hospOS: A Platform for Service Robot Orchestration in Hospitals

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Abstract: In a time where an ageing population, nurses shortage and manual labor routines are limiting rural healthcare, Service Robots (SR) are emerging. While SR could increase hospital staff efficiency, their healthcare use remains limited. Barriers are the robot's task-specific inflexibility and a lack of interoperability. Existing SR are usually closed systems and focus on a single robot designed to fulfill all functional requirements, which results in complex and expensive solutions. In contrast, we propose to utilize and combine existing SR for various tasks. We argue that with the growing integration of SR in healthcare, a SR management system has become a necessity. We propose hospOS, a centralised system for SR orchestration in healthcare facilities. hospOS addresses this gap by providing a modular, flexible, user-friendly platform that seamlessly integrates SR into hospital IT infrastructures, alleviating the shortage of care workers and thus improving patient care. The platform is built with a focus on interoperability, modularity, and compliance with regulations. We evaluated hospOS in two rural hospitals by realising three example use cases: Telemedicine, transport, and orientation services. This paper offers an architecture blueprint and discusses the functionalities, and potential benefits of hospOS, along with its implementation in healthcare scenarios. The results from deployments indicate improvements in service delivery and operational management.

1 INTRODUCTION

As demonstrated during the recent COVID pandemic, most western countries are on the verge of a healthcare crisis caused by a demographic shift. The aging society increases the number of those in need of care, and at the same time the number of caregivers is stagnant. Like most of its European neighbor countries, Germany faces rising healthcare demands, intensified by multi-morbidity, chronic diseases, and COVID-19's impacts on Healthcare Workers (HCWs) and system limitations (Parliament, 2022; Lützerath et al., 2022; Kramer et al., 2021; Kroczek and Späth, 2022; Scharf et al., 2019). A predicted shortage of 500,000 nurses by 2023 and rising care costs are prompting political actions to cut services due to economic constraints (OECD, 2023). Moreover, nurses report insufficient time for direct patient care, urging supportive solutions (Sommer et al., 2024b).

At the same time, robots are gaining importance in addressing the healthcare shortages (Köppen and Busse, 2023). Although in the last decade, surgical robots became popular, Service Robots (SRs) are now following due to affordability, advancements in compute power, autonomous navigation, and human interaction (Shen et al., 2020; Holland et al., 2021; Maalouf et al., 2018). Germany's initiative lags behind Japan's adoption of robotics for healthcare in "smart hospitals", necessitating a catch-up in areas like Telemedicine applications (TMeds) (Kwon et al., 2022; Vogt and König, 2021; OECD, 2023). Robots, collaborating with human HCWs, could alleviate the staff shortage (Gimpel et al., 2021). Capable of performing repetitive tasks, interacting with infectious patients, and operating tirelessly, robots offer patient guidance, entertainment, transportation, and TMeds without the need for rest or maintenance (Holland et al., 2021; Asgharian et al., 2022; Kwon et al., 2022). Shifting such non-empathic tasks to robots got positive responses from HCWs (Sierra Marín et al., 2021; Radic et al., 2019). Still, their integration in healthcare faces challenges: A fragmented technology landscape and manufacturer-specific ecosystems limit interoperability (Huang et al., 2023; García

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et al., 2023; Radic et al., 2019). In addition, the use of closed source software and the absence of universal interfaces prevent operation across different SRs, leading to limited collaboration (García et al., 2023; Gordon et al., 2023; Maalouf et al., 2018).

The complexity of hospital environments, necessitating integration with existing systems and ensuring safe operation around vulnerable individuals, demands reliable technologies e.g., collision avoidance. However, hospitals lack the technical expertise and HCWs for seamless robot integration, limiting their ability to use SRs capabilities (Schnack et al., 2022). A close exchange and testing among developers, researchers, and HCWs are recommended for implementation (Holland et al., 2021).

To solve these challenges, we propose hospOS, a system which facilitates the interaction between SRs, building infrastructure, and stakeholders, while ensuring compliance in hospitals. hospOS begun within the research project "SMART FOREST 5G Clinics" and is currently under development in a prototype state. Currently, we are evaluating the system in a real-world setting in two clinics in Lower Bavaria and extending it as the project progresses. As hospOS is currently a work in progress, we did not cover security, version control, diagnostics, remote monitoring, cyber security, stability, and persistence in detail in this paper. Code from the research project is continuously updated and available as open source[1]. Our paper argues for and contributes a blueprint of a centralized robot orchestration platform to connect to existing hospital infrastructure and ease the administration of SRs.

