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6G & ROBOTICS

A Methodology to Identify Potential Service Requirements for 6G-empowered Robotic Use Cases

WHITE PAPER

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Scope

One6G Association acknowledges the increasing demand for robotic applications in several vertical areas such as logistics, automation, healthcare assistance and delivery, to name a few. We recognise the integration of wireless sensing, communication and computation capabilities in robotic systems as key enablers for increased reliability, capability and operational efficiency at lower complexity and cost. It is therefore envisioned that the future 6G communication system can empower robotic applications. The mobile communication industry is further identifying system requirements of robotic applications for the design of the future 6G communication system. A detailed requirement analysis is necessary to determine precise technical problems and challenges of robotic applications. The accurate identification of said technical problems will guide the development of adequate technical solutions from a communication system perspective.

The previous 6G & Robotics one6G white paper [1] proposed multiple robotic use cases (UCs) and pinpointed the potential future role of the upcoming 6G communication system. We described a diverse set of robotic UCs in healthcare assistance and industry-related usage scenarios including remote operation, automation and inventory management. The whitepaper took a step forward and classified the robotic UCs based on the type of interaction between involved robots, humans and controllers, namely: robot-to-robot, human-to-robot, robot-to-human and robot-to-controller interactions. This classification helped recognize the potential role of the 6G communication system to enable the envisioned robotic UCs. A high-level common set of key communication system requirements were presented to enable robotic UCs. These system requirements include highly accurate sensing, high data rate and ultra-low latency communication links, in-network computation support, AI/ML support and a tighter integration between network functionalities such as communication, sensing and computation (including those within network and/or belonging to third-party applications). We therefore require a methodology to specify service requirements across all these UCs.

The goal of this white paper is to present a methodology to determine the requirements of 6G robotic UCs across different dimensions namely, wireless sensing, communication, computation and support of AI/ML methods. The proposed methodology represents robotic UCs as a composition of different phases (i.e., set up, perception and task execution), atomic functions (e.g., registration, environment model establishment, task definition and task sharing) and UC-specific atomic function handlers (e.g., event handlers for human behaviour perception, task handler for human robotic interaction and task handler for motion planning). Depending on the robotic UC, the atomic functions will interact in different ways and each of the different atomic functions will have specific requirements in the dimensions outlined above. The present methodology is further described based on examples from the UC classifications derived in the previous white paper [1] to demonstrate how to establish system requirements for robotic UCs. Different categories of baseline system requirements of robotic applications, wireless sensing, communication and AI/ML have been derived for a distinctive atomic function and handler per UC class example. By having detailed system requirements per atomic function, the future 6G system may be optimised to provide these network services for each of the atomic functions that compose robotic UCs in the most cost-effective and sustainable way.

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1. Definitions

In this section, we present a set of definitions for terms related to Methodology, Robot Capabilities, UCs, as well as different KPIs. The KPIs are defined in terms of system requirements for robotic applications, perception and sensing, connectivity and AI/ML support.

1.1. Methodology

Phase: is the sequence of steps associated to a self-contained function of a robotic UC. Phases of a robotic UC may include e.g., set-up phase, object perception phase, environment perception phase, task and motion planning phase, etc. Upon a network request, the 6G communication system may orchestrate the different phases associated with a particular robotic UC.

Atomic Function: refers to an independent and compact function implemented in an entity (e.g., robot or network) that interacts with other independent functions over defined interfaces. The atomic function concept allows the decomposition of each phase into smaller components performed by UC actors (e.g., robots). Multiple atomic functions may be associated to a phase. An atomic function may be common to multiple UCs.

Atomic Function Handler: is a type of atomic function that is specific to a UC and therefore it is specialized to a certain type of UC. An atomic function handler triggers the execution of other atomic functions specific to a UC. Different handlers are associated to different types of actions performed by robot, e.g. perception or cognition actions (defined below).

Robotic UC class: is a template of atomic functions and handlers common to all robotic UCs that belong to a specific class. There is a one-to-one mapping of each robotic UC interaction type group to each robotic UC class.

Actor: performs a specific role in the system. Multiple actors can operate on a UC. An actor can be a person, such as a customer or operator, or a computation entity, such as a database system or server in a cloud.

Pre-conditions: are events or elements that must happen before a UC can start. In our context, it refers to the deployment of sensing or wireless communication infrastructure, as well as capabilities of robots and/or 6G communication system.

Service Flow: refers to all necessary steps to execute a UC from start to end.

System Requirements: refer to the required performance level in terms of wireless communication and sensing, AI/ML support and robotic application that future 6G communication system must fulfil to enable robotic UCs.

1.2. Robotic UC capabilities

This part is a summary taken from one6G 6G & Robotics whitepaper vol. 1 [1].

Perception: refers to the key capability of the robot to perceive and comprehend about unstructured (real) environments in which they operate and act. 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: 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.

Actuation & Control: 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.

1.3. 6G Robotic UCs

Motion Plan: is the sequence of valid spatial configurations that mobile robot executes to perform motion from source to destination location. It may be computed locally by robot or computed externally by network or other robots [3].

Autonomous: refers to the robot's ability to deal with its environment on its own, and work for extended periods of time without human intervention [4]. Different autonomy level may also imply the dependency of the robotic system with the communication system. As an example, an autonomous mobile robot receives a list of waypoints from the central fleet management and also a regular update of the environment map in order to compute the detailed manoeuvre and trajectories on the local controller.

Service Availability: is the percentage value of the amount of time the end-to-end communication service is delivered according to a specified quality of service, divided by the amount of time the system is expected to deliver the end-to-end service [3].

Transfer interval: is the time difference between two consecutive transfers of application data from an application via service interface to network [3].

1.4. Communication terms and KPIs

Communication Direction: refers to who transmits to whom over a wireless channel, i.e., from network to robot (downlink), from robot to network (uplink) and robot to robot (sidelink).

Communication Mode: refers to the number of involved transmitters and receivers in the wireless communication. Unicast corresponds to one-to-one communication, groupcast corresponds to one-to-many communication, fusion refers to many-to-one and broadcast corresponds to one-to-all communication.

Communication Availability: refers to the ability of the communication service to perform as required for a given time interval, under given conditions [3].

Communication Data Rate: refers to the amount of data bits transmitted over a wireless channel during a defined time window [Bits/s] [3].

Communication Reliability: refers to the proportion of transmitted bits that are correctly decoded by receiver within a given time period (%) [3].

Communication Latency: refers to the amount of time it takes to transfer a packet from source transmitter to destination receiver, measured at the communication interface [msec] [3].

Communication Jitter: refers to the variation of communication latency from consecutive packets that have arrived at the receiver [msec].

1.5. Wireless sensing terms and KPIs

Wireless Sensing: is the capability of the 6G communication system to get accurate information about objects within environment (e.g., shape, size, velocity, orientation, location or distances or relative motion between objects) using wireless signals (either reusing communication signals or using dedicated sensing signals) [2].

Accuracy of Positioning Estimate: describes closeness of measured sensing result (i.e. position) of target object to its true position value [m] [2].

Accuracy of Velocity Estimate: describes the closeness of the measured sensing result of the target object's velocity to its true velocity [m/s] [2].

Refresh Rate: is the inverse of the time elapsed between two successive sensing results [1/s] [2].

Sensing Resolution: describes minimum difference in measured magnitude of target objects (e.g., range, velocity) to be allowed to detect objects in different magnitude [2].

1.6. AI/ML support KPIs

Max allowed downlink end-to-end latency (Model Transfer): in the context of AI/ML model distribution, is the maximum time a robot may wait to receive an AI/ML model transfer from network [6].

Max allowed downlink end-to-end latency (AI/ML split inference): in the context of AI/ML split inference, is the maximum time a robot may wait to receive an AI/ML intermediate result from network [6]. Split inference refers to when AI/ML model (e.g., a neural network model) is split among multiple entities during inference.

Max allowed uplink end-to-end latency (AI/ML split inference): in the context of AI/ML split inference, is the maximum time a network application (e.g., implemented in an edge server) may wait to receive an AI/ML intermediate result from robot [6].

2. Methodology

The field of robotics continues to evolve significantly, with new applications emerging regularly. Robotic software applications are adopting a modular approach, in which new functionality can be incrementally added to robots [5]. In contrast to a monolithic architecture, future robotic applications may be able to easily and incrementally incorporate novel functionality with same hardware. Each of the new functionalities may have specific and distinct requirements along different dimensions. The future 6G communication system will facilitate the process of incorporating new and more performant functions in robotic applications at a reduced cost. The expected key enablers are the integration of communication and wireless sensing, as well as high data rate, high service availability and low-latency wireless access to *data processing* functions and AI/ML services. Fundamental *Perception*, *Cognition* or *Control* & *Actuation* sub-tasks performed by robots (discussed on Whitepaper vol 1 [1]) enable different robotic UCs.

