Design and Performance Evaluation of a Modular Mobile Robot for Autonomous Hospital Logistics

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***Abstract*—Hospital logistics can significantly benefit from autonomous robotic technologies capable of alleviating personnel workload, reducing operational costs, and streamlining internal workflows. This paper introduces HOSBOT (HOSpital roBOT), a modular and cost-effective robotic system designed to enhance hospital logistics and workflow management through autonomous missions and real-time monitoring of transported items. HOSBOT combines a commercially available autonomous mobile robot with a customisable non-motorised cart, the SmartRack, which accommodates standalone, sensorised SmartBoxes equipped with Radio Frequency IDentification technology. This paper describes the overall design of HOSBOT, including its mechanical, electrical, and software interfaces. The system has been validated in three pilot experiments in real hospital environments across Europe, demonstrating good levels of acceptability, usability and efficacy. This innovative robotic solution highlights the potential for scalable integration of autonomous mobile robots in healthcare and other indoor logistics settings.**

***Note to Practitioners*—This paper is motivated by the need to optimise logistics in hospital settings, which heavily relies on the manual transportation of consumable goods from storage to operational areas, placing a daily workload on hospital staff. The article describes current solutions employed in hospitals for logistics operations and discusses how autonomous mobile robots are among the most versatile and flexible approaches, capable of integration into various settings. In this context, HOSBOT (HOSpital roBOT) is introduced, a logistics robot composed of modular multiscale units that can be freely configured and combined with different autonomous mobile robotic bases. This robot is advantageous not only because it can be customised according to the client's needs and available resources but also due to the use of intelligent containers called SmartBoxes, which can operate as standalone units and track transported contents through integrated RFID-based electronics. This system has been validated in three hospital environments with different logistical requirements, demonstrating its compliance and potential for optimising logistics flow in healthcare settings.**

***Index Terms*—Collaborative robots, digital health, hospital logistics, mobile robots, RFID.**

I. INTRODUCTION

HOSPITAL logistics constitutes a complex and multifaceted task involving the management of several items, including sterile equipment, food trays, bedding, diagnostic samples, and more. The hospital supply chain can be subdivided into external and internal [1]. The external supply chain deals with the transactions between the suppliers and the hospital. In contrast, the internal supply chain refers to the connections between the central warehouse and point-of-use locations and patients. Although logistics represents the second most significant cost driver for hospitals, there are no consolidated solutions or clear guidelines to standardise its practices [1], which are time-consuming and prevent nurses and practitioners from taking care of patients. Studies conducted in the USA, Canada, and Germany report that 30-40% of nurses' time is spent in non-nursing activities that might be replaced by innovative logistics solutions [2], [3].

As detailed in [4], many logistics solutions with different characteristics are available to hospitals. These solutions include Automated Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), automated vacuum collection systems, overhead transportation systems, and pneumatic tube systems. Among these options, AMRs stand out as a versatile solution for their ability to independently execute logistics tasks around the clock, even in complex and crowded scenarios. Moreover, unlike systems that rely on fixed drop-off or collection stations, AMRs can deliver items directly to the final point of use, addressing what is often referred to as the "last 50 metres" challenge in hospital logistics [4]. Thanks to the integration of sensors such as laser scanners and depth

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This work involved human subjects or animals in its research. The ODIN project was overseen by a central Ethics Board, which supervised all ethical and regulatory aspects of the experiments in coordination with the local Ethics Committees at the hospitals where the tests were conducted. Whenever participants were involved, the information sheet, informed consent form, and privacy policy were appropriately adapted and approved. All data were anonymised to protect the privacy of the participants.

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cameras, along with vision algorithms, AMRs exhibit a high level of adaptability to dynamic environments, ensuring safety by avoiding collisions with humans and both static/dynamic objects. While many AMRs for hospital logistics have emerged in the market, as surveyed in [5], their widespread adoption is hindered by substantial purchasing costs, thereby limiting the applicability of this promising solution. Furthermore, commercial products often lack modularity and may not be suitable for every hospital setting.

This paper introduces an innovative, modular and cost-effective system called HOSBOT (HOSpital roBOT). Focusing on the internal supply chain, HOSBOT is designed to meet hospital needs for transporting objects (*e.g.*, consumables, diagnostic samples) from hospital storage rooms to point-of-use locations (*e.g.*, a care unit or an operating room). The system comprises an AMR and a custom non-motorised cart called SmartRack, which can be arranged to carry removable boxes of different sizes. The SmartRack can be moved manually by an operator or autonomously by the AMR, following mission planning through a Human-Machine Interface (HMI) available on the dedicated tablet and authorised edge devices. Each transported box, called SmartBox, is a smart, standalone, battery-powered unit enabling real-time monitoring of carried goods through Radio-Frequency IDentification (RFID) technology to track carried items labeled with dedicated tags. Each component is tracked across the operative area by Real-Time Localisation Systems (RTLS).

This paper is organised as follows: Section II discusses the state-of-the-art and contributions of the proposed system. Section III presents the ODIN platform, a digital health platform that allows the orchestration of digital and robotic technologies. Section IV details HOSBOT, an innovative autonomous mobile robot system for hospital logistics. The SmartRack and SmartBox are described here, detailing their electromechanical interfaces and software development. Section V describes the extensive real-world pilot tests conducted in three European hospitals. These tests have validated the interaction of HOSBOT with the ODIN platform, autonomous navigation, and human-robot collaboration. Quantitative results and questionnaires are presented to discuss the pilot tests. Finally, Section VI concludes this paper and discusses the lessons learned from the three pilots and future work.

II. RELATED WORK AND CONTRIBUTION

In hospital logistics, AMRs stand out for their flexibility. The earliest AMR designed for hospital logistics was HelpMate [6], whose development began in the late 1980s. HelpMate was designed to transport various items using separate embedded containers and was capable of autonomous navigation. A transparent approach to the use of AMRs in hospital logistics is presented in [7], which describes a towing AMR capable of autonomously transporting hospital carts without requiring major modifications to their chassis. State-of-the-art AMR-based hospital logistics solutions include Aethon robots (Aethon Inc., USA), which offer indoor logistics via hospital cart collection and transportation (T3 robot) or monolithic configurations (Zena and Zena RX robots). These systems provide secure access to transported contents and support high payloads, although they offer limited flexibility in configuring the internal layout of the cabinet. Slim monolithic robots such as Hospi (Panasonic, Japan) and Relay (Relay Robotics, USA), as well as humanoid robots with manipulation capabilities such as Moxi (Diligent Robotics, USA), offer lower payload capacity compared to cabinet-based systems. However, their slim profile, combined with audio and visual interaction, makes them suitable for reception tasks and personal delivery. Mobile Industrial Robots (MiR, Denmark) has demonstrated the use of its AMRs in hospital logistics [8]. Their systems feature both cart transportation and monolithic racks with drawers, offering solutions for a range of logistical needs.

While the surveyed systems present diverse and compelling approaches to hospital logistics through AMRs, their broad adoption still requires further research and development to meet the demands of complex healthcare environments [4]. Moreover, to the best of our knowledge, real-time traceability of the transported items is not reported in existing hospital-operating solutions.

HOSBOT introduces a novel combination of traceability, standalone operation, and multiscale modularity, distinguishing it from existing hospital logistics solutions. Traceability is improved through the integration of RFID technology, proposed as an innovative strategy for object-level monitoring during transportation, and RTLS which enable continuous tracking of the robot and its modular components within the hospital environment. Standalone operation is enabled through both manual and autonomous transportation of SmartRacks, with added multifunctionality: the ability to withdraw individual SmartBoxes to perform logistics tasks independently of the AMR. The system architecture supports modularity at multiple levels: in the SmartRack configuration, which is cost-effective and built from aluminium profiles, and therefore customisable in terms of overall size and number of transported containers; in the possibility to integrate with different AMR bases, allowing the users to select the AMR carrier and configure the system in compliance with their availabilities and needs (*e.g.*, reuse an existing AMR); finally, in the ability to carry several carts with just one robotic carrier, thanks to multi-agent coordination via the orchestrating digital ODIN platform (Section III). This work contributes to advancing the state-of-the-art by presenting a paradigm shift solution for AMR-based hospital logistics and validating it across three relevant hospital scenarios. Specifically, the system has been built within the context of the ODIN EU project to meet the requirements of aided logistics support and disaster preparedness [9].

III. ODIN PLATFORM

HOSBOT operates within the broader ODIN platform, which is essential for enabling the integration and coordination of digital and robotic technologies in smart hospital environments. The ODIN platform, developed within the homonym European project [9], provides the necessary framework for data communication, resource management, and task orchestration, allowing technologies such as robotics, Internet of Things (IoT), and Artificial Intelligence (AI) to function cohesively.

The core of the ODIN platform is the Resource Gateway layer, which facilitates communication between the platform's diverse components. This layer primarily consists of the Enterprise Service Bus (ESB), a multi-channel component designed to ensure interoperability among systems and components. The ESB operates on an asynchronous messaging architecture, primarily based on Apache Kafka, enabling efficient and scalable data exchange.

This platform functions as a central hub, facilitating the seamless connection and communication of these technologies within a secure and scalable framework. It also allows the registration and management of individual resources through the Resource Management System, enabling operators to define and manage the resources available in the hospital environment. To ensure interoperability, an ontology provides a formal and extensible knowledge representation method regardless of the specific communication protocols or data organisation schemas used by the Key Enabling Resources (KERs). This standardises information exchange, enabling effective communication between KERs.

The following describes the key *connected robotics* components of the ODIN platform that support the operation of HOSBOT.

A. Human-Machine Interface

The first *connected robotics* component is the Human-Machine Interface (HMI). This interface provides hospital staff with a user-friendly graphical user interface (GUI) to interact with robotic devices, monitor statuses, assign tasks, and receive alerts. The HMI is a web application that interfaces with HOSBOT, SmartBoxes, and other ODIN modules, such as the integrated sensorised platform for environmental monitoring in healthcare [10]. The web application is accessible on SmartRacks (Figure 1) and on authorised personal edge devices, requiring user identification through username and password for access. Users can view and monitor robot data using a dynamic and interactive set of graphical elements, with the flexibility to rearrange and resize objects such as buttons, menus, and text as needed.

The web application is a gateway interface designed using client-server logic to connect with HOSBOT via a series of RESTful Application Programming Interfaces (APIs). It adopts a HyperText Transfer Protocol (HTTP)-based API to connect, send, and get data to and from the robot. The program efficiently routes user requests through the ODIN API gateway, which routes all HTTP requests to the appropriate registered KERs. Additionally, it can concurrently manage several user requests on various platforms, including smartphones and tablets.

To facilitate user interaction, the application leverages a scalable GUI built using the Flask framework. Flask, a Python lightweight web server gateway interface, is used for building flexible and easily extendable web applications. In this implementation, Flask serves as the back-end engine that handles user interactions, API requests, and rendering of the GUI. The Flask app is designed to respond to HTTP requests from client devices, such as tablets or smartphones, and routes these requests to specific Flask routes that connect with the ODIN API. The front-end is based on CSS and JavaScript, making the web interface dynamic and responsive. Jinja2 allows real-time updates to be pushed to the interface, enabling hospital staff to monitor robot data and task statuses live. Additionally, its built-in scalability supports concurrent user sessions across multiple devices, maintaining session states and user authentication through its integration with secure login systems. To ensure smooth and safe multi-user interaction, the HMI maintains continuous awareness of the state of the robot by interfacing in real time with HOSBOT and the ODIN modules through the RESTful APIs. Based on the current operational status of the robot, new user-issued commands are either queued for later execution to the Fleet Management System (Section III.B) or rejected. This mechanism helps avoid conflicts, ensures orderly task handling, and maintains operational continuity even under high-demand conditions. Furthermore, the system supports role-based access control, isolating user sessions and logging all actions for traceability. An emergency stop function is also integrated into the interface, which overrides all active or pending commands and brings the robot to an immediate and safe halt, ensuring safety for both personnel and patients.

B. Fleet Management System

The second *connected robotics* component of the ODIN platform is the Fleet Management System (FMS). The FMS enables centralised control and orchestration of multiple robotic devices within the hospital environment, optimising their deployment and allocation for efficient logistics management. The FMS achieves this by performing several key functions.

First, it maintains a comprehensive database of points of interest within the hospital, such as patient rooms, nursing stations, and storage areas. This spatial awareness is essential for navigation, task allocation, and efficient robot movement throughout the hospital.

Second, the FMS integrates with RTLS to track the position of robots and assets within the hospital. These data are essential for enabling dynamic task allocation and route planning.

Third, the FMS leverages intelligent algorithms to automatically assign tasks to the most suitable robot, considering factors such as proximity, battery life, and task-specific capabilities. By combining these factors, a centralised market-based approach [11] is adopted for task allocation, relying on criteria such as energy efficiency [12], obstacle-free navigation [13], and pre-defined task requirements stored in a lookup table [14]. Robots with low battery levels are excluded from long-duration or mission-critical assignments to prevent mid-task failure. When a robot battery level drops below a predefined critical threshold, typically around 10%, a high-priority docking command is automatically issued. This prompts the robot to return to the nearest available charging station immediately, minimising downtime and maintaining service continuity. Additionally, the FMS redirects robots to docking stations during idle time to optimise charging cycles during low-demand periods, ensuring availability during peak hospital hours. By automating this process, the FMS ensures tasks are completed efficiently, and resources are utilised optimally.

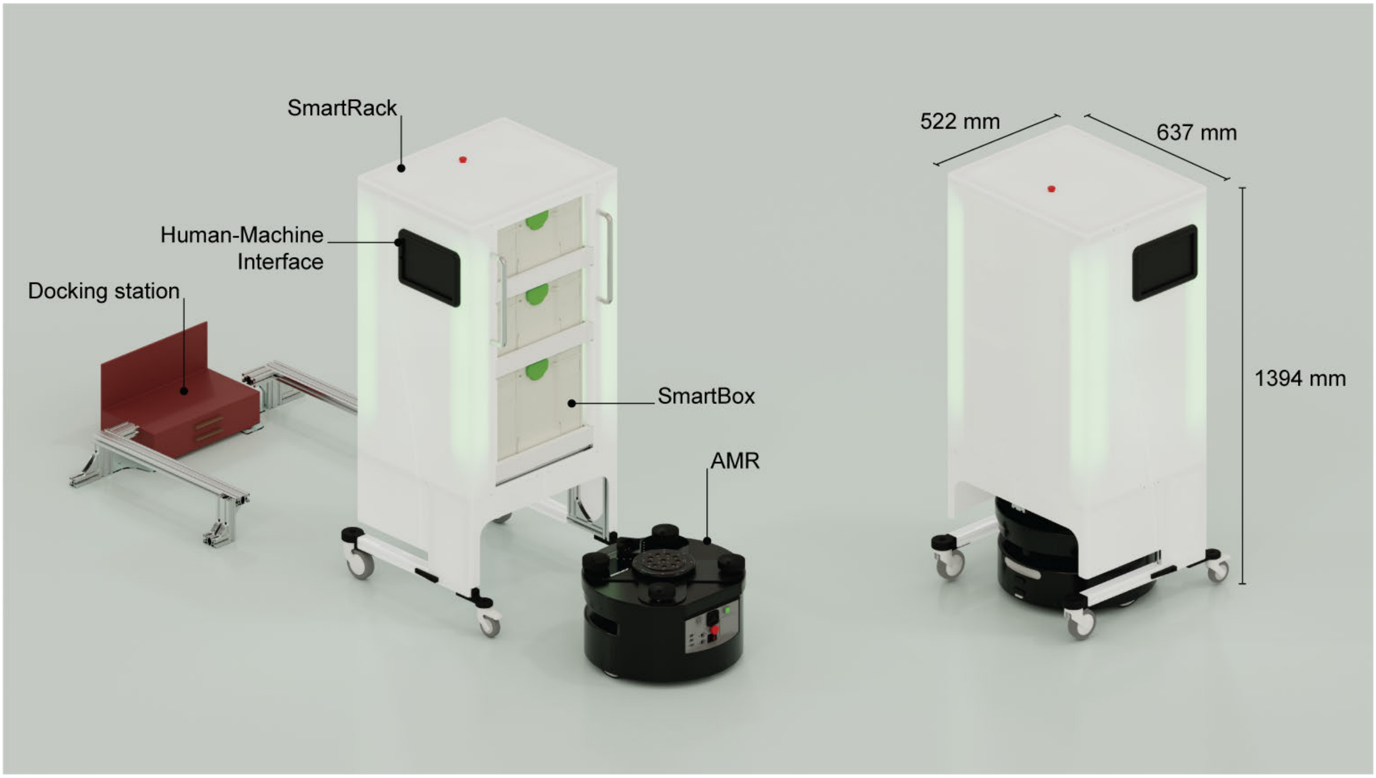

Fig. 1. HOSBOT is comprised of an autonomous mobile robot (AMR) and a SmartRack, which carries standalone, removable SmartBoxes with onboard RFID technology. A Human-Machine Interface is available at a tablet located on one side of the SmartRack and can be used to plan autonomous logistics tasks. The docking station is used to position HOSBOT for autonomous charging and collection.

Fourth, the FMS continuously monitors the status of each robot in the fleet, including location, battery level, operational status, and task availability. This real-time monitoring allows for proactive management of the robotic fleet, anticipating potential issues and ensuring uninterrupted operation.

C. Data Protection

HOSBOT exchanges information through the Message Queuing Telemetry Transport (MQTT) protocol, and the ESB is configured with Transfer Layer Security (TLS) to ensure privacy and data protection.

IV. HOSBOT Design and Validation

This section details the design of HOSBOT, including its SmartRack and SmartBox components. Moreover, laboratory tests to validate the reliability of the system are described.

A. HOSBOT: Design

The separation between the AMR and the SmartRack provides flexibility, allowing for the cost-effective simultaneous management of multiple SmartRacks with a single robotic carrier. Both the SmartRack and the SmartBoxes are standalone modules that can be manually moved throughout the hospital while being localised through RTLS. Additionally, the SmartRack can be transported by the AMR when executing an autonomous mission planned through the HMI. An overview of HOSBOT and its components is presented in Figure 1.

1) SmartRack Design: In this work, the SmartRack was specifically designed to interface with an RB-1 BASE AMR (Robotnik Automation S.L., Spain), which experimentally demonstrated a towing payload of at least 100 kg. The SmartRack configuration is customisable in terms of width, height, and number of carried SmartBoxes. The structure is made of aluminium profiles, pursuing a trade-off among cost, robustness, stiffness, and ease of assembly. The width is designed to accommodate SmartBox drawers and other necessary components while also complying with the width requirements of most hospital doors and elevators. The bottom of the structure is cut to avoid obstructing the laser scanner of the RB-1 BASE robot. This modular approach allows interfacing, with minimal modification, with various AMRs featuring different payloads and dimensions, facilitating operations in different environments with specific dimensional requirements. In this way, HOSBOT may be manufactured in compliance with the user's AMR availability.

The height of HOSBOT falls within the range of other similar robots, typically between 1.0 m (*e.g.*, the Swisslog Relay) and 1.4 m (*e.g.*, the Panasonic Hospi). This enables users to easily see over the robot, maintaining clear visibility of people and objects behind it. The inner aluminium frame is covered with polymethyl methacrylate (PMMA) covers. Two reflective stripes attached to the back side of the SmartRack, positioned at a height compliant with the laser scanner of the RB-1 BASE, serve as reference coordinates for the local frame of the robot during autonomous pick up.

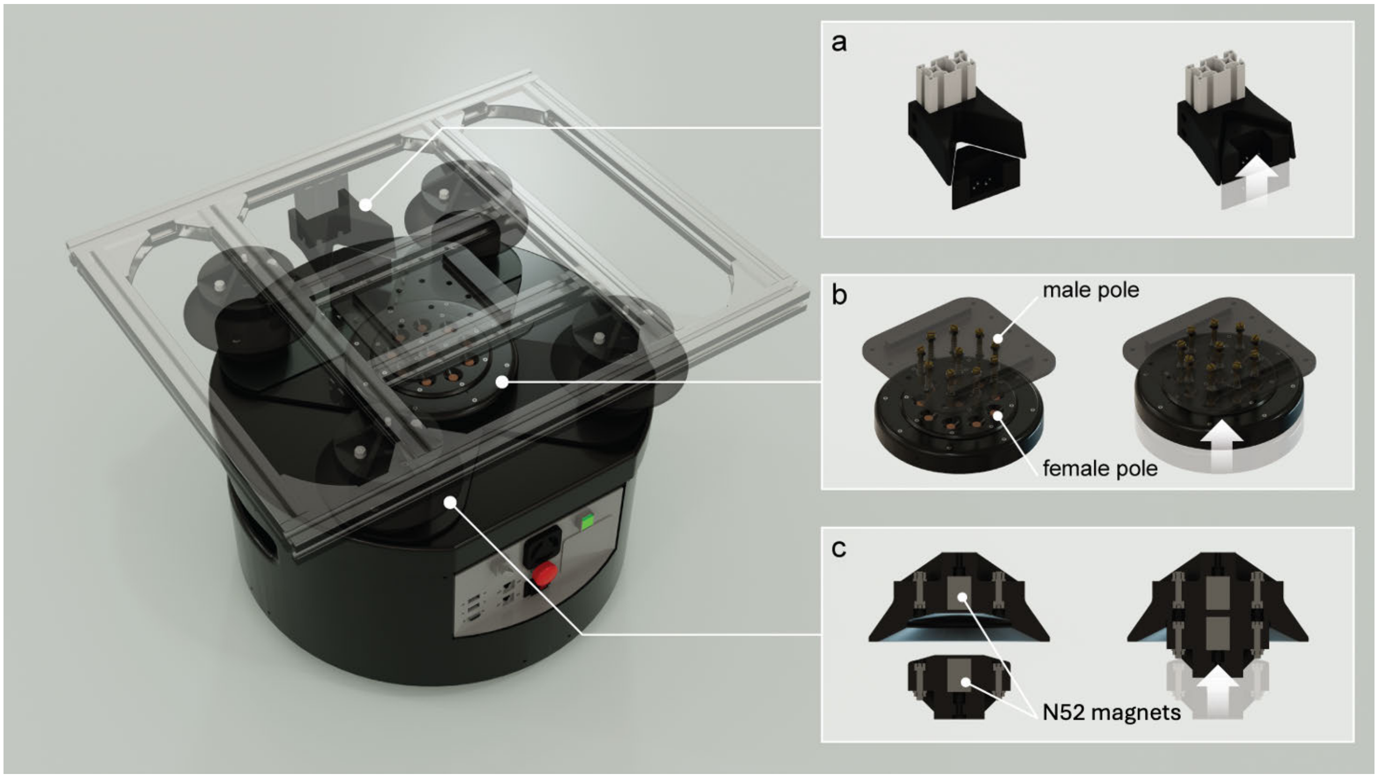

Fig. 2. AMR-SmartRack connectors. (a) Yaw angle alignment connector. When driving forward to collect the SmartRack, this connector provides self-alignment through yaw angle adjustment. (b) Electrical connector. A 3D-printed support installed on the SmartRack hosts ten male poles made of spring-loaded brass screws. On the AMR, a 3D-printed counterpart hosts ten female poles made of copper plates. (c) Magnetic connector. Inside the truncated cone-shaped connectors, N52 NdFeB magnets provide a pulling force of 80 N per couple, corroborating the connection with the SmartRack.

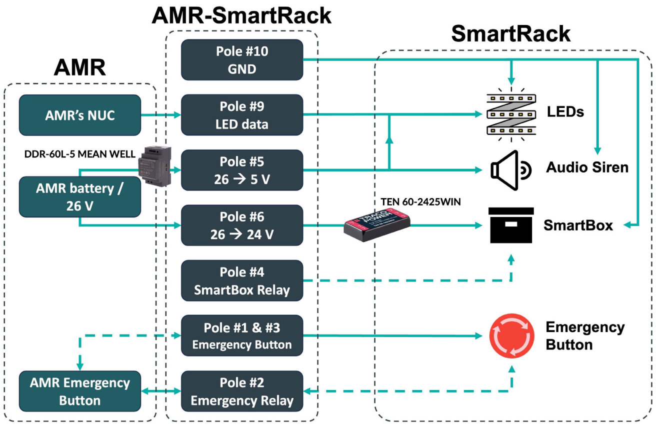

Fig. 3. Schematic of the electrical lines connecting the AMR to the SmartRack. Eight of the ten available poles are employed both for powering and data transmission.

Different sets of wheels are positioned at the front and back of the structure. The front wheels, larger in size, are designed to overcome bumps along the path. The back wheels are equipped with manual brakes that can be pressed to stop the SmartRack when necessary. Consequently, the dimensions of the SmartRack measure 637 × 522 × 1394 mm, and its weight is about 35 kg with three empty SmartBoxes.

The employed AMR is equipped with a linear actuator, hereafter called elevator, which allows moving the top surface of the robot 35 mm upwards. The elevator is engaged to pick up the SmartRack and establish a mechanical and electrical connection through 3D-printed connectors. Before pick up, the AMR centres itself with respect to the reflective stripes placed on the SmartRack. Then, it navigates forward until the 3D-printed centring parts meet, achieving alignment around the yaw angle and geometrical interlock (Figure 2.A). Once the yaw angle alignment is achieved, the elevator is engaged, and the AMR is connected to the SmartRack via four pairs of magnetic connectors. The shape of these connectors (truncated cones) compensates for misalignments through surface sliding. This solution enables the AMR to drag the SmartRack by transmitting forces horizontally, while embedded N52 NdFeB magnets provide a stabilising vertical pull of approximately 80 N each, without exceeding the actuation force of the elevator (Figure 2.C).

Simultaneously, an electrical connection is established between the two HOSBOT modules. While the AMR has an onboard battery with 10-hour autonomy, the SmartRack is passive. Therefore, an electrical connection between the two is necessary to power safety devices, including an accessible emergency stop button, an acoustic emitter, and light signals. To this end, a 10-pole connector is installed on top of the AMR, and a corresponding one is placed on the bottom of the SmartRack (Figure 2.B). The poles are realised with spring-loaded brass screws and copper plates. The electrical lines, outlined in Figure 3 include:

- n.1 5V power line for powering an acoustic emitter and light-emitting diode (LED) strips used as light signals;
- n.1 data line for controlling the LED strips;

- n.2 lines for the emergency button on the SmartRack;
- n.1 26V power line for charging the SmartBox;
- n.2 ground poles;
- n.1 pole within the AMR to switch a relay to activate the SmartBox charging line when the AMR is charging and the elevator is raised (indicating SmartRack pick up);
- n.1 pole within the AMR to switch a relay to connect the AMR and SmartRack emergency stop lines in series when the latter is picked up;
- n.1 unused pole.

Once a connection is established, pressing either the emergency button on the SmartRack or on the AMR stops HOSBOT. While navigating, an acoustic emitter located inside the SmartRack signals the presence of the moving robot by emitting a beeping sound at a frequency of 1 Hz. Perimetral LEDs installed on the frame of the SmartRack are programmed to lighten up to patterns and colors based on the state of the robot:

- continuous green LEDs indicate that the robot is navigating straight without obstacles;
- continuous blue LEDs signal a system error;
- flashing yellow LEDs function as turn signals during navigation;
- continuous red LEDs indicate that the robot is stopped due to the emergency stop being pressed;
- blinking red LEDs indicate that the robot is reversing.

With the described connectors, the AMR can navigate to a docking station while carrying a SmartRack, autonomously recharging both its own battery and the SmartBoxes. The docking station (Figure 1) comprises a commercial charging station (provided by the AMR manufacturer) connected to a custom mechanical structure made of aluminium profiles and laser-cut PMMA. This structure centres the SmartRack upon manual or autonomous placement, facilitating smooth robotic pick-up. The centring aluminium profiles come in contact with the HOSBOT wheel connectors, serving as bumpers. Reflective bands installed on the docking station aid the AMR in precise centring.

2) SmartBox Design: The SmartBox is a standalone device, operating with its own battery, System-on-Module (SoM), and other electronics. Within HOSBOT, it serves as the central logistics component thanks to its tracking capabilities based on RFID. As illustrated in Figure 4, the SmartBox comprises a commercial box integrated with a custom enclosure that houses the electronics to power:

- RFID technology to track labeled items, such as medications, drugs, surgical instruments, and diagnostic samples;
- an SoM to unlock the SmartBox and connect it to the network infrastructure.

The logistics pipeline starts at the hospital warehouse, where the personnel labels each item with passive RFID tags. Ideally, the external supply chain should handle the provision of pre-labeled items. Each RFID tag encodes a distinctive alphanumerical identifier, distinguishing even objects of the same type. RFID technology has been explored as an alternative to bar codes for logistics purposes, and many healthcare applications have emerged in recent years, as surveyed in [15] and [16].

The container constituting the SmartBox is a commercial product (Systainer[3], Festool Group GmbH & Co. KG, Germany). These containers have been selected for their availability in various sizes, low weight, modularity, and potential compliance with regulations regarding the transportation of biological samples (*e.g.*, UN 3373 category B). Each SmartBox can carry a payload of 20 kg.

Within the custom enclosure, various essential components are housed to support the functionalities of the SmartBox. These include an RFID tag reader (R4320C, CAEN S.p.A., Italy) and two antennas for RFID tag identification (WANT020 Quad, CAEN S.p.A., Italy). The antennas operate in the electromagnetic frequency range of 865.6 ÷ 867.6 MHz and are designed for short/medium-range applications. In this frequency range, metal and water impair the functionality of the technology [17]. To overcome this issue, liquid and metal-compatible tags are used. The enclosure also accommodates a 14-hour autonomy battery to ensure uninterrupted operation during a work shift, an SoM (Argon, Particle Industries Inc., USA) for efficient control and coordination, a fan for ventilation, an audio emitter for sound-based alerts, a linear actuator for locking the SmartBox to prevent unauthorised access, and a custom printed circuit board (PCB) designed to manage all electrical components and signals effectively. Moreover, the container hosts a photodiode to signal the opening of the lid. This is placed outside of the enclosure, within the box, and connected to the custom PCB. The SmartBox electrical scheme is illustrated in Figure 5.

SmartBoxes are standalone devices. When positioned in a SmartRack, they are electromechanically secured when inserted in a drawer. To withdraw a SmartBox, the drawer is unlocked by activating the linear actuator which electromagnetically lifts the locking mechanism, upon user identification. Once unlocked, the drawer can be opened by lifting its handle and pulling it out, within a 5-second window. Re-locking the drawer is achieved mechanically by pushing the drawer towards the SmartRack. The battery of the SmartBox may be recharged manually or during the autonomous docking of HOSBOT. The locking counterpart on the SmartRack hosts charging electrical poles identical to those used in the SmartRack-AMR connection.

To shield RF waves, prevent leakages, and avoid misreadings, a custom aluminium-covered Forex® insert was designed to fit within the SmartBox, acting as a Faraday cage. Indeed, only contained tags and no external ones should be detected. Shielding is accomplished by covering the internal walls of the insert and of the custom enclosure with 0.15 mm thick aluminium tape. This thickness was determined through experimental tests and validated analytically. Shielding tests evaluated whether an RFID label was detected when positioned in proximity to the SmartBox and when moved around it. Analytically, the effectiveness of RFID shielding can be quantified in terms of the reduction of electromagnetic field strength when passing through a material, measured in dB [18]. Focusing on the absorption loss, hypothesising an infinite sheet with no edge effects and a perfect RF source, the effect

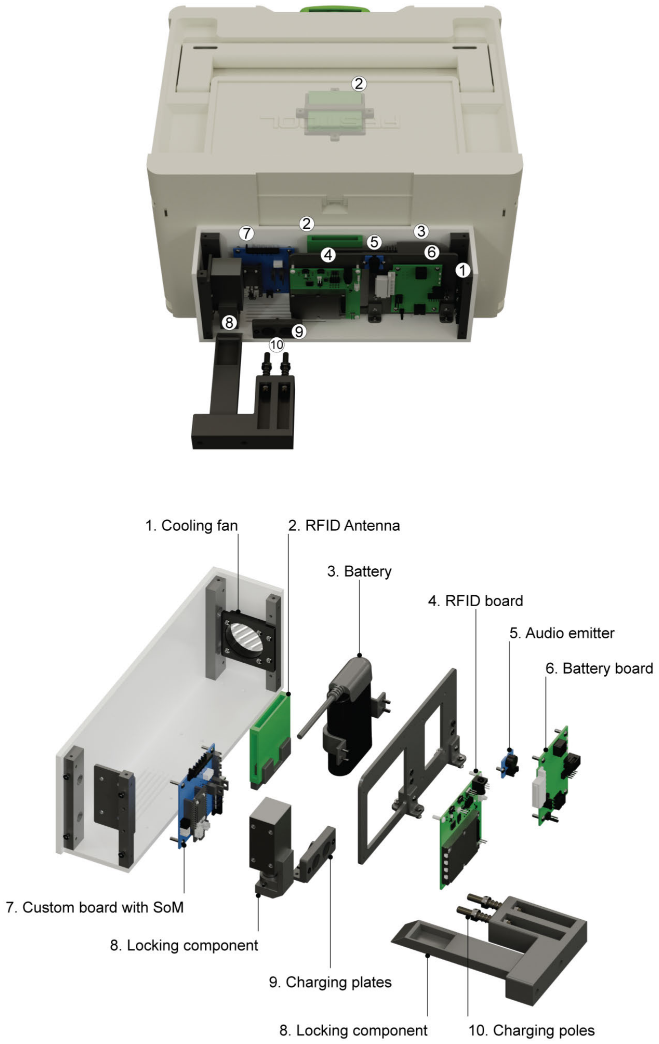

Fig. 4. The SmartBox and its components.

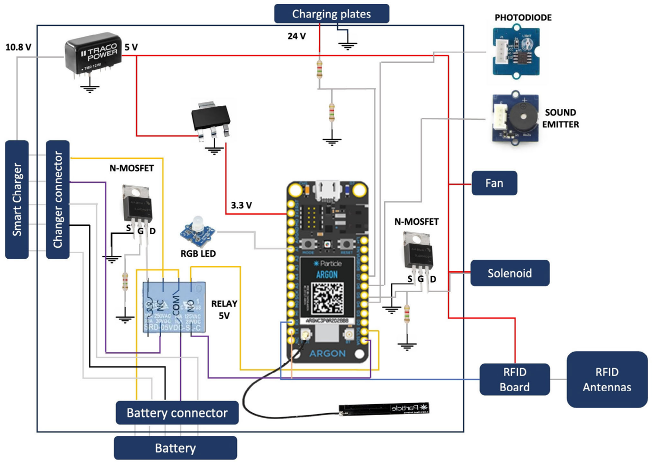

Fig. 5. The electrical scheme of the SmartBox.

is measured by:

$$SE = 20\log_{10}\frac{E_i}{E_t} \tag{1}$$

where E_i and E_t are the incident and the transmitted electromagnetic field strengths, respectively. In this simplified case, the shielding effectiveness can be estimated by the skin depth at the specific electromagnetic frequency. The skin depth δ is the depth of penetration of the electromagnetic wave in the conductor:

$$\delta = \frac{1}{\sqrt{\pi\mu_0\sigma f}} \tag{2}$$

where μ_0 is the vacuum magnetic permeability, σ is the conductivity of the material, and f is the frequency. Given the thickness of the material d, the fraction of the incident field that passes through the sheet can be approximated by:

$$\frac{E_i}{E_t} = e^{\frac{d}{\delta}} \tag{3}$$

Therefore, given our data, the shielding effectiveness is about 450 dB, which is widely acceptable for the application.

B. HOSBOT: Autonomous Navigation

The AMR operates within a dynamic map of the environment that is continuously updated using sensor data from a 2D laser scanner and an RGB-D camera. This dynamic map is based on a manually refined static 2D map of the hospital environment, generated using the *gmapping* ROS package, which is a wrapper for OpenSlam's Gmapping library, a highly efficient Rao-Blackwellised particle filter to learn grid maps from laser range data. Subsequently, this map is adjusted to preserve key static landmarks that enhance localisation robustness. These adjustments ensure the robot achieves a localisation accuracy within a few centimetres, sufficient for safe and precise navigation in hospital settings.

To self-localise, the robot uses Adaptive Monte Carlo Localisation (AMCL), which fuses data from odometry, an IMU, the 2D laser scanner, and the RGB-D camera. Additionally, the AMCL approach and the 2D *costmap* layer incorporate sensor fusion techniques to improve environmental perception. For instance, 3D camera data is projected onto a 2D plane using the *spatio_temporal_voxel_layer*, enabling the robot to detect elevated obstacles that the laser scanner might miss.

The navigation stack is implemented in ROS Noetic, chosen over ROS 2 for its ecosystem maturity, hardware compatibility, and the team's existing experience. The navigation system is built using the *move_base* package, with the *GlobalPlanner* as the global planner and the *teb_local_planner* as the local one, selected for its ability to generate time-efficient trajectories that respect the robot's kinematic constraints in real time.

The global path planner operates on a modified version of the static map, where restricted zones have been manually marked to prevent navigation in unauthorised areas. Dynamic obstacles, such as people or equipment, are added to the global map only if they persist for a predefined period, which helps filter out transient noise. Inflation in costmaps is used to maintain a safe buffer around obstacles: global obstacles are inflated by 0.5 metres, while obstacles in the local map (within 10 metres of the robot) are inflated by 0.8 metres. This larger inflation value compensates for partial detections, such as table legs that are only partially captured by the laser scanner.

The TEB (Timed-Elastic Band) controller works with a layered *local costmap* anchored to the robot's base footprint frame, allowing it to navigate complex indoor environments.

A custom low-level controller translates the velocity commands from TEB into wheel-specific commands, based on a differential-drive kinematic model. This controller also computes joint states and odometry from encoder and IMU data, then sends motor commands via a Controller Area Network (CAN) protocol.

In terms of operational logic, the AMR can be programmed to autonomously drop off the SmartRack at any docking station defined within the map. When not dropped off autonomously, the SmartRack must be manually placed at one of the hospital's docking stations. These stations serve dual purposes: they are both charging points and predefined pickup locations, as their exact positions are stored in the robot's dynamic map.

To assist in locating SmartRacks, the system uses an RTLS, which offers room-level accuracy using low-energy adhesive tags and wall-mounted antennas. During pilot tests, two commercial RTLS solutions were used: MYSPHERA's RTLS solution (MYSPHERA, Spain), and Wirepas Massive (Wirepas Ltd, Finland). The RTLS provides the estimated position of each SmartRack, allowing HOSBOT to navigate to the appropriate docking station for collection. In multi-agent scenarios, the Fleet Management System (FMS) leverages this information to assign the AMR to the nearest available SmartRack.

Finally, the low-level controller dynamically adjusts the robot's speed and acceleration depending on whether a SmartRack is being carried. When loaded, HOSBOT's acceleration is reduced to account for the additional weight, enhancing safety and stability during transport.

C. HOSBOT: HMI

The HMI (Section III.A) is a web application developed to interface with HOSBOT. It can be accessed via the SmartRack tablet (Figure 1) and other edge devices, and provides the following functionalities:

- monitoring the location of the AMR, SmartRacks and SmartBoxes - achieved through RTLS components;
- monitoring battery level - enabling the maintenance of a fleet of operating devices;
- planning logistics missions - such as charging or delivery missions;
- unlocking SmartBoxes from SmartRacks - to access their content upon user identification;
- monitoring items carried in SmartBoxes - to consult the inventory;
- placing and removing items in SmartBoxes.

The AMR recharges its battery and the SmartBoxes' when off-duty or when their level is below a threshold, following the FMS. Alternatively, HOSBOT can be sent to recharge by planning a recharging mission. Users can decide to stop HOSBOT at any location within the hospital map and interface with it to pick up items carried in SmartBoxes or to withdraw SmartBoxes altogether, as illustrated in Figure 6.

Monitoring items carried in the SmartBoxes is a key logistics capability of HOSBOT, allowing real-time inventory. The identification of objects is enabled by using a high-performance RFID reader connected to the SoM that shares the identified tags with the HMI. The reader can simultaneously scan up to four antennas. The SoM is programmed to communicate with the reader via the Universal Asynchronous Receiver-Transmitter (UART) protocol. This communication allows the SoM to activate the antennas, dynamically adjust their power, and initiate a continuous inventory task. The antennas are activated when the photodiode within the SmartBox detects the opening of its lid, given by a sudden change in light intensity. Their functionality is controlled at the HMI. The antenna within the enclosure operates at a power of 20 mW, while the one on the lid operates at 10 mW. The latter is set to a lower power to prevent the misreading of objects already inside the box or immediately outside of it.

Tags identified by the antennas are received by the SoM as 12-bit-long strings representing the tag ID. This tag ID is temporarily stored in a map structure, where each ID serves as a unique index key corresponding to an object in storage. Therefore, each tag ID is received and compared to the pre-allocated list of objects and tags providing the sequence of detected objects. This information is then shared with the HMI through the MQTT protocol.

Pressing the SmartBox button on the HMI provides access to multiple options, such as checking stored goods, inserting/removing objects in the box, and also checking the scan history, as illustrated in Figure 6. By pressing the *Insert* button, a command is sent to the SoM inside the SmartBox, which activates the antenna positioned in the enclosure to detect the presence of inserted objects in real time. Audio feedback is emitted each time a new object is inserted. By pressing the *Remove* button, a different command is sent to the SoM, activating the antenna positioned on the lid of the SmartBox. The user scans each object in front of the lid, allowing the antenna to detect its removal. Thereafter, different audio feedback is provided, and the inventory is updated after every insertion/removal. After scanning, the user is directed to a dedicated web page where the quantity and the type of the scanned objects are reported.

D. HOSBOT: Experimental Validation

To validate the performance of the SmartBox and its integrated use with the HMI, insertion and removal tests were conducted. With the HMI controlling the SmartBox, 20 insertion and removal episodes were executed for each of four RFID-labeled objects of mixed types. These objects were selected to simulate the full range of medical items transported within a hospital ward. The objects used were:

- object #1: a sealed envelope with a consumable needle, which contains metal and is non-rigid;
- object #2: a cardboard box containing a plastic container;
- object #3: a small cardboard box containing a 133 ml container with liquid;
- object #4: a large-size 500 ml glass container with liquid.

Both the insertion and removal success rates of all objects were 100%. However, in some instances, the removal of object #4 was more complex than that of the other objects. The object had to be moved in front of the lid antenna up to five times, all within a window of 10 seconds. This could be attributed

Fig. 6. The HOSBOT HMI is available on authorised edge devices and on the SmartRack tablet. The starting page allows users to plan a HOSBOT mission or interface with the SmartBoxes. Once the SmartBox button is pressed, a menu is shown, allowing to unlock specific SmartBoxes, monitor consumables within them, perform a scanning operation of the included content, consult previous scans, and insert/remove objects. SmartBoxes are standalone devices and can be withdrawn from the SmartRack upon user authorisation.

to the lower power operation of the lid antenna, which is less sensitive than the insertion antenna in order to minimise misreadings of neighboring RFID tags while working with the lid open. Additionally, the presence of liquid in the container, primarily water, tends to absorb radio frequency signals, potentially contributing to the need for repeated adjustments. As expected, after each object recognition, audio feedback (different for insertion and removal) was provided to the user and the HMI accurately displayed the inventory, indicating objects present in the SmartBox and a history of previous scans.

V. PILOT TESTS

Three pilot tests were conducted to demonstrate HOSBOT's functionality in real hospital environments. This section details the outcomes of these tests, focusing on successes, key performance indicators (KPIs), and lessons learned. As shown in Table I, the pilots increased in complexity, incorporating the testing of additional functionalities alongside navigation in progressively longer and more crowded environments. A first two weeks long experimental pilot test was conducted at the Medical University of Łódź, Poland, and confirmed the ability of HOSBOT to autonomously deliver boxes containing biological samples between different hospital areas in real-world settings. A second executive pilot test at Hospital ClÍnico San Carlos in Madrid, Spain, introduced the SmartBox and its RFID tracking capabilities to monitor the delivery of medical objects across various hospital rooms, demonstrating real-time inventory. This pilot lasted four weeks and allowed to gain insights from a system usability questionnaire (SUS, Figure 7) administered to 25 users. A third and final executive pilot test, also two weeks long, was carried out at the University Medical Center Utrecht, The Netherlands. It involved logistics operations in a high-traffic area where carts, bins, and other large objects were being moved by logistics personnel, demonstrating the collaborative performance of HOSBOT in a complex scenario. Here, 16 users filled in the system usability questionnaire (Figure 9).

During all pilots, the AMR navigated the testing site with a minimum of 0.5 metres of free space on each side and a clearance height of 2.1 metres between the cart and fixed structures along the path, ensuring it operated within a designated zone according to current regulations (UNI EN ISO 3691-4:2020). In the first two pilots, MYSPHERA's RTLS Solution was used for dynamic tracking of the SmartRack, whereas a Wirepas RTLS was utilised in the final pilot.

All pilots featured the seamless installation of the ODIN platform (Section III) in the local hospital servers, following the security protocols (Section III-C).

A. Pilot 1: Medical University of Łódź

At the Medical University of Łódź (MUL), the first experimental pilot aimed to evaluate the ability of HOSBOT to autonomously transport biological samples, which were simulated with empty vials. The pilot did not involve the use of RFID tracking.

TABLE I

Pilot Characteristics and Key Performance Indicators (KPIs)

Pilot characteristic — KPI	**Pilot 1 (MUL)**	**Pilot 2 (SERMAS)**	**Pilot 3 (UMCU)**
Environment	Patient-free area of the Hospital Emergency Department	Patient-free area of the Hospital Smart Health Center	Active area of the Hospital Logistics Department
Path length	40 meters	120 meters	230 meters
Number of users	1	25	16
Objectives	Autonomous navigation; delivery & preservation of biological samples	Autonomous navigation; delivery of medical objects with the SmartBox	Autonomous navigation; delivery of medical objects with the SmartBox
Navigation success rate	15/17 (88.24%)	19/20 (95%)	15/15 (100%)
Distance travelled per pilot [m]	33.94 ± 5.60	114.1 ± 3.5	234.04 ± 1.85
Time per pilot [s]	45 ± 42	6’22 ± 32	7’23 ± 58
Average speed [m/s]	0.22 ± 0.05	0.30 ± 0.02	0.54 ± 0.07
Integration with RTLS	MYSPHERA RTLS ✓	MYSPHERA RTLS ✓	Wirepas RTLS ✓
Compatibility with hospital environment	✓ Monitoring of the Emergency Department performance during the pilot	N/A	N/A
SmartBox temperature stability	✓	N/A	N/A
SmartBox success rate	N/A	83% real-time; 100% offline	92% real-time; 100% offline
Average acceptability	N/A	70.60% (25 users)	71.40% (16 users)
Preference vs manual transportation	N/A	N/A	65% – 4 logistics staff
Time for manual & robotic transportation [s]	N/A	N/A	1’40 ± 4 – 2’51 ± 10

1) Pilot 1: Objective: The primary objective at MUL was to assist in the execution of care and diagnostic procedures by using robotic systems to transport blood sampling vials from the emergency department to the central laboratory. The clinical scenario focused on alleviating the burden of physically demanding tasks associated with patient management. The need for robotic assistance arises from the fragility of certain clinical specimens, such as blood sampling vials, which cannot be safely transported via pneumatic systems due to their sensitivity to impact. By automating the delivery process with mobile robots, the workload and physical strain on nursing staff can be significantly reduced. As a result, medical personnel may experience less fatigue and be able to devote more attention to higher-level patient needs, including social interaction and emotional support, which are critical in the high-pressure environment of an emergency department. The deployment of HOSBOT in this context is expected to enhance the quality of life for patients and hospital personnel by enabling faster testing and diagnosis, ultimately improving their overall wellbeing.

2) Pilot 1: Testing Environment: The pilot was carried out in a dedicated space within the hospital, located in a patient-free section of the working Emergency Department. HOSBOT followed a path of approximately 40 metres. This controlled environment enabled testing without interfering with the hospital’s schedule. On the other hand, the testing site was located close to standard infrastructures of the Emergency Department, including a computer network, cardiomonitors, and imaging equipment. The performance of this equipment was closely monitored throughout the testing phase to identify any potential interferences.

Being the first experimental pilot, the testing environment at MUL was initially free of people and other dynamic obstacles. However, in the second phase of the pilot, members of the testing team were actively present in the testing environment, simulating both healthcare professionals and patients while interacting and occasionally interfering with the robotic transportation. Moreover, the robot was commanded to navigate at a maximum speed of 0.6 m/s, equal to about half the average human gait speed (*i.e.*, 1.1 m/s [19]) in order to ensure safety during operation.

During the pilot, the AMR performed tasks based on messages received from other modules via the ESB (Section III). Before autonomously navigating in the hospital, the AMR mapped the operative area as discussed in Section IV-B.

The robot operated across four distinct areas, a corridor and three specialised rooms, each serving a function within the pilot (an example map from the third pilot is illustrated in Figure 8):

- ROOM 1–Home: this area serves as the primary station for HOSBOT, where it returns to recharge its batteries at a docking station. This room also serves as a secure space for maintenance and downtime between tasks;
- ROOM 2–First destination: this room contains the proximity sensor, an IoT device connected to the ODIN platform. Upon receiving a contactless request, the robot is directed to a target point within this room, where it may collect medical supplies/biological samples for delivery. This room may represent the emergency department;
- ROOM 3–Second destination: the robot proceeds to this final room to deliver the collected objects. This room may represent the central laboratory requiring the transported blood sampling vials.

3) Pilot 1: Modules: The modules employed in this pilot included:

- HOSBOT: equipped with a tablet running the HMI and carrying three standard boxes (without RFID);
- the proximity sensor: a standalone capacitive sensor connected to the ODIN platform used to call the autonomous mobile robot (AMR) without physical contact [20];
- RTLS gateways and tags (MYSPHERA’s RTLS Solution, MYSPHERA, Spain) allow the AMR to localise the SmartRack for autonomous pick up.

4) Pilot 1: Testing Protocol: During the first pilot, a testing protocol consisting of this sequence of operations was followed:

1) the AMR is positioned arbitrarily within the mapped area (*e.g.*, ROOM 1). A human operator activates the proximity sensor located in ROOM 2;
2) the AMR receives the message transmitted by the sensor:
   - if the SmartRack is already collected by the AMR, proceed to Step 3;
   - if the SmartRack has not yet been collected by the AMR, the robot moves to collect it after localising it through the RTLS.
3) the AMR navigates to the target point in ROOM 2, where a human operator is stationed;
4) the operator interacts with HOSBOT, placing blood sampling vials into one of the boxes, and uses the HMI on the SmartRack tablet to initiate the next action;
5) HOSBOT moves to the target point in ROOM 3. There, the operator withdraws the blood sampling vials and uses the HMI to command the AMR to release the SmartRack and return to its home position in ROOM 1.

5) Pilot 1: Results: The first pilot test was successful, demonstrating the potential of automating healthcare logistics with HOSBOT. A Python-based logging system was implemented to track the performance of HOSBOT throughout the tests, recording key data such as test duration, start and end times for each task, the position of the robot at all times, the total traveled distance, and the average velocity during each test. Moreover, the integration of the IoT proximity sensor within the operative workflow was successful.

From this data, the following KPIs were derived:

- navigation efficiency: of the 17 conducted protocol runs, 15 were successful, resulting in a success rate of 88.24%. Two tests were unsuccessful due to issues in autonomous path planning;
- time and distance metrics: the average navigation time during a protocol run was 3 minutes and 45 ± 42 seconds. The robot covered an average distance of 33.94 ± 5.60 metres per test, with an average velocity of 0.22 ± 0.05 m/s, maintaining a balance between safety and timely delivery of medical goods. Although the velocity of the AMR was set at a speed lower than the maximum allowed speed (1.5 m/s), this metric provides a valuable insight into HOSBOT's performance during the experimental pilot;
- seamless integration with MYSPHERA's RTLS: the RTLS allowed the localisation of the SmartRack used to execute autonomous navigation missions;
- compatibility with the hospital environment: the performance of the standard Emergency Department infrastructure was monitored throughout the testing period, with no harmful interferences detected;
- temperature control: the temperature within the SmartBox remained stable during transit, demonstrating safe transport conditions for biological samples.

6) Pilot 1: Discussion: Overall, the first experimental pilot at MUL demonstrated the successful implementation of HOSBOT with its dedicated HMI and integrated with an IoT device, the proximity sensor, achieving high levels of reliability and efficiency. MYSPHERA's RTLS was integrated and tested successfully, tracking the SmartRack. Despite minor setbacks from server communication issues due to an unstable network connection, and two interruptions in autonomous navigation during path planning in front of an obstacle, HOSBOT demonstrated its capability to autonomously transport fragile medical samples, highlighting its potential to enhance hospital logistics workflows. The pilot lasted two weeks and its success provided a foundation for the next one, where RFID tracking was incorporated to improve real-time inventory management and object tracking across different hospital areas.

B. Pilot 2: Hospital Clínico San Carlos

The second executive pilot at Hospital ClÍnico San Carlos, Madrid, Spain, introduced RFID tracking through the SmartBox and involved 25 users to assess the usability of the system. The transported goods included a variety of medical consumables, encompassing both solid and liquid items.

1) Pilot 2: Objective: The hospital, which is part of the Madrid Health Service (SERMAS), faces a significant challenge in managing medical consumables due to the lack of an effective system for tracking their movement from storage to operating rooms. The absence of effective record-keeping makes it difficult to monitor or verify the path of consumables within the hospital, complicating cost justification and purchase planning. Additionally, inefficiencies in handling unused consumables often lead to resource losses or inappropriate use.

To address these challenges, the SmartBox enables real-time monitoring of material movement within the hospital, improving inventory control accuracy, while HOSBOT allows autonomous transportation of SmartBoxes and timely delivery. By automatically recording the usage of each item, the system not only enhances the efficiency of consumable handling but also optimises resource management, reducing waste and ensuring the appropriate availability of materials necessary for operations.

2) Pilot 2: Testing Environment: Pilot 2 was deployed in a limited hospital area within the Smart Health Center (SHC) at SERMAS. During this second executive pilot, the testing environment was filled with static obstacles positioned randomly and one person interfered with the robot, acting as a dynamic obstacle. As in pilot 1, the robot was commanded to navigate at a maximum speed of 0.6 m/s, equal to about half the average human gait speed [19] to ensure safety during operation.

The AMR map used for autonomous navigation was generated following the same process described in pilot 1. The operative area consisted of three rooms connected by a corridor.

Each room had a designated function:

- ROOM 1–Home: similar to pilot 1, this room houses a charging station and serves as the main area for maintenance and downtime between tasks. This room simulates a storage room, and here medical consumables are inserted in the SmartBox;

- ROOM 2–First destination: HOSBOT is directed to this room, which also simulates a storage room. Here, another docking station is available, and additional medical consumables are placed in the SmartBox, with their presence being recorded;
- ROOM 3–Second destination: in this room, which simulates an operating room, some of the previously inserted medical consumables are removed from the SmartBox.

3) Pilot 2: Modules: The modules employed in this pilot included:

- HOSBOT: equipped with a tablet running the HMI and carrying a SmartBox;
- RTLS gateways and tags (MYSPHERA's RTLS Solution, MYSPHERA, Spain): allowing the AMR to localise the SmartRack for autonomous pick up.

The server infrastructure employed in this second pilot mirrored the one used in the first pilot.

4) Pilot 2: Testing Protocol: The testing protocol followed in pilot 2 consisted of this sequence of operations:

1) the AMR is positioned arbitrarily within the mapped area (*e.g.*, ROOM 1). A human operator located in ROOM 1 requests to pick up the HOSBOT SmartRack by selecting a command at the HMI;
2) the AMR receives the message and navigates to a predefined location in ROOM 1, where the SmartRack is located, as communicated by the RTLS. Here, the SmartRack is picked;
3) the operator interacts with the HMI to unlock the SmartBox and inserts some medical consumables inside;
4) the operator commands HOSBOT to move to ROOM 2. Here, an operator interacts with the HMI to unlock the SmartBox and insert more medical consumables;
5) HOSBOT is commanded to move to ROOM 3. Here, an operator withdraws some consumables and uses the HMI to command the AMR to release the HOSBOT SmartRack and return to its home position in ROOM 1.

Moreover, during the pilot:

- the AMR can be commanded to bring the HOSBOT SmartRack home: it navigates to ROOM 1, where the HOSBOT SmartRack was originally picked up, deposits it, and returns to its resting position;
- the AMR can be commanded to release and go home: the SmartRack is left in its current location, and the AMR returns to its resting position.

5) Pilot 2: Results: The second pilot test was successful and demonstrated the functionality of the SmartBox in combination with the navigation of HOSBOT in a larger environment compared to the first pilot. The same data logging infrastructure used in pilot 1 was employed, collecting the following KPIs:

- navigation efficiency: 20 navigation tests were performed prior to user testing in a more complex environment than the one employed during the protocol runs, with up to 10 randomly placed obstacles along the robot's path. 19 tests were successful, resulting in a success rate of 95%. One of the tests was interrupted due to issues in path planning in front of an obstacle, after which the system was manually guided to complete the test;
- time and distance metrics: the average navigation time during a protocol run was 6 minutes and 22 ± 32 seconds, with an average space traveled of 114.1 ± 3.5 metres per test. The average speed was 0.30 ± 0.02 m/s. Again, although the velocity of the AMR was set at a speed lower than the maximum allowed speed (equal to 1.5 m/s per regulation), this metric provides a valuable insight into HOSBOT's performance during the executive pilot;
- accuracy of the RFID tracking system through the SmartBox: while the SmartBox achieved a 100% detection success rate as registered on a local database, 83 out of 100 objects were communicated in real time through the network infrastructure, resulting in a success rate of 83%;
- seamless integration with MYSPHERA's RTLS: the RTLS allowed the localisation of the SmartRack used to execute autonomous navigation missions;
- average level of acceptability from 25 users: 70.60 out of 100.

The latter KPI was extracted from a system usability questionnaire. Each user ran one experimental protocol after a brief induction on the system and answered 10 related questions. The responses were rated using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) and averaged. The results of the questionnaire are illustrated in Figure 7 alongside demographic and professional user data. The right-hand side of the Figure illustrates the average scores ± one standard deviation for each question. The "Result average (%)" is calculated as the mean of these scores, following a linear conversion of the Likert scale where 1 corresponds to 0% and 5 corresponds to 100%.

6) Pilot 2: Discussion: Pilot 2 introduced the SmartBox and demonstrated its RFID tracking capabilities while testing the navigation of HOSBOT in a larger environment, where the robot traversed approximately three times the distance covered in the first pilot per protocol run. MYSPHERA's RTLS system had a broader deployment, successfully validating the dynamic tracking of the SmartRack with a larger number of users. The system was extensively tested by 25 users with no prior experience over the course of four weeks, and HOSBOT's acceptability and usability were evaluated through a questionnaire that indicated a good level of user satisfaction. Certain areas of improvement emerged, such as the need to enhance the network performance to minimise communication issues, along with hardware and HMI refinements. On the hardware side, improvements focused on assessing the lifecycle of 3D-printed components, which were prone to breakage. For the HMI, users suggested enhancements such as the addition of visual feedback to improve usability. These insights helped prepare for the final executive pilot, where HOSBOT was tested in a larger and highly trafficked environment.

C. Pilot 3: University Medical Center Utrecht

At the University Medical Center Utrecht (UMCU), a third and final executive pilot test was conducted to demonstrate the

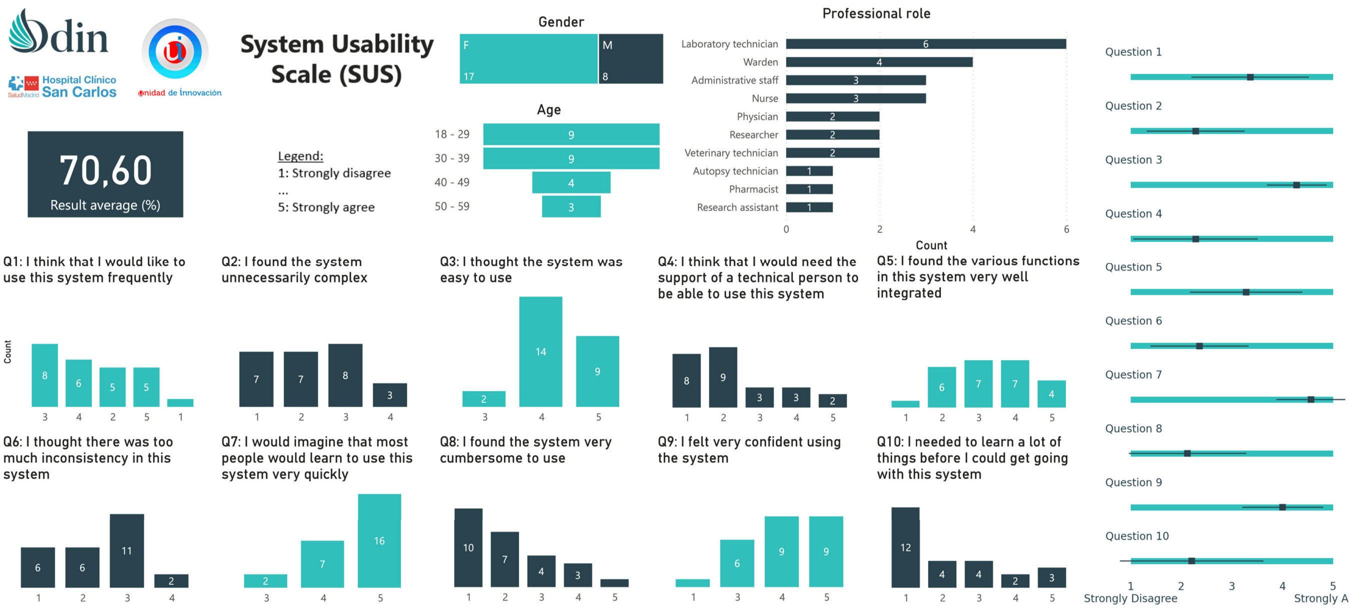

Fig. 7. Results from the system usability questionnaire at Hospital ClÍnico San Carlos (SERMAS). An average acceptability score of 70.60% was achieved (100% being the highest acceptability). The average scores ± one standard deviation for each question are illustrated on the right-hand side.

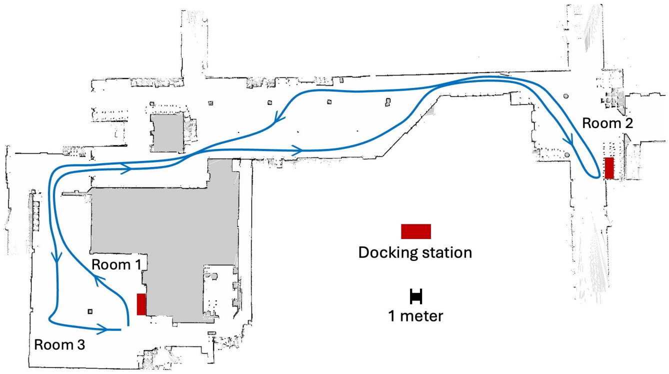

Fig. 8. The map used by HOSBOT for navigation at the University Medical Center Utrecht. The blue arrows represent a typical trajectory during navigation tests. Three rooms and a corridor can be identified, which make up the operative area.

operation of HOSBOT in a large and crowded environment filled with logistics workers, hospital personnel and numerous guided vehicles, constituting dynamic obstacles. This environment presented the most complex challenges among the three pilots.

1) Pilot 3: Objective: At UMCU, a highly active macrologistics network manages the transportation of large pallets using guided vehicles, while micrologistics, the transportation of individual items within these pallets, is handled manually. From the warehouse, carts are filled with 24-hour supplies for patient rooms. The task of transporting these carts is physically demanding for the logistics staff, so the aim of this pilot was testing whether a robot can be used to transport these supplies autonomously while tracking them around the operative area. This would help reduce the physical strain on employees, allow for more efficient staff deployment, and enable a 24/7 operation with on-call availability during evenings and nights. Workers at UMCU deliver objects by taking the elevator and walking across hospital wards and corridors. During the pilot, it was explained that HOSBOT could autonomously operate elevators if connected through WiFi and integrated with the elevators' control system. This feature was not implemented for practicality. In fact, the route followed by HOSBOT during a protocol run closely mimicked the path logistics workers typically take to go to the obstetrics ward, allowing a meaningful comparison while working in a controlled environment and testing the process without interfering with the hospital schedule.

2) Pilot 3: Testing Environment: A large area of the logistics department crowded with dynamic obstacles and people constituted the operative area of pilot 3. The area was mapped prior to navigation, mirroring the process followed in pilots 1 and 2.

The typical path followed by HOSBOT at UMCU is shown in Figure 8. Each room served a purpose:

- ROOM 1 - Home: as in the previous pilots, this room serves as the primary area for maintenance and downtime between tasks. It simulates a storage room where objects are placed into the SmartBox;
- ROOM 2 - First destination: similar to pilot 2, this room contains another docking station and simulates a storage room. Objects are placed into the SmartBox here;
- ROOM 3 - Second destination: this room simulates a hospital ward and is part of the large space that includes ROOM 1. Its location was chosen because the distance from ROOM 2 mirrors the distance between this part of the hospital and the obstetrics ward. In this room, some previously inserted objects are randomly removed from the SmartBox.

Building on the confidence gained in terms of acceptability and reliability during previous pilot tests, HOSBOT was commanded to move at a faster speed compared to the previous two pilots and equal to the average human walking speed of 1.1 m/s [19].

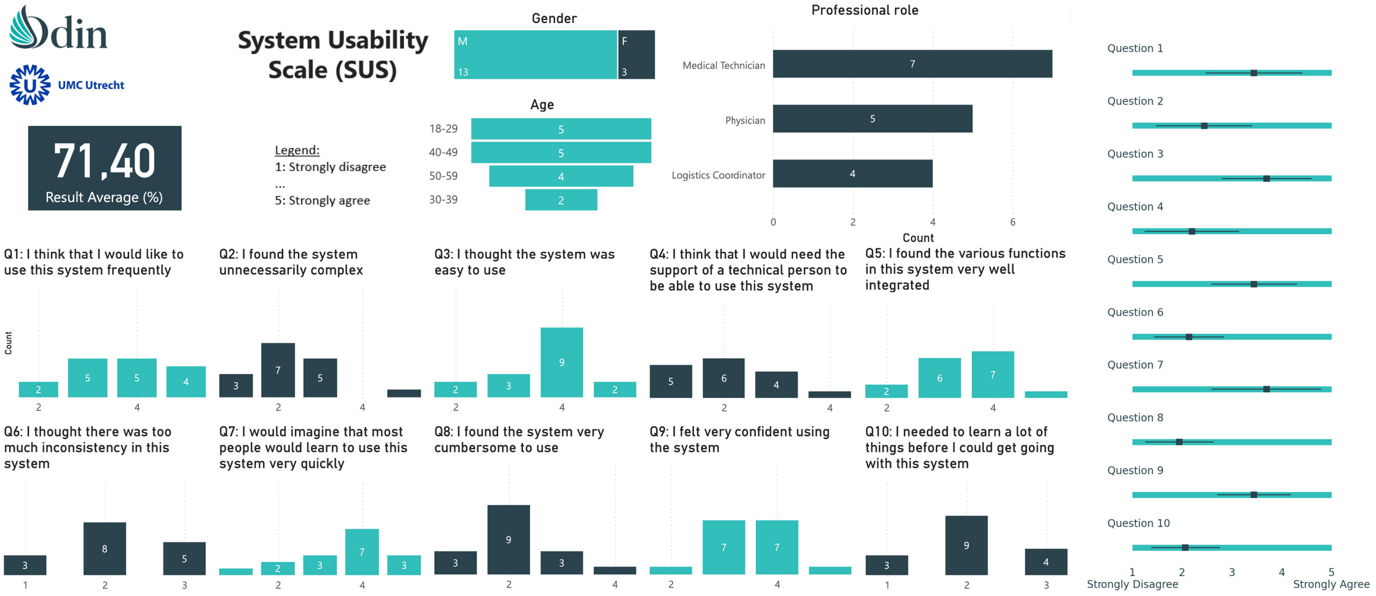

Fig. 9. Results from the system usability questionnaire at University Medical Center Utrecht (UMCU). An average acceptability score of 71.40% was achieved (100% being the highest acceptability). The average scores ± one standard deviation for each question are illustrated on the right-hand side.

3) Pilot 3: Modules: The modules used in this pilot were the same as those in pilot 2, with the exception of a different RTLS system provided by UMCU (Wirepas Massive, Wirepas Ltd, Finland). The server infrastructure, similar to previous pilots, was installed at UMCU in compliance with hospital security protocols. Insights from the two previous pilots improved the robustness of HOSBOT and the ODIN platform, particularly in server reliability. A new version of the HMI was deployed to improve its communication reliability. These improvements were implemented and tested in the preliminary phases of the pilot to ensure the network infrastructure at UMCU was fully prepared.

4) Pilot 3: Testing Protocol: The testing protocol for pilot 3 mirrored the one used during pilot 2.

5) Pilot 3: Results: The third pilot was an executive test demonstrating a fully integrated system operating in a large, dynamic environment and also validated the functionality of the SmartBox. As in pilots 1 and 2, the same data logging infrastructure was used, collecting the following KPIs:

- navigation efficiency: navigation was completed successfully in all 15 of the protocol runs conducted. However, some server communication errors occurred during 2 tests, requiring manual mission commands to be issued through a terminal connected to the state machine of the robot;
- time and distance metrics: the average navigation time for a protocol run was 7 minutes and 23 ± 58 seconds, with an average traveled space of 234.04 ± 1.85 metres per test. The average speed was 0.54 ± 0.07 m/s. These data should be interpreted as indicated in the results section of pilots 1 and 2;
- accuracy of the RFID tracking system through the SmartBox: while the SmartBox achieved a 100% detection success rate as registered on a local database, 72 out of 78 objects were communicated in real time through the network infrastructure, resulting in a success rate of 92%;
- comparison of autonomous and manual transportation times: a logistics task performed using HOSBOT took 2 minutes and 51 ± 10 s, compared to 1 minutes and 40 ± 4 s with manual transportation;
- seamless integration with the Wirepas Massive RTLS: the RTLS allowed the localisation of the SmartRack used to execute autonomous navigation missions;
- level of acceptability by professional staff: 71.40 out of 100;
- level of preference for automated transportation by logistics staff: 65 out of 100.

The last two KPIs were extracted from a system usability questionnaire. The questionnaire results are illustrated in Figure 9 alongside demographic and professional user data. The same system usability questionnaire presented in pilot 2 was administered to the pilot 3 users. Sixteen users from different professional backgrounds, gender, and age group followed the testing protocol after a short induction on the system. 14 users followed the protocol solo, while a couple of users joined together. As for Pilot 2, the "Result average (%)" score was calculated as the mean of the average scores of each question, reported on the right-hand side of the Figure. An additional question was posed to Logistics Coordinators, asking whether they would prefer manual object transportation or using HOSBOT in their daily activities. Out of 4 Logistics Coordinators, this question obtained a result of 65% (100% being the maximum agreement), indicating a mild preference in using the robotic system.

The time required for a human operator to manually insert one object into a container in ROOM 2, carry the container (a light box) to ROOM 3, and leave it there was measured in four tests with four different individuals. The average time to complete this task was 1 minute and 40 ± 4 s. In comparison, HOSBOT took an average of 2 minutes and 51 ± 10 s for the same task. This suggests that the average human operator is 71% faster than HOSBOT. However, this time difference should be considered in the context of the operational workflow of HOSBOT. While the time discrepancy is significant, HOSBOT can transport multiple items simultaneously using up to three SmartBoxes, each capable of carrying up to 20 kg, while continuously monitoring their content. This process automates much of the manual object transportation that would otherwise require human operators to navigate the hospital. Moreover, HOSBOT was commanded to navigate at a speed of 1.1 m/s, lower than its maximum speed of 1.5 m/s (compliant with regulations).

6) Pilot 3: Discussion: Pilot 3 demonstrated a large-scale proof of concept of HOSBOT in a highly dynamic environment and interfaced the system with professionals from various backgrounds while diving into their daily activities. The pilot was a success overall, gaining participation from 16 users who had not seen the system before.

VI. CONCLUSION

The use of AMRs in hospital logistics presents a promising outlook, particularly as these solutions become more accessible and cost-effective. Their primary advantage lies in their navigational flexibility, enabled by advanced algorithms and sensing technologies, that allow them to adapt to dynamic and evolving environments such as hospitals.

Despite the maturity of the technology and the existence of commercial solutions, the widespread adoption of service and logistics robots in hospitals faces challenges, including the cost of the technology and societal acceptance of robotic systems [4]. Furthermore, existing AMR systems exhibit limited modularity and can hardly be tailored to specific applications. HOSBOT represents a technological paradigm shift, embracing a modular design that aligns with the specific needs of each user. This approach offers options such as choosing the mobile robot, performing multiscale logistics via SmartBoxes and multi-agent coordination via multiple SmartRacks, as well as defining the overall design and dimensions of SmartRacks.

HOSBOT was integrated within the ODIN ecosystem [9] and successfully deployed in three hospital environments, demonstrating safe operation, compatibility with hospital infrastructures, and user acceptance. Its real-time tracking and modular architecture offer a scalable solution for internal hospital logistics, potentially enabling data-driven inventory management and reducing staff workload.

Lessons learned during the hospital tests gave important feedback on the main strengths and weaknesses of the current system. The RTLS is an essential component for enabling asset and fleet management by enabling dynamic task allocation and route planning. This, in turn, ensures that robots are efficiently dispatched to the appropriate location based on real-time needs and resource availability. The modular design of HOSBOT enables multitasking, and users expressed interest in detaching a SmartBox from the SmartRack to assist with tasks such as surgical procedures. Although still in its prototype stage, the SmartRack's design and dimensions were well received by users. Additionally, the LEDs and siren effectively aided in identifying the robot within the hospital without disturbing the environment.

The identified key areas of improvement include the enhancement of the HMI, which requires a more robust error handling, prevention of system freezes, and an improved GUI with action confirmation and clearer task visibility. Indeed, the HMI should be regarded as a functional prototype rather than a final product. Additionally, the programmability of HOSBOT needs improvement to support more flexible routing and dynamic reprogramming of navigation tasks. While several established algorithms could be employed for path planning and navigation, we adopted a navigation pipeline selected for its robustness and hardware compatibility to demonstrate a reliable and deployable logistics platform for complex healthcare settings. Nevertheless, improving navigation performance through systematic algorithmic comparison remains an important direction for future work. A preliminary discussion on the need for standardised evaluation of navigation strategies for autonomous hospital robots has been presented in our previous work [21], alongside an evaluation of disinfection methods of this robot in hospital environments to explore the risk of infection [22]. The AMR-SmartRack connectors performed reliably, ensuring a robust connection between the two. However, some electrical connections failed, resulting in LEDs not activating. Future iterations will focus on improving the reliability of the electrical connector. Finally, further testing in large environments with dedicated network infrastructures is crucial to demonstrate full proficiency and address server communication errors. The gap in the SmartBox success rate between the local and the real-time shared databases is primarily attributed to network disconnections, likely influenced by environmental factors within the hospital, such as areas with plumbed walls. Enhancing the network configuration and selecting devices better suited to these challenging conditions may significantly improve connectivity. While the local database was successfully saved, future work will focus on sharing these data across the network in real time, to ensure seamless communication and integration with the automatic inventory. The two system usability questionnaires indicate a moderate user satisfaction, and future work will focus on improving this metric. Specifically, we believe that the HMI is the key area for improvement, as it facilitates user interaction with the robotic system and ensures a transparent visualisation of the task at hand. By analysing user feedback, the overall SUS score is expected to improve through more comprehensive training sessions that enhance user familiarity and technology acceptance.

As a prototype implementation, HOSBOT was designed to demonstrate the feasibility of introducing modular AMR systems in hospital environments with no prior robotics experience. While the current results are promising, future work must address scalability to larger hospital settings, focusing on robust multi-robot coordination and network reliability. Additionally, although the system was developed using cost-effective materials to lower adoption barriers, a detailed cost-benefit analysis will be essential to assess long-term viability at scale.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are not openly available due to sensitivity reasons and are available from the corresponding author upon reasonable request. Data are stored in a controlled access data storage at the Scuola Superiore Sant'Anna.

INFORMED CONSENT

All participants in the system usability evaluation questionnaire provided informed consent, agreeing to the collection of anonymised data, including their sex, birth date, and profession.

CONFLICT OF INTEREST

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