( one6G )

Taking communications
to the next level

# 6G & ROBOTICS

## Use Cases and Potential Service Requirements

WHITE PAPER

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one6g.org

# Scope

one6G has recognized that there is a growing demand for robotic applications. Robotic applications are envisioned to penetrate several application areas and societal sectors. Alongside this growth, there are several ongoing developments in the mobile communications industry towards enabling diverse services in vertical industries. Discussions related to integrating mobile communication capability into robotics systems are gaining significant momentum. It is foreseen that this integration can give rise to new possibilities to address relevant industrial and societal challenges.

To successfully support the foreseen rise in robotics applications in different scenarios, and following previous one6G's *6G & Robotics* discussions [1], communication systems must be capable of supporting a higher density of communication links (including inter-robot and intra-robot communication) with stringent performance requirements, ensure service availability at almost all times, everywhere, provide highly accurate environment awareness e.g. positioning, support highly dynamic QoS adaptation mechanism for safety when in close proximity with humans, and enhance sensing capability for robot operation efficiency and functional safety, among others. Apart from enhancing communication system performance, developing robotics systems with a much higher-degree of programmability by exploiting capabilities such as cloud and AI (e.g., distributed ML) technologies is required to help develop cost-effective and flexible robot operation in diverse scenarios [1]. In general, we already see huge deviations for AI regulations between Europe, China and US. These must be reflected in robotics system development.

The scope of this white paper is to identify robotics use cases and recognize the potential role of mobile communication systems, particularly 6G systems. To understand the involvement of mobile communication systems, the robotic system requirements for each use case are identified. For each of the robotic system requirement the potential contribution of the communication system is determined. Based on this analysis, additional capabilities that 6G systems might need to fulfil for efficiently supporting robotic use cases are outlined.

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# 1. Introduction

The 5G communication system has triggered the digital transformation of many vertical industries by focusing on three usage scenarios. These usage scenarios include: enhanced broadband (eMBB), ultra-reliable and low latency (URLLC), and massive machine type communications (mMTC). Robots are among the devices that are envisioned to be connected in these scenarios. From mobile communication system development and standardization point of view, several use cases, for example in standard development organization such as 3GPP, are being discussed to support robotic applications. Other global consortia such as the Industrial IoT Consortium (IIC) [2], International Federation of Robotics (IRF) [3], and the euRobotics aisbl (Association Internationale Sans But Lucratif) [4] have been working to establish common standards and best practices for the use of wireless networks in robotics.

In addition to the industrial applications of robots, several societal needs are driving the adoption of robots. This is also reinforced by the growing market for different robot types discussed in [1]. Some of these societal changes include a shrinking workforce due to aging population in several countries, and a shortage of personnel in key sectors such as healthcare. Developing efficient and safe robotic applications has the potential to complement and compensate for human capabilities.

Given the potential demand for robots, and the need for robots to be efficient and safe, mobile communication technologies are considered to be a revolutionary enabler of robotic applications. These systems have shown to penetrate well into different application domains due to the wide coverage, and capability to meet quality-of-service requirements, among others. In order to understand how wireless technology, and particularly 6G technology, can meaningfully support robotic services, the first step is to understand the usage scenarios. The scope of this white paper is to describe robotic use cases, and analyse the potential impact of mobile communication systems on these use cases. Additionally, based on the analysis, some potential gaps current mobile communication systems may need to address in order to efficiently support the use cases are identified.

Before diving into the use case descriptions, the following sections discuss the fundamental capabilities of robots, and the potential role mobile communication technologies could play in robotics systems.

## 1.1. Fundamental capabilities of robots

Over the last years, robots are being increasing utilized in several application domains [5]. For each of these domains, robots have their own unique features, capabilities, and form factor. However, a common thread or a fundamental aspect across such a diverse category is the existence of a connection between robot's perception and actions [6]. Robot perception is typically facilitated by a variety of sensor types, including vision, tactile, infrared, and force sensors. On the other hand, the movements and functions of robots are enabled by actuators. These actuators allow the robot to move to do path planning and motion control (i.e., arm rotation).

The proliferation of robots in different application domains and diverse scenarios, possibly with more complex interactions, is triggering the need to develop *intelligent* connection between robots' perceptions and actions. Traditional approaches of loading pre-configured software to carry out robot operation may not be sufficient to carry out operations in complex and unknown environments. One way to adapt robotic systems in such environments is by processing relevant data in real-time. For successful operation of robots in all scenarios, perception and control functions of the robots will need to depend on data processing/*intelligence* capability going forward. Based on this reasoning, the three fundamental capabilities of robots considered in this white paper include: *Perception*, *Cognition*, and *Actuation & Control*. These fundamental capabilities of the robot are described below:

- *Perception*: It refers to the key capability of the robot to perceive and comprehend about unstructured (real) environments where they operate and act in. Perception is required in many applications, and is typically enabled by sensory data and artificial intelligence/machine learning (AI/ML) techniques. Examples of perception capability include object detection, scene understanding, human/pedestrian detection, activity recognition, object modelling, among others.
- *Cognition*: It refers to a robot's ability to reason, learn, and make decisions based on its perception of the environment, which involves higher-level cognitive processes such as planning, decision-making, and problem-solving to perform complex tasks autonomously [7].
- *Actuation & Control*: It refers to a robot's ability to act on its environment based on its perception and cognition, which involves the manipulation of physical objects and the execution of motor commands to move the robot's body. Control also includes the integration of perception and cognition to generate motor commands that enable the robot to move to the task's location [8].

## 1.2. Role of communication system in robotics applications

Considering the three capabilities discussed above, integrating communication capability in robotics systems has the potential to expand the services offered by robots in several ways. This integration can be enabled by, a) communication within components of a robot (aka intra-robot communication), b) communication between robots (aka inter-robot communication), c) communication between humans and robots (aka human-in-the-loop), and d) communication between robot(s) and their controller (e.g., in cloud/edge) (aka cloud robots). The different ways of integration are described below.

a) Communication within components of a robot: Internal connectivity of the different robots' capabilities over wireless links can allow more flexibility in robot motion. For instance, sensors could be mounted on different parts of the robot and be connected to actuators over wireless links. Additionally, it has the potential to reduce the wear and tear of some of the components connecting the different parts due to repetitive motion of the robot.
b) Communication between robots: Moving beyond enhancing the internal capabilities of a robot, availability of wireless links can also allow multiple robots to coordinate and collaborate with one another. By sharing, for example, the movement trajectory or motion plan, the robots can collectively plan their actions in a safe and efficient manner. This is particularly useful in areas where the tasks are collaborative, or requires a team of robot to operate, for example in dangerous scenarios, in rescue operations, among others. Another example is the communication within a swarm of robots to allow coordination of multiple robots as a system which consist of large numbers of mostly simple physical robots pursuing a specific goal.
c) Communication between humans and robots: Interactions between human and robot can be categorised depending on the service recipient: Human-to-Robot interactions refer to applications where a human operator uses consoles such as remote control or haptic wearables to control and operate a robot in the same environment or remotely. An example scenario is when a robot performs tasks to assist humans in the factory floor for lifting and carrying heavy objects. In the second category of Robot-to-Human interaction, human is the recipient of the service such as: (1) personal service robot, (2) professional

service robot, used for a commercial task, (3) health robots including care giver, and wearable robots for patient monitoring in the residents' homes.

d) Communication between robot(s) and their controller (e.g., in cloud/edge): This relates to offloading certain computation load of the robotics operations, due to reasons such as, limited form factor, or battery capacity on the robot. This can allow the robot to exploit computational and storage resources beyond what is locally mounted on the device. The externally available resources can aid in perception, cognition and remote control of robots. Another option is to run in parallel local and global processes supported by wireless offloading for a higher degree of functional safety.

Considering the above background on robot capabilities and the potential role of communication systems, some of the robotics use cases are discussed in the following sections.

# 2. Use cases

## Description and potential service requirements

The robotic use case descriptions follow the template similar to that is used in [9]. Seven use cases are described and analysed based on contributions from one6G partners. Preliminary conclusions are drawn from the analysis of these use cases.

## 2.1. Use case 1: Cooperative carrying with robots

This use case was briefly discussed in one of the previous publications [9] of one6G. Cooperative carrying refers to a set of mobile robots cooperating with each other to transfer objects e.g. metal frames, or parcels, from one place to another, for example, in factories. Depending on the object characteristics, e.g., fragility, texture, etc., and number of mobile robots, the level of cooperation may vary. The level of cooperation indicates the requirements in terms of coordination between the mobile robots. For example, a rigid, fragile and heavy object requires more precise coordination among the mobile robots compared to a soft elastic object. Additionally, the robots may be capable of carrying several different kinds of objects with varying characteristics. These object types/characteristics needs to be appropriately identified in order to determine the level of cooperation and enable the execution. Figure 1. provides a high-level illustration of the use case.