2 RELATED WORK

Healthcare SRs cover a variety of tasks, from providing assistance in carrying goods to offering assistance to hospital staff, patients, and visitors. In the healthcare sector, SRs primarily focus on cleaning, hospital logistics, remote monitoring, and TMeds, a trend accelerated by COVID-19 (Holland et al., 2021). Robots reduce the physical strain on HCWs, for example, by transporting heavy loads, thereby easing their workload (Radic et al., 2019).

2.1 Challenges in SR Orchestration

Existing SRs focus on solving one specific task, e.g. cleaning, the requirement for a technical solution is to cover many functionalities from teleconsultation to transport (Maalouf et al., 2018; Holland et al., 2021). Therefore, it seems beneficial to use one system able to manage different SRs.

Integrating SRs into the large area of hospitals, with elevators, old infrastructure, non-electrical fire doors, movable obstacles and vulnerable people poses plenty of challenges for SR integration. As SRs lack interoperability, all these challenges have to be solved per robot base or via a robot management system (García et al., 2023; Gordon et al., 2023).

Many SRs do neither align with national data protection regulations, nor are they customizable to meet the hospital needs. The varied software frameworks (ROS, OpenRTM, OPROS) and the proprietary nature of these systems lead to high costs and complexities in customization, making them less feasible for budget-constrained healthcare (Min Ho Lee et al., 2015).

Healthcare providers have a knowledge gap in SRs management (Shen et al., 2020). This leads to the need for accessible tools that do not require extensive programming knowledge. The absence of technicians in hospitals further amplifies this challenge, calling for user friendly solutions (Shen et al., 2020).

2.2 Existing Solutions

Software exist to organize and support healthcare, such as managing patients' food orders through tablets in patient rooms. These systems streamline the process, directing requests efficiently to nurses.

TMeds SRs primarily focus on video broadcasting, providing additional information, and offering limited hardware support. Some SRs also function as platforms, organizing networks of specialized doctors, thereby facilitating remote consultations and treatments (Vogt and König, 2021).

Robot manufacturers offer control solutions for their SRs, including smartphone apps that can manage multiple SRs from their product range. However, these systems are limited to the manufacturer's own products and their built-in functions, lacking cross-compatibility with other systems. Most commercially available robots are built using the open source robot operating system (ROS) making their internal software architecture similar. Their internal software is often closed and application programming interfaces (APIs) are limited in order to vendor lock users into a walled garden. Thus, an app must be built and run on each robot to make robots hospOS compatible. In Section 4 we detail the requirements for a robot manufacturer-provided API to be integrated with hospOS.

Specialized healthcare SRs, mostly developed in

[1]The code is available at https://mygit.th-deg.de/smart-forest-5g-clinics

research, are becoming more prevalent. Companies are beginning to adopt SRs from the hospitality sector for healthcare use. In Germany, notable examples include Fraunhofer's Care-o-bot and Charite's ERIC. However, these non-commercial prototypes often don't meet hospital regulations, are expensive, require high maintenance, have limited availability, and are complex technical systems (Holland et al., 2021; Kwon et al., 2022; Shen et al., 2020).

Robot management systems, capable to orchestrate single SRs exist in the industry (Holland et al., 2021). However, the requirements are different: In industrial context has a stronger focus on process optimization with more freedome according to sensors e.g. radar on the hall ceiling. As this is not possible in hospitals, hospOS relies on different robot's internal mapping data and building plans, from which a shared common map is calculated. To make this even harder, while industrial SRs are open systems that are designed for external control, SRs are closed systems with far fewer interfaces. HospOS includes functions such as TMeds and must meet regulations.

3 BENEFITS OF hospOS

A more holistic, multi-robot system can address the range of healthcare tasks and therefore support the adoption of SRs in hospitals (Holland et al., 2021; Morgan et al., 2022; da Veiga et al., 2020). hospOS serves as a centralized system to orchestrate SRs, aiming to enhance SRs efficiency. It aims to address the staff shortage by automation, improve service delivery, and the functionality of SRs.

hospOS is built as an independent modular system, and thus harnesses the strengths of different SRs while reducing their complexity and offering interoperability with existing hospital IT systems. hospOS is designed to facilitate the widespread adoption of SRs in healthcare by supporting a range of use cases and allowing hospitals to customize the system to their specific needs. Its focus on user-friendliness and seamless integration with existing systems shall reduce the IT burden on hospitals.

hospOS features an interface developed with the input of HCWs, prioritizing user-centeredness for wider acceptance (Ozturkcan and Merdin-Uygur, 2022). hospOS improves patient safety and compliance by automating routine tasks, allowing clinicians to focus on direct patient care. hospOS's consistent operation and real-time surveillance possibilities adhere to hygiene standards, certification guidelines, and local rules and regulations in Germany.

