios. Additionally, Puspitasari *et al.* [144] explored integrating machine learning into the CCC framework to improve adaptability and responsiveness in 6G networks, addressing challenges such as throughput enhancement, energy efficiency, and secure communication.

Central to the CCC framework is cognitive multi-connectivity, which enables devices to connect and communicate across multiple networks simultaneously, optimizing data flow and enhancing situational awareness. This capability is essential for applications requiring real-time data processing and decision-making, particularly in autonomous systems and immersive technologies.

Recent advancements in this area focus on leveraging multidimensional connectivity patterns to enhance information exchange among devices. However, the extraordinary emergent capabilities of large language models (LLMs), such as in-context learning and chain-of-thought reasoning, have yet to be fully utilized, especially at the intersection of robotics and communications. The impressive cognitive and semantic abilities of LLMs, which integrate knowledge from pre-trained foundation models, can significantly contribute to the autonomous deployment and operation of 3D networks populated with AMRs and AGVs.

Together, ISAC, connected perception, and goal-oriented communication form a cohesive CCC framework that is pivotal for advancing the capabilities of autonomous systems within the 6G landscape [137]-[144].

4.6. Mapping with Robotic Functional Blocks and High-Level Architecture

As robotics applications advance, the convergence of sophisticated network technologies and intelligent algorithms becomes paramount. This section elucidates the evolution of network slicing and the integration of AI and ML within 6G networks, emphasizing their profound implications for enhanced robotic capabilities.

4.6.1. Evolution of Intelligent and Dynamic Resource Management

Network slicing, a pivotal feature of 5G and envisioned to be significantly enhanced in 6G, is advancing towards more agile and adaptive configurations. This evolution prioritizes the creation of dynamic slices with tuneable parameters, thereby fostering enhanced Key Performance Indicator (KPI) pipelines that seamlessly integrate communication and computation resources [183]. Usage of AI/ML methods to manage slices is instrumental in achieving dynamic and autonomous slice management [145]. A central focus remains on optimizing latency and reliability to meet the stringent requirements of robotic applications [191].

A key advancement lies in the concept of intent-based networking (IBN), which facilitates seamless interactions between robotic applications and underlying network infrastructure. This approach enables the translation of high-level, human-readable service requests—expressed in formats such as JSON—into actionable network configurations [196]. Advanced AI models such as Large Language Models (LLMs) are ideal solution for mapping human-readable intents into lower-level network configuration commands across different network domains [146]. Consequently, groups of robots can more effectively manage and orchestrate network resources to support their operational demands. As robotic services become increasingly granular and adaptable, the prioritization of network slice customization based on specific user intents is further amplified [185].

4.6.2. Network Support for AI/ML in 6G

The integration of AI and ML into 6G networks is critical for supporting the burgeoning computational and decision-making needs of advanced robotics [188]. By enabling the execution of AI/ML algorithms directly within the network fabric, previously unrealizable levels of real-time data processing and autonomous decision-making become possible (3GPP TS 23.548). This paradigm shift facilitates enhanced network performance and adaptive resource allocation tailored to the evolving demands of robotic systems.

The Network Data Analytics Function (NWDAF) framework is poised to play a pivotal role in this transformation by leveraging distributed and federated learning methodologies to optimize network functionalities and predictive capabilities [195]. Concurrently, the Radio Access Network (RAN) domain, supported by initiatives such as the AIRAN alliance [147], is focusing on harnessing AI to optimize RAN performance through dynamic slicing that encompasses both communication and computation resources. This dynamic approach is of particular importance for robots that demand high-intensity AI-driven vision computation, enabling real-time object recognition, scene understanding, and path planning [181].

Furthermore, the advent of agentic introduces an innovative approach wherein autonomous agents can, based on the context, autonomously execute non-trivial task sequences without any human intervention to address emerging service requests [148]. Agentic AI is a promising concept whose development and integration in robotic applications necessitates new agents to address emerging tasks or service requests that necessitate additional functionalities such as self-learning (as described in section 2.1.4). This self-learning and adaptive capability hold significant potential for enhancing the resilience and autonomous operation of robotic deployments in dynamic and unpredictable environments.

Table 5: Key technology enablers for robotic functional blocks

Robotic Functional Block	Key Technology Enabler
Sensing	ISAC, Semantic Communication, 6G High Bandwidth, AI for Data Interpretation, Sensor Fusion (e.g., GPS, vision, radar)
Perception	Semantic Communication, 6G Ultra-low Latency, 6G Massive Connectivity
Cognition	Semantic Communication, Cognition Communication Continuum, AI for Decision Making, 6G Network Slicing for Dedicated Resources
Actuation	6G Ultra-low Latency for Precise Control, AI for Location Estimation and Motion Planning

Sensing: The sensing functional block in 6G networks encompasses network-based and device-based sensing, enhancing robotic board sensors by simplifying operations. This approach involves wireless-connected actuators and internal sensors, which improve reliability by reducing or eliminating the need for wired connections.