Our proposed methodology consists of decomposing the service flow of a robotic UC into phases. As defined in Section 1, phases are sequences of steps associated to a self-contained and loosely-coupled function of a robotic UC. Each phase is composed by one or multiple atomic functions. In this work, we label fundamental robotic subtasks as an atomic function. An atomic function is a compact and independent function that interacts with other independent functions over defined interfaces. We describe a robotic UC as a composition of atomic functions in each UC class and UC specific handlers. An atomic function is mapped to a fundamental robotic capability, namely: Perception, Cognition and Actuation & Control, as outlined in *6G & Robotics* one6G white paper [1]. An atomic function has the following characteristics:

- has a specific objective,
- the service flow of an atomic function is not impacted by the overall description of the UC,
- can be re-used multiple times within the same UC (e.g., in case of multiple actors, at multiple time instants and at different phases) without affecting the objective,
- may be common in different UC classes.

3. UC Classification

The previous *6G & Robotics* one6G white paper [1] presented a robotic UC grouping based on the type of interactions between key entities in the robotic UC. The type of interactions in robotic UCs are:

Robot-to-Robot interaction (R2R): This type of interaction concerns cases when multiple robots collaborate between each other to achieve a common task. Robot-to-robot interaction enables a group of robots reach consensus on how to execute a common task. The shared information may include motion plans, perception information, as well as collaborative control actions. The communication direction in the communication system that enables robot-to-robot interaction is sidelink.

Human-to-Robot interaction (H2R): This type of interaction concerns the cases where human teleoperates a robot via consoles, such as haptic wearables. The communication direction in the communication system that enables human-to-robot interaction is uplink and/or downlink.

Robot-to-Human interaction (R2H): This type of interaction concerns when robots interact with humans using multiple modalities (e.g., audio/tactile). The communication direction in the communication system that enables robot-to-human interaction is uplink, downlink and/or sidelink.

Robots-to-Controller interaction (R2C): This type of interaction concerns when robots communicate with controller for computational offloading or remote control. The communication direction in the communication system that enables robot-to-controller interaction is uplink and/or downlink.

The presented methodology is not limited for the above selected interaction classes. Other type of interactions may also include robot avatars, humanoids or communication over the metaverse.

4. Atomic Functions and Handlers for Robotic UC Classes

We perform a detailed UC analysis using the proposed methodology for the four UC group classification outlined in Section 3. We map each interaction type to a robotic UC class. A robotic UC class is a template of atomic functions and handlers common to all robotic UCs that belong to that class. Robotic UCs from different classes have distinct atomic function handlers. We characterise four robotic UC classes with one UC example that falls within that class. The analysed robotic UC classes are: R2R class using the *Cooperative Carrying of an Object* UC, H2R class using the *Collaborative Robots in Industrial Environments* UC, R2H class using the Service *Robots for Healthcare Assistance* UC and R2C using the *Robots in Inventory Management* UC as examples.

The following subsections present a detailed UC analysis to demonstrate how the proposed atomic function methodology principles (outlined in Section 2) can be used to identify potential service requirements. The levels of different functions in the robotic UCs in each phase are categorised as atomic functions and atomic function handlers. Each atomic function is characterised with a description, actors, inputs and outputs. Such description per atomic function help elicit system requirements. Atomic functions within phases may follow a specific order (e.g., robots register to network first and then robots receive group configuration). Atomic functions within handlers do not follow a specific order as they are called by the atomic function handler when an event occurs (e.g., robot is executing path plan and suddenly a human appears on its vicinity).

4.1. R2R class: Cooperative carrying robots

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 (e.g., in a factory). Depending on the object characteristics (e.g., fragility, texture, etc.), and number of mobile robots, the level of cooperation may vary. Further details of this UC are described in UC Cooperative Carrying with Robots in 6G & Robotics one6G white paper [1, Sec. 2.1]. Figure 1 presents an illustration of three robotic UC phases and the atomic functions and handlers that support the goal of each phase and the interactions between the phases.

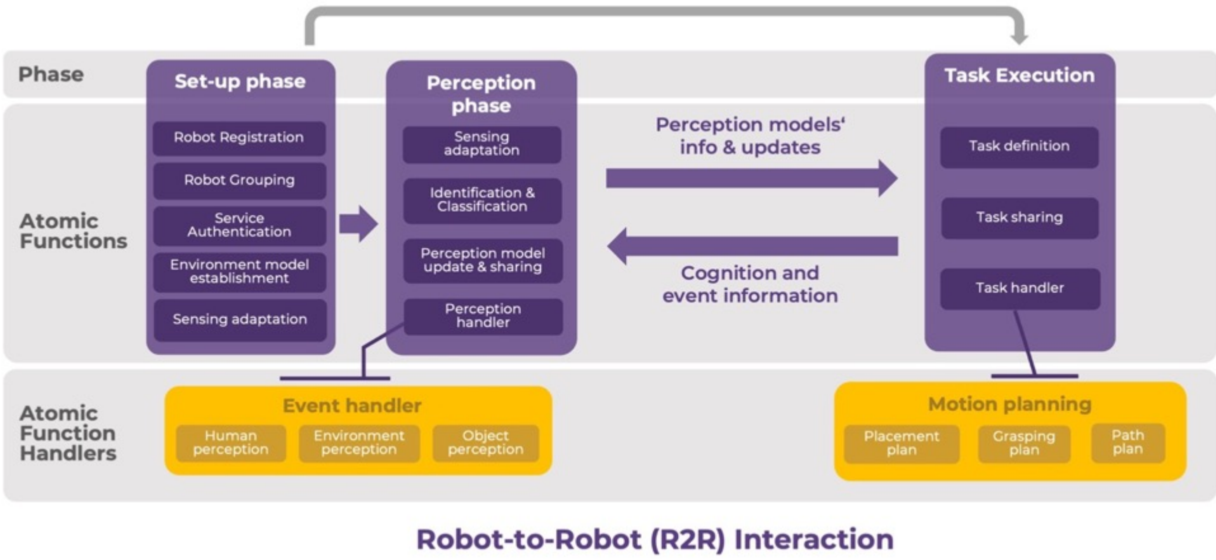

Figure 1: Atomic functions and handlers for R2R class: cooperative carrying robot example

Mobile robots, mobile network operators, and third-party service providers (e.g., for AI services) are the main actors of the three phases. The three phases are described in the following:

Set-up Phase

S.1 Robot Registration

Description: Robots broadcast their presence over a wireless channel. The network becomes aware of the robots and responds with network information such as default radio bearer for the communication link and sensing capability indicator. The robots register to the network with relevant information including robot type as well as computational, motion and sensing capabilities.

Actors: Robots, relevant radio access and/or network core entities.

Input: Network sends network information to robots.

Output: Robots successfully register to network by communicating relevant robot information related to their capabilities.

S.2 Robot Grouping

Description: The robots notify the network of their task capabilities and request relevant configuration to network. The network, upon reception of this request, orchestrates the necessary phases to enable the execution of the desired task. The network configures the robots from a communication and robotics system perspective to collaboratively carry an object from initial location X to end location Y. The robotic system configuration includes group/pairing decisions so that two or more robots form a working group to aid in task completion. A robot is configured as leader based on the requirements of the task and the relative capabilities of the robots. The remaining robots are configured as follower robots. Robots configure their sensors (e.g., cameras). The sensors operate at a configured refresh rate to be able to capture dynamicity in the environment and have the capability to adjust camera's refresh rate as needed. Network sensing and on-board wireless sensing capabilities are configured to detect mobile and static objects in environment, as well as the characteristics of the object to be carried.

Actors: Registered robots, relevant radio access and/or network, atomic function for task definition.

Input: Upon reception of desired task, network communicates relevant configuration to robots.

Output: Upon reception of configuration, robots configure their robotic and communication system according to the received configuration.

S.3 Service Authentication

Description: Network authenticates robots to be able to access different services of the network. Service authentication will determine the functionalities for each registered robot. Services may include access to environment perception and object perception services together with grasping and path plan services, to name a few. According to privileges verified during service authentication, robots may read and write data to systems and applications (e.g., asset management system of a factory).

Actors: Robots, relevant radio access and/or network core entities.

Inputs: Robot ID and/or information provided during registration.

Output: Robots, according to their privileges, are authenticated to access services and perform tasks.

S.4 Environment Model Establishment

Description: Multimodal data is configured to be collected by robots using on-board sensors and network sensing. Sensor data is collected and fused centrally by the task leader, according to the requirements on computing capability. A detailed model of the environment is created from the fused sensor data, with a specific spatial resolution and update time depending on the nature of the desired task.

Actors: Robots, relevant radio access and/or network core entities, AI/ML methods for collecting data and performing sensor fusion.

Input: Multimodal data is configured to be collected by robots.

Output: Task leader establishes environment model.

S.5 Sensing Adaptation

Description: The goal of the different sensing modalities of the on-board sensors and network sensing is to maintain an updated environment model of the physical environment. As the robots start moving, the area of view of their on-board sensors and relevant network sensing area will change and blind spots could appear. The task leader can be either the network or a leader robot. Task leader defines a sensing adaptation policy to address different areas of view from different sensing modalities (e.g., cameras, radio-based sensing, LIDAR, etc.) based on sensing requirements. The sensing adaptation configuration enables a complete environment model as the robots move within the physical environment.