4 DESIGN AND FUNCTIONS OF hospOS

Figure 1 shows the hospOS architecture which is comprised of the core and three key components. The core component encapsulates smart logistic planning, a shared common map derived from the building plan, and individual maps of SRs, the task to robot matching logic, and the communication system. In addition, the connector component contains connectors to different SR models, SR peripheral hardware, e.g., an additional camera for TMeds, and building technology, e.g., elevators and doors. hospOS provides services for each use case, e.g., TMeds, transportation, and orientation. Individual touchpoints per stakeholder and service are also served by hospOS in order to adapt the user experience to the user group.

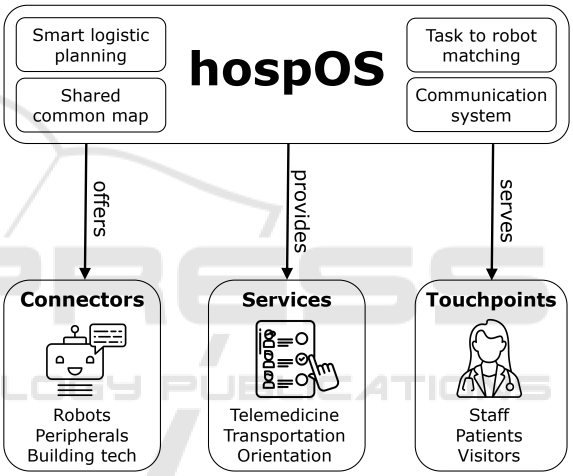

Figure 1: hospOS architecture and its components: (i) Connectors to SRs, peripherals, and building technology, (ii) Services bundling all use cases, and (iii) Touchpoints to adapt the user experience to the specific stakeholders.

Application Interface Requirements. Due to the varying technical specifications (sensors, operating systems, APIs) of different SRs, hospOS provides a generalized interface for robot-system interaction. This interface requires SRs to supply information of the following four types:

1. **Heartbeats** incl. the robot's current status (charging, ready, doing, error), battery level, and IP.
2. **Map data** comprising a point cloud or image and the robot's position on the map.
3. **Task** types which are implemented and can be processed by the robot.
4. Robot **functionalities** e.g., navigation or UI.

On each SR type, a dedicated application needs to be implemented with the interface functions of hospOS, tailored to the SRs technical characteristics.

System Integration. Integrating SRs into hospOS involves setting them up in the orchestration system, accessible via a web-based interface designed for hospital staff and IT administrators. SRs are registered in the system using their IP address. Once registered, SRs are managed through hospOS by different roles, like IT administrators assigning updates. hospOS can trigger maintenance, like charging.

hospOS ensures that each SR is effectively utilized within its capabilities, enhancing the efficiency of hospitals. Instead of engineering a complicated robot which can offer all services, we aim to combine SRs with few skills.

User Interface Requirements: Due to the variety of users interacting with hospOS, the interfaces should be adapted to meet their specific needs and requirements and thus enhance acceptance (Ammenwerth, 2019).

- **HCW** can utilize the system to request services provided by hospOS e.g., TMeds, transport of materials, and patient orientation services.
- **Patients** can utilize the system to order goods to their room and take part in TMeds consultations.
- **Visitors** can utilize the system for guidance, orientation and information, e.g. opening hours.

The user interaction can occur via SRs and their tablets or via local web apps, accessed by computers or smart phones.