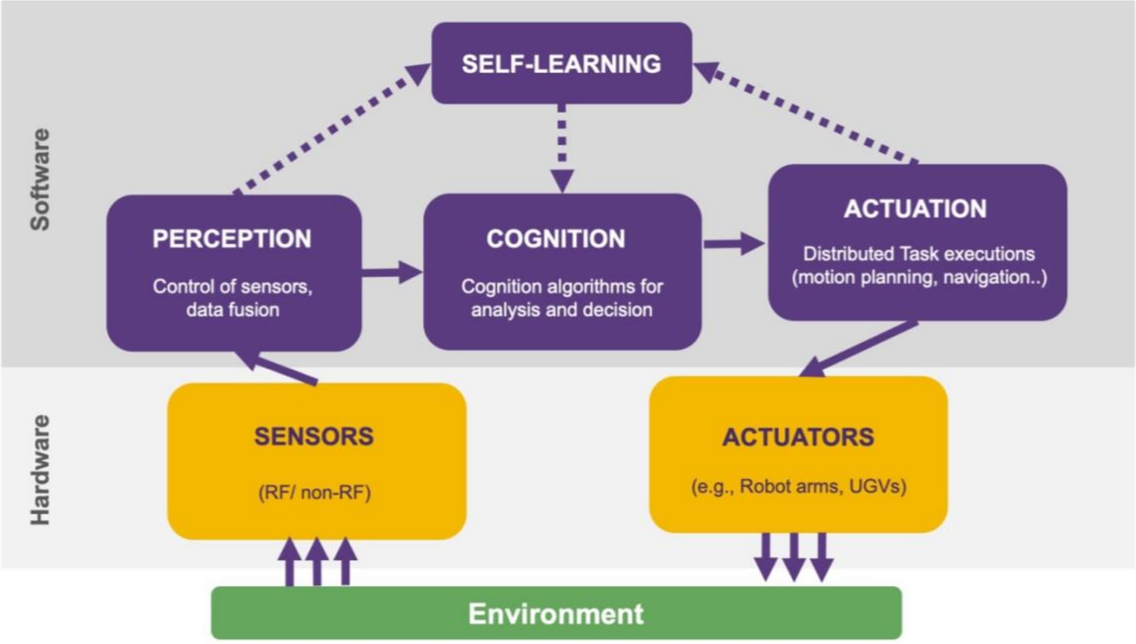


Figure 5: Two level architecture

Key Points:

- **Enhanced Perception Capabilities:** Wireless-connected sensors allow for easy and scalable extension of perception capabilities without introducing additional hardware complexity.
- **6G Advancements:** 6G introduces new features through ISAC Capabilities, offering the potential to complement or replace existing sensing systems.
- **Customized Design:** Wireless-connected subsystems enable on-demand, easy, and modularized design, facilitating customization and flexibility in sensor deployment.
- **Multi-Purpose Devices:** Devices integrating communication and sensing functionalities offer versatility and efficiency in diverse applications.
- **6G ISAC Capabilities:** 6G ISAC-capable devices provide advanced functionalities such as material classification and flexible safety zone management, showcasing the innovation potential of integrated sensing technologies in 6G networks.

Perception plays a vital role in network systems by gathering and analyzing data from sensors, including information from ROS. In the network context:

- **Distributed Processing:** Networks facilitate flexible distributed processing and function splitting, enhancing efficiency
- **Trust in Processing:** 6G networks ensure trusted perception processing within secure network environments.
- **External Communication:** Wireless connectivity enables seamless communication with the cloud, allowing for data offloading and enhanced computing capabilities. This integration supports efficient data management and processing in network systems.

Cognition in network systems involves understanding tasks based on different autonomy levels - manual control, semi-autonomous, and fully autonomous. In the network domain:

- **Cognitive Modeling:** Networks support the creation of a cognitive model that represents the robot, its environment, and interactions, aiding in task comprehension.
- **Data Management:** Comprehensive data management within networks enables remote intra- and inter-robotic coordination, eliminating storage and computing constraints.
- **AI and Data Fusion:** Network AI and data fusion processes leverage native intelligence to enhance robotic cognition by abstracting knowledge from diverse fused data sources, fostering an advanced level of cognitive capabilities in robotic applications.

Actuation involves executing tasks such as motion control, force control, and impedance control to drive robotic actions, guided by cognitive inputs from the perception layer. In the network context:

- **Control Execution:** Robotics control applications are executed on the robot, at the edge, or in the cloud, tailored to the robot type, use case, or user solution strategy.
- **Enhanced Tasks:** AI and communication technologies enhance tasks like motion planning, and optimizing operations.
- **Cloud Integration:** Cloudification enables distributed machine actuation functions, like motion planning and navigation, to be relocated on demand.
- **Performance Standards:** Network systems strive for extreme performance with ultra-short control cycles and high-density links for rapid control and actuation responses.
- **Control Protocols** Utilization of common middleware like ROS and industrial protocols such as EtherCAT, ProfiNet, and OPC-UA ensure efficient control mechanisms that contribute to the flexibility and intelligence of robotic control systems, for instance in Flexible Manufacturing Systems.