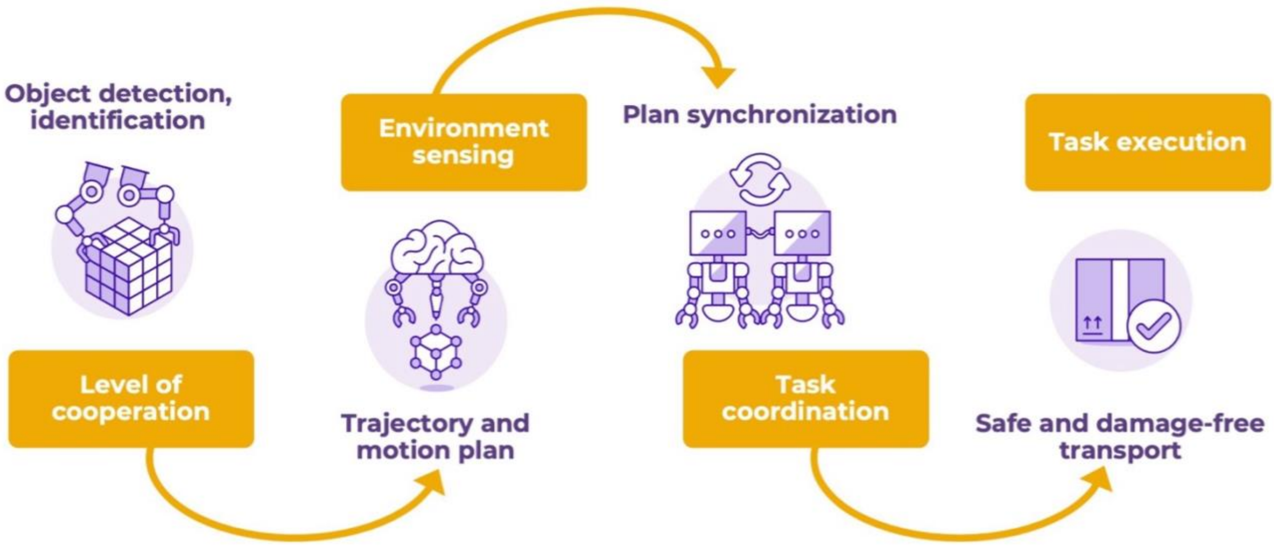


*Figure 1: UC1 - Cooperative carrying with robots execution illustration*

### Actor

Mobile robots, mobile network operator, third party service providers (e.g., for AI services)

### Pre-condition

- Pre-determine the number of industrial robots and their capabilities
- Mobile robots capable of the following functionalities:
    - Sensing the surrounding environment (e.g., other dynamicity in the vicinity).

- Movement trajectory planning and motion control (e.g., collision avoidance and arm movement).
- Sensing task relevant aspects (e.g., orientation of the object).
- Communicating with other involved robots (e.g., to share control commands, or action status).

## Service flows

For the task of cooperative carrying, robots start by first identify characteristics of the objects. This is done by relying on the available sensing capability of the robot. After identifying the object characteristics, the robots establish a communication link with other robots. Each robot communicates with other robots the coordination plan and sensing related information of the ongoing task, e.g., stability, orientation of the object to enable efficient coordination. Sensing of the environment will enable safe transportation of the object despite dynamicity such as humans crossing the path. Based on the communicated information, the robots execute their actions. The speed for transportation also depends on the response time for sensing.

## Post-condition

Successful (damage-free) and safe transportation of objects within factories by a group of mobile robots.

## Potential service requirements

Below are the requirements from robot perspective to perform the task/use case. Based on the above description the following four service requirements are identified for the use case:

S1: Identification of characteristics of the object to be carried:

- The robots need to be able to identify the characteristics of the object carried to determine the level of cooperation among the robots.

S2: Sensing of the surrounding environment and tracking of ongoing task:

- To enable safe operation of cooperative carrying that robots need to ensure they avoid accidents as well as not cause damage to the carried object.

S3: Task coordination between involved robots:

- The robots need to coordinate their motion (including finger tracking) and trajectory plan in order to avoid uncoordinated behavior.

S4: Execution of the cooperative carrying task:

- The robots need to act based on the developed plan to carry the object.

The role of communication system for each of the above robot service requirements is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 1 presents the discussed mappings.

*Table 1: Communication system requirements - UC cooperative carrying with robots*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S1: Identification of characteristics of the object to be carried | Cognition | • Enable reliable short-range imaging.<br>• Enable access to (edge) cloud (e.g., AI based control unit) to identify object characteristics in real-time. |
| S2: Sensing of the surrounding environment and task specific aspects | Perception, Cognition | • Enable short-range and long-range sensing, for collecting task specific and vicinity related information.<br>• Allow seamless coordination among different sensors and devices.<br>• Transfer sensing data to (edge) cloud (e.g., AI based control unit) to derive perception information from sensing data.<br>• Transfer sensing data between different robots.<br>• Offer data processing capability to derive perception information from sensing data. |
| S3: Task coordination between involved robots | Cognition | • Offer data storage capability for storing robot capabilities and characteristics.<br>• Enable mobile robots to seamlessly access (edge) cloud (e.g., database) for retrieving robotic system relevant information for enabling task coordination.<br>• Enable highly reliable communication links at all times. between different mobile robots despite robot mobility. |
| S4: Execution of the cooperative carrying task | Actuation & Control | • Enable highly reliable communication links and sensing among the involved robots for task execution. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- Enable synchronization between different robot-to-robot links to avoid triggering uncoordinated operations.
- Fulfilment of communication link KPIs in terms of metrics such as latency, throughput, reliability, etc. across multiple links simultaneously or notified in advance if they cannot be fulfilled.
- Support seamless operation of the use case throughout operation by proactively synchronizing and adapting the involved communication links based on the dynamicity in the environment.

Sensing requirements:

- Short-range imaging to identify object characteristics.
- Short- and long-range sensing to identify dynamicity in the vicinity.
- Fulfilment of use case specific sensing KPIs in terms of metrics such as positioning and shape accuracy, velocity accuracy, sensing latency, sensing resolution, etc.
- Synchronization between sensing and communication functions. For instance, it might be necessary to complete the sensing function before initiating the communication function.

AI support requirements:

- Support for real-time AI/ML model downloading and distribution among robots based on their new tasks.
- Support for distributed split learning and inference among multiple robots, due to their processing limitation.
- Enable constant monitoring of the model at the robot to ensure optimal performance.

## 2.2. Use case 2: EduBots - Interactive robots in education

Interactive robots can be used in teaching and tutoring to provide personalized and engaging student learning experiences. The Education roBots (EduBots) with sensing and Natural Language Processing (NLP) capabilities can interact with students in a more personalized way and address their doubts and questions efficiently thus adapting to students' learning preferences. The robot can also provide feedback on the student's progress, identifying areas where the student is struggling and providing additional support as needed. This personalized learning approach can help to keep students engaged and motivated while also improving their academic outcomes. In addition, educational robots can be used to teach social and emotional skills, such as empathy and teamwork, through interactive scenarios and role-playing exercises. In addition to close verbal interaction, these robots could work in close proximity to students and assist them in, for example, art and craft activities. Figure 2. provides a high-level illustration of the use case.

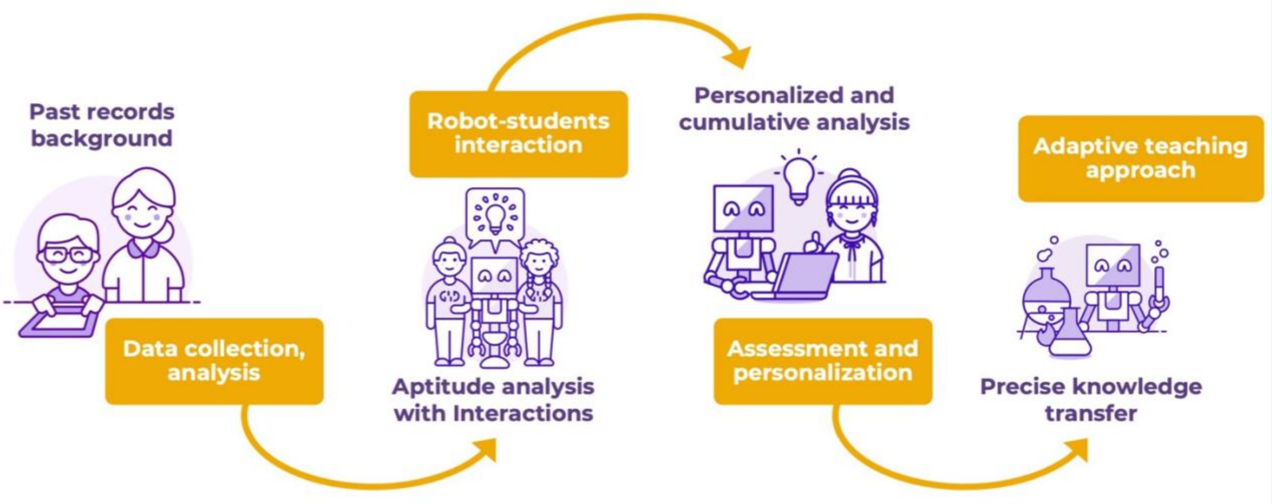


*Figure 2: UC2 - EduBot execution illustration*

### Actor

Service Robots, third-party service providers, mobile network operator, edge or cloud service provider(s)

### Pre-condition

- Educational robots are equipped with sensors, actuators, and motors, that enable them to move and interact with the environment in a natural and intuitive way.
- Train robots to be familiar with teaching subject, scope and relevant application areas.
- Robots should be pre-trained to understand and respond to the social and cultural norms of their environment.

## Service flows

The robot starts by greeting and indulging students in conversation to assess their current knowledge or skill level. Based on this assessment, the robot provides personalized instruction and learning activities, monitoring the student's progress throughout the session to identify areas where they may be struggling. Robots can incorporate immersive technologies like Augmented Reality (AR) and Virtual Reality (VR) into teaching to enhance learning experience. The robot provides feedback and additional support as needed, encouraging and motivating the student to continue learning and improving. At the end of the session, the robot assesses the student's learning outcomes and provides reports to teachers or parents.

## Post-condition

Enhanced student engagement and motivation, while also providing a more personalized and effective learning experience.