4.1 Communication Flow

A streamlined communication flow between users and SRs has been developed in hospOS, offering a abstraction for SRs type and system integration independence. The process involves the system flow, ensuring a seamless interaction between HCWs and SRs, optimizing task allocation and operational efficiency. After web interface registration, the robot communicates its available tasks i.e., its skill set, to hospOS. This information is stored as a task set in hospOS, facilitating later identification of SRs for functions. hospOS retrieves and forwards key robot information, including its status (heartbeat), battery level, IP address, stored map, and current location, to the relevant subsystem. Hospital staff can request services in various ways, including through the web interface or IoT hardware, such as a button in the ward. Requests are abstract and contain only essential information, such as the structure of a transport request. An example transport request is shown in Listing 1.

```json
{
"fromLocationIdentifier":"station1",
"fromLocationTitle":"Station 1",
"toLocationIdentifier":"labGF",
"toLocationTitle":"LaboratoryGF",
"observeExecutingID":"be084a1a71",
"type":"TRANSPORT",
"requirements":["LOCKABLE","COOLING"],
"size":"SMALL",
"orderSubmitterID":"station1-pc1",
"creationTime":1701261465016
}
```

Listing 1: Transport Request in JSON Format (Excerpt).

Incoming requests are translated into routines comprising specific tasks, as depicted in Figure 2. A routine acts as a carrier class, managing a tree structure of various tasks. These tasks can range from robot functions like *MovementTask* or *ShowViewTask* to *TimerTasks*, which simply block time. After creating such a routine, the task is compared with each robot's capabilities to assign a suitable robot: One that is able to handle all specific task types in the routine and is not currently engaged in another job or in an error state. A simple example is the transport of blood samples: The robots must to be able to drive autonomously and to store small capacities. Additionally, the samples can not be transported openly, so there is the need for a lockable tray as well as for cooling.

The final step involves sending the created routine to the chosen SRs. Converted into JSON format, the routine is processed by the robot, which executes only the specified tasks, ensuring robot independence. The SRs status is set to *doing* until completion. Meanwhile, new requests can be received and processed as per the earlier step, creating an operational cycle.

4.2 Common Challenges

Infrastructure Adoption. Integrating various SRs types involves significant challenges, particularly in navigation. A key task is merging different robot maps into one common map and to convert locations between SRs. Using the floor plan as a base, three calibration points on both the robot's map and the floor plan enable scaling and rotation alignment. This allows accurate SRs positioning and Point of Interests (POIs) on the unified map. Another major challenge is adapting existing building doors for SRs access. The approach depends on the door's existing capabilities: (i) For doors that open electrical (common for accessibility), a standard Shelly module conver-

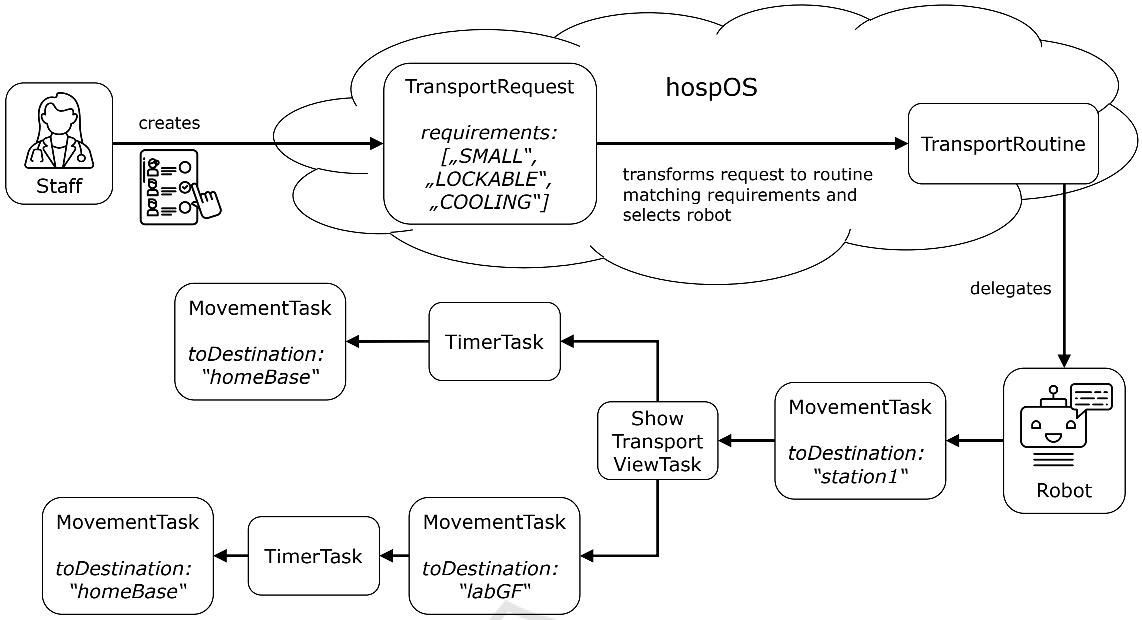

Figure 2: Workflow of hospOS handling a request for transportation of blood samples created by staff working at Station 1. First, a staff member uses the web application to create a transport request, which is matched to a robot available and capable of performing the task by hospOS. Second, hospOS delegates the task using a TransportRoutine to the robot. Subsequently, the robot executes the tasks inside the TransportRoutine to fullfil the task.