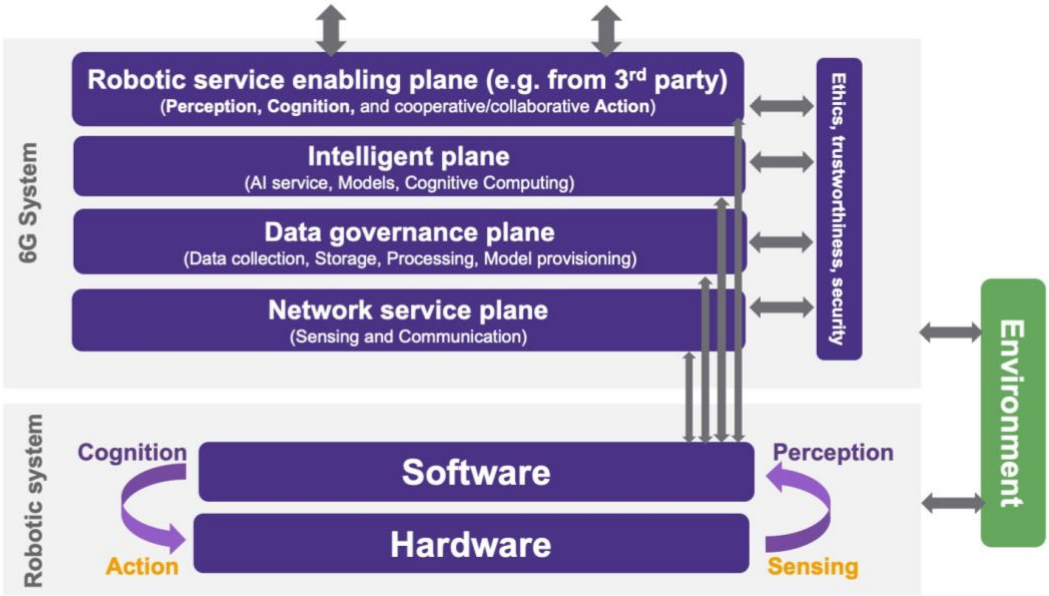


Figure 6: High level architecture

The network service for robotics applications may comprise more functions detailed.

5. Overarching Considerations

Privacy and ethical considerations related to AI models and techniques, especially in robotics and 6G technologies, necessitate responsible algorithmic design and data handling. Trustworthiness is essential for building public confidence in these emerging technologies. By prioritizing ethical and ideally rights considerations, such as transparency and user consent, we can ensure that AI and robotics developments align with societal values and regulatory frameworks. This approach not only enhances public trust but also supports the sustainable and responsible integration of advanced technologies into everyday life.

5.1. Privacy and Ethical Considerations of AI Models and Techniques

Considerations for AI models and techniques in processing multimodal information from robots or 6G sensing involve identifying potential privacy and ethical aspects. Addressing these concerns is vital for ensuring responsible and secure data handling in robotics and 6G environments [149]-[155].

Trustworthiness has emerged as a critical issue for the general public to feel at ease with the new technologies entering the market and their lives. By prioritizing privacy, ethics, and trustworthiness in the design and implementation of AI models for robotics and 6G sensing, we can foster trust resulting in greater public confidence and acceptance of these transformative technologies.

IEEE, through its various standards development activities, is playing a crucial role in addressing these concerns. For example, the IEEE 7000 standard focuses on ethical considerations in the design of autonomous and intelligent systems, while the IEEE 7003 standard specifically addresses algorithmic bias considerations.

By aligning with these IEEE initiatives and incorporating privacy, ethics, and trustworthiness into the core of AI development for robotics and 6G sensing, we can ensure that these technologies are deployed in a responsible and beneficial manner, ultimately enhancing public trust and acceptance.

As the social impact of technologies becomes more pronounced, it is crucial for those responsible for specification, design, architecture and design/development to consider the social implications, including cultural values and context of deployment. Key considerations include:

- The ethical considerations surrounding trustworthiness in AI are not adequately protected nor sufficiently addressed by existing legal frameworks. Transparency and fairness, while essential, do not encompass the full spectrum of rights and values outlined in the UN declarations and national laws.
- The importance of communication as a conduit within robotic infrastructures. Achieving high-speed integration within a distributed robotics ecosystem is essential, as it mitigates bottlenecks associated with centralized control.
- The need to eliminate wired components in robotic design pose integrity and security vulnerabilities, as cabling has proven to be a significant challenge.
- The potential of communication technology to facilitate interoperability among robotic systems, paving the way for comprehensive robotic manufacturing and the establishment of relevant standards.

5.2. Service Robots and Human in the Loop Scenarios

- **Privacy Protection:** Ensuring that AI techniques used in service robots and humanoids respect user privacy by implementing robust data protection measures and minimizing data collection.
- **Transparency:** Developing AI systems that provide clear explanations of their decisions and actions, fostering user understanding and trust in robotic cognition and interactions.
- **Fairness and Non-Discrimination:** Implementing algorithms that promote equitable treatment across diverse user groups and contexts, avoiding biases that could lead to unfair outcomes or reinforce stereotypes.
- **Accountability:** Establishing clear accountability mechanisms for the actions of service robots and humanoids, ensuring that developers and operators are responsible for the ethical implications of AI technology.
- **User Consent:** Prioritizing informed consent processes for users, allowing them to understand how their data will be used, stored and exchanged and giving them control over their personal information.
- **Cultural Sensitivity:** Designing AI systems that are aware of and respect different cultural values and norms, ensuring that service robots and humanoids can operate effectively in various social contexts.
- **Continuous Ethical Assessment:** Encouraging ongoing evaluation and adaptation of AI techniques to address emergent properties/behaviors leading to ethical concerns and societal impacts, ensuring that service robots and humanoids align with evolving ethical standards.