## Potential service requirements

The interactive educational robots aim to aid and support to students while also improving the efficiency and effectiveness of educational services. The requirements for these robots include:

S1: Human machine Interaction including NLP:

- Robots understand and interpret natural language to communicate effectively with students, including colloquialisms and jargon.
- Robots should be capable of adapting their teaching style and content based on individual student's needs, abilities and learning progress.
- Robot should have a model that can understand the student's background, strengths, weaknesses and learning goals to tailor its teaching.

S2: Data collection, analysis and personalization:

- Robots must be able to provide personalized feedback and guidance to individual students, based on their progress, interests and learning style.
- Robots must be able to collect data and estimate if a student needs special care.

S3: Interaction, engagement, and assessment:

- Robots should be able to use the facilities available around like audio/visual devices to deliver learning materials, such as videos, images, and text, in a dynamic and interactive way.
- Robots can increase engagement by incorporating immersive technologies to demonstrate verbal or textual instructions to keep students engaged and motivated throughout the learning process. This requires the robot to have the ability to use multimodal interaction, such as gestures, facial expressions, and voice intonation, to communicate and connect with students.
- Robots must be able to engage in natural and empathetic conversation with students, providing emotional support and reassurance.

- Robots should be able to assist with tasks such as grading, monitoring student progress and providing support for repetitive administrative tasks.

S4: Safety, privacy and security:

- Robots must be designed with safety features to avoid any physical harm to the students, such as collision avoidance, and have the capability to shut down in emergency situations.
- Robots should incorporate proper design and configuration to ensure that the privacy of learners is respected, and data from one user is not accessible or shared with others unintentionally.
- Robots should implement strong security measures, software updates and network security protocols to mitigate the risks of cyber threats like malicious attempt to exploit vulnerabilities in the robot's software, hardware, or communication channels.
- Robots should implement content verification mechanisms, employing trustworthy sources to provide accurate and reliable educational content to eliminate the risk of delivering manipulating or harmful content.

S5: Physical mobility for navigation and obstacle avoidance:

- Robots should be able to navigate through the environment and avoid obstacles while moving around.

S6: Adaptive learning, collaboration and integration:

- Robots require a communication system to share information and coordinate their actions.
- Robots should be able to learn from past experiences and adapt to changes.
- Robots should be able to integrate with existing educational technology systems and tools, to provide a seamless learning experience for the students and teachers.

The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 2 presents the discussed mappings.

*Table 2: Communication system requirements – UC EduBots - Interactive robots in education*

| **Service requirements** | **Robot fundamental capabilities** | **Potential role of communication system (high-level description)** |
|---|---|---|
| **S1:** Human machine interaction including NLP | Perception, cognition | • Enable the capability to recognize and interpret human gestures, facial expressions, and voice commands via sensing.<br>• Enable the ability to access online educational resources and databases by offering stable communication links for multiple students simultaneously.<br>• Enable the ability to receive and process natural language queries from students and access to expert systems for answering complex questions by establishing real-time bi-directional communication links for students. |

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| | | • Support immersive experience by enabling ultra-low latency multi-modal interactions. |
| **S2:** Data collection, analysis and personalization | Perception, cognition | • Enable high-speed data transmission for real-time data collection and analysis.<br>• Enable the ability to process and analyze large amounts of data using machine learning algorithms.<br>• Enable seamless integration of third-party educational service with educational analytics software for personalized learning.<br>• Enable secure storage and transmission of sensitive student data. |
| **S3:** Assessment, interaction and engagement | Cognition, actuation & control | • Enable reliable connectivity for real-time assessment and feedback.<br>• Enable high-quality video and audio streaming for engaging virtual interactions.<br>• Enable immersive educational services based on AR/VR capabilities offered by networks.<br>• Enable integration and synchronization among multiple third-party service providers (e.g., assessment software, NLP software) with communication system. |
| **S4:** Safety, privacy and security | Cognition | • Enable robust authentication, security and access protocols for protecting sensitive student data and prevent potential security breaches.<br>• Enable integration with privacy and ethical compliance software and platforms to ensure reliability and trustworthiness of robot's actions. |
| **S5:** Physical mobility for navigation and obstacle avoidance | Perception, actuation & control | • Enable high-precision sensing and positioning capabilities for accurate navigation.<br>• Enable integration of network-based sensing and positioning services with third party service providers (e.g., obstacle detection and avoidance software applications).<br>• Enable real-time monitoring of environmental conditions.<br>• Enable real-time coordination with service provider for trajectory and motion planning. |
| **S6:** Adaptive learning, collaboration and integration | Cognition, actuation & control | • Enable integration of adaptive learning software for personalized learning experiences.<br>• Enable robot to adapt to new technologies and educational practices.<br>• Enable low-latency connectivity for real-time collaboration and integration with multiple software providers (e.g., NLP providers, teaching material relevant software providers). |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- High-bandwidth and low-latency connectivity to ensure real-time immersive interaction based on AR/VR and communication between the robot and students/teachers.
- Reliable and robust connectivity to ensure that the robot can maintain a reliable connection to the network, even in areas with limited or obstructed connectivity.

Sensing for safety requirements:

- High accuracy sensing to detect and recognize objects, students, and teachers to ensure safe operation, collision-free operation.
- Detection and notification of physical damage to the robot.

AI-support requirements:

- Support advanced analytics and machine learning model lifecycle management to enable the robot to analyze data and personalize its interactions with individual students based on their learning needs and preferences.
- Seamless integration of multiple third-party services (e.g., existing educational software and learning management systems) along with network services such as sensing and AI/ML model lifecycle management support, to enable the robot to access relevant educational content and resources.

Privacy and Security requirements:

- Secure authentication mechanisms to prevent unauthorized sharing of student or teacher information and robot control through/within communication system.
- Incorporate by-design data minimization, anonymization and aggregation mechanisms to enable data privacy and reusability.

## 2.3. **Use case 3:** Robots in inventory management

Robots have emerged as game-changers in inventory management by transforming traditional supply chain operations by automating tasks, improving accuracy, and boosting efficiency. With their advanced capabilities in inventory tracking, stock replenishment, order picking, sorting, and packing, robots offer unprecedented benefits that drive productivity, reduce costs, and enhance overall operational performance. It improves efficiency, accuracy and reduce costs. Robots can be programmed to access and retrieve data from multiple systems and applications, such as Enterprise Resource Planning (ERP) and Customer Relationship Management (CRMs), to update and maintain accurate stock levels, orders, and shipments records. Figure 3. provides a high-level illustration of the use case.

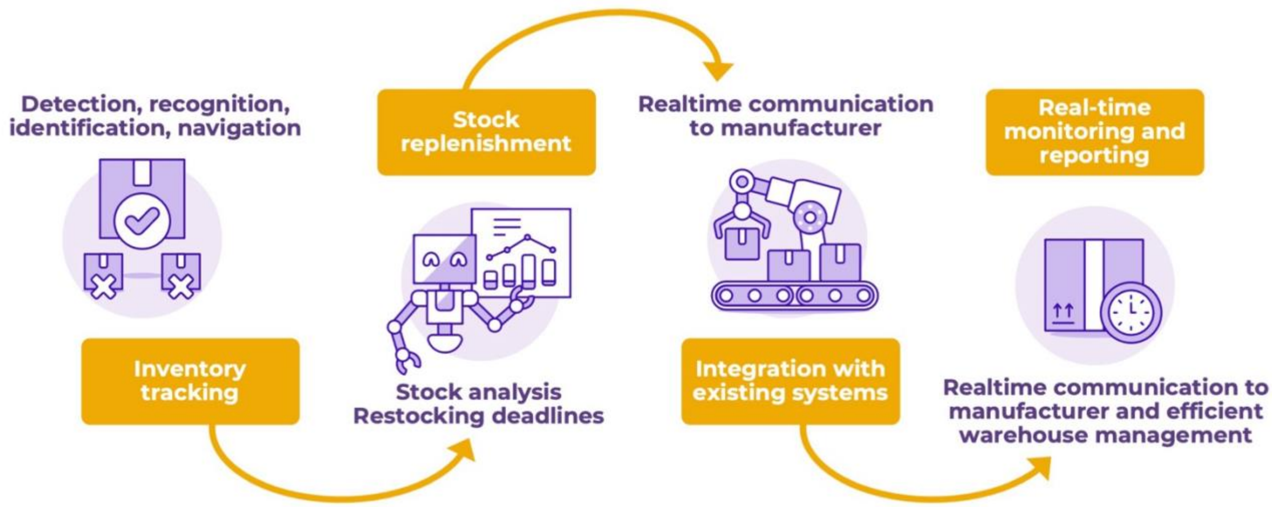


*Figure 3: UC3 - Robots in inventory management execution illustration*

### Actor

Industrial Robots (Mobile Robots), controller, cloud service provider(s), mobile network operator(s), third party service providers (e.g., for AI services)

### Pre-condition

- Clearly defined processes: Before deploying robots, it is important to have well-defined inventory management processes, workflow processes, and workflows within the supply chain.
- Robotic system configuration: The robotic system, including hardware and software components, should be configured and customized to suit the specific requirements of the inventory management operations, which includes programming robots for navigation, object recognition, and task execution in line with the warehouse layout and operational needs.

## Service flows

The first step is to identify the processes and workflows within the supply chain where robots can be deployed to automate the process line. This may involve analyzing existing processes and workflows to identify areas where robots can be most effective. Once the processes have been identified, robots need to be designed and developed to automate the identified tasks. This involves programming the robots to retrieve and process data from various systems and applications within the supply chain. Before deploying the robots, testing and validating their performance and ensuring they operate correctly is essential. This may involve running the robots through various scenarios and identifying errors or issues. Once the robots have been tested and validated, they can be deployed within the supply chain. Monitoring the robots' performance continuously is important to ensure they are operating correctly and to identify potential issues.