sion suffices. (ii) Non-electrified doors require fitting with an electric motor. This cost-effective solution also integrates a Shelly, ensuring uniform implementation across different door types.

Compliance with Regulations. To meet data protection standards, the system operates on a locally hosted solution. All systems function without internet access, requiring only a local network for SRs communication. Furthermore, CE certification, compatibility, freedom from interference, and ethical considerations should be taken into account.

Accessibility. Eventhough patient data needs to be stored and proceeded very secure, the user interfaces like web apps needs to be accessible with low technical hurdles. This implies the need for a sophisticated data security policy, including a controlled data flow between different data endpoints.

5 USE CASES

We collected input from doctors, HCWs, and hospital managers. From the input, we derived the system requirements for use cases in hospitals. The following three use cases were implemented in two hospitals in Bavaria, Germany between 2021 and 2024.

5.1 Use Case 1: Telemedicine

We aim to assess a TMed robot, building on previous findings (Sommer et al., 2023b). Our hospOS approach extends beyond conventional TMed by integrating a mobile TMed robot. This innovation aims to provide economic savings and staff relief by reducing the need for physician travel. A future study will quantify these savings for on-call doctors and evaluate the TMed robot's effectiveness in healthcare.

We will conduct a quantitative secondary data analysis of hospital billing data to determine the cost savings from using a TMed robot for physician on-call services. Specifically, we are planning to analyse the usage of TMed robots in neurology and estimate their potential to relieve staff and reduce ward expenses, with projections for the entire hospital.

The study anticipates economic benefits including reduced travel time and associated costs, lower material expenditures (especially for TMed in isolation rooms), and decreased personnel expenses. We will also explore intangible benefits, such as improved workplace attractiveness for medical professionals.

Feedback emphasized the robot's autonomous mobility as crucial, improving flexibility and reducing nursing workload. Doctors noted the robot's superior audiovisual quality, enhancing patient communication and diagnostics. hospOS ability to control peripherals (external cameras, robotic arms, door openers, monitors) is beneficial, allowing customization for specialities like neurology and surgery. Modular camera equipment and an adaptable interface support additional functionalities, such as visual animations or wound size measurements.

5.2 Use Case 2: Transport

A previous study in two hospitals identified frequent, short-duration transportation tasks in clinical nursing, particularly meal transportation, which incurred significant expenses (Sommer et al., 2024a). Particularly, the findings indicate substantial needs in the areas of non-medical and medical supplies, pharmacotherapy, and other categories such as meals and drinks. Most transports had a factual transport time of under a minute, with patient transport and lab samples displaying more variability. In total, 77.15% of all observed transports (N=1629) were made by hand. Especially in transporting meal and drinks, the application of SRs seems beneficial, as the economic perspective shows an annual cost-saving potential of approximately 10,000 Euro per hospital. Nevertheless, for the implementation of SRs that facilitate efficiency, a user friendly and synergy oriented, cost effective robot orchestration tool like hospOS is needed.

Drawing from the study, stakeholder feedback, and discussions with robot manufacturers, we derived system requirements for transport SRs in hospitals, including the following requirements:

- SRs need to be capable of *navigating autonomously* in hospital environments, coping with dynamic settings.
- Handling of clinical goods should be efficient, with a balance between *capacity and agility*.
- Hospitals have *high hygiene standards* to which SRs must adhere, e.g., SRs must withstand cleaning alcohol and be easy to clean.
- *Transport needs are diverse*, resulting in various requirements, such as temperature and access controlled compartments.
- hospOS serves different stakeholder groups which require *individual and easy to user interfaces*, e.g., for managing transport requests and monitoring delivery status.