By focusing on these considerations, developers can enhance the trustworthiness and ethical deployment of AI in service robots and robots operated by humans, ultimately leading to more responsible and user-friendly technologies.

In light of the evolving landscape of 6G technology and its potential implications, it is imperative to prioritize transparency, accountability and ethical considerations in research. The following recommendations outline key activities that should be undertaken to address these critical issues:

- **Establishing Ethics Profiles for the Network Dimension:** Develop comprehensive ethic profiles that consider the unique challenges posed by the network dimension of 6G. This involves identifying ethical dilemmas, potential biases, and societal implications associated with the deployment of advanced connectivity systems employing 6G technologies.
- **Conducting Studies on the Social Impact of 6G Architecture:** Initiate research studies aimed at assessing the social impact of 6G architecture. This should include evaluations of how 6G will affect various stakeholders, including vulnerable populations, and how it can be leveraged to promote social good.
- **Focusing on Ethics Profiling Activities:** In the absence of a finalized 6G architecture, the focus should shift to ethics profiling activities. This includes establishing baselines related to cyber resilience and ensuring compliance with the AI Act in Europe. These foundational efforts will create a framework for effective and consistent ethical considerations as 6G develops.
- **Conducting Outreach Studies for AI Deployment:** Research should be conducted to address the outreach necessary for AI deployment, considering potential conflicts with existing policies and EU laws concerning privacy and accountability. Understanding these dynamics is crucial for fostering public trust and ensuring responsible AI integration.

- **Collaboration under the one6G Initiative:** It is recommended to work collaboratively under the one6G initiative, which aims to align research efforts across various domains. This collaboration will facilitate sharing of insights and resources, ultimately contributing to a more comprehensive understanding of the ethical landscape surrounding 6G.
- **Presenting Findings to IEEE P1955:** Plan to present the findings from these research activities as a pre-draft to the IEEE P1955 standard within the next year. This engagement will not only contribute to the development of industry standards but also ensure that ethical considerations are integrated into the foundational frameworks of 6G technology.

By implementing these recommendations, researchers can proactively address the ethical and social implications of 6G technology, ensuring that its deployment aligns with rights, societal values and regulatory frameworks. This approach will foster a responsible and inclusive environment for the advancement of telecommunications and AI in the years to come.

5.3. Trustworthiness Considerations for Automation and Monitoring by AMRs, UGVs and UAVs

Robotic systems can automate the monitoring and maintenance of the smart grid infrastructure. Drones and robotic vehicles can inspect power lines, substations, and renewable energy sources, reducing the need for human intervention in potentially hazardous environments. That said, insecure communication between robots and Distributed Energy Resources (DERs) could allow malicious entities to manipulate energy flows, resulting in grid instability. Similarly, if robots are hacked during emergency operations, they could provide false information or disrupt recovery efforts. Therefore, while robots can gather real-time performance data, detect anomalies, and monitor environmental conditions, a full range of security challenges impact the system’s trustworthiness. To this end, we explore the shortcomings of conventional Model-Based Fault and Cyber Attack Detection in Autonomous Robots, Uncrewed Aerial Vehicles (UAVs), and Uncrewed Ground Vehicles (UGVs) [156].

Model-based fault detection and diagnosis (FDD) systems are essential for ensuring the reliability and safety of autonomous robots, drones, and UGVs. However, these systems face several shortcomings that can hinder their effectiveness in real-world applications. Some of the shortcomings of existing cyber-attacks in the presence of a robotics system are:

- **Complexity of Models:** Model-based FDD relies on accurate mathematical models of the system being monitored. Developing these models can be complex and time-consuming, particularly for highly dynamic environments where the behaviour of robots can change rapidly. If the model does not accurately represent the system's behaviour, it may lead to false positives or missed detections of faults. This complexity increases with the number of variables involved, making it difficult to maintain accurate models over time [157].
- **Sensitivity to Noise and Disturbances:** Model-based approaches often struggle with noise in sensor data and external disturbances. Small variations in input signals can lead to significant discrepancies in model outputs, resulting in incorrect fault diagnoses. This sensitivity can be particularly problematic in environments where conditions are unpredictable, such as during adverse weather for UAVs or in cluttered spaces for UGVs [158].
- **Limited Adaptability:** Many model-based FDD systems are not designed to adapt to new operating conditions or changes in system configuration. In scenarios where robots are deployed in unfamiliar environments or when they undergo modifications, existing models may become obsolete or inadequate. This lack of adaptability can severely limit the effectiveness of fault detection mechanisms [2].