## Post-condition

By automating repetitive tasks and optimizing workflows, robots can help organizations to streamline their supply chain operations.

## Potential service requirements

Based on the above description of the use case, the following robot requirements are identified.

S1: Environment perception:

- Robots need to have a comprehensive understanding of the Supply Chain Management (SCM) process, including the steps involved in data entry, order processing, and inventory management and need to be trained on the specific systems and software applications used.

S2: Data collection and analysis:

- The robot should be capable of collecting and analyzing data from various sources such as sensors, scanners, and databases. This includes capturing data related to inventory levels, shipment tracking, and order processing.

S3: Inventory tracking:

- Robots can navigate aisles and shelves to track inventory levels and provide real-time stock quantities and location updates.

S4: Stock replenishment:

- Robots can assist in restocking shelves by automatically retrieving items from the inventory and delivering them to the appropriate locations.

S5: Integration with existing systems:

- The bot should be able to integrate with existing SCM systems such as warehouse management systems (WMS), enterprise resource planning (ERP) systems, and transportation management systems (TMS).

S6: Real-time monitoring and reporting:

- The robot should be capable of monitoring supply chain operations in real-time and generating reports on key performance indicators (KPIs) such as order fulfillment, inventory levels, and delivery times.

S7: Adaptive learning:

- The robot should be able to learn from past experiences and adapt to changes in the supply chain environment, which includes identifying patterns and trends in data and making recommendations for process improvements. The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 3 presents the discussed mappings.

*Table 3: Communication system requirements – Robots in inventory management*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S1: Environment perception | Cognition | • Enable availability of communication links to enable remote installation and/or update of robot software.<br>• Enable availability of communication links for AI/ML model training to support robot operation.<br>• Enable communication link availability in factories and/or warehouses in underserved areas (e.g., basements). |
| S2: Data collection and analysis | Perception | • Advanced perception systems for accurate object recognition to identify and locate inventory items.<br>• Sensing to detect warehouse status, such as inventory levels. |
| S3: Inventory tracking | Actuation & control | • Enable high accuracy sensing and positioning to allow seamless navigation through aisles and shelves to track inventory levels.<br>• Enable real-time updates of stock quantities and locations to, for example, central inventory management systems.<br>• Enable access to cloud-based resources, such as storage and processing power, for efficient process automation. |
| S4: Stock replenishment | Perception, cognition, actuation & control | • Enable real-time data exchange between different SCM components to ensure inventory status and enable restocking.<br>• Enable access to cloud-based resources, such as storage and processing power, for efficient error detection and correction. |

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S5: Integration with existing systems | Actuation & control | • Enable real-time data exchange to ensure accurate and efficient process automation, providing seamless data exchange and coordination with other supply chain components. |
| S6: Real-time monitoring and reporting | Cognition, actuation & control | • Enable real-time data extraction and analysis from various sources, such as IoT devices and sensors, to make informed decisions and adapt to changes in the supply chain.<br>• Enable access to cloud-based resources, such as AI and machine learning models, for learning and adaptation.<br>• Enable monitoring of real-time supply chain operations via sensing. |
| S7: Adaptive learning | Cognition | • Enable access to cloud-based resources, such as AI and machine learning models, for learning and adaptation. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- Reliable and low-latency connectivity for real-time data exchange between robots, inventory management systems, and other supply chain components.

Sensing requirements:

- High-accuracy sensing and positioning systems to enable object detection and safe navigation in warehouses
- Application-specific sensing such as inventory levels.
- Integration of network sensing with different types of sensor information and data sources, such as databases, ERP systems, and web services.

AI-support requirements:

- Support machine learning algorithms development and deployment to enable robots to learn from data and improve their performance over time.

Security and privacy requirements:

- Secure communication protocols to protect sensitive data and prevent unauthorized access and it require to comply with data protection regulations and standards, such as GDPR.

## 2.4. Use case 4: Drone enabled remote inspections

Remote inspections using drones are becoming increasingly popular in various industries, including infrastructure management. Drones equipped with advanced sensors and cameras can be used to perform inspections of critical infrastructure, such as power lines, pipelines, and bridges, providing real-time video and cooperatively assisting to resolve the inspected issues, for example by removing detected obstacles. With the high-bandwidth and low-latency capabilities of a 6G network, the potential for real-time streaming of high-definition video and data is even greater. Figure 4 provides a high-level illustration of the use case.

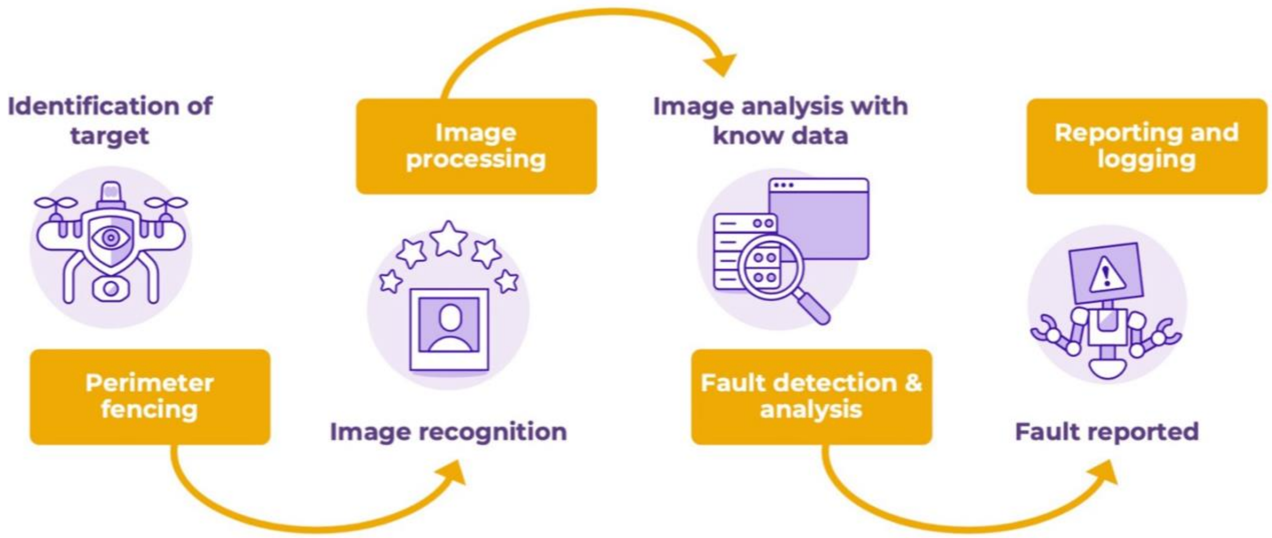


*Figure 4: UC4 - Drone enabled remote inspection execution illustration*

### Actor

Mobile Robots; Drone Operators/Inspector; Infrastructure Owners/Managers; Network Service Providers; Maintenance Teams.

### Pre-condition

- The infrastructure to be inspected must be within the range of the 6G network.
- The drones must have advanced sensors and cameras to stream high-definition video and data in real-time.
- The inspector (drone monitor) must have access to a console device capable of receiving and analyzing real-time video and data from the drone.

### Service flows

The drones are first deployed to the location of the infrastructure to be inspected. The drones are connected to the mobile communication network, which provides high-bandwidth and low-latency connectivity for real-time video and data streaming. The drones begin the inspection, using their advanced sensors and cameras to capture high-definition video and data. Upon inspection, the drones' streams the video and data in real-time to the inspector's console device.

The inspector receives and analyzes the real-time video and data, detected potential issues and hazards in the critical infrastructure. The drones can be notified by the inspector to cooperatively act and resolve the detected issues.

## Post-condition

- The inspector has identified any potential issues and hazards in the critical infrastructure.
- Any necessary repairs or maintenance can be carried out by the drones or scheduled based on the inspector's findings.

## Potential service requirements

Based on the above description the following robot requirements are identified for the use case:

S1: Cooperative navigation and obstacle avoidance:

- The drones must navigate autonomously, communicate with each other over designated areas while avoiding obstacles such as trees, buildings, and power lines.

S2: Cooperative object detection and recognition:

- The drones must be able to capture high-resolution images and enable identification of potential issues in the inspected infrastructure.

S3: Cooperative environment sensing:

- The drones must be able to sense and interpret their surroundings to navigate to its destination safely, avoid obstacles, and maintain a stable flight trajectory.

S4: Cooperative payload management:

- The drones must be able to secure the object to be carried and adjust its flight parameters to ensure that it remains stable during transport during maintenance work.

S5: Communication and control:

- The drones must be able to communicate with a remote operator or a central control system to receive commands, report its status, and adjust as necessary.

S6: Energy management:

- The drones must have sufficient battery life to complete its task and return to its home base, and it may need to monitor its energy consumption and adjust its flight trajectory to conserve power.

The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 4 presents the discussed mappings.

