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HIGHLIGHTS

- Review of 2015-2025 robot architectures.
- Unintegrated robots increase staff workload.
- Biological payload integrity and safety.
- Enterprise integration over isolated engineering

Clinical Logistics Robots: Architecture, HIS Integration, and Operational Safety

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ABSTRACT

The critical personnel shortage and increasing logistical burden in global health systems are making hospital operations unsustainable, turning autonomous solutions into a strategic necessity. This study synthesizes the literature from 2015–2025 within the PRISMA protocol framework to examine the causal relationship between the technical architecture and clinical performance of autonomous mobile robots (AMR) in hospital logistics. Due to data heterogeneity, a qualitative synthesis method was adopted, and robotic systems were structured along the axes of "navigation, task, and kinematics." The findings reveal that despite the technological evolution from infrastructure-dependent vehicles to autonomous systems, a "high intelligence, low integration" paradox prevails in the clinical setting. The impact of architectural trade-offs, particularly between drive kinematics (holonomic and differential) and payload security, on clinical outcomes is significant. The most striking finding of this review is that robots with high technical autonomy capacity remain as "digital islands" disconnected from the workflow due to their inability to establish deep integration with Hospital Information Systems (HIS), thereby creating an "invisible workload" on staff. Consequently, the study proves that enhancing the clinical value of autonomous robots depends not on singular engineering improvements but on the adoption of standardized reporting protocols and the integration of technology as an institutional "infrastructure component."

Keywords: Hospital logistics, autonomous mobile robot, systematic review, clinical integration, robotics in healthcare.

I. INTRODUCTION

Global health systems are under pressure not only from acute shocks like pandemics but also from permanent and structural bottlenecks triggered by demographic transformations. The World Health Organization [1] predicts a global shortage of approximately 11 million healthcare workers by 2030. The COVID-19 pandemic solidified the operational fragility produced by an over-reliance on human resources in managing isolated patients; this situation has made the importance of automation solutions that will improve processes in preparation for future crises more visible [2]. In this context, hospitals face the necessity of rationalizing resources and optimizing workflows; the automation of logistics processes stands out as a strategic area of intervention with direct value-creation potential [3]. During the pandemic, the use of IoT-based remotely controlled patient service robots in clinical settings to reduce the infection risk for healthcare workers has also been reported in the literature [4].

Increasing structural pressures in healthcare services have driven the workload of clinical staff to an unsustainable level. When the reflection of this trend on technological solutions is examined, it is observed that although the general attitude of participants toward robotic systems remains “neutral” at a rate of 60%, 65.8% of experienced personnel prioritize the use of these systems for physically demanding logistical tasks—such as medication and food distribution—within the context of Smart Healthcare Logistics (SHL) [5]. While theoretical estimations suggest that autonomous systems could assume up to 62.37% of the overall workload, technical failures encountered in field deployments and inefficiencies in loading processes significantly widen the gap between projected potential and practical performance [6]. Nevertheless, the burnout induced by manual workflows and the associated risks to patient safety indicate that automation, despite existing technical limitations, should be regarded not as a matter of convenience but as an operational necessity for ensuring system sustainability.

Automation initiatives in intra-hospital logistics historically began with Autonomous Guided Vehicles (AGVs) dependent on fixed infrastructure. Although these systems, which follow deterministic routes via magnetic stripes or optical lines, provided a certain standardization, they have proven inadequate in most scenarios inadequate for the dynamic and interruption-prone environment of hospitals. Their inability to generate alternative routes when faced with unforeseen obstacles, causing them to stop, can lead to disruptions in critical clinical flows [7], [8]. These constraints have accelerated the transition to Autonomous Mobile Robots (AMRs) with higher decision-making capabilities. AMRs using SLAM and sensor fusion technologies can process environmental data in real time to create dynamic routes; thus, the technology is evolving from "fixed-route carriers" to "system actors capable of making decisions."

However, despite this transformation in AMRs technology, the pace of widespread adoption in the clinical field has remained limited. It is reported in the literature that the general perception of medical service robots is mostly positive, and there are high expectations, especially for tasks like guidance [9]. However, the realization of this potential remains contested, primarily due to insufficient consideration of end-user requirements and persistent challenges in system integration. For example, long-distance patient transport is not merely a mechanical transportation problem; it requires a multi-layered interaction between the nurse, patient, and robot, and necessitates user-oriented interfaces that enable passive patient monitoring [10].

A significant portion of existing academic studies is clustered at two extremes: on one hand, there are narrow-scope engineering studies focused on optimizing navigation algorithms, and on the other hand, there are approaches that address socio-technical barriers [11]. In contrast, there appears to be a limited number of synthesis studies that holistically examine how architectural engineering decisions—such as drive kinematics, modular design, and communication protocols—affect clinical performance (safety, integration, cost) through specific mechanisms [12]. The positioning of robots as "digital islands" disconnected from the hospital ecosystem is one of the main obstacles complicating the scaling of laboratory outcomes to the clinic. These limitations indicate that existing reviews insufficiently capture how robotic architectures interact with hospital infrastructure and operational safety constraints at deployment scale.

Existing review studies on autonomous robots in healthcare logistics can broadly be grouped into three streams. The first stream focuses on algorithmic and navigation-level performance, emphasizing SLAM accuracy, path planning, and obstacle avoidance under controlled conditions. The second stream adopts a socio-technical perspective, examining user acceptance, ethical concerns, or human–robot interaction in clinical contexts. A third group concentrates on task-specific automation (e.g., medication delivery or guidance robots), often reporting short-term pilot deployments. While each of these strands provides

valuable insights within its scope, they commonly abstract robotic systems away from the hospital infrastructure that hosts them, offering limited analysis of how architectural engineering decisions interact with physical layouts, facility readiness, and operational safety constraints. This review departs from prior syntheses by explicitly treating the hospital environment not as a passive backdrop, but as an active architectural constraint shaping robotic performance and safety. Rather than cataloging technologies in isolation, the present study articulates a causal chain linking robot typology, architectural design choices, and clinically relevant performance outcomes.
Specifically, the contributions of this review are threefold:
(i) it integrates hospital infrastructure characteristics (e.g., layout constraints, circulation spaces, vertical transportation) into the architectural analysis of logistics robots;
(ii) it consolidates system integration and interoperability issues, including HIS connectivity and communication redundancy, as first-order determinants of deployability rather than secondary implementation details; and
(iii) it reframes performance evaluation toward long-term operational reliability, safety, and invisible workload, moving beyond short-term kinematic or algorithmic benchmarks.

To operationalize these contributions, this systematic review presents an analytical framework that examines hospital logistics robots through the causal chain of "Robot Types → Architectural Engineering Decisions → Clinical Performance Outcomes.

The article is structured as follows: Section 2 presents the systematic review methodology followed; Section 3 presents the taxonomy classifying robotic systems on the axes of navigation and kinematics. Section 4 analyzes the engineering building blocks (mechanical, perception) of the systems; the effects of these decisions on operational performance are evaluated in Section 5. Section 6 discusses design trade-offs in light of the findings and outlines the future research agenda, and the study is concluded in Section 7.

II. METHOD AND PROCEDURE

This systematic review aims to examine the literature on the use of autonomous mobile robots (AMR) in the context of hospital logistics in a transparent and reproducible manner, in accordance with the PRISMA 2020 principles. Title/abstract screening and full-text eligibility assessment were conducted independently by two researchers. Disagreements between the reviewers were resolved by consensus; where necessary, a joint re-evaluation procedure was applied.

2.1 Research Design and Databases

The literature search was conducted in the IEEE Xplore, ScienceDirect, PubMed, and Google Scholar databases. The search strategy employed the key terms "Autonomous Mobile Robot," "Hospital Logistics," "Healthcare Robotics," and "Medicine Delivery" in various combinations using Boolean operators (AND/OR).

The primary literature review focused on studies published between 2015 and 2025. Earlier studies were included only when they provided foundational architectural or methodological insights necessary to contextualize subsequent developments in autonomous mobile robot deployment within clinical logistics.

The screening process was completed during the first week of November 2025 (04 November 2025). For Google Scholar searches, a date-range filter was applied, and the initial result set was screened based on relevance ranking. In addition, the bibliographies and citation chains of selected core studies were manually reviewed.

2.2 Selection Criteria and Screening Process

Inclusion criteria were: (i) focusing on systems that address logistics-transport tasks.(e.g., delivery of medication, samples, or sterile materials) in a hospital/clinical setting, (ii) having accessible full text in Turkish or English, and (iii) being a peer-reviewed journal article or conference paper. Exclusion criteria were: surgical robots (e.g., Da Vinci), rehabilitation/exoskeleton systems, studies that were only theoretical drafts, and commercial brochures. The selection process is presented in the PRISMA 2020 flow diagram in Figure 1.

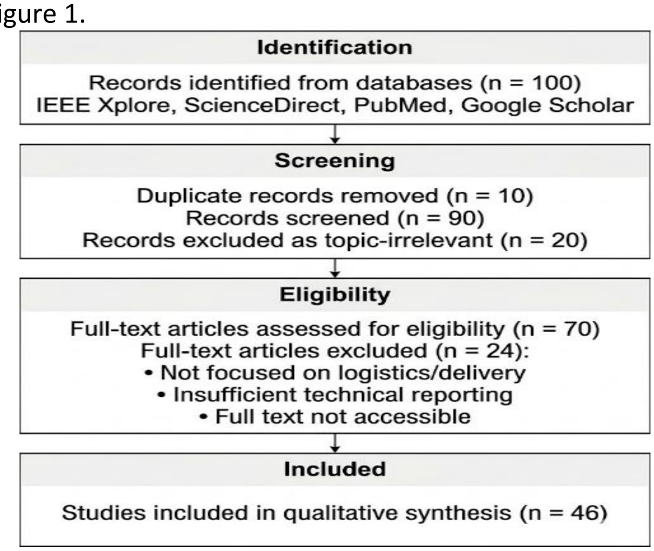

Figure. 1. PRISMA Flow Diagram for Literature Identification and Screening

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2.3 Data Analysis and Synthesis

As a result of the systematic search, an initial 100 records were obtained; after the removal of duplicate records (n=10) and the exclusion of off-topic studies (n=20), 70 publications were subjected to full-text eligibility review. In the full-text evaluation, 24 studies that were not focused on logistics/delivery, had insufficient technical data sets, or whose full text was inaccessible were excluded; the final corpus included in the qualitative synthesis was limited to 46 publications.

Since the methodological designs and reporting formats of the included studies were heterogeneous, and the quantitative parameters required for meta-analysis (e.g., sample size, standard deviation/confidence interval) were missing or not reported in a comparable manner in most studies, a quantitative meta-analysis was not preferred. Instead, the findings were thematically grouped and a qualitative synthesis approach was adopted along the axes of (i) a taxonomic classification based on system types and task scope (Section 3), (ii) engineering building blocks covering sensor fusion, motion kinematics, communication infrastructure, and payload/manipulation architectures (Section 4), and (iii) the reflection of design decisions on logistics performance, safety, human-robot interaction, and economic indicators (Section 5).

III. TAXONOMY OF HOSPITAL LOGISTICS ROBOTS

This study approaches the literature on hospital logistics robots not merely by describing application examples, but through a multi-layered synthesis framework that makes visible how architectural design decisions translate into outcomes in the clinical field. This framework is structured with the "classification → architecture → performance" chain conceptually summarized in Figure 2. Accordingly, this section classifies hospital logistics robots not by "what they do," but by how they behave based on which architectural choices, thereby providing a consistent reference plane for the subsequent engineering evaluations (Section 4) and clinical impact discussions (Section 5).

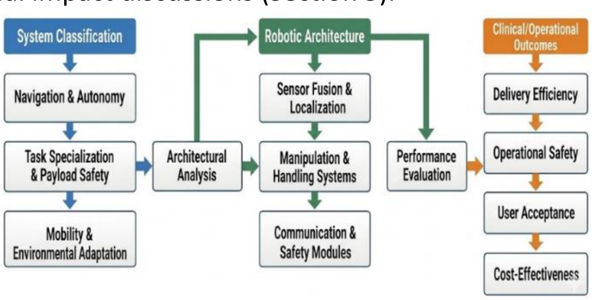

Figure. 2. Multi-Layer Analytical Framework Illustrating the Relationship Between Robot Taxonomy, Architectural Design Choices, and Clinical/Operational 0utcomes in Hospital Logistics.

3.1 Architectural Taxonomy for Hospital Logistics Robots

The field success of autonomous mobile robots in intra-hospital logistics is determined not only by the "accuracy of the algorithm" but by the combination of architectural decisions that make this accuracy sustainable in clinical reality. For this reason, the systems in the literature have been classified along three engineering axes: (i) navigation and autonomy, (ii) task specialization and payload security/manipulation, and (iii) motion mechanics and environmental adaptation. These axes can directly affect clinical outcomes such as patient safety, operational continuity, staff workload, and integration cost. For example, an infrastructure-dependent autonomous guided vehicle (AGV).For example, a line-following robot has been reported to stop its task and send an alarm to an operator when it encounters an obstacle, waiting until the obstacle is removed before resuming operation [13]. In contrast, while an infrastructure-free autonomous mobile robot (AMR) can generate a new route in a narrow space, it has been reported that the vibration profile of holonomic drive may pose a risk to the integrity of sensitive samples [14]. This classification approach is also consistent with current review studies that consider autonomous ground vehicles and unmanned aerial vehicles used in the healthcare field together [15].

3.2 Navigation and Outonomy

The navigation strategy is the primary architectural decision that determines the "flexibility–reliability–infrastructure cost" triangle in clinical logistics. Two main paradigms stand out in the literature: infrastructure-dependent systems. The AGV approach generates navigation behavior by following predefined physical routes, such as magnetic strips [16] or optical lines [8]. When an obstacle is encountered along the route, these systems have been reported to stop operation and send a signal to an operator, rather than generating an alternative path [13]. Consequently, while AGVs represent an option for fixed and repetitive routes, they may face challenges in maintaining operational continuity in dynamic environments.

In contrast to infrastructure-dependent Automated Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs) rely on simultaneous localization and mapping (SLAM) to sustain task execution in dynamic clinical environments. Kottuppallil [17] demonstrates that LiDAR, depth camera, and IMU fusion within a ROS 2 framework enables real-time path replanning and dynamic obstacle avoidance within a 1.5 m radius using the Dynamic Window Approach (DWA); however, this adaptability introduces significant computational and energetic trade-offs, as high-fidelity sensor fusion on embedded platforms such as the Raspberry Pi 5 induces planner synchronization delays and sustained hardware load [17]. Operational evidence further indicates that while low-activity modes may permit up to 7 hours of autonomy, continuous SLAM-driven navigation can deplete approximately 78% of battery capacity, reducing effective operation to nearly 1.5 hours [18]. Beyond onboard computation, system-level robustness remains constrained by network dependencies, with Zachariae et al. [10] identifying pull-only communication with task management databases as a critical bottleneck that creates single points of failure under latency or connectivity loss, particularly in emergency scenarios. Consequently, the literature supports a bifurcated deployment paradigm in which AGV-based systems remain preferable for fixed and predictable logistics due to their reliability and lower power demands [7], whereas AMR-based systems are indispensable for hospital environments characterized by spatial uncertainty, frequent layout changes, and dense human traffic [14].

3.3 Task Specialization, Manipulation, and Payload Security

Hospital logistics is not limited to the function of "transport"; it imposes requirements for security, traceability, and authorization for payloads such as medications, samples, and sterile materials. Therefore, the design of the transport unit should be considered as the second main axis that determines the clinical value of the robot.

Passive carrier architectures are defined as systems in which loading and unloading operations are performed by humans, while the transportation task is undertaken by robots. It has been reported in various studies that open shelf- or tray-based designs used within this architecture can pose operational risks, such as the accidental dropping or mixing of surgical instruments during transport [19]. To mitigate these risks, locked drawer systems have been developed, in which access control mechanisms such as fingerprint or password-based authentication are reported to be employed to enhance security [14]. Similarly, modular cabinet systems are designed with locking mechanisms to prevent distribution errors; however, the literature indicates that such structures may introduce additional complexity in system installation, maintenance, and integration with hospital information systems [12]. In the context of clinical logistics, studies have examined this architectural class by associating it with operational objectives such as rapid deployability and the reduction of time losses resulting from staff walking.

In healthcare environments, the deployment of autonomous mobile robots for logistical tasks is gaining significant traction due to their potential to mitigate human dependency and alleviate staff workload [14]. By automating the transport of materials such as medications, meals, and laboratory specimens, these systems enable medical personnel to reallocate their focus toward critical patient care activities [2]. However, the evolution of these platforms into 'active manipulation architectures' through the integration of robotic arms introduces novel engineering challenges. Specifically, the integration of multi-degree-of-freedom manipulators, as exemplified by platforms like HoLLiE Cares and Care-O-bot 4, substantially escalates hardware complexity [10]. Furthermore, the execution of dynamic and complex tasks necessitates the development of sophisticated control architectures, such as behavior trees [10]. Concurrently, increased hardware and task complexity render energy consumption a critical design constraint, particularly concerning the autonomy duration of these systems [14]. At the current level of technological maturity, significant barriers hinder the widespread clinical adoption of these architectures. These obstacles stem from a lack of clearly defined technical performance and safety standards for clinical scenarios [20], as well as user-centric and organizational challenges, including the neglect of end-user concerns and the low perceived utility of the systems [11]. Consequently, facilitating widespread deployment requires the systematic generation of evidence regarding the safety, efficacy, and real-world utility of these systems.

3.4 Motion Mechanics and Environmental Adaptation

The hospital floor and its micro-geometry (e.g., epoxy corridors, wet cleaning transitions, thresholds, and narrow inter-bed spaces) significantly influence robot performance. Consequently, the selection of kinematics ceases to be merely a mechanical detail; rather, it constitutes a critical design parameter directly correlated with clinical risk and operational continuity.

Differential drive architectures offer the distinct advantages of cost-efficiency and mechanical simplicity, providing sufficient stability for logistics in wide corridors. However, empirical evidence indicates that differential kinematics are susceptible to relative sliding between the wheels and the ground during acceleration and steering, which undermines the fidelity of encoder-based odometry [21], [22]. This challenge is exacerbated by the heterogeneous surface materials and transitions frequent in hospital environments [23]. Crucially, such accumulated localization errors have been reported to compromise the estimation of the docking station's position, thereby threatening the reliability of autonomous charging and precise maneuvering [14].

Conversely, holonomic (Mecanum) drive architectures provide superior omnidirectional maneuverability, offering a tactical advantage in clinically constrained spaces [24]. Nevertheless, this agility may come at the cost of reduced traction on rough surfaces or carpeted areas; furthermore, the associated vibration profile poses a potential integrity risk when transporting sensitive biological samples [14]. Therefore, the kinematic choice must be evaluated based on the triad of 'space geometry, payload sensitivity, and docking requirements'.

3.4.1 Hospital infrastructure readiness (corridor geometry, floor conditions, elevators, doors, sensing)

Hospital infrastructure readiness is a distinct and testable design constraint that must be treated as an integral part of the robot's architecture rather than an external contingency. The triad of corridor geometry (clear width, usable turning radii and passing niches), floor micro-geometry (surface material, thresholds, ramps, drainage / cleaning transitions) and vertical access (elevator control interfaces, shaft clearance, and queuing policies) determines which locomotion families and docking strategies are feasible in practice. Where corridors are narrower than a platform's design turning radius, or where sequences of thresholds and ramps are recurrent, certain kinematic classes (for example, some holonomic or high-speed platforms) become operationally infeasible or require intrusive and costly infrastructure remediation.

In addition to physical geometry, access-control points (automatic doors, manual doors, secured doors) and environmental sensing/communication readiness (prevalence of glass partitions and reflective surfaces, lighting variability, and wireless/RTLS coverage) directly constrain perception reliability and orchestration. A hospital lacking consistent sensing anchors (for example, reliable wireless coverage, elevator control APIs, non-reflective sightlines) effectively converts an AMR deployment into a human-supervised pilot: routine exceptions (manual elevator calling, door unlocking, or manual rerouting) reintroduce operational overhead and negate expected autonomy benefits. These facility constraints should be stated explicitly as deployment boundary conditions and included as checklist items in comparative architecture tables and in the methods of future field studies.

3.5 Section summary and design implications

This section demonstrates that there is no single "best" architecture for hospital logistics robots; rather, the most suitable architectural combination must be selected according to the clinical context. The design decision requires the simultaneous evaluation of three axes:

- Navigation choice determines the balance between the level of autonomy and operational flexibility–infrastructure cost (AGV ↔ AMR).
- Task architecture determines the trade-off between security/traceability and labor handover (passive transport ↔ active manipulation).
- Kinematic choice determines floor compatibility and payload integrity (differential ↔ holonomic).

The following section (Section 4) will systematically detail the engineering components (sensors, processors, communication, energy, and security architecture) that make these taxonomic classes possible, discussing the relationship between architectural choices and clinical outcomes at a more detailed level.

IV. CENGINEERING ARCHITECTURE BULDING BLOCKS IN HOSPITAL LOGISTICS ROBOTS

While the taxonomy presented in Section 3 categorizes hospital logistics robots based on their clinical functions and architectural forms, the practical deployability of these systems is contingent upon the seamless integration of their constituent subsystems: perception–localization, actuation, payload integrity, computation, and safety. Empirical literature demonstrates that these architectural configurations dictate the operational boundaries of safe navigation and task continuity within unstructured environments [23], [20], while simultaneously influencing user acceptance in congested corridor traffic, as reported in both early and subsequent studies [2], [25]. Consequently, rather than viewing robotic systems as monolithic technologies, this section deconstructs them into their fundamental engineering layers and systematically evaluates the design trade-offs inherent to each layer in the context of clinical integration.Importantly, the hospital facility itself functions as an implicit and determinative architectural layer — corridor geometry, floor micro-geometry, vertical access (elevators), door/threshold design, and environmental sensing/communication readiness materially enable or invalidate robotic autonomy.

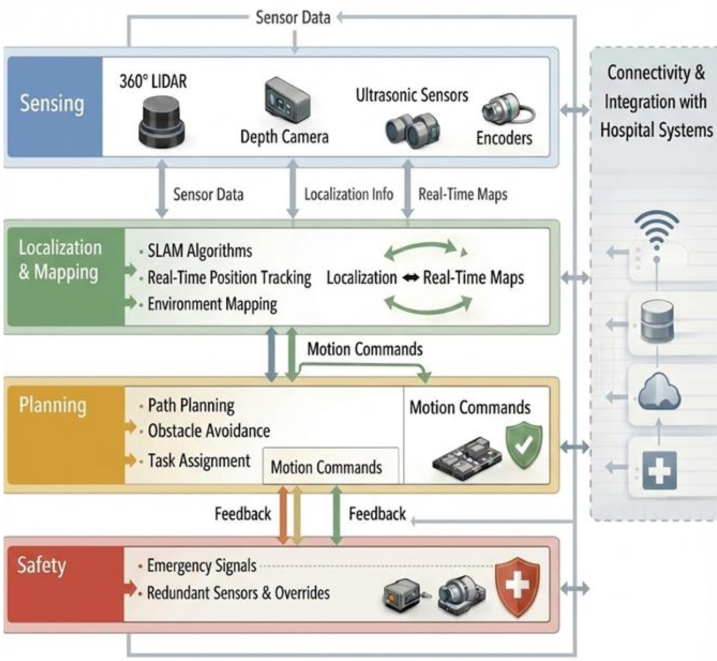

Figure 3. summarizes the "layered architecture" approach that forms the logical skeleton of this section, through the perception → planning → control → safety chain. Additionally, Figure 4 presents the reliability/safety perspective, a critical determinant of clinical-scale sustainability, as a "failure modes → mitigation strategies" matrix (defense-in-depth approach).

The architectural components discussed below are summarized comparatively in Table 1 through example systems reported in the literature. The purpose of Table 1 is not to describe each robot individually, but to make visible at a glance which design patterns are reported with which constraint/risk profiles.

Table 1. Comparative Summary of Architectural Components and Constraints Reported in Hospital Logistics Robots, Based on the Reviewed Literature

Study (Reference)	Locomotion Architecture	Perception/ Sensors	Navigation Method	Architectural Contribution / Novelty	Primary Limitation / Risk
D.O.T. PAQUITOP [26]	Pseudo-omnidirectional	LiDAR + Tracking Camera (T265)	SLAM + Dynamic Obstacle Avoidance	Rest-pose stability strategy	Mechanical and control complexity
Terapio [18]	Differential (Power-assisted)	Five LRFs (3 Horizontal + 2 Vertical)	Clinically safe following and mapping	Vertical LRFs for obstacle detection	Data logging and operational stability
Omni-AGV [27]	MY3-based omnidirectional	Ultrasonic + IR sensors	Kinematic control	Real-time control using FPGA	Sensor signal interference
TurtleBot3 Burger [19]	Differential	360° LiDAR + Camera	Hector SLAM + Identity Authentication	Face recognition (~90% accuracy)	Low payload capacity
Med-Serving Robot [28]	Differential (DC motors)	PIR + Ultrasonic + Camera	Line-following navigation	Autonomous medication delivery cycle	Dependency on predefined routes
Temi Robot [29]	Differential	LiDAR + RGB camera	Autonomous following and docking	Interaction in isolation rooms	Privacy and data security concerns
iBeacon-TB3 (Thesis) [30]	Hybrid (Bluetooth + Mobility)	Bluetooth (iBeacon)	Trilateration / TOA	GPS-denied localization experiment	Signal drift and interference

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4.1 Mechanical chassis and actuation architecture

In the domain of hospital logistics, the chassis configuration dictates not only mobility, physical footprint, and maneuver geometry but also transport safety and compliance with sterilization protocols. Particularly in scenarios characterized by high hygiene sensitivity—such as sterile material distribution or operating room logistics—the surface design and accessible cleaning geometry constitute critical determinants of operational suitability [19]. However, as the requirement for maneuverability in narrow corridors and room entrances intensifies, significant engineering trade-offs emerge. While omnidirectional architectures offer superior agility, empirical studies indicate that they generate mechanical vibrations which undermine the integrity of sensitive biological payloads [14] and necessitate additional mechanical damping solutions [30]. Furthermore, the kinematic redundancy required for such agility imposes a burden of complex motion planning to ensure dynamic stability [26], while the chassis geometry itself (e.g., cylindrical vs. square) serves as a decisive factor for navigating confined spaces without entrapment [30].Collectively, these findings indicate that omnidirectional mobility should not be interpreted as a universal upgrade, but rather as a context-dependent design choice constrained by payload sensitivity, vibration tolerance, and control complexity.

While differential drive architectures are ubiquitous in prototyping due to their inherent mechanical simplicity and cost-efficiency [31], empirical literature highlights significant operational limitations regarding traction dynamics. Specifically, relative slippage between wheels and the ground during acceleration or steering maneuvers undermines the fidelity of encoder-based odometry [21], [22]. This physical decoupling results in accumulated position drift, often necessitating auxiliary sensor fusion strategies to maintain localization accuracy [30]. In contrast, although omni-directional platforms provide superior lateral maneuverability, this agility imposes non-trivial engineering penalties regarding stability and control precision. As substantiated in Table 1, the kinematic redundancy inherent in platforms like PAQUITOP necessitates intricate motion planning to prevent the system's stability from being jeopardized under dynamic conditions [26]. Similarly, despite their holonomic capabilities, architectures such as the Omni-AGV have been reported to exhibit significant trajectory tracking degradation at specific drive angles (e.g., 45°), confirming a critical trade-off between kinematic freedom and control robustness [27].From an architectural perspective, these observations underscore that locomotion selection directly bounds achievable control fidelity and localization reliability, rather than serving as a purely kinematic preference.

The power-assist paradigm presents a clinical value proposition distinct from fully autonomous alternatives by hybridizing manual nurse input with active propulsive support. This synergy is designed to preserve the operator's tactile feedback during precision maneuvers while significantly mitigating the physiological strain associated with manipulating heavy payloads (up to 80 kg) within confined clinical spaces [18]. However, regarding the electromechanical dimensioning of such systems, literature indicates that reliance on nominal velocity metrics is inadequate for the heterogeneous topography of hospital environments. Instead, the selection of actuation units must be rigorously grounded in the computation of resistant power, which explicitly accounts for gravitational forces on gradients ($M \cdot v \cdot g \cdot \sin \alpha$) and surface friction dynamics [14], [31]. Consequently, specific architectural obstacles—such as climbing capabilities (e.g., +5°) and threshold clearance (e.g., 15 mm)—serve as the primary boundary conditions for torque specification rather than secondary design features [18].This shift from abstract performance metrics to environment-driven boundary conditions reflects a broader transition from laboratory-oriented design assumptions toward clinically grounded engineering constraints.

4.2 Perception, Localization, and Navigation Software Stack

While infrastructure-dependent navigation strategies—such as line-following or IR-based reactive schemes—offer implementation simplicity, they are increasingly regarded as insufficient for dynamic clinical workflows due to their operational rigidity. Primary literature indicates that the requirement to retrofit facility infrastructure (e.g., installing artificial landmarks) presents a prohibitive logistical barrier in many existing healthcare settings [14]. Furthermore, the obstacle recovery capability of such systems is typically restricted to a rudimentary 'halt-and-alarm' protocol, necessitating manual operator intervention rather than autonomous deviation [13]. Consequently, the research locus has decisively shifted toward LiDAR-driven SLAM architectures, which inherently decouple navigation from environmental modification. Empirical validations demonstrate that these systems not only generate occupancy grids that correlate accurately with physical floor plans [24] but also achieve 100% mapping success rates in structured corridors [17], while maintaining quantitative mapping error margins below 3% [21].From a systems perspective, this transition reflects a fundamental redefinition of autonomy—from route execution within predefined infrastructure to adaptive spatial reasoning under uncertainty.

However, SLAM-based autonomy cannot be reduced to single-sensor accuracy; relying exclusively on 2D LiDAR architectures introduces critical perception blind spots that exacerbate safety risks. Specifically, planar scanning inherently fails to detect overhanging obstacles (e.g., table tops, shelves) due to height-constrained fields of view [17], while neglecting floor-level hazards such as cables and threshold differences that lie below the scan plane [26], [18]. Furthermore, the physics of laser transmission renders these sensors blind to transparent surfaces, such as glass partitions common in clinical wards [30]. Consequently, multi-sensor fusion—integrating LiDAR with depth cameras or tilt-laser units—is reported not merely as an enhancement, but as a robust necessity for comprehensive obstacle avoidance [17], [23]. In parallel, for GPS-denied environments where visual features may be unreliable, BLE beacon-based trilateration offers a complementary localization layer [30]. Crucially, reported performance metrics for SLAM systems predominantly quantify mapping fidelity rather than end-to-end task resilience, underscoring that navigation reliability emerges from architectural redundancy and recovery behavior rather than sensor precision alone. Figure 4 consolidates the recurring logic in this section—'failure modes (blind spots, slippage) → mitigation strategies (fusion, redundancy)'—visualizing why architectural design must be interpreted through a strict 'risk mitigation' perspective.

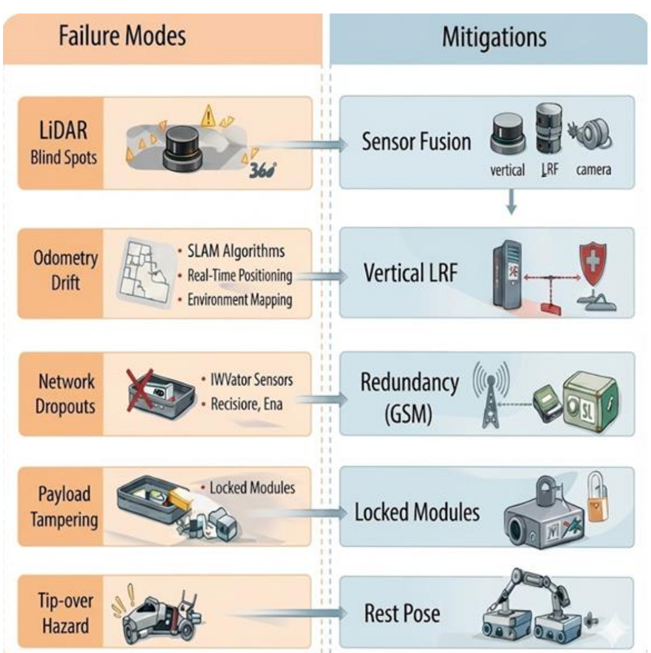

Figure. 4. Risk–Mitigation Matrix Summarizing Recurring Failure Modes in Hospital Logistics Robots and the Corresponding Architectural Countermeasures Reported in the Literature.

Safety encompasses more than mere collision avoidance; logical access control and authorization are integral components of the navigation architecture in clinical environments. In this context, implementations utilizing deep metric learning to generate 128-dimensional face embedding vectors illustrate how workflow efficiency and information security converge on the same computational stack [30]. By authenticating identity through high-dimensional feature abstraction rather than raw image retention, such systems inherently align with *Privacy by Design* principles [32]. Nevertheless, while these mechanisms demonstrate architectural feasibility, their scalability within public healthcare systems raises unresolved governance and compliance challenges that extend beyond navigation performance and warrant separate analysis (Section 5).

4.3 Payload Tansport and Manipulation Architecture

In the context of hospital logistics, the conveyance of payloads—ranging from pharmaceuticals to biological samples—transcends simple material transfer; it constitutes a regulated chain of custody necessitating strict authorization and traceability. Consequently, the architectural configuration of the payload unit acts as a primary determinant of the robot's clinical viability. Although open-shelf designs provide verifiable advantages regarding manufacturing frugality and operational throughput [31], they are functionally unsuited for high-stakes inventory due to their inherent susceptibility to unauthorized retrieval [14] and medication dispensing errors [12]. To reconcile this security deficit, robust architectures have adopted tamper-evident designs featuring electronically locked compartments, authorized exclusively via multi-factor protocols such as fingerprint biometrics or encrypted PIN entry [14]. This architectural evolution signifies a paradigmatic shift from efficiency-driven logistics toward compliance-enforcing design, in which payload structure actively embeds regulatory control into the robotic system.

The integration of robotic manipulators fundamentally expands the operational envelope to encompass complex handling sequences, specifically the 'picking–verifying–placing'cycle.Literature documents robust implementations where 6-DOF robotic arms are embedded within mobile logistics platforms to execute these tasks [26], [7]. However, while the addition of manipulation capabilities significantly augments clinical utility, it concomitantly elevates the stringency of safety and reliability prerequisites. In this

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context, dynamic stability and the mitigation of tip-over hazards emerge as paramount determinants of clinical safety. Consequently, engineering interventions designed to optimize the center of gravity—such as the adoption of a 'rest pose' configuration during transit—are identified as critical components of the safety architecture [26]. Crucially, manipulation capability induces a non-linear increase in system complexity, transforming payload handling from a supporting function into a dominant driver of mechanical risk, failure probability, and maintenance burden.

As delineated in Table 2 regarding the PAQUITOP platform [26], the juxtaposition of functional contributions against 'maintenance and mechanical complexity' underscores a fundamental trade-off: clinical scalability is predicated not solely on functional capability, but critically upon operational sustainability.

Therefore, payload and manipulation architectures must be evaluated as lifecycle-bound subsystems, where clinical value is inseparable from long-term operational sustainability, maintenance load, and risk containment.

4.4 Computation, Communication, and System Integration

Hospital logistics mobile robotics systems increasingly adopt a distributed control architecture, characterized by the utilization of heterogeneous processing units tailored to specific task requirements. At the foundational level, microcontroller-based units are deployed to manage deterministic hardware abstraction and low-level motor actuation [19]. Conversely, high-level cognitive processes—including SLAM, path planning, and image-based facial recognition—are offloaded to single-board computers (e.g., Raspberry Pi) capable of sustaining heavy computational loads [30]. Furthermore, to address latency-critical constraints, field-programmable gate arrays (FPGAs) are integrated into specific architectures to ensure strict real-time performance [27]. This stratified allocation of computation reflects a fundamental design principle: clinical robustness is achieved not through maximal computational power, but through architectural isolation of failure domains and preservation of deterministic control paths.

Communication infrastructure constitutes a parallel determinant of system reliability.While Wi-Fi/WLAN constitutes the de facto communication standard in clinical environments [30], [13], inherent architectural limitations—specifically coverage gaps and latency during access point handoffs—frequently induce critical signal dead zones [10], [12]. To guarantee uninterrupted telemetry and control, redundant communication strategies have evolved from basic GSM/GPRS modules [28] to sophisticated, automated 4G LTE failover mechanisms managed by onboard network switches [12].

These developments signal a conceptual shift in which communication is no longer treated as a best-effort service, but as a safety-relevant subsystem whose degradation directly constrains autonomy and necessitates architectural mitigation.

Beyond mere connectivity, deep integration with Hospital Information Systems (HIS) and IoT infrastructures is a prerequisite for real-time task orchestration and traceability. Validated architectures demonstrating such seamless interoperability via IoT platforms [12]. suggest that a robot's clinical efficacy is determined less by its 'standalone' mechanical performance and more by the robustness of its 'ecosystem integration'.

Accordingly, computation and communication architectures must be evaluated as enablers of institutional interoperability, where robotic autonomy derives its clinical value from seamless participation in the hospital’s information and governance infrastructure rather than from standalone technical sophistication.

4.5 Energy, Safety, and Clinical Usability

In clinical environments, the adoption of autonomous hospital logistics robots is ultimately governed not by peak performance metrics, but by sustained availability and verifiable safety under routine operating conditions. From an energy perspective, empirical evidence consistently indicates that manual charging workflows introduce operational discontinuities that erode scalability, reliability, and staff acceptance. As a result, autonomous docking and self-charging infrastructures are not auxiliary conveniences but foundational requirements for achieving continuous, 24/7 user-independent operation [14].This dependency reveals that energy autonomy functions as a system-level enabler of clinical continuity, directly shaping whether robotic assistance reduces or redistributes workload within hospital operations.

Safety architecture constitutes an equally decisive determinant of clinical admissibility. Compliance with harmonized standards such as ISO 13482:2014 mandates that residual risks be mitigated to acceptable levels through the integration of deterministic hardware and software safeguards [20]. Accordingly, clinically viable platforms increasingly embed hardware-level fallback mechanisms—including industrial-grade bumpers and emergency stop circuits [20]—to guarantee fail-safe behavior in the presence of sensor degradation, software faults, or unforeseen environmental interactions.These deterministic safeguards are further reinforced by redundant perception layers, such as proximity [26] and ultrasonic sensing [27], forming a multi-layered defense-in-depth safety architecture.Importantly, this layered design philosophy reflects a fundamental recognition that clinical safety cannot be assured through probabilistic perception accuracy alone, but requires deterministic failure containment mechanisms that remain effective under worst-case conditions.

Beyond technical compliance, energy management and safety architecture exert a direct influence on clinical usability and user trust. Systems that demand frequent human intervention for charging, fault recovery, or safety supervision implicitly reintroduce cognitive and logistical burden onto healthcare staff, undermining the very efficiency gains that automation is intended to deliver.Consequently, energy autonomy and safety must be interpreted as core usability attributes, where clinical acceptance depends on the robot's ability to operate predictably, transparently, and with minimal disruption to established workflows rather than on nominal autonomy claims.

4.6 Section Summary and Design Implications

Architectural viability in hospital logistics relies on balancing functional complexity with operational robustness. While omnidirectional mobility and SLAM offer agility, they require compensatory damping [30] and sensor fusion [17], [23] to overcome critical vibration risks [14] and perception blind spots [26]. For clinical payloads, the design paradigm must shift from open efficiency to "chain of custody" security, utilizing biometric locking mechanisms to prevent unauthorized access [12], [14]. Finally, sustainable operation depends on "ecosystem integration," necessitating redundant communication strategies (GSM/LTE) to counter Wi-Fi dead zones [12], [28] and ensuring seamless HIS interoperability [19]. Collectively, these observations indicate that clinical-scale viability is dictated less by isolated technical excellence and more by the coherence of architectural trade-offs across mechanical, perceptual, computational, and organizational layers. Building upon these architectural fundamentals, the subsequent analysis shifts the focus from technical feasibility to operational reality, evaluating how these design choices translate into verifiable clinical performance, safety outcomes, and economic viability. Thus, clinical-scale viability depends as much on hospital infrastructure readiness (corridor widths, threshold design, elevator APIs, lighting and wireless coverage) as on individual robot capabilities — without this alignment, architectural trade-offs collapse into operational liabilities rather than deployment benefits.

V. CLINICAL AND OPERATİONAL IMPACT ANALYSIS: PERFORMANCE, SAFETY INTEGRATION, AND ECONOMICS

Although the architectural layers delineated in Section 4 establish the technical capacity of autonomous hospital robots, their actual clinical value is predicated on operational reliability within "unstructured and heterogeneous" environments [20]. The literature highlights a pronounced implementation gap, explicitly reporting that systems validated in controlled simulations often fail to perform as expected when navigating the operational reality of hospital infrastructure [10]. In contrast to these challenges, robotic drug dispensing systems demonstrate that, despite substantial initial capital and maintenance outlays, a positive Return on Investment (ROI) is achievable over long-term horizons (e.g., seven years) [33], concurrently reducing median dispensing times from 60 to 23 seconds and mitigating error rates [34]. Accordingly, this section synthesizes this dichotomy through an analysis of common failure modes and measurable outcomes across the axes of performance, safety, integration, and economics, as conceptually frameworked in Figure 5.

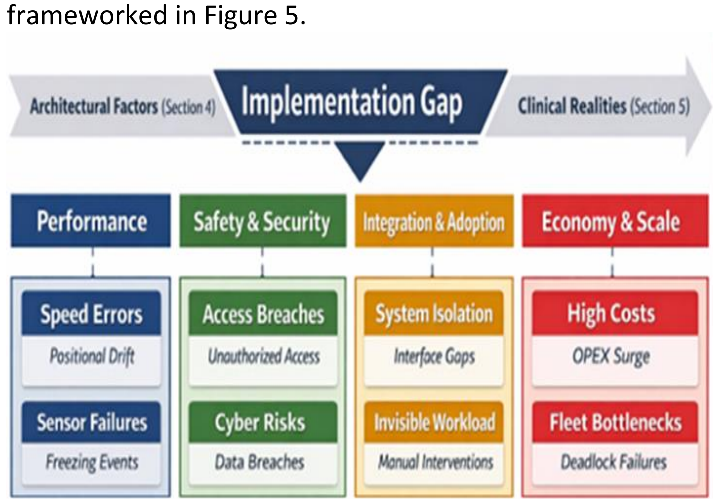

Figure. 5. Implementation Gap Framework for Hospital Logistics Robots.

5.1 Operational Performance: the Speed–Safety–Precision Trade-Off

Although robotic performance is often reported in terms of speed and task completion time in many studies, these metrics must be considered together with safety and precision in a clinical environment.

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5.1.1 Kinematic Constraints and Navigation Errors

Increasing operational velocity does not necessarily yield net efficiency gains in clinical logistics, primarily due to the non-linear correlation between speed and localization fidelity. Sempere and Casino [30] provided empirical evidence that in TurtleBot3-based architectures, mechanically restricted to a maximum velocity of 0.22 m/s by XL430-W250 actuators, localization drift can escalate to an average of 0.30 m during navigation tasks. Elucidating the etiological basis of such deviations, Wu et al. [35] attribute these errors to motion distortion within LiDAR point clouds, a phenomenon that invalidates the rigid transformation assumption essential for precise scan matching. This distortion precipitates feature degeneracy, resulting in cumulative drift within LiDAR-inertial SLAM algorithms that progressively diverge from physical ground truth. Moreover, within the stochastic environment of hospital corridors, Xiao et al. [23] emphasize that hospital corridors constitute inherently stochastic environments, where fluctuating pedestrian density introduces intermittent sensor occlusion and variable reflection intensities, further destabilizing localization reliability. Taken together, these findings indicate that navigation accuracy in clinical environments is constrained less by absolute kinematic limits and more by the interaction between velocity profiles and perception robustness.

Accordingly, the operational paradigm must shift from velocity maximization toward adaptive speed regulation. In this context, Xiao et al. [23] demonstrate that the Dynamic Window Approach (DWA) effectively converts speed constraints into a real-time optimization problem via the evaluation function $Score = \alpha \cdot heading + \beta \cdot distance + \gamma \cdot velocity$. This methodology enables the system to dynamically recalibrate the weighting of velocity against obstacle proximity and heading, ensuring operational safety in high-density environments without forfeiting logistical throughput.

5.1.2 Sensor Blindness and "Freezing" Behavior

While LiDAR and visual SLAM architectures exhibit robustness in static domains, the stochastic complexity of clinical environments characterized by dense dynamic obstacles, frequently precipitates planner failure, commonly manifesting as the “freezing robot problem” [25]. Ethnographic data presented by Mutlu and Forlizzi