- **Computational Demands:** The computational resources required for real-time model-based FDD can be substantial, especially for systems that need to process large volumes of data from multiple sensors simultaneously. This demand can lead to latency issues that are unacceptable for time-sensitive applications like emergency response or autonomous navigation [159]
- **Cybersecurity Vulnerabilities:** Model-based systems can also be susceptible to cyber-attacks that target their operational integrity. If an attacker gains access to the system's models or alters sensor data, they could manipulate fault detection mechanisms, leading to catastrophic failures. Ensuring robust cybersecurity measures while maintaining model accuracy is a significant challenge.

While model-based fault and cyber-attack detection has its advantages, it also faces several shortcomings when applied to autonomous robots, UAVs, and UGVs. Addressing these challenges requires ongoing research and development, with a focus on enhancing model adaptability, reducing computational demands, and improving the overall robustness of detection systems.

5.4. Dynamic and Smart Safety Zones enabled by 6G ISAC

With digital transformation, significant growth in autonomous systems, machine-type communication, and human machine collaboration, a fundamental imperative will be safe co-existence and interaction among machines (e.g. robots, UAVs), and within human machine shared spaces. Mechanisms such as those that provide dynamic trajectory plans and collision avoidance ensure safe and reliable operation.

In the context of human machine collaboration, a growing number of regulations and compliance requirements are expected. A leading example is the set of safety standards established by the European Union. The following provides a concise overview of the regulatory framework:

- The Machinery Directive is mandatory for all robots operating in industrial settings, such as factories and intralogistics (ISO/DIS 10218-1.2:2021).
- International Organization for Standardization (ISO) technical specification (TS), ISO/TS 15066 complements EN ISO 10218-1 by introducing a model of the human body with 29 points across 12 areas, which is designed to limit the force and power exerted by robots.
- Deutsches Institut für Normung (German Institute for Standardization) European Norm (EN), DIN EN ISO 13482:2014 [161] specifies safety requirements for personal care robots.
- International Electrotechnical Commission (IEC) IEC-80601-2-70 establishes standards for robots utilized in medical care, while IEC Systems Committee (SyC) Active Assisted Living (AAL) focuses on active assisted living.

These standards are essential to ensuring the safety and efficacy of human-robot collaboration in various contexts.

The 6G ISAC system possesses the capability to devise innovative solutions for the establishment of smart and dynamic virtual fences. In this context, several key use cases derived from existing regulations may be streamlined through the application of 6G ISAC technology:

- **Dynamic Safety Zones (DSZ):** The implementation of adaptable safety zones that can change in response to environmental conditions and operational requirements.

- **Speed and Separation Monitoring (SSM):** As delineated in ISO 10218-1.2:2021, this involves the continuous assessment of speed and spatial separation among robots and human operators to ensure safety.
- **Virtual Interaction Zones (VIZ):** The creation of task-specific interaction areas that facilitate safe collaboration between humans and robots.
- **Real-Time Interface Safety Functions (RTISF):** As outlined in ISO/DIS 10218/1, this refers to safety functions that operate in real-time to monitor and control interactions.
- **Transient Contact Avoidance (TCA):** In line with ISO/TS 15066, which complements EN ISO 10218-1, this involves strategies to prevent unintended contact between robots and humans during operation.

Utilizing service requests from both the robot operator and robot controller, the 6G system—comprising access points, base stations, and user equipment—can effectively sense the defined safety zones as illustrated in Figure 7. Furthermore, it can identify and characterize all objects (including passive entities, humans, and robots) within these designated areas, thereby enhancing operational safety and efficiency.

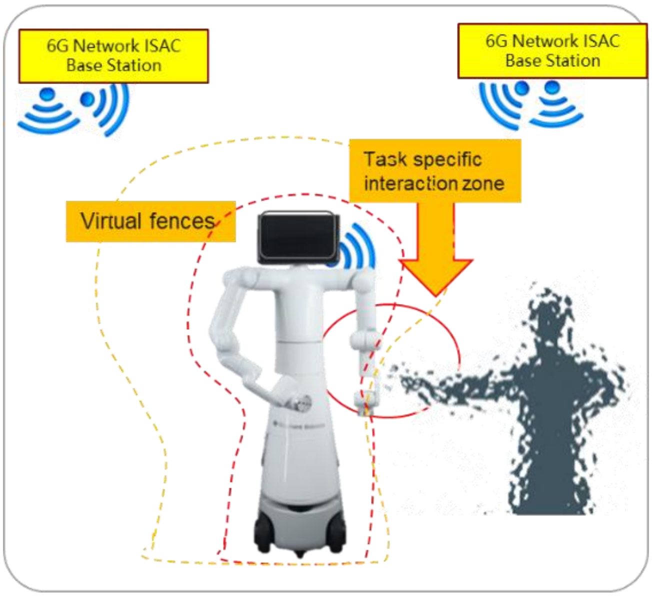


Figure 7: Virtual fences and smart interaction zones

5.5. Advancing Robotics for Sustainability with 6G-Enhanced Capabilities

Eco-friendly practices and energy-efficient robotics are essential for addressing environmental challenges and supporting the growing demand for sustainable industrial applications. Integrating 6G technology into robotics for sustainability-focused applications enhances operational efficiencies while ensuring scalable, environmentally responsible automation.