*Table 4: Communication system requirements – Drone enabled remote Inspection*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S1: Cooperative navigation and obstacle avoidance | Perception, cognition, actuation & control | • Enable development and deployment of self-adapting algorithms for optimizing the drones' flight trajectory.<br>• Enable cloud-based AI algorithms for real-time object recognition and classification. |
| S2: Cooperative object detection and recognition | Perception | • Enable reliable transmission of high-resolution sensing data from the drone to a remote operator or control system for analysis and decision-making.<br>• Enable cloud-based AI algorithms for real-time object recognition and classification. |
| S3: Cooperative environment sensing | Perception | • Enable reliable high-data rate and low-latency communication between the drones and the inspector to facilitate the real-time exchange of sensed data and sensing related information.<br>• Allow seamless coordination among different sensors and devices.<br>• Offer data processing capability to derive perception information from sensing data. |
| S4: Cooperative payload management | Cognition | • Enable reliable low-latency communication to facilitate the real-time exchange of instructions and status updates related to payload management among the drones, and between drones and inspector.<br>• Enable development and deployment of self-adapting algorithms for optimizing the drone's flight trajectory and payload management based on real-time data analysis. |
| S5: Communication and control | Cognition | • Enable always-on communication link between the drones and between the drones and the remote operator or control system.<br>• Enable real-time decision-making based on drones' sensor data by offering communication and computation capabilities. |
| S6: Energy management | Cognition, actuation & control | • Enable real-time monitoring of battery life, i.e. real-time transmission of battery life data between the drones to optimize their lifetime cooperatively and/or share with a remote operator or control system.<br>• Enable development and deployment of self-adapting algorithms for optimizing the drone's flight trajectory and energy consumption based on real-time data analysis. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- High data rate and low latency communication links: To facilitate the real-time transmission of high-resolution imaging and sensor data between the drones and/or the remote operator or control system.
- Reliability and fault tolerance communication links: To ensure that the communication link remains operational even in the presence of interference or other disruptions.
- Encryption and security enabled communication links: To protect the confidentiality and integrity of the transmitted data.

Sensing requirements:

- Multi-sensor support: To enable the transmission of data from multiple sensors on the drone.
- Sensor fusion: To enable data integration from multiple sensors to improve object detection, localization, and tracking.

AI-support requirements:

- Cloud connectivity: To enable the drone to access cloud-based AI algorithms for real-time decision-making and optimization.
- Edge computing capabilities: To enable the drone to perform onboard data processing and analysis, reducing the need for constant communication with the cloud.
- AI model management: To facilitate the deployment and management of AI models on the drone or in the cloud.

Other relevant requirements:

- Interoperability: To enable the communication system to work with different types of drones and control systems.
- Scalability: To enable the communication system to support multiple drones and control systems simultaneously.
- Cost-effectiveness: To ensure that the communication system is affordable and practical for widespread use in drone applications.

## 2.5. **Use case 5:** Collaborative robots in industrial environments

The use of collaborative robots (cobots) is gaining significant attention in industrial applications. They are seen as an enabler for more flexible factory floors by allowing, among others, dynamic assembly lines and enhancing utilization of factory space. Among the different levels of collaborations that can exist between humans and robots, the focus of this use case is on coexistence and cooperation. Coexistence refers to humans and robots sharing the workspace, while cooperation refers to humans and robots working simultaneously on the same object/task. With cobots foreseen to tightly collaborate with humans, they must be aware of human movements/actions and autonomously adapt their behavior to prevent accidents with humans or other objects/robots. The use case considers that the human collaborator and robots are working on the same task. The use case also considers the presence of a remote human operator to take over in case of unforeseen scenarios. Figure 5. provides a high-level illustration of the use case.

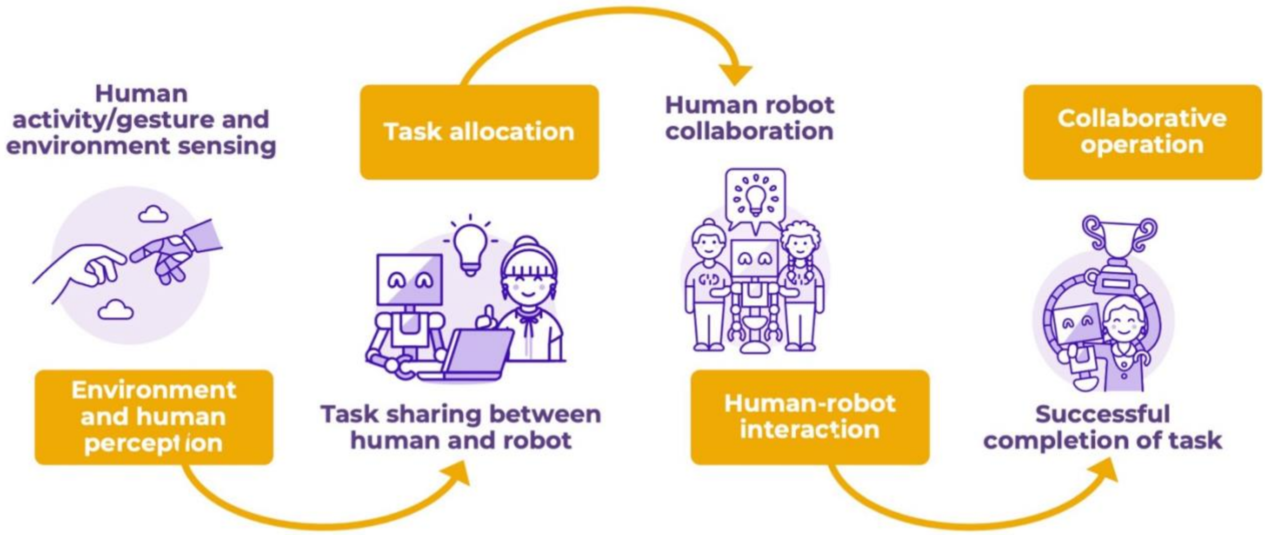


*Figure 5: UC5 - Collaborative robots in industrial environments execution illustration*

### Actor

Industrial cobots, remote human operators, mobile network operator, third party service providers, on-site human collaborator with robot

### Pre-condition

Robots must be enabled with the capability to:

- Sense the surrounding environment (e.g., other dynamicity in the vicinity).
- Sense cooperative task relevant aspects (e.g., orientation of the human and human touch).
- Perform local computations (e.g., to asses risk to humans).
- Support human-machine interaction.

## Service flows

The collaboration between human and robot starts by the robot first sensing the environment and human behavior (including movement) in the space. After perceiving the environment from the sensing results, depending on the level of collaboration, the robot-human pair distribute the task or are notified of the tasks by a remote operator. The distribution and execution of the task can be enabled by multi-modal human-machine interface mounted on the robot. Such an interface can enable human and robot to exchange information and actions by audio, video, and/or haptic means. A multi-modal interaction capability allows tight collaboration between the human and robot, as both are aware of the current scenario and can autonomously adapt their operations to prevent accidents and ensure a safe working environment. Additionally, the remote operator has the capability to intervene at any point during the collaboration operation, for example, in case of emergency.

## Post-condition

Successful (accident-free) and safe collaboration between human and robot.

## Potential service requirements

Based on the above description the following four service requirements are identified for the use case:

S1: Operational environment and human behavior perception:

- The robot must be capable of perceiving its environment and actions/activities of human collaborator.

S2: Task allocation/sharing:

- The robot must be capable of/should be informed in a timely manner about how the tasks are shared or allocated between the human collaborator and itself.

S3: Human-Robot interaction:

- The robot must offer the capability for humans to interact with it in one or multiple ways, e.g., speech, gesture, etc.

S4: Collaborative operation:

- The robot must be able to collaboratively perform the task with human collaborator.

The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 5 presents the discussed mappings.

*Table 5: Communication system requirements – Collaborative robots in industrial environments*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| **S1:** Operational environment and human behavior perception | Perception, cognition | • Enable high accuracy sensing.<br>• Enable real-time modeling of the operational environment based on sensing information. |
| **S2:** Task allocation/sharing | Cognition | • Enable access to edge (cloud)/remote operator for:<br>o efficient task execution plan (e.g., based on capabilities of humans and robots, flexibility to adapt the robot motion, complexity of task, sensing information).<br>o verifying (all/partial) pre-conditions before executing the task.<br>• Offer resources (e.g., computation, sensing) within mobile networks to enable the above. |
| **S3:** Human-robot interaction | Cognition, actuation & control | • Enable multimodal synchronization between robot HMI device and network node/(edge)cloud (e.g., for AI capabilities) for interpreting human inputs accurately. |
| **S4:** Collaborative operation | Cognition, actuation & control | • Enable efficient monitoring of human and robot actions throughout its operation via sensing.<br>• Proactively setup communication link with remote operator based on sensing information in case of detecting emergency situations. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- Reliable and ultra-low latency communication links between robot and (edge) cloud/remote operator.
- Support cyclic communication pattern with required latency budget between robot and (edge) cloud. For example, robots share human inputs on the uplink (for instance, when it cannot be processed by the robot locally) and receive downlink response to trigger appropriate actions in the robot. Another example includes, robot sending a request for verifying pre-conditions before executing an action on the uplink, and receiving a response to before executing an action.

Actuation and control requirements:

- Support communications and control co-design by measuring information freshness in remote monitoring and control scenarios based on metrics such as age of information (AoI), age of incorrect information (AoII), urgency of information (UoI), and Value of Information (VoI), among others.

Sensing requirements:

- High accuracy and robust sensing of human actions/activities.
- Continuous and efficient sensing service at all times as long as the collaborative task is ongoing.

- Coordination among sensors for covering blind spots that cannot be in the field of view of sensors on the robot.

AI-support requirements:

- AI-support for developing accurate operating environmental model, interpreting human inputs, and assisting in developing task execution plan.
- Optimization of AI/ML models considering both performance and privacy. For example, by dividing the AI/ML operation/model into various segments based on the task and environments. This allows delegating the computation-intensive and energy-intensive segments to network endpoints, while retaining the privacy-sensitive and delay-sensitive sections on the robot itself.
- Fulfilment of stringent communication link KPIs for distributed AI/ML model execution along multiple communication links between the robot and involved network nodes.
- Adapting the communication link KPIs based on the processing time at different computing/processing nodes.
- Support in the process of uploading the locally trained model to the centralized node and downloading the global model from the centralized server.