Actors: Robots, relevant radio access and/or network core entities executing sensing adaptation.

Input: Task leader defines a sensing adaptation policy to cover blind spots with different sensing modalities.

Output: Robots and network configure sensing adaptation policy.

Perception Phase

P.1 Sensing Adaptation

Description: Based on the sensing adaptation configuration within the set-up phase and new triggered events, the configured sensing adaptation policy is adapted. New events may correspond to the start of a new task or cognition/event information (e.g., change in motion plan) incoming from task execution phase. Event information may correspond to changes in motion plan or visit of new area. The sensing adaptation policy adapts network sensing and/or sensing from on-board sensors on the robots.

Actors: Robots, relevant radio access and network core entities executing sensing adaptation capabilities.

Input: Sensing adaptation policy is configured and new event is triggered.

Output: Sensing is adapted based on different area of view of the different sensing modalities.

P.2 Identification & Classification

Description: Multiple robots perform collaborative sensing to perceive the environment and detect objects. Robots identify objects or obstacles within their field of view with on-board sensors and/or network sensing. AI/ML models embedded in the network and/or on the robot process input sensor data. Objects are classified according to some abstract characteristic (e.g., relevance or danger).

Actors: Robots, relevant radio access and/or network core entities executing AI/ML identification and classification methods.

Input: Robots identify objects in their proximity. Sensing is adapted based on the triggered event (e.g., visit of new area).

Output: Identified and classified objects in the proximity of robots.

P.3 Perception Model Update & Sharing

Description: Robots and the network continue publishing sensor information to enable dynamicity of the environment model. If a significant change in the physical environment is detected (e.g., moving from one room to another), an environmental model update may be triggered. The environmental model update involves a retraining function within the task leader. If needed this updated model is communicated to the leader robot. Follower robots may request an environment model update or the update may be pushed automatically. A specific request may include metrics of interest, refresh rate and area of interest.

Actors: Robots, relevant radio access and/or network core entities with stored models or with computation capabilities.

Input: A significant change in the physical environment is detected.

Output: Environmental model is updated at Task Leader and faithfully replicates physical environment.

P.4 Perception Handler

Description: Events can trigger changes in perception actions in robots. The Perception Handler handles events such as cognition events (i.e., changes in multi-stage motion planning) and event information (e.g., disturbance in motion plan) incoming from task execution phase, as well as perception models' information (e.g., detected obstacles) and updates (e.g.,entering unknown scenario) with perception actions. When an event is triggered, the perception handler handles the event with the atomic function handler associated to perception.

Actors: Robots, relevant radio access entities executing perception actions to handle events

Input: A new event is triggered (e.g., detecting a new dynamic obstacle along path).

Output: Event is handled with one or more of the following atomic functions: object perception and environment perception.

P4.1 Object Perception

Description: Based on new triggered event (e.g., target object to be carried is identified), leader robot broadcasts information to all other robots about requirements and task of identifying object characteristics. As robots are employing a collaborative perception technique, each robot relies on either its own sensors or sensing information from other sources such as network-based wireless sensing to identify the characteristics of the object (such as size, shape, material, stiffness, estimated weight, absolute/relative position and distance of the object). Wireless sensing is used as part of the multimodal sensing setup of the robot. Depending on the wireless sensing capabilities of robots, robots determine a set of parameters like distance, shape/image, material characteristics as well as possible object locations where robot grippers can grasp object optimally. Leader robot communicates optimal grasping points to follower robots.

Actors: Robots, relevant radio access entities with wireless sensing capabilities and/or core entities with computation capabilities

Input: Perception or cognition event is triggered.

Output: New target object is perceived.

P4.2 Environment Perception

Description: Based on new triggered event (e.g., target object is grasped) task leader broadcasts information to follower robots about requirements and task of determining proximity to other objects in operating environment. All the robots, relying on their own sensors or other sensors, such as network sensing capability estimate proximity to other objects in the operating environment. As notified by the task leader, all robots publish relevant topics. Task leader fuses information and shares consolidated environment map to follower robots.

Actors: Robots, relevant radio access entities with wireless sensing capabilities and/or core entities with computation capabilities.

Input: Cognition and event information are triggered (e.g., execution of motion plan starts).

Output: Objects in the environment are sensed. An environment model is maintained, synchronised with physical environment.

Task Execution Phase

T.1 Task Definition

Description: Network communicates task definition information to leader and follower robots. A task definition is a machine-readable description of the task. Task definition can be defined by production / logistic management system or authorised actor (e.g., factory employee). Description of the task includes but it is not limited to a link to an asset data base of the target object, physical start and end location of task. Robots configure task definition.

Actors: Robots, relevant radio access and/or core entities accessed by management and/or authorised actors.

Input: Leader and follower robots receive task definition from network.

Output: Robots configure task definition.

T.2 Task Sharing

Description: Task sharing information is included within task definition information. Task sharing refers to how task is split into subtasks and shared with multiple actors. Task sharing information defines which authenticated actor (e.g., network) is responsible for which phase during task execution. Robots configure task sharing.

Actors: Robots, relevant radio access and/or core entities accessed by management and/or authorised actors.

Input: Robots configure task definition.

Output: Robots configure task sharing.

T.3 Task Handler

Description: Events can trigger execution changes in robot. When event is triggered (e.g., environment is perceived fully), task handler performs events with atomic function handlers associated to cognition (e.g., multi-stage motion planning).

Actors: Robots, relevant radio acc$ess entities executing cognition actions to handle events.

T.H.3.1 Multi-robot Placement Plan

Description: Upon reaching consensus on object characteristics and environment, leader robot determines and shares execution plan. The execution plan comprises of a sequence of sub-tasks to be executed by each group member to collaboratively carry an object from initial location X to end location Y. Execution plan consists of a multi-robot placement, grasping and path plan. The motion planning phases take as input fused results from environment perception phase as well as the task specification defined in the Task Definition atomic function. Task Leader computes a global multi-robot placement plan and communicates it to follower robots. Global motion planning is the process of determining movement/trajectory of the group towards target goal. Global motion planning may be based on a relatively low resolution map (covering a larger area) with lower update frequency to enable more complex planning. The placement plan is the orientation, posture and position around target object. Follower robots determine their local placement plan based on the received global multi-robot placement plan. Local motion planning is the process of determining the movement of robot actuators, arms, torso and end-effector(s). Local motion planning takes place in a high resolution map (covering a smaller area directly surrounding the robot) with high update frequency to account for e.g. emergency obstacle avoidance.

Actors: Robots, relevant radio access entities executing cognition actions to handle events.

Input: After robots reach consensus on object characteristics and environment, leader robot determines and shares execution plan to follower robots.

Output: Robots determine their local placement plan.

T.H.3.2 Multi-robot Grasping Plan

Description: Once robots determine local placement plan, task leader computes a global multi-robot grasping plan and communicates it to follower robots. In this case, global multi-robot grasping plan is computed based on a high resolution map with high frequency updates. Grasping plan consists of the movement, position and orientation of end-effectors that will take part in the grasping action to reach, load and lift target object. Robots determine their own local grasping plan depending on the capabilities of each robot with respect to the degree of freedom of arms and gripper type (e.g., hands). Local grasping plan takes material characteristics (e.g., metal, plastic, foam, etc.) into account sensed with on-board or external sensors such as wireless sensing. Extreme high frequency updates of the tension, push and pull forces determine safe grasping. Follower robots may employ impedance control to reduce interaction forces and the need to have high force gain over multiple robots [7]. Grasping planning has also impact on the local motion planning of the entire robot in case it has to move closer or away from object.

Actors: Robots, relevant radio access entities executing cognition actions to handle events.

Input: After robots determine local placement plan, task leader determines and communicates multi-robot grasping plan to follower robots.

Output: Robots determine their own local grasping plan based on the degrees of freedom of their arms and gripper together with material characteristics of target object.

T.H.3.3 Multi-robot Path Plan

Description: Task leader computes global multi-robot path plan and communicates it to follower robots. Path plan consists of the movement, position and trajectory of robots to reach location Y from location X. Upon reception of global multi-robot path plan, follower robots determine local path plan based on their motion capabilities (e.g., legs or wheels).

Actors: Robots, relevant radio access entities executing cognition actions to handle events.

Input: After robots determine local grasping plan, task leader determines and communicates multi-robot path plan to follower robots.

Output: Robots determine own local path plan based on their motion capabilities. Robots execute successfully collaborative task.

Annex A (see Table A.1) describes a potential set of baseline requirements in terms of wireless communication and sensing, AI/ML support and computational offloading of the Cooperative Carrying Robot UC. The requirements are described for main functions of the UC, and not for all the atomic functions of the UC. The baseline requirements are described for a distinctive function of the UC.