Advanced robotics and AI are critical for addressing challenges in hazardous environments, particularly in the disassembly of complex products such as Electric Vehicle (EV) batteries [163]. EV batteries are a rich source of critical materials essential for sustainability and achieving Net Zero 2050 goals [163]. However, their disassembly for reuse and recycling poses significant environmental, societal, and safety risks, including potential fire hazards, explosions, and toxic gas emissions [164].

The diversity of EV battery designs, combined with these challenges, requires AI-driven robotic solutions capable of adapting to varied battery models and other complex products, such as electric motors and wind turbines[165]. To address these issues, AI-based vision-guided manipulation techniques [166],[167] enhanced with telerobotics [168] and mixed-reality [169] technologies have been developed to automate the processes of testing [170], disassembly [171], and sorting [172] EV batteries. Additionally, machine learning, particularly neural networks, can estimate the state of health of batteries to determine whether they can be reused or should be recycled [173], [174].

By combining AI's adaptability with the high-speed connectivity of 6G, robots can achieve real-time decision-making and operational efficiency. This synergy enables robots to dynamically adapt to changing conditions and maintain optimal performance, even in challenging environments. These advancements significantly enhance precision and safety, providing scalable solutions to address the inherent risks of EV battery disassembly.

The exploitation of AI-powered robotics and 6G technologies in sustainability applications, such as EV battery recycling, contributes to the development of efficient and environmentally friendly processes. These innovations also support the principles of a circular economy[176] by enabling the recovery and reuse of valuable materials, thereby fostering a greener and more sustainable future. Table 6 maps key 6G capabilities to their relevance in advancing robotics with respect to sustainability, ethics and trustworthiness.

Table 6: 6G capabilities and their relevance to robotics

6G Capabilities	Relevance to Robotics
Integrated Sensing and Communication (ISAC)	Enables real-time data collection and processing by sensing the surrounding environment, allowing robots to optimize energy use and reduce operational waste while ensuring user privacy through robust data protection measures.
Ubiquitous Connectivity	Facilitates continuous communication between robots and centralized systems, enhancing coordination and ensuring transparency in AI decisions to foster user trust.
AI and Machine Learning Integration	Allows robots to adapt to environmental changes, optimizing their functions for minimal resource use, promoting fairness and non-discrimination across diverse user groups
HRLLC	Ensures that critical communications are timely and reliable, which is essential for safety and efficiency in autonomous and semi-autonomous systems, with clear accountability mechanisms for AI actions.
Support for Massive Communication	Ensures that numerous robots such as cobots can communicate simultaneously, enhancing collaboration in tasks like resource sharing, energy efficiency, and prioritizing user consent and cultural sensitivity in interactions.
Multimodal Applications Support	Enables robots to process and respond to various types of sensor data, enhancing their ability to operate efficiently, ensuring ongoing ethical assessment of AI techniques to address emerging societal impacts in diverse environments.

6G Capabilities	Relevance to Robotics
Edge Computing Support	Enables robots to process data locally, reducing latency and energy consumption, which is crucial for real-time applications in remote and hazardous environments and addressing cybersecurity vulnerabilities to maintain system trustworthiness.
Energy Harvesting and Management	Supports sustainable operations by enabling robots to monitor and optimize energy consumption dynamically, contributing to ethical deployment through continuous evaluation of energy consumption practices.
Enhanced Security Features	Ensures secure communication between robots and central systems, protecting sensitive data and enabling accountability to prevent unauthorized access in critical applications.
Ultra-Precise Localization	Enables robots to navigate complex environments with high precision, which is vital for tasks in hazardous or dynamic settings while providing transparency and ethical considerations in robotic deployments.

By leveraging these 6G capabilities, robotics for sustainability-focused applications can achieve higher operational efficiency, reduce environmental impact, and adapt seamlessly to changing industrial demands. The convergence of 6G technologies with advanced robotics enables smarter, safer, and more efficient systems that align with global sustainability goals. The overarching capabilities will accelerate innovation across industries, enhancing resource efficiency, circular economy adoption, and scalable automation, ultimately paving the way for a greener, more resilient future.

6. Standardization Landscape for 6G Empowering Robotics

The transition to 6G technology is set to significantly impact various verticals, particularly in the field of robotics. As we move towards the anticipated commercial launch of 6G by 2030, standardization efforts are crucial for ensuring that the technology meets the diverse needs of robotic applications. This section outlines the current landscape of standardization related to 6G and its implications for robotics.

6.1. 3GPP Standardization for Robotic Services

The 3rd Generation Partnership Project (3GPP) Technical Specification Group (TSG) Service and System Aspects (SA) is responsible for the overall architecture and service capabilities of systems based on 3GPP specifications. Within this group, several subgroups focus on different topics, including SA1: Services, SA2: Architecture, SA3: Security, SA4: Codec, SA5: Telecom Management, and SA6: Mission-critical Applications. In particular, SA1 gathers requirements from vertical use cases, including those from the robotics sector. The 5G System (5GS) was designed to provide service-based, highly reliable communications (e.g., URLLC, Time-Sensitive Communications, Edge Computing) to support industrial automation. Despite significant progress, many existing and new use cases remain unaddressed, particularly those with stringent requirements necessary for robotic and tactile services over 5GS.