## 2.6. Use case 6: Service robots for healthcare assistance at home

Interactive Companion Robots are designed to provide emotional support and companionship to patients and elderly. It engages in conversations, offers comfort, and helps alleviate stress and loneliness. These companion robots can also assist to help navigate patients to their respective rooms/units. Companion robots are autonomous machines designed to interact with humans in a social context, using natural human-like communication and behavior. These robots are equipped with sensors, processors, and software that enable them to perceive and interpret human behavior and respond to it in a meaningful and socially acceptable way. They are typically designed to perform tasks that require social interaction, such as providing companionship, assisting with communication, stress-reliever or serving as personal assistants.

Recent technological advances like emotion recognition, voice recognition and NLP enable more informal, non-transactional communication with machines, that enable these robots to communicate in a wide range of modalities, including speech, gestures, facial expressions, and body language. These robots are capable to adapt their behavior to suit different social situations and individual preferences using machine learning algorithms to learn from their interactions. Figure 6. provides a high-level illustration of the use case.

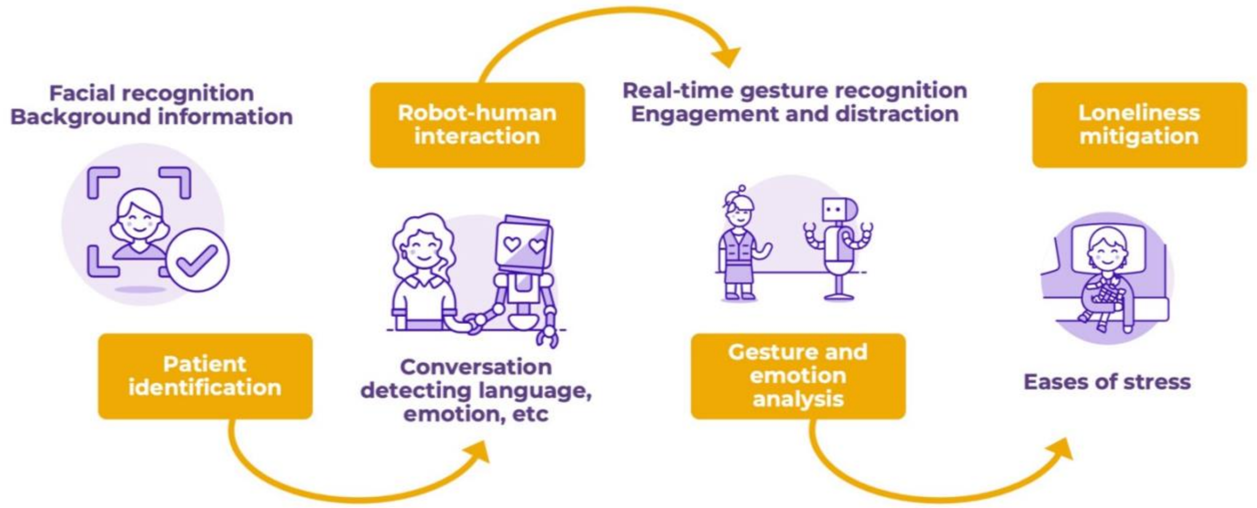


*Figure 6: UC6 - Service robots in healthcare assistance at home execution illustration*

### Actor

Service Robots, Humanoid Robots, Mobile network operator(s), Third-party service provider(s).

### Pre-condition

- Humanoid robots are equipped with sensors, actuators, and motors, that enable them to move and interact with the environment in a natural and intuitive way.
- Robots are trained to be familiar with home environment like floor maps and potential obstacles.

- Robots are pre-trained to understand and respond to the social and cultural norms of their environment.

## Service flows

In a home environment, companion robots are designed to emotionally support the patients, ease out stress and help them navigate around the facility. The companion robot identifies and approaches the patient, introduces itself, and explains its purpose, emphasizing that it provides support and assistance, using facial recognition or other identification methods to address the patient by name. It initiates a conversation, actively listens, and responds empathetically, offering comfort and alleviating stress. It can help patients navigate around the place by providing directions and information about different departments, rooms, or facilities. Also, it can guide them to their destination by walking with them or providing verbal instructions.

## Post-condition

Reduced stress levels and induces a sense of calmness in patients.

## Potential service requirements

The goal of companion robots in healthcare is to emotionally support patients and eases their stress and anxiety. Hence, the following requirements are identified for the robots.

S1: Environment perception:

- Robots must be able to understand the natural language of the patients and healthcare providers, including colloquialisms and jargon.
- Robots must recognize facial expressions and body language to understand the patient's emotional state.
- Robots must know the medical domain, including common medical conditions and treatments, to provide appropriate support and guidance to the patient.
- Robots must be aware of the environment to help navigate patients around.

S2: Data collection and analysis:

- Robots must be able to collect and analyze patient's health data.
- Robots must be able to collect data about the patient's lifestyle and habits to provide personalized recommendations.

S3: Interaction and engagement:

- Robots must be able to engage in natural and empathetic conversation with patients, providing emotional support and reassurance.
- Robots must be able to provide entertainment and companionship to patients, helping to alleviate feelings of loneliness, anxiety, stress and social isolation.
- Robots must be able to interact with the human body without safety compromises.

S4: Safety, privacy and security:

- Robots must be designed to ensure patient safety, including avoiding collisions and preventing harm from moving parts.
- Robots must have secure data transmission and storage protocols to protect patient privacy and ensure compliance with data protection regulations such as HIPAA.
- Robots must have safety mechanisms in place to prevent unauthorized access to patient data and protect against cyber threats.

S5: Physical mobility for navigation and obstacle avoidance:

- Robots should be able to navigate through the environment and avoid obstacles while moving around.
- Robots must enable safe navigation of the patients as well.

S6: Maintenance and support:

- Robots must have a reliable power source and charging infrastructure to ensure continuous operation.
- Robots must have a system for regular maintenance and updates to ensure optimal performance and minimize downtime.
- Robots must have a support system in place to address any technical issues or malfunctions that may occur.

S7: Adaptive learning:

- Robots should be able to learn from past experiences and adapt to changes.
- Robots should identify patterns and process improvements.

S8: Collaboration and coexistence with humans:

- Robots require a communication system to share information and coordinate their actions with patients.
- Robots should be able to coexist with humans without causing any harm or disruption.
- Robots should be designed with safety in mind and to have the ability to recognize and respond appropriately to human behavior and communication.

The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 6 presents the discussed mappings.

*Table 6: Communication system requirements - Service robots in healthcare assistance at home*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S1: Environment perception | Perception | • Enable the capability to recognize and interpret human gestures, facial expressions, and voice commands by offering computation capability.<br>• Enable the ability to identify individuals and their personal information such as patient identification number via sensing capability.<br>• Enable the ability to navigate and move around the house via sensing and computation capabilities. |
| S2: Data collection and analysis | Perception, cognition | • Enable reliable and real-time data exchange with other systems (e.g., healthcare facility (cloud) server) to ensure data validation, accuracy and consistency of collected information such as patient's health status, lifestyle and habits, and medication usage. |
| S3: Interaction and engagement | Perception, cognition, actuation & control | • Enable the ability to provide personalized responses based on patient history, behavior and needs by supporting AI/ML such as NLP algorithms.<br>• Ability to provide emotional support by engaging in natural language dialogue, interactive activities, and understanding medical conditions by offering ML model lifecycle management for third party AI services providers.<br>• Providing mental and emotional support to patients through, for example, conversation or interactive activities by incorporating immersive technologies. |
| S4: Safety, privacy and security | Cognition | • Secure access and transmission of patient data/information among the involved stakeholders.<br>• Ability to coordinate with healthcare professionals and access patient information securely.<br>• Ensure patient safety while navigating through the facility by detecting and mitigating risks of collision by incorporating sensing capabilities. |
| S5: Physical mobility for navigation and obstacle avoidance | Perception, cognition, actuation & control | • Enable the ability to navigate and move within an unstructured home environment by relying on additional perception, and cognition capabilities hosted in other devises such as cloud.<br>• Enable cloud-based AI algorithms for real-time object recognition and classification. |
| S6: Maintenance and support | Cognition, actuation & control | • Enable efficient power utilization at the robot via offloading capabilities to mobile communication networks for data processing, partial sensing, etc.<br>• Enable remote software update of robot systems.<br>• Enable remote access to service providers to take control in case of any malfunction. |

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S7: Adaptive learning | Cognition | • Enable access to cloud-based resources, such as AI and machine learning models, for learning and adaptation.<br>• Ability to collect data from patient interactions and adapt behavior accordingly. |
| S8: Collaboration and coexistence with human | Perception, cognition, actuation & control | • Enable continuous risk assessment by design (by means of, for example, data processing, sensing, and communication capability) to have the ability to recognize and respond appropriately to human behavior and communication. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- High-data rate and ultra-low-latency to support real-time interactions with patients.
- Reliable and secure connectivity to prevent data breaches or unauthorized access.
- Robust communication links to ensure seamless communication between the robot and other devices in the healthcare environment.

Sensing requirements:

- High accuracy sensing to detect and track patient movements, emotional state, and gestures.
- Environmental sensing capabilities to detect changes in temperature, humidity, and other environmental factors that may impact patient health.