4.2. H2R class: Collaborative robots in industrial environments

With cobots foreseen to tightly collaborate with humans, they must be aware of human movements/actions and autonomously adapt their behaviour to prevent accidents with humans or other objects/robots. This UC considers that the human collaborator and robots are working on the same task. This UC also considers the presence of a remote human operator to take over in case of unforeseen scenarios. Figure 2 presents an illustration of three phases and the atomic functions and handlers that support the goal of each phase and the interactions between the phases.

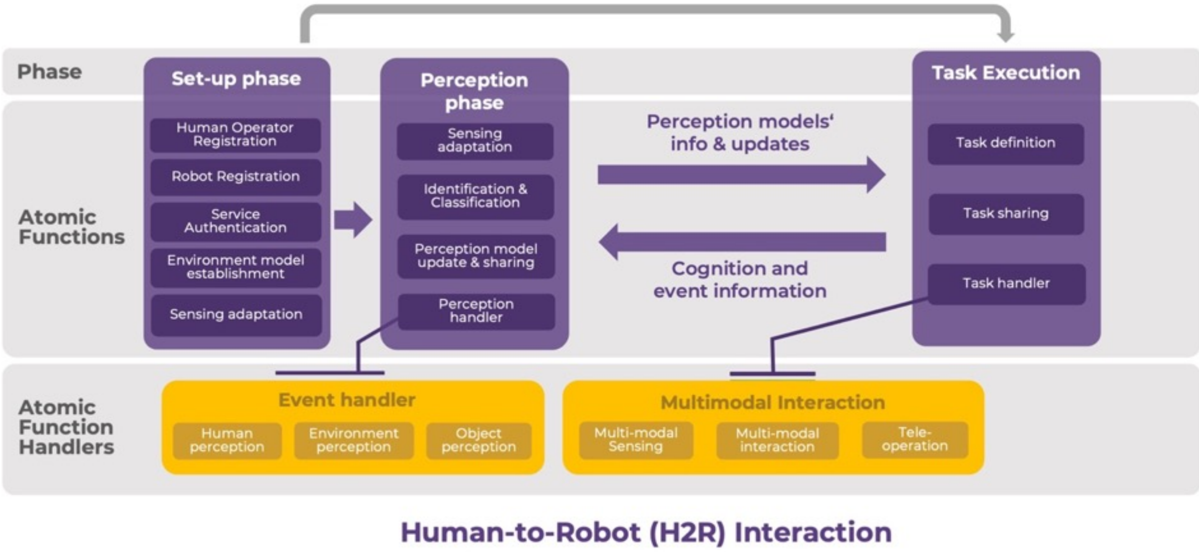

Figure 2: Atomic functions and handlers for H2R Class: Collaborative Robots in Industrial Environments example

This UC follows the description of UC Collaborative Robots in Industrial Environments in 6G & Robotics one6G white paper [1, Sec. 2.5]. Multiple Robots and humans work simultaneously to achieve a common task. In case that an unforeseen scenario occurs, a remote human operator takes control of robot(s). The focus of the UC is on the teleoperation of the robot by human.

Industrial cobots, remote human operators, mobile network operator, third party service providers and on-site human collaborator with robot are the main actors of the three phases. The three phases are described in the following:

Set-up Phase

S.1 Human Operator Registration

Description: Human operator registers with network. Human shares required information such as their ID and biometric information. This information will be subsequently used for identification, authorisation and setting up access rights in atomic function S.3.

Actors: Remote human operators, mobile network operator, third party service providers, on-site human collaborator with robot.

Input: Human operator sends information to the network over user interface to be registered.

Output: Human operator successfully register to network to operate robots remotely.

S.2 Robot Registration

Atomic function is common with S.1 from R2R class.

S.3 Service Authentication

Description: Registered human operator(s) is authorized to use specific services of robotic applications according to their ID and/or biometric information. Services may include access to remote perception services, multi-modal interaction services and teleoperation services, to name a few. According to privileges verified during service authentication, the registered human operator will be able to teleoperate robot and use different robot functionalities over the network.

Actors: Remote human operators.

Inputs: Human operator (remote/on site) sends information to the network over user interface to be registered.

Output: Authorised actors that are registered to network to teleoperate robots.

S.4 Environment Model Establishment

Atomic function is common with S.4 from R2R class. In this UC, humans are part of the environment. Humans may also share physical information to characterise human behaviour (gesture) in environment model. Gesture recognition can be performed by AI/ML or motion capture-based methods.

S.5 Sensing Adaptation

Atomic function is common with S.5 from R2R class.

Perception Phase

P.1 Sensing Adaptation

Atomic function is common with P.1 from R2R class.

P.2 Identification & Classification

Atomic function is common with P.2 from R2R class.

P.3 Perception Model Update and Sharing

Atomic function is common with P.3 from R2R class.

P.4 Perception Handler

Atomic function is common with P.4 from R2R class.

Actors: Remote human operator.

P.H.4.1 Object Perception

Atomic function handler is common with P4.1 from R2R class.

P.H.4.2 Environment Perception

Atomic function handler is common with P4.2 from R2R class.

P.H.4.3: Human Perception

Description: Human in teleoperation centre visualises remote environment with perception data as observed by the on-board sensors on robot or sensors in the physical environment. Environment includes other robots, other humans and physical environment. Perception data (e.g., processed video stream with objects classified or object grasping points) captured by the P.H.4.2 and P.H.4.3 atomic functions is transferred to human operator over a wireless channel.

Inputs: Multimodal and haptic feedback from robot, operation environment.

Outputs: Multimodal telepresence and teleoperation information.

Task Execution

T.1 Task Definition

Atomic function is common with T.1 from R2R class.

T.2 Task Sharing

Atomic function is common with T.2 from R2R class.

T.3 Task Handler: Human to Robot Interaction

Description: Events can trigger execution changes in robot. When event is triggered (e.g., human is detected or detection of human behavioural pattern), task handler handles events with atomic function handlers (e.g., multi-modal sensing/interaction or teleoperation).

T.H.3.1 Multi-modal Human to Robot Sensing

Description: So that human operator perceives environment as if it were on the remote location, it receives multi-modal sensing information from robot or network via a wireless channel. Multimodal sensing (e.g., audio/visual, tactile) can be implemented with multiple sensors in the same device or through the fusion of data from several distributed sensors. In both cases, wireless communication is key to convey the information to where it will be processed, enabling the offload of this processing to powerful devices, as well as data fusion when needed. At the same time, sensors that estimate the position of objects often rely on wireless transmission, used for localisation or radar techniques.

Actors: Remote human operator.

Inputs: Sensor information (tactile, audio/visual, …).

Outputs: Multimodal information required for the multimodal interaction and action handlers.

T.H.3.2 Multi-modal Human-to-Robot Interaction

Description: The multimodal interaction handler should synchronise between robot interface device with the human operator and network node/(edge)cloud (e.g., for AI capabilities). The human inputs are accurately sent towards teleoperated robot and robotic feedback information is returned to the remote human operator. One important application of AI/ML modules is tele-operation via shared autonomy, which requires a closed-loop controller to react to human action feedback interactively in real-time. Human in teleoperation centre can also give voice commands to remote robot. Teleoperated robot replicates audio from human to communicate with robots and humans in its vicinity.

Actors: Human-robot communication and command interface.

Inputs: Multi-modal sensing output.

Outputs: Multi-modal sensing output, Human-robot communication and commands for actions.

T.H.3.3 Tele-operation

Description: Once multi-modal information arrives to the human operator via the human robot interface (e.g., wearable devices), human can perform remote actions aware of the remote environment. Human operator teleoperates and executes task plan according to the capabilities and flexibility of robot (e.g., degrees of freedom) and adapts robot actions (including motion). Path plans may be additionally computed by remote robot or by the teleoperation centre. These path plans may be displayed in the screen of the teleoperation centre as motion recommendation to aid human perform task specified in atomic function T.1.

Actors: Robot (e.g., robot arm), remote human operator's wearable devices, teleoperation centre.

Inputs: Multimodal interaction output.

Outputs: operation process e.g., moving a robot arm to grasp an object.

Annex B (see Table B.1) further describes a potential set of baseline requirements in terms of wireless communication and sensing, AI/ML support and computational offloading of the Collaborative Robots in Industrial Environments UC. The baseline requirements are described for a distinctive atomic function of the UC, based on multi-modal sensing and multi-modal interaction. The requirements are described for main functions of the UC, and not for all the atomic functions of the UC.

4.3. R2H class: Service robots for healthcare assistance

In a hospital environment, companion robots are designed to emotionally support patients reduce stress and help them navigate around the facility. The companion robot identifies and approaches the patient, introduces itself, and explains its purpose, emphasising 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 the hospital 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. This UC follows the description of UC Service Robots for Healthcare Assistance in 6G & Robotics one6G white paper [1, Sec. 2.7].