Currently, several 3GPP Working Groups (WGs) are active on robotics-related topics. One notable study item is the SA1 SOBOT (Study on Network of Service Robots with Ambient Intelligence), which includes major players. Although this feature has faced criticism regarding its operational approach, its existence indicates a growing recognition of service robots within 3GPP discussions. Key vertical use cases, especially in factory and process automation, are studied in 3GPP SA WG1 (SA1) under document 3GPP22.104. In addition, 3GPP has approved investigations into architectural enhancements for Extended Reality and Media (XRM) services that require high data rates and low latency. To address these challenges, documents such as 3GPP TR 22.847 (multi-modality feature) and 3GPP TR 23.700 (XRM feature) aim to conduct gap analyses between new potential requirements and existing functionalities supported by 3GPP. Release 19 works on sensing, positioning, etc., and ongoing work on compiling and refining 6G use cases. Ongoing 3GPP activities include the R19 RAN1 Study Item on channel modelling for ISAC in new radio (NR) (RP-234069), focusing on models for UAVs, humans, vehicles, AGVs, and objects creating hazards on roads and railways, as well as the R20 SA1 Study Item on 6G use case and service requirements (SP-241391), which explores ISAC applications such as coordination of search and rescue missions in disaster areas, low-altitude UAV supervision, safety assistance for vulnerable pedestrians, high-resolution topographical mapping, environmental object reconstruction, and road digitalization.

Requirements under consideration include parallel transmission of multiple modality representations associated with the same application, and reliability, availability, security, privacy, charging, and KPI identification specific to use cases. The multi-modality feature illustrates how new requirements can motivate enhancements to 5GS to meet demanding applications in sectors like healthcare.

6.2. Other Key Organizations and Their Roles

Several organizations play crucial roles in standardizing robotic services within the context of 6G:

- **Internet Engineering Task Force (IETF):** The IETF has discussed Tactile Internet as a use case requiring improved networking technologies to meet stringent resource demands.
- **ITU-T Focus Groups (FGs):** The ITU-T FG on Technologies for Network 2030 identified Tactile Internet as a representative use case among others like holographic communications. The recently established Metaverse focus group aims to analyze technical requirements for enabling technologies across various domains.
- **Alliance for IoT & Edge Computing Innovation (AIoTI):** AIoTI promotes innovation in IoT and Edge Computing while enhancing European digitization and competitiveness. It has established several workgroups focusing on standardization efforts relevant to robotics.
- **International Electrotechnical Commission (IEC):** IEC TC100 is working on standardizing ultra-low latency communication technologies needed for control-centric applications in MR environments.
- **Institute of Electrical and Electronics Engineers (IEEE):** The development of standards for autonomous system operation and control applications is crucial for robotics. As noted in IEEE P1955 [198], there is a need for service requirements that cater specifically to robotic systems operating within complex environments. This includes ensuring advanced sensing, and reliable communication between robots and their control systems to facilitate real-time decision-making.
- **The European Robotics Association Internationale Sans But Lucratif (euRobotics AISBL)** [199] serves as a vital unifying force for stakeholders in the European robotics sector, driving competitiveness and industrial leadership. Its partnership with the European Commission, particularly through the Public-Private Partnership in Robotics (SPARC) under Horizon 2020, has established a strategic roadmap for robotics research and innovation. As the robotics market is set to exceed 90 billion EUR by 2030, euRobotics highlights the critical need for standardization to facilitate the integration of advanced technologies like 6G. By promoting the uptake of robotics and fostering excellence in European robotics science, euRobotics aligns with the goals of 6G, enhancing connectivity, interoperability, and AI-driven solutions in robotics. This alignment positions euRobotics as a key player in shaping the future of robotics empowered by next-generation mobile networks.

Based on identified robotic SDOs and associations [177]-[178], this section maps industry associations and SDOs according to their functionalities, use cases, sectors, and geographical scope. Key organizations include ISO as the main robotics SDO with relevant communication scope; IEEE Robotics and Automation Society (RAS); International Federation of Robotics (IFR); euRobotics aisbl; and A3 as a prominent industry association.

Figure 8: Standardization landscape for 6G empowering robotics services (revised from [177])

Figure 8 illustrates the standardization landscape for 6G technologies, emphasizing their pivotal role in empowering robotics services. This landscape highlights key standards, frameworks, and stakeholders involved in the development and deployment of 6G networks. By establishing a cohesive framework, these standards aim to facilitate seamless communication, enhance interoperability, and drive innovation in robotic applications across various industries.