AI-support requirements:

- Support for executing advanced analytics and machine learning algorithms to process large amounts of data collected by the robot and provide actionable insights to healthcare providers to offer patient specific personalized services and emotional support.

Security requirements:

- Since the communication system is expected to offer additional capabilities such as data processing, the communication system could support detection and response to security threats by means of, for example proactive notification mechanisms to the applications to ensure secure and stable healthcare robotics systems.

Privacy requirements:

- Privacy by design is crucial from communication system perspective, particularly when offering data processing and storage capabilities.
- Robust authentication mechanisms to allow different stakeholders of healthcare ecosystem to be able to access their desired information.

## 2.7. **Use case 7:** Flexible robots for healthcare services

Healthcare service robots could be utilized to deliver medications, manage cleanliness, and transport supplies, among others, within healthcare facilities. These healthcare facilities could be confined to a single indoor environment or span across multiple building in campus like setting. In any case, relying on medical robots for such operations requires them to firstly navigate autonomously in extremely dynamic and relatively unorganized hospital environments resulting from movements of, for example, medical staff, patients, other people (such as visitors), and medical equipment.

It is widely known that autonomous navigation relies on accurate environment perception. Environment perception requires processing the data collected through the sensors and determining the next steps in the trajectory. Considering the wide variety of critical scenarios that a medical robot could encounter, it is extremely crucial for the robot to maneuver safely without harming any person or object within the facility.

In addition to safe navigation, the medical robot is expected to perform an action upon reaching the destination. These actions could include (correlating to the tasks discussed above), appropriately handing over the medications to patients, determining which areas need to be cleaned, and delivering the supplies to the intended recipient. For the medical robots to perform tasks such as those discussed above in a safe and efficient manner, it requires real-time and precise situational awareness and possibly come in close contact with humans. Fulfilling such a requirement can be highly data and processing intensive, for example, if dependent on data-driven models to recognize highly dynamic environments, enable motion planning, and enable decision making to take quick actions.

Furthermore, healthcare facilities and medical robots themselves can be constrained with respect to space and form factor. The form factor of the robots could limit the devices that can be mounted on the robots that aid them in performing all the desired tasks. Thus, the goal of this use case is to enable task specific autonomous medical robots to be able to safely and efficiently carryout their tasks despite the size constraints of the robots.

In order to address the above requirements, this use case considers *flexible robots,* which are robots whose functionalities and tasks can be updated from time-to-time based on the requirements in the medical facility.

The need for *flexible* robots in healthcare is further motivated by staff shortage in this sector. For example, staff requirement in long-term healthcare sector is expected to be 263,000 – 500,000 in Germany by 2030 [10]. Figure 7 provides a high-level illustration of the use case.

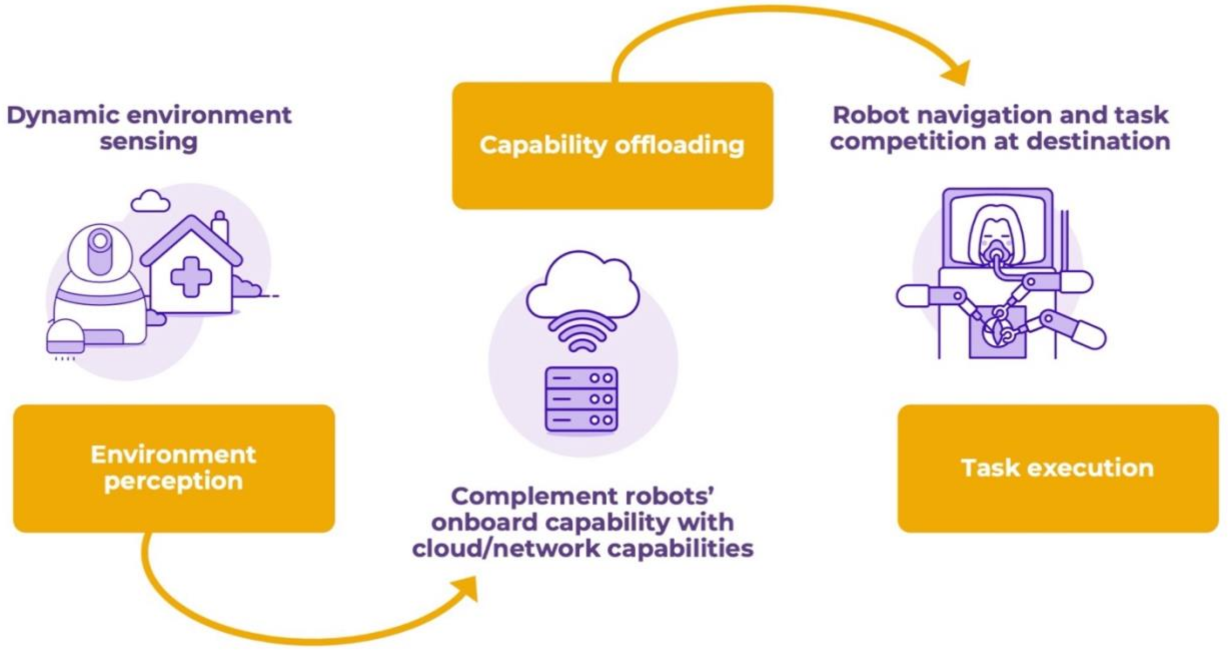


*Figure 7: UC7 - Flexible robots in healthcare services execution illustration*

## Actor

Mobile service robots, mobile network operator(s), third party service provider(s), healthcare facilities, remote (edge) cloud server(s).

## Pre-condition

- Robots are equipped with sensing and communication capabilities.
- Robot(s) interact with human or other objects with implicit or non-implicit task assignment.
- Robot with limited form factor, local control and AI capability.
- Robot with limited battery.
- Human as a service recipient.

## Service flows

The robot starts by first receiving command from the healthcare facility about the task that it needs to execute, for example, delivering medication to a patient in a specific room, or disinfecting a specific room. Upon receiving the command, the robot verifies if it has the required capabilities in terms of *perception*, *cognition*, and *Actuation & Control* to carry out the task. Upon detecting a need for additional support to carry out the intended task, the robot establishes a communication link to a remote server (hosted by a third-party service provider or healthcare facility) to support its operations. The support could range from fully remote operation of the robot, offloading some robot tasks to the remote server, or only sharing appropriate models to the robot to carry out its task. By relying on the support from remote server, the robot is guided to accomplish the desired task.

## Post-condition

The robot is able to cater the intended service in a safe manner. Additionally, the robot is able to flexibly adapt the services it can offer.

## Potential service requirements

Based on the above description the following three robot service requirements are identified for the use case:

S1: Environment perception in dynamic environments:

- The robots need to able to perceive unstructured and dynamic hospital environment, including movement of medical personnel, patients, visitors, and other objects, among others

S2: Offloading robots' on-board capabilities on a remote server:

- Considering the potential diversity in the environment and tasks, the robots need to be able to leverage additional resources (e.g., computational, storage) for robust perception and cognition.

S3: Task execution:

- The robots need to be able to not only reach their destination, but also perform the intended task at the destination, such as delivering medication to patients. Robots must be able to interact with the human body without safety compromises.

The role of communication system for each of the above robot service requirement is discussed below, along with the mapping to fundamental capabilities of the robot (Section 1.1). Table 7 presents the discussed mappings.

*Table 7: Communication system requirements – Flexible robots for healthcare services*

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| **S1:** Environment perception in dynamic environments | Perception, cognition | • Enable accurate long-term and short-term sensing of objects in the vicinity with low sensing latency (due to dynamicity in the environment introduced by random movement of people).<br>• Support real-time environmental map generation by combing sensing result to assist efficient robot navigation.<br>• Enable privacy-aware sensing, in order to comply with constraints of healthcare facilities. |
| **S2:** Offloading robots' on-board capabilities on a remote server | Perception, cognition, actuation & control | • Enable access to remote server at all times to ensure safe operation of the robot.<br>• Allow privacy aware data sharing between robot and remote server.<br>• Support timely update and distribution of models (e.g., based on AI/ML for situation awareness, robot control, etc.) for improving the efficiency of the robot task and safety in the vicinity. |

| Service requirements | Robot fundamental capabilities | Potential role of communication system (high-level description) |
|---|---|---|
| S3: Execution of task | Cognition, actuation & control | • Enable robot to operate in a functionally safe manner, particularly when in close proximity to patients/other humans.<br>• Support multimodal synchronization of communication and control. |

Based on the potential role of communication system, the generic technical requirements on communication system falls under several broad categories discussed below:

Connectivity requirements:

- Secure communication links between the robot and cloud server.
- Availability of reliable communication link at all times between robot and cloud server satisfying the necessary requirements (from loose to stringent requirements depending on the task) in terms of KPIs such as data rate, latency, reliability, among others.

Sensing requirements:

- Long range sensing for the determining the dynamicity in the environment.
- Shirt range sensing (e.g., human activity recognition) when operating in close proximity of humans.
- Privacy-aware sensing, meaning the sensing functionality needs to adapt based on the privacy requirements, such as avoiding sensing in certain areas, anonymizing the sensing data.

AI-support requirements:

- Support privacy preserving AI/ML techniques such as distributed/federated learning. Providing the participants the ability to send their local trained model to a centralized server. This can be achieved by relaying the model through multiple network nodes. Additionally, all participants should be able to successfully download the global model from the server.
- If the malicious participant is detected during distributed/federated training, the network should be capable of restricting the connectivity of that participant.
- Support Quality-of-Service (QoS) requirements relevant for executing privacy-preserving AI/ML techniques (e.g., the objective of wireless network to support federated learning is to provide 1 Gbit/s data rate for uplink and downlink between a robot and the server [11]).
- Support AI/ML model lifecycle management.