5.3 Use Case 3: Orientation

In December 2022, we executed a seven-day observational study at a Hospital Reception (HR). Among all recorded requests (N=1,499), most were from visitors (51.3%) and patients (38.5%). Common inquiries included COVID-19-related questions and patient room numbers (Sommer et al., 2023a). Patients also frequently asked about appointment registrations, emergency procedures, and directions (Sommer et al., 2023a). These findings indicate that SRs could efficiently handle many requests, reducing the burden on staff. To reassess the information needs post-COVID, we conducted another evaluation in November 2023, including a SR in the HR to answer FAQs. The results are anticipated in 2024.

Based on our research, we identified key requirements for a robot-assisted orientation and wayfinding:

- *Humanoid Robot Usage*: Employ humanoid SRs like Pepper for higher interaction rates.
- *Current Information Access*: SRs should access an up-to-date hospital information repository.
- *Navigation Support*: Support Pepper with other SRs to coordinate for extended guidance tasks.
- *User-Friendly Interface*: Integrate an intuitive interface, such as a touchscreen, for wayfinding.
- *Staff Control Functionality*: Enable hospital staff to control the robot easily, e.g. via a web app.

6 DISCUSSION

hospOS addresses the impending nurses shortage projected for 2030 by digitizing hospital processes. hospOS offers cost savings and improved care quality, aligning with market trends driven by an aging population and increasing healthcare demands. hospOS's manufacturer-independent, versatile system reduces IT efforts for hospitals and caters to specific clinical needs, with scalability potential due to its software.

Integrated robot orchestration systems are essential in complex healthcare environments for monitoring robot activities (Holland et al., 2021; Ragno et al., 2023; Huang et al., 2023). The need for smart hospitals highlights the lack of interfaces in SRs, compounded by economic constraints and staff shortages. The lack of interoperability in robotic solutions limits potential (da Veiga et al., 2020). Research gaps exist in robot-robot interaction and human-robot collaboration (Gordon et al., 2023). Compliance with regulations, such as CE Certification are crucial.

The use of SRs in healthcare is expected to increase over the next decade, emphasizing the importance of hospOS (Asgharian et al., 2022). Investments in user-friendly SR management solutions are crucial (Maalouf et al., 2018). German hospital reform currently underestimates the potential of SRs in addressing staffing issues. Financial support for SRs and standardized frameworks, like the HL7 standard for device interfaces, are necessary for integration into cross-device platforms (da Veiga et al., 2020).

7 CONCLUSION

We presented hospOS, a platform for service robot orchestration in healthcare facilities. Our approach addresses key challenges in healthcare robotics, including integration complexity, interoperability, and stakeholder specific user interfaces.

By offering a centralized, modular, and adaptable orchestration system, hospOS bridges the gap between diverse robotic functions and the existing hospital IT infrastructure. The platform's focus on user-centredness and compliance with local regulations, e.g. GDPR, makes it a viable solution for integrating SRs in healthcare facilities.

Our ongoing evaluation of hospOS for the three use cases TMeds, transport, and orientation has demonstrated its potential in improving operational efficiency, patient safety, and staff workload.

8 FUTURE WORK

Future work will focus on improving the functional and non-functional aspects of the three introduced use cases. Regarding TMeds, functionalities for special requirements in medical fields e.g. geriatrics and surgery will be extended. Thus, e.g. wound measurement or vital data from the processed video stream can be made available to the doctor. In case of transport, the focus will be to integrate more and different robot models. Therefore, the system will be able to choose from a broader range of available SRs according to the requirements of the request, e.g. transport with cooling, locking or the need for a larger storage. Orientation SRs as well as the web app interfaces will benefit from further iterations of usability tests and engineering, adapting the user interfaces as good as possible to the needs of the defined stakeholder groups.

In terms of non-functional aspects, improving regulatory compliance is the main focus. As analogue processes are replaced by hospOS, it is built as a redundant service layer without integrating critical paths (e.g. implementations of emergency alarms). There are no plans to use hospOS to replace certified security systems or add security-critical dependencies to hospOS. However, in a hospital environment hospOS and its connected robots must follow predictable behaviour patters, even in case of a full or partial system failure, e.g. robots may not block hallways in case of a system failure. Thus, we implement hierarchical error handling strategies to achieve this. On a technical protocol level, we will use the MQTT last will feature to ensure a predictable behaviour even in case of a lost connection. For example, a robot should drive to an area, where it does not disturb other processes in the hospital – e.g. its home base or the side of the hallway in case of a system failure.

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