Zooming in Ethics as one of the overarching features, we provide a summary of standardisation activities related to ethical considerations in autonomous and intelligent systems:

- **IEEE Ethically Aligned Design for Autonomous and Intelligent Systems (EAD):** This outlines a vision that prioritizes human well-being in the design of autonomous and intelligent systems. It emphasizes the importance of ethical considerations in technology development to align with societal values (IEEE, 2019) [149].
- **EU Ethics Guidelines for Trustworthy AI:** Developed by the High-Level Expert Group on Artificial Intelligence, these guidelines provide a framework for ensuring that AI systems are trustworthy, addressing issues such as transparency, accountability, and fairness (European Commission, n.d.) [150].
- **IEEE Standard Model Process for Addressing Ethical Concerns during System Design (IEEE 7000-2021):** This standard outlines a systematic approach for identifying and addressing ethical concerns throughout the design process of systems, ensuring that ethical considerations are integrated from the outset (IEEE, 2021)[151].
- **IEEE CertifAIEd™ – Ontological Specification for Ethical Privacy:** The certification focuses on principles related to privacy in AI systems, providing guidelines for ethical data handling and user privacy (IEEE, 2023) [152] .
- **IEEE CertifAIEd™ – Ontological Specification for Ethical Algorithmic Bias:** This specification addresses the identification and mitigation of algorithmic bias in AI systems, promoting fairness and equity in AI applications (IEEE, 2022)[153].
- **IEEE CertifAIEd™ – Ontological Specification for Ethical Transparency:** This certification document emphasizes the need for transparency in AI systems, ensuring that users understand how decisions are made and that AI systems are accountable for their actions (IEEE, 2022)[154].

- **IEEE CertifAIEd™ – Ontological Specification for Responsible Governance:** This specification outlines best practices for governance in AI systems, ensuring that ethical standards are upheld and that governance structures support the responsible use of AI technologies (IEEE, 2024.[155]

These standardisation activities [177]-[190] collectively contribute to the understanding and implementation of ethical principles in the development and deployment of AI technologies, fostering trust and accountability in autonomous systems.

7. Conclusion and Recommendations

This white paper has explored the transformative potential of 6G technology in advancing robotic applications across various sectors. As we transition from IMT-2020 (5G) to IMT-2030 (6G), we recognize that the enhancements in communication capabilities, such as AI, Integrated Sensing and Communication (ISAC), ultra-reliable low-latency communication (URLLC), energy efficiency, resilience, and ubiquitous connectivity, are crucial for developing more intelligent, efficient, and responsive robotic systems.

The analysis presented highlights the essential extensions of 5G technologies and the introduction of new capabilities that will empower robotics. These advancements will enable robots to operate in more complex, unstructured and dynamic environments and tasks, enhancing their functionality and user interaction through improved shared control frameworks, particularly in applications that involve close and even physical interaction between humans and robots.

Focusing on ethical considerations like transparency and user consent ensures that AI and robotics developments align with societal values and regulatory frameworks. This strategy not only builds public trust but also promotes the sustainable and responsible integration of advanced technologies into daily life. Additionally, the white paper highlights the significance of addressing broader issues such as sustainability, privacy, and ethical implications. Future research and innovations, along with global standardization, must prioritize not just technological advancements but also their societal impacts, ensuring that they are designed with user-centric principles and ethical standards in mind.

Therefore, one6G makes the following recommendations for the next stage of the process related to IMT-2030 for the robotics and automation vertical:

- New features to be introduced on-demand with minimum impact on existing core robotic services, reflecting customer needs and generating additional value.
- Importance of global standards for mobile networks through consensus-based standards organizations, such as 3GPP, which are essential to drive economies of scale and support the significant investment required in developing new robotic products for IMT-2030.
- Any new communication protocols for robotics must demonstrate significant benefits over and above IMT-2020 in key metrics such as spectral efficiency, energy efficiency, overall energy consumption reduction, and cost effectiveness.
- Further exploration is necessary to understand the commercial imperatives for, and feasible enablement of, any extreme requirements of IMT-2030. This understanding will be vital in guiding future developments and ensuring alignment with market needs.

one6G association fosters a collaborative and forward-thinking approach to the integration of 6G capabilities within the robotics sector, ensuring that advancements are both sustainable and beneficial to society at large. Continued collaboration among researchers, industry stakeholders, and policymakers will be vital in shaping the future of robotics, ensuring that these technologies are sustainable, trustworthy, and beneficial for society as a whole. Future directions should include exploring new communication protocols, sensing capabilities and agentic AI, balancing autonomy with user control, and fostering innovations that leverage the full potential of 6G to create intelligent and responsive robotic systems.

Abbreviations

3GPP	3rd Generation Partnership Project
5GS	5G System
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
Cobots	Collaborative Robots
DUST	Dual User Shared Task
eMBB	enhanced Mobile Broadband
EV	Electric Vehicle
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
ISO	International Organization for Standardization
KPI	Key Performance Indicators
LLM	Large Language Model
ML	Machine Learning
mMTC	massive Machine Type Communication
NR	New Radio
QoS	Quality of Service
RAN	Radio Access Network
ROS	Robot Operating System
SDO	Standardization Development Organization
SLAM	Simultaneous Localization and Mapping
SOBOT	Service Robot
TR	Technical Report
UAV	Uncrewed Aerial Vehicles
UGV	Uncrewed Ground Vehicles
UC	Use Case
URLLC	Ultra-reliable and low-latency communication
V2X	Vehicle-to-Everything
WG	Working Group
WI	Working Item
XRM	Extended Reality and Media Services

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