# 3. Summary

The seven use cases collected in the section 2 can be mapped into four broad categories with respect to robot-interactions described in subsection 1.2, as: Robot-Robot interaction, Human-Robot interaction, Robot-Human interaction, and Robots-Controller interaction. In Table 8, each of the identified robotic use cases with reference to potential 6G services is mapped to one of the above categories. Along with the mapping, based on the analysis in section 2, some communication system aspects that could be in the scope of potential 6G systems are identified in Table 8.

*Table 8: Use case families*

| Usage scenario | Context | 6G implications | | Whitepaper UC title |
|---|---|---|---|---|
| | | UC specific potential 6G scope | Key enablers | |
| **Robot-to-Robot** | | | | |
| Manufacturing, logistics | Collaborative transport of heavy objects in manufacturing and logistics | • Offer high-accuracy sensing and imaging capability<br>• Coordination between sensing and communication functionalities<br>• Multi-link sensing and communication operation synchronization<br>• In-network computing capability to support real-time decision making | • Reliable low latency communication links among the robots<br>• Computational capability for real-time decision-making on path plan and motion plan<br>• Advanced sensors for object identification, and collaborative motion and path plan execution | Cooperative carrying with robots |
| Infrastructure, construction | Cooperative inspection and monitoring of infrastructure such as bridges, buildings, and pipelines, cooperatively resolving detected issues, e.g. by carrying blocking objects | • Cooperative sensing capability<br>• Sensing-assisted communications to enable proactive wireless link adaptation<br>• In-network computing to support real-time decision making<br>• AI/ML model lifecycle management<br>• Develop/enhance communication system protocols and mechanisms for robot control | • High-data rate and low-latency communication between robot and remote operator<br>• Computing capability for real-time decision-making<br>• Advanced cooperative sensors for monitoring and mapping the infrastructure<br>• AI/ML for data analysis and predictive maintenance<br>• Support different kinds of drones and control systems | Drones enabled remote inspections |

| Usage scenario | Context | 6G implications | | Whitepaper UC title |
|---|---|---|---|---|
| | | UC specific potential 6G scope | Key enablers | |
| **Robot-to-Human** | | | | |
| Healthcare | • Assisting healthcare professionals in patient care at home<br>• Providing social support to patients<br>• Monitoring patient health<br>• Companion for elderly at home | • Offer computational and data storage capability/resources for AI/ML related tasks<br>• Seamless integration of third-party services with computational and storage capability offered by networks<br>• Privacy-aware handling of data in communication systems and complying to regional, global, industry specific data regulations<br>• High-accuracy sensing of the environment including human activities, gestures, and emotions<br>• Robust authentication mechanisms to enable multiple stakeholders to access patient data | • High-data rate and ultra-low-latency communication<br>• Computing capability for real-time decision-making related to environment perception, robot trajectory, human emotions/behavior<br>• Advanced sensors for patient monitoring and interactions | Service Robots for Healthcare Assistance at Home |
| | • Providing personalized assistance to patients in performing daily activities<br>• Assisting healthcare professionals in patient care | • Sensing capability<br>• Dynamic shift of computational and sensing workload between robot and network/third-party service provider<br>• Privacy-aware sensing to avoid transfer of unauthorized sensing information or sensing in unauthorized areas<br>• AI/ML model lifecycle management<br>• Multimodal communication and control | • High-data rate and ultra-low-latency secure communication links,<br>• Dynamically varying computing capability for real-time robot operation with opportunity for data/compute offloading,<br>• Advanced sensors for patient monitoring and interaction<br>• AI/ML algorithms for environment perception and human activity/behaviour recognition | Flexible robots for healthcare services |
| Education | • Assisting teachers in classroom management,<br>• Providing personalized learning experiences to students, | • Communication links capable of supporting AR/VR services<br>• Privacy-aware handling of data in communication systems and complying to regional, global, industry | • High-data rate and ultra-low-latency communication for multimodal interactive learning purposes,<br>• Computing capability for real-time decision-making based on | EduBots - Interactive Robots in Education |

| Usage scenario | Context | 6G implications | | Whitepaper UC title |
|---|---|---|---|---|
| | | UC specific potential 6G scope | Key enablers | |
| | • Delivering educational content | specific data regulations<br>• Multimodal communication synchronization<br>• Seamless integration of third-party services with computational and storage capability offered by networks<br>• AI/ML model lifecycle management | student learning behavior,<br>• Advanced sensors for student monitoring and interaction,<br>• AI/ML algorithms for personalized learning | |
| **Human-to-Robot** | | | | |
| Manufacturing | • Collaborative assembly and manufacturing<br>• Increasing productivity and efficiency in industrial environments | • Sensing capability<br>• Sensing-assisted communications to enable proactive wireless link adaptation<br>• Multimodal sensing and communication operation synchronization | • Reliable continuous ultra-low-latency communication link between robot and remote human operator for spontaneous intervention<br>• Edge computing for real-time decision-making related to task sharing, environment perception<br>• Advanced sensors for precise human activity recognition | Collaborative robots in industrial environments |
| **Robot-to-Controller** | | | | |
| Industry | • Automating repetitive tasks in supply chain management such as data entry, invoice processing, and inventory management | • Application specific sensing capability such as inventory tracking, shipment tracking, product scanning<br>• Seamless integration of network-based sensing with multiple third-party services operating in the warehouse<br>• Reliable communication links in limited connectivity areas such basements, underground warehouses | • Integration of multiple third-party inventory related services<br>• AI and machine learning for continuous process optimization and prediction<br>• Sensors for activity monitoring during supply chain management processes | Robots in inventory management |

# 4. Conclusion

In this white paper, seven robotic use cases are described. These use cases are grouped based on the kind of interaction that exists between the key actors: robot-robot, human-robot, robot-human, and robot-controller (e.g., edge/cloud). For each of the categories, one or more use case scenarios are discussed along with the potential role of mobile communication systems to support them. Figure 9 summarizes the use case scenarios discussed in this white paper.

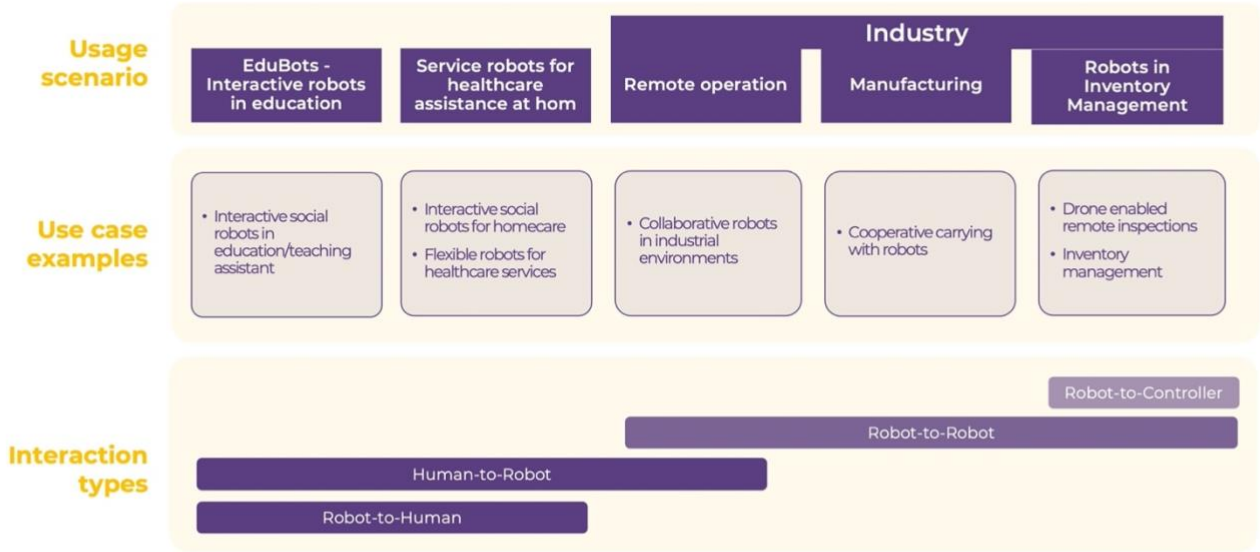


*Figure 9. Mapping of the use cases and robotic interaction types*

Despite the diversity of the use cases, most of the use cases have identified key communication system requirements that largely fall within the domains of:

- high-accuracy sensing,
- in-network computational support,
- AI/ML model lifecycle management support, reliable wireless connectivity in underserves areas,
- high data rate and ultra-low latency communication links,
- multimodal synchronization of communication and control,
- support for multiple third-party service providers for a single service,
- privacy-aware and secure communication links and data exchange mechanisms,
- enhancement to communication system protocols and mechanism specific for robot control,
- tighter integration between network functionalities such as communication, sensing, and compute functionalities,
- tighter integration between communication, sensing, and compute functionalities and applications/one or more third-party service providers.

In order to address such requirements, several discussions related to technology enablers are ongoing in one6G. These enablers include: THz frequencies, 6G Radio Access, Next Generation MIMO, Integrated Sensing and Communication, Distributed Federated AI, Intelligent User Plane, In-Network Computing, and Flexible Programmable Infrastructure [12].

As next steps, the discussed use cases and their identified technical requirements in this whitepaper will be further investigated. A more detailed requirement analysis is crucial to help identify the precise technical problems and develop appropriate technical solutions. In addition to deeper analysis, one6G will continue to identify novel and relevant use cases and scenarios for *6G and Robotics*.

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