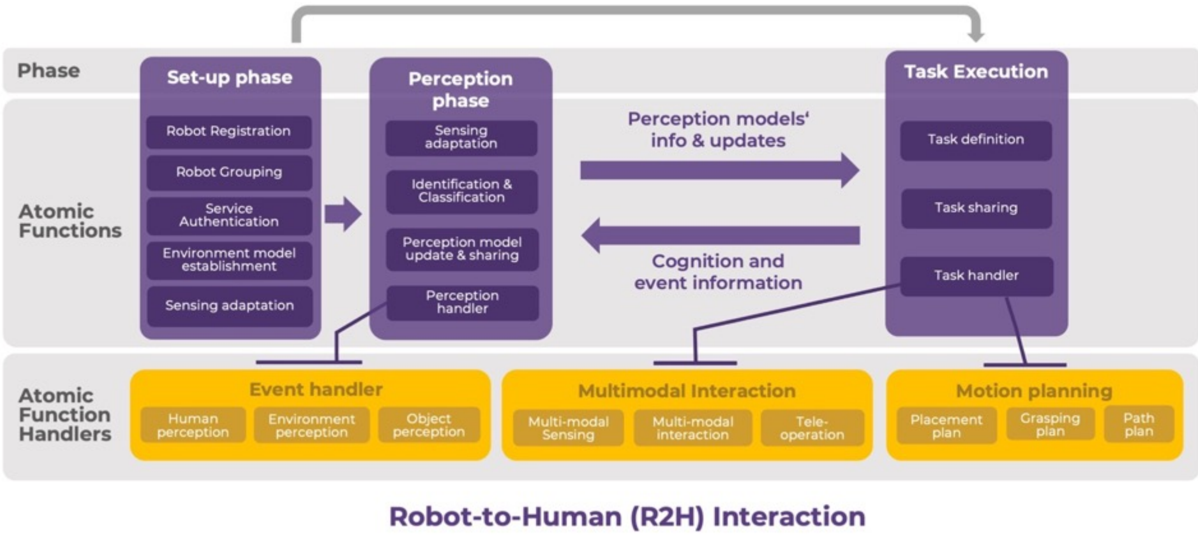

Figure 3: Atomic functions and handlers for R2H Class: Service Robots for Healthcare Assistance example

Mobile service robots, humanoid robots, mobile network operator(s), third party health service provider(s), healthcare facilities, remote (edge), cloud server(s) are the main actors of the three phases that are described in detail in the following.

Set-up Phase

S.1 Robot Registration

Atomic function is common with S.1 from R2R class.

S.2 Robot Grouping

Atomic function is common with S.2 from R2R class.

S.3 Service Authentication

Atomic function is common with S.3 from H2R class.

Description: Service robots (companion robots in this context) in hospitals or homes should be registered. They should be medically certified as a device and registered on the hospital network. Authentication can happen via the network or with assistance from a human operator on-site. Companion robots should be autonomous after network registration (refer to [1]). The goal of the service authentication is for the registered service robots to have access to operate over the network and provide care service to the patients.

Actors: Service robots, hospital profile (third party service providers), network authentication function.

Inputs: Robot ID.

Output: Authorised robots that are registered to network to operate the service to patients.

S.4 Environment Model Establishment

Atomic function is common with S.4 from R2R class.

S.5 Sensing Adaptation

Atomic function is common with S.5 from R2R class.

Perception Phase

P.1 Sensing

Atomic function is common with P.1 from R2R class.

P.2 Identification and Classification

Atomic function is common with P.2 from R2R class.

P.3 Perception Model Update and Sharing

Description: This atomic function incorporates concurrent handling of perception handler tasks and integration of sensory information or information obtained from interaction with human. Perception processing should occur concurrently with interaction, allowing the detection of the destination or a human to be interleaved with other information required to perform the task.

Actors: Service robots, hospital profile (third party service providers), network authentication function and relevant radio access and/or network core entities with stored models or with computation capabilities.

Input: A significant change in the physical environment is detected.

Output: Environmental model is updated at Task Leader and faithfully replicates physical environment.

P.4 Perception Handler: Event Handler

Description: handles cognition events related to human and object/destination perception (i.e., walk until a human is detected), event information (e.g., disturbance in motion plan) from task execution phase as well as perception models' information (e.g., detect obstacle) and updates (e.g., entering unknown scenario). Event is handled with one or more of the following atomic sub-functions: object/human perception and environment perception.

P.H.4.1 Human/Object Perception

Description: Based on new triggered event (e.g., obstacles encountered on detected destination and information obtained from interaction with an encountered human), robot broadcasts requirements to identify new target object. Service Robot determines a set of parameters like distance, shape, and material as well as performs localisation mapping.

Actors: Service robots, relevant radio access entities with wireless sensing capabilities and/or core entities with computation capabilities.

Input: A new event is triggered (e.g., detecting a new path to destination and information obtained from interaction with human).

Output: Service robots perceive target object or human.

P.H.4.2 Environment Perception

Description: Robot is equipped with on-board sensors. At the start, the on-board sensors are unaware of the robot's location and where any of the access points are in the environment. As the robot moves, the sensors communicate sensing beacons to access points and listen for their replies, using them as landmarks. Every incoming and outgoing wireless signal carries its own unique physical information (e.g., an angle of arrival and direct path length to (or from) an access point). This information is used to figure out where the robot and access points are in relation to each other. This information can be extracted by SLAM algorithms using the combination of other input sensor information (e.g., LIDAR). In addition, service robots can also collaborate with other robots (e.g., other service robots which are in the vicinity) to perform environment perception. As the call and response continues, the sensors pick up more information and can accurately locate where the robot is going.

Input: Cognition and event information are triggered (e.g., execution of motion plan is starting).

Output: Objects in the environment are sensed. An environment model is maintained synchronised with physical environment.

Task Execution Phase

T.1 Task Definition

Atomic function is common with T.1 from R2R class.

T.2 Task Sharing

Atomic function is common with T.2 from R2R class for the AGVs case. For humanoid robot case, task will be predefined and task sharing among robots is not always expected. In case of multiple humanoid robots, atomic function will be common with T.2 from R2R class.

T.3 Task Handler

Atomic function is common with T.3 from R2R class.

T.H.3.1 Task Handler: Robot to Human Interaction

T.H.3.1.1 Multi-modal Sensing

Atomic function is common with T.3.1 from H2R class.

T.H.3.1.2 Multi-modal Interaction

Atomic function is common with T.3.2 from H2R class.

T.H.3.1.3 Remote Action

Atomic function is common with T.3.3 from H2R class.

T.H.3.2 Task Handler: Motion Planning

Atomic function is common with T.3.3 from R2R class.

Annex C (see Table C.1) describes a potential set of requirements in terms of wireless communication and sensing, AI/ML support and computational offloading of the **Service Robots for Healthcare Assistance** UC. The requirements are described for main functions of the UC, and not for all the atomic functions of the UC.

4.4. R2C class: 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. Robots improve efficiency, accuracy and reduce costs in inventory management. 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 orders, and shipments records. Figure 4. provides the atomic functions and handlers for the **Robots in inventory management** UC based on the 6G & Robotics one6G white paper [1, Sec. 2.3].

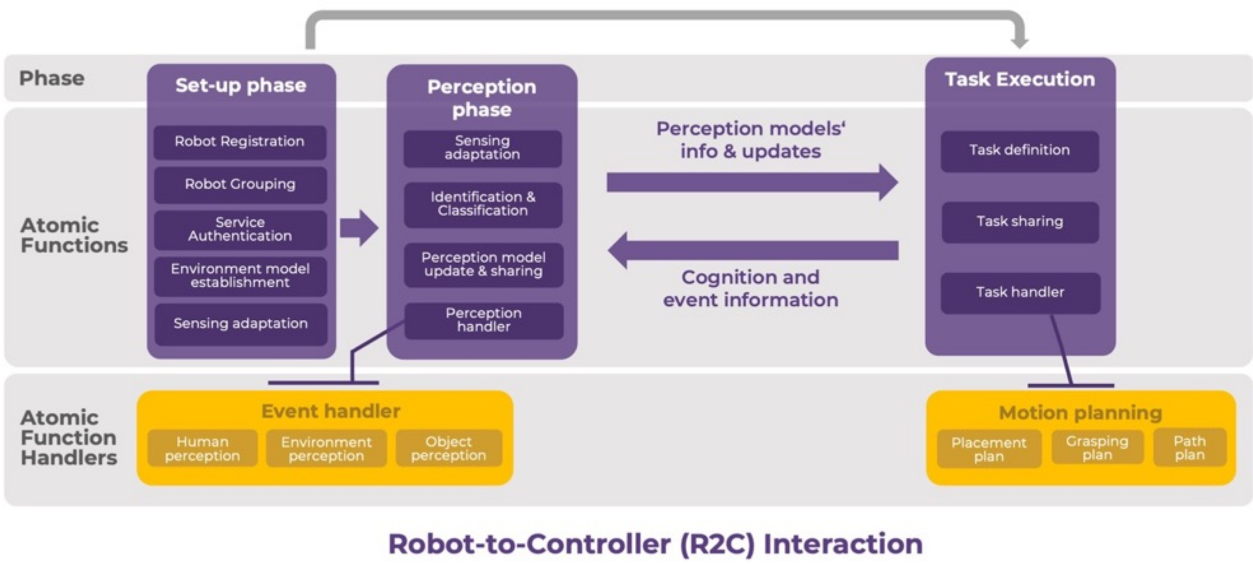

Figure 4: Atomic functions and handlers for R2C class: Robots in inventory management

Set-up Phase

S.1 Robot Registration

Atomic function is common with S.1 from R2R class.

S.2 Robot Grouping

Atomic function is common with S.2 from R2R class.

S.3 Service Authentication

Atomic function is common with S.3 from R2R class.

S.4 Environment Model Establishment

Atomic function is common with S.4 from R2R class.

S.5 Sensing Adaptation

Atomic function is common with S.5 from R2R class.

Perception Phase

P.1 Sensing Adaptation

Atomic function is common with P.1 from R2R class.

P.2 Identification & Classification

Atomic function is common with P.2 from R2R class.

P.3 Perception Model Update and Sharing

Atomic function is common with P.3 from R2R class.

P.4 Perception Handler

Atomic function is common with P.4 from R2R class.

P.H.4.1 Object Perception

Atomic function handler is common with P4.1 from R2R class. Robots track inventory items and provide real-time stock quantities and location updates. Once robots sense an item from inventory, they communicate real-time updates of stock quantities and locations to, for example, a central inventory management system.

P.H.4.2 Environment Perception

Atomic function handler is common with P4.2 from R2R class. Robots are able to sense factories and/or warehouses environment in underserved areas.

Task Execution

T.1 Task Definition

Atomic function is common with T.1 from R2R class. Robots are assigned to different inventory management and workflow processes.

T.2 Task Sharing

Atomic function is common with T.2 from R2R class.

T.3 Task Handler: Motion Planning

Atomic function is common with T.3 from R2R class.

T.H.3.1 Path Plan

Atomic function is common with T.H.3.3 from R2R class. A distinction in this UC is that there is no leader robot and the coordination is performed at the controller (on-board, network edge/core or cloud).

T.H.3.2 Path Optimisation

Description: As the robots select and pick items from warehouse to move the items to target locations, the controller located at the network monitors the factory floor traffic efficiency of all robots. Based on the target location from the robots, the controller orchestrates the trajectory path of all robots to reach to an optimal movement efficiency at the warehouse.

Actors: Robots, controller collocated at relevant radio access or core entities.

Input: Movement information from robots (e.g., position, path plan, velocities, carried item information, etc).

Output: Optimised path plan for each robot.

Annex D (see Table D.1) describes a potential set of requirements in terms of wireless communication and sensing, AI/ML support and computational offloading of the Robots in Inventory Management UC. The requirements are described for main functions of the UC, and not for all the atomic functions of the UC.

5. Conclusion and Next Steps

In this whitepaper, we present a methodology to analyse robotic UCs. Our proposed methodology is to decompose robotic UCs into phases, which are further decomposed into atomic functions. Following the robot interaction types defined in previous *6G & Robotics* one6G white paper, we identify the common atomic functions and phases among the different robot interaction classes. Using the proposed methodology, we select four robotic UC classes: R2R class with *Cooperative Carrying Robots* UC, H2R class with *Collaborative robots in industrial environments* UC, R2H class with *Service robots for healthcare assistance* UC, and R2C class with *Robots in Inventory management UC*.

Analysing robotic UCs with our proposed methodology indicates that along the lifetime of a robotic UC (i.e., a communication session), the system requirements in terms of wireless communication, wireless sensing, AI/ML support, and computational offloading may vary significantly within an active session. The nature of robotic UCs implies that the future 6G communication system would have to adapt quickly and efficiently to scale with the expected penetration of robots in multiple domains. Resource overprovisioning to meet the system requirements of the most demanding atomic function in a robotic UC is not sustainable. Preliminary system requirements in terms of wireless communication, wireless sensing, AI/ML support and computational offloading were identified.

Building upon the accurate identification and description of phases, atomic functions and handlers in a robotic UC, we established the basis for performing a detailed system requirement analysis per atomic function using a detailed UC analysis template (see Table A.1 to D.1 in Annex Sections). Identifying the detailed key system requirements per atomic function of a robotic UC will enable the development of precise technical solutions that cater to the required service in the most resource efficient way. Going forward, it will be important to perform a detailed analysis for common atomic functions of multiple UCs individually to identify precise requirements of robotic UCs. While we have explored the methodology for four robotic interaction classes, the same principles can apply for other type of interactions that may include robot avatars, humanoids and communication over the metaverse. Identifying key system requirements per atomic function also allows us to validate when a robotic UC may stretch the capabilities of the system. By means of conventional resource provisioning (i.e., actuation, communication, computation and sensing resources), future 6G communication system can meet most demanding requirements. However, technology directions such as the co-design of communication and control may help relax system requirements of the different robotic use cases and therefore meet system requirements in a more sustainable way. In this way, 6G communication system can scale more efficiently and enable an increased penetration of robotic applications in different vertical domains.

Potential societal, environmental, and economic impacts of the discussed UCs are discussed in Annex E. The ability for mobile networks to scale in a sustainable, energy efficient and cost-effective way to the growth in demand for robotic applications in future decades requires further study.

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Annex A

UC within R2R class: Cooperative Carrying with Robots

<table>
<tr><th colspan="2">Cooperative Carrying with Robots</th></tr>
<tr><td>Description</td><td>Cooperative carrying refers to a set of mobile robots cooperating with each other to transfer objects e.g. metal frames, 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.</td></tr>
<tr><td>Pre-condition</td><td>Pre-determined number of mobile robots
Atomic Functions are available and orchestrated by network
The leader and followers are pre-determined
Mobile robots capable of the following functionalities:
Sensing the surrounding environment (e.g., movements of robots/people and other dynamicity in the vicinity)
Path 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, sensor measurements or motion plan)
The leader or network performs global task planning and global motion planning of group</td></tr>
<tr><td>Service flow</td><td>See R2R class Subsection 4.1. Service flow is decomposed into phases and atomic functions.</td></tr>
<tr><td>Postcondition</td><td>Successful (damage-free) and safe transportation of objects within factories by a group of mobile robots.</td></tr>
<tr><th colspan="2">Potential Requirements</th></tr>
<tr><td>Existing 5GS features partly or fully covering the UC requirements</td><td>Network-based positioning
High downlink data rates
Support for ultra-reliable and low latency</td></tr>
</table>

Potential 6GS system requirements (sensing/communication/computation) to enable Perception and Task Execution phase

- Support for real-time AI/ML model downloading and distribution among robots based on their new tasks.
- Integration of communication and control
- Extremely high uplink data rates for computational offloading with low latency
- New sensing capabilities to infer object physical characteristics to find grasping points.
- Fulfilment of sensing KPIs, e.g., sensing resolution, positioning
- Dynamic adaptation to change requirements within user session
- Extremely high resource efficiency to support increasing robot penetration

Identified KPIs for the UC incl. justification/references to enable distinctive atomic function handler

NOTE: Requirement analysis currently includes requirements of a main distinctive atomic function handler (namely, environment perception (P5.2 defined in Subsection 5.1)) of the UC class. Further system requirements per atomic function in UC (e.g., wireless sensing to identify grasping points, etc.) are left for further study.

Robotic Application Requirements

Service Availability: 99.9999% availability is required to maintain successful operation of the robot-to-robot interaction (e.g., cooperative carrying of object). Reliable communication and synchronization between the different cooperating (e.g., robots) is required along the execution of robotic task [9].

Transfer Interval: 7 ms for environment perception data generated from on-board sensors on robots. Transfer Interval is low to allow operation robots to perform fast reactive object avoidance from shared sensing data. 33 ms for uncompressed video stream generated by on-board sensors on robots to offload computation tasks to the network [9].

Table A.1 System Requirements for P5.2 atomic function from Cooperative Carrying with Robots UC

Environment Perception with On-board Sensors	
Wireless Sensing (1)	**KPI Value**
Accuracy of Position Estimate	<0.5 m
Accuracy of Velocity Estimate	0.5 m/s
Range Resolution	0.5 m
Velocity Resolution	0.5 m/s
Max Sensing Service Latency	<100 msec
Wireless Communication (2):	**KPI Value**
Uplink	NA
Downlink	NA
Sidelink (unicast or groupcast)	Data rate: <1 Mbit/s per Robot

	Reliability: 99.9999 %
	End-to-end latency: 7 msec
Network-assisted Environment Perception (Computational Offloading)	
Wireless Communication (3)	**KPI Value**
Sidelink	NA
Uplink (unicast or groupcast)	300-500 Mbits/s per Robot (one camera per Robot)
	Reliability: 99.9999%
	End-to-end Latency: 33 msec
Downlink (unicast or groupcast)	Data rate: <1 Mbit/s
	Reliability: 99.9999 %
	End-to-end Latency: 7 msec
AI/ML model transfer (4)	**KPI Value**
Max allowed download end-to-end latency	1 sec
Model weight factors	Reliability: 99.9%
Data transmission of model topology	Reliability: 99.999%
AI/ML model split inference (5)	**KPI Value**
Max allowed uplink end-to-end latency	2 msec
Reliability	99.9%

Justification (1): 3GPP outlines this sensing service is required to detect objects (e.g., humans, tools) in vicinity. Wireless sensing can also be performed by network. Sensing with network introduces additional errors (due to compounding errors of two separate positions) [2].

Justification (2): Communication streams occur between robots with environment perception data (e.g., object(s) in environment detected/recognised with signal processing/AI/ML algorithms). Latency is low to minimise the time to reach consensus on environment, and communication reliability is high to enable reliable dynamic interaction and reactive object avoidance from shared sensing data [9, Mobile Autonomous Navigation & Environmental Sensing UC]. Control commands are also sent in sidelink.

Justification (3) for Network-assisted Environment Perception (Computational Offloading): Communication stream is raw video stream data in uplink (e.g., object(s) in environment detected/recognised with AI/ML algorithms at edge server) [9, Mobile Autonomous Navigation & Environmental Sensing UC]. Control commands are sent in downlink. High communication reliability may be required to guarantee significant degrees

	of noise-free input to AI/ML methods operating in real-time which may be sensitive to noise. Justification (4): AI/ML model distribution for image recognition. Required data rate will depend on the transferred AI/ML model (e.g., 1.1 Gbits/s for 138 Megabyte size model) [6, Table 8.1-2]. Communication reliability is high even though some errors in model weight factors are permissible. Justification (5): AI/ML model distribution for image recognition. Required data rate will depend on the AI/ML model and the splitting point. [6, Table 8.1-1]. Communication reliability is high for model topology (e.g., computation graph of a convolutional neural network) since mismatch in dimensions of input data and weight matrices can make model unusable.

Annex B

UC within H2R class: Collaborative Robots in Industrial Environments

Collaborative Robots in Industrial Environments	
Description	Collaborative robots (Cobots)must be aware of human movements & autonomously adapt their behaviour to prevent accidents with humans or other robots in a hybrid cell. In case that an unforeseen scenario occurs, a remote human operator takes control of robot(s). The focus of the UC is on the teleoperation of the robot by human. A *hybrid cell* refers to a shared workspace between humans and robots.
Pre-condition	• Pre-determined number of mobile robots • Humans collaborate with robots • Atomic Functions are available and orchestrated by network • Remote human teleoperates robot • No safety zones • Mobile robots capable of the following functionalities: – Sensing the surrounding environment (e.g., movements of robots/people and other dynamicity in the vicinity) – Path planning and motion control (e.g., collision avoidance and arm movement) – If teleoperated robot has ability to perform multi-modal sensing – Communicating with other involved robots
Service flow	See H2R class in Subsection 4.2. Service flow is decomposed into phases and atomic functions.
Postcondition	• Successful collaboration between mobile robots and humans • Remote human teleoperates the robot successfully
Potential Requirements	
Existing 5GS features partly or fully covering the UC requirements	• Network-based positioning • High downlink data rates • Support for ultra-reliable and low latency

<table>
<tr>
<td>Potential 6GS system requirements (sensing/communication/computation) to enable Perception and Task Execution phase</td>
<td>

Support for real-time AI/ML model downloading and distribution among robots based on their new tasks
Enhanced Multimodal communication support
Integration of communication/control
Extremely high uplink data rates for computational offloading with low latency
Fulfilment of sensing KPIs, e.g., sensing resolution, and positioning
Dynamic adaptation to change requirements within user session
Extremely high resource efficiency to support increasing robot penetration

</td>
</tr>
<tr>
<td>Identified KPIs for the UC incl. justification/references to enable distinctive atomic function handler</td>
<td>
NOTE: Requirement analysis currently includes baseline requirements of a main distinctive atomic function handler of UC (namely, multi-modal sensing (T.H.3.1.1) and interaction (T.H.3.1.2) both defined in subsection 5.2. More details on system requirements per atomic function in each UC (e.g., wireless sensing to identify grasping points, etc.) require further study.

Table B.1 System Requirements for T.H.3.1.1 and T.H.3.1.2 atomic functions in Collaborative Robots in Industrial Environments UC

<table>
<tr><th colspan="2">Multi-modal Human to Robot Sensing KPIs</th></tr>
<tr><th>Wireless Sensing (1)</th><th>Range</th></tr>
<tr><td>Accuracy of Position Estimate</td><td>1 mm</td></tr>
<tr><td>Accuracy of Velocity Estimate</td><td>NA</td></tr>
<tr><td>Range Resolution</td><td><0.1 m</td></tr>
<tr><td>Velocity Resolution</td><td>NA</td></tr>
<tr><td>Max Sensing Service Latency</td><td><1 msec</td></tr>
<tr><td>Wireless Communication (2):</td><td>Range</td></tr>
<tr><td>Sidelink</td><td>NA</td></tr>
<tr><td>Downlink</td><td>NA</td></tr>
<tr><td rowspan="3">Uplink (unicast)</td><td>Data rate: 50-100 Mbits/s</td></tr>
<tr><td>Reliability: 99.999%</td></tr>
<tr><td>End-to-end latency: 10-15 msec</td></tr>
<tr><th colspan="2">Multi-modal Human to Robot Interaction KPIs</th></tr>
<tr><th>Wireless Communication (3)</th><th>Range</th></tr>
<tr><td>Sidelink</td><td>NA</td></tr>
<tr><td rowspan="3">Downlink (unicast or groupcast)</td><td>Data rate: <1 Mbit/s</td></tr>
<tr><td>Reliability: 99.9999%</td></tr>
<tr><td>End-to-end latency: 10-100 msec*</td></tr>
<tr><td>Uplink</td><td>NA</td></tr>
</table>
</td>
</tr>
</table>

AI/ML model transfer (4)	Range
Max allowed download end-to-end latency	1 sec
Model weight factors	Reliability: 99.9%
Data transmission of model topology	Reliability: 99.999%
AI/ML model split inference (5)	**Range**
Max allowed uplink end-to-end latency	2 msec
Reliability	99.9%

Justification (1): Position estimation with cm-level accuracy. Sub-cm precision of sensing could be required by the spatial resolution of gripper for an accurate haptic feedback – i.e., the smallest separation at which one can two points are touched [8].

Justification (2): 3GPP outlines that a truly immersive experience with 120fps with resolutions up to 8K per eye to remove graphics pixilation. This translates into bit rates of tens of Mbits/s in downlink [13].

Justification (3): 3GPP outlined video-operated remote-controlled robotics can operate with 10-100 ms [4]. NOTE: If requirement includes force interaction (e.g., haptics data), latency requirement would be higher.

Justification (4): 99.9% for model weight factors, 99.999% for data transmission of model topology [6, Table 8.1-2] AI/ML model distribution for speech recognition. Required data rate will depend on the transferred AI/ML model (e.g., 640 Mbits/s for an 80 Megabyte size model) [6]. Communication reliability is high even though some errors in model weight factors are permissible. Communication reliability is higher for model topology (e.g., computation graph of a convolutional neural network) since mismatch in dimensions of input data and weight matrices can make model unusable.

Justification (5): AI/ML split inference for image recognition. Required data rate will depend on the AI/ML model and the splitting point [6, Table 8.1-1]. Communication reliability is high even though some errors in the output of computations are permissible.

Annex C

UC within R2H class: Service Robots for Healthcare Assistance

Service Robots for Healthcare Assistance	
Description	Service robots provide emotional support and companionship to patients and elderly. Service robots in this UC are designed to interact with humans in a social context, using human language and behaviour. Service robots interact in a wide range of modalities including speech, gestures, facial expressions and body language [1].
Pre-condition	• Pre-determined number of service robots • Safe navigation in the presence of moving people to destination • Atomic Functions are available and orchestrated by network • Gesture and face recognition (for social robots) • Speech recognition and natural language understanding • Speech generation, knowledge representation, and social interaction with humans (for social robots) • Edge computation capabilities • Mobile service robots are capable of the following functionalities: – Sensing the surrounding environment (e.g., visual tracking of people, signs, and landmarks) – Path planning and motion control (e.g., path plan) – Communicating with other involved robots.
Service flow	See R2H class in Subsection 4.3. Service flow is decomposed into phases and atomic functions.
Postcondition	Execution of tasks with human safety and satisfactory social interaction.
Potential Requirements	
Existing 5GS features partly or fully covering the UC requirements	• Network-based positioning • High downlink data rates • Support for ultra-reliable and low latency

<table>
<tr>
<td>Potential 6GS system requirements (sensing/communication/ computation) to enable Perception and Task Execution phase</td>
<td>

Support for real-time AI/ML model downloading and distribution of Natural Language Processing models (NLP) (e.g., large language models, speech recognition, etc.)
Enhanced Multimodal communication support
Extremely high uplink data rates for computational offloading with low latency
Fulfilment of sensing KPIs, e.g., sensing resolution, and positioning
Dynamic adaptation to change requirements within user session
Extremely high resource efficiency to support increasing robot penetration

</td>
</tr>
<tr>
<td>Identified KPIs for the UC incl. justification/references to enable distinctive atomic function handlers</td>
<td>
NOTE: Requirement analysis currently includes baseline requirements of a main distinctive atomic function handler of UC (namely, multi-modal sensing (T.H.3.1.1) and interaction (T.H.3.1.2)). Both atomic functions are defined in Subsection 5.3.

Table C.1 System Requirements for T.H.3.1.1 and T.H.3.1.2 atomic functions in Service Robots for Healthcare Assistance UC

<table>
<tr><th colspan="2">Multi-modal Robot-to-Human Sensing & Offloading KPIs</th></tr>
<tr><th>Wireless Sensing (1)</th><th>Range</th></tr>
<tr><td>Accuracy of Position Estimate</td><td>+/- 1-10 cm</td></tr>
<tr><td>Accuracy of Velocity Estimate</td><td>NA</td></tr>
<tr><td>Range Resolution</td><td><0.1 m</td></tr>
<tr><td>Velocity Resolution</td><td>NA</td></tr>
<tr><td>Max Sensing Service Latency</td><td><1 ms</td></tr>
<tr><th>Wireless Communication (2): Computational Offloading</th><th>Range</th></tr>
<tr><td>Sidelink</td><td>NA</td></tr>
<tr><td>Downlink</td><td>NA</td></tr>
<tr><td rowspan="4">Uplink (unicast)</td><td>Data rate: 147-441 Mbits/s (2 cameras per Robot @ 30 frames per second and 640 x 480 resolution)</td></tr>
<tr><td>Reliability: 99%</td></tr>
<tr><td>End-to-end latency: (sub-ms) 1ms</td></tr>
<tr><td>Jitter: 1 ms</td></tr>
<tr><th colspan="2">Multi-modal Robot-to-Human Interaction KPIs</th></tr>
<tr><th>Wireless Communication (3)</th><th>Range</th></tr>
<tr><td>Sidelink</td><td>NA</td></tr>
<tr><td rowspan="3">Downlink</td><td>Data rate:
3 Mbits/s (control)
4.6 Mbits/s (control + audio)</td></tr>
<tr><td>Reliability: 99.99999%</td></tr>
<tr><td>End-to-end latency: 5 ms</td></tr>
</table>
</td>
</tr>
</table>

Uplink	NA
AI/ML model transfer (4)	**Range**
Max allowed download end-to-end latency	1 sec
Model weight factors	99.9%
Data transmission of model topology	99.999%
AI/ML model split inference (5)	**Range**
Max allowed uplink end-to-end latency	2 msec
Reliability	99.9%

Justification (1): To naturally and safely interact with human in subsequent interaction atomic function, service robot must be able to sense human with +/- 1 – 10 cm resolution of physical characteristics as well as sense mood and health information. The safety aspect is covered by the aggressive object/human avoidance algorithms and safety distances often employed on these types of robots (e.g. robots may stop moving entirely if humans get within 1m of robot, for example) [8].

Justification (2): To enable fast sensing of human mood and behaviour, service robots (with insufficient computation resources) must provide multi-modal sensor data sensed from humans (e.g., radio-sensing performed by robot, video stream, images) to a data processing function in network with high computation resources [12][13].

Justification (3): To enable natural and multi-modal interaction of service robots with human, service robots (with insufficient computation resources) must receive multi-modal control actions (e.g., motion, force control, text/audio output from AI/ML model, etc.) [12] [13].

Justification (4): AI/ML model distribution for speech recognition and generation. Required data rate will depend on the transferred AI/ML model (e.g., 640 Mbits/s for an 80 Megabyte size model). Much higher data rate required for large language models [6, Table 8.1-2]. Communication reliability is high even though some errors in model weight factors are permissible. Communication reliability is higher for model topology (e.g., computation graph of a convolutional neural network) since mismatch in dimensions of input data and weight matrices can make model unusable.

Justification (5): AI/ML split inference for image recognition. Required data rate will depend on the AI/ML model and the splitting point [6, Table 8.1-1]. Communication reliability is high even though some errors in the output of computations are permissible.

Annex D
UC within R2C class: Robots in Inventory Management

Robots in Inventory Management	
Description	Robots automate tasks, improve accuracy and boost efficiency in inventory management by order picking, sorting, monitoring and replenishing stocks in a warehouse.
Pre-condition	• Pre-determined number of mobile robots • Safe navigation in the presence of moving people to destination; • Atomic Functions are available and orchestrated by network • Edge computation capabilities • Mobile robots capable of the following functionalities: – Sensing the surrounding environment (e.g., inventory tracking). – Path planning and motion control (e.g., path plan to replenish stock, order picking and sorting). – Communicating with other involved robots.
Service flow	See R2C class in Subsection 4.4. Service flow is decomposed into phases and atomic functions.
Postcondition	Robots automate repetitive tasks and optimise workflows.
Potential Requirements	
Existing 5GS features partly or fully covering the UC requirements	• Network-based positioning • High downlink data rates • Support for ultra-reliable and low latency offloading
Potential 6GS system requirements (sensing/communication/ computation) to enable Perception and Task Execution phase	• Extremely high uplink data rates for computational offloading with low latency • Integration of communication/control • Fulfilment of sensing KPIs, e.g., sensing resolution, and positioning • Dynamic adaptation to change requirements within user session. Extremely high resource efficiency to support increasing robot penetration.

<table>
<tr>
<td>Identified KPIs for the UC incl. justification/ references to enable distinctive atomic function handler</td>
<td>
NOTE: Requirement analysis currently includes baseline requirements of a main distinctive atomic function handler of UC (namely, path optimisation (T.H.3.1.2 defined in Subsection 4.4)).
Table D.1 System Requirements for T.H.3.1.2 atomic functions in Robots in Inventory Management UC
<table>
<tr><th>Wireless Communication KPIs (1)</th><th>Range</th></tr>
<tr><td>Sidelink</td><td>NA</td></tr>
<tr><td rowspan="3">Downlink (unicast or broadcast)</td><td>Data rate: <1 Mbit/s per Robot</td></tr>
<tr><td>Reliability: 99.9999%</td></tr>
<tr><td>End-to-end latency: 10-100 msec</td></tr>
<tr><td rowspan="3">Uplink</td><td>Data rate: <1 Mbit/s per Robot</td></tr>
<tr><td>Reliability: 99.9999%</td></tr>
<tr><td>End-to-end latency: 10-100 msec</td></tr>
<tr><td>Device Density</td><td>106 per km2</td></tr>
</table>
Justification (1): 3GPP outlined video-operated remote-controlled robotics can operate with 10-100 msec [3]. Communication reliability is significantly high to guarantee path plans reach robots in downlink or controller in uplink.
</td>
</tr>
</table>

Annex E
Potential Environmental and Economic Impacts of the UC Classes

Environmental impact including energy consumption	**R2R class:** Energy, as the product of power and time, could be an important input parameter to optimise the volatile service flows. Additionally, computational offloading could reduce the battery-life requirements on robots, therefore reducing the overall environmental impact of robots. **H2R class:** Increase human safety. **R2H class:** Battery operated robots; network energy performance - 0@0load. **R2C class:** Increase working efficiency and working safety.
Technology gap relative to 5G	**R2R & H2R classes:** • THz radio-based situational awareness sensing, • Enhanced AI/ML support (e.g., split inference and model transfer, distributed learning, transfer learning and multi-agent learning support, etc.), • More granular QoS differentiation for multi-modal data, • Sensing-assisted Communication **R2H & R2C classes:** Enhanced computational offloading support to access to AI resources at ultra-fast speed.
Impact on existing network infrastructure	High-precision positioning and detailed sensing capabilities from network surroundings are main requirements that will demand that sensing is integrated as a new type of network capability.
Feasibility relative to physical and economic constraints.	The services may arise in 5-10 years, therefore a long-term UC.
Industry growth opportunity [< 10% (low), <50% (mid) >50% (high)]	>50% (low in short term and high in long term)
Disruptive impact on 5G	**R2R class:** Reduced user terminal energy consumption **H2R class:** Enhanced Sensing and AI support with integration of communication and sensing **R2H class:** Zero-energy devices **R2C class:** Reduced user terminal energy consumption
SDO's related features and activities	ITU-T, ITU-R, 3GPP (e.g, Cyber-CAV, SOBOT)

Abbreviations

5G-ACIA	5G Alliance for Connected Industries and Automation
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
CAV	Connected and Automated Vehicle
CRM	Customer Relationship Management
ERP	Enterprise Resource Planning
3GPP	3rd Generation Partnertship Project
5GS	5G System
6GS	6G System
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunications Union
KPI	Key Performance Indicators
LIDAR	Light Detection and Ranging
ML	Machine Learning
NA	Not Applicable
NLP	Natural Language Processing
NR	New Radio
RRC	Radio Resource Control
SDO	Standardization Organization
SLAM	Simultaneous Localization and Mapping
SOBOT	Service Robot
TR	Technical Report
UC	Use Case
WG	Working Group
WI	Working Item
XR	Extended Reality
XRM	XR and Media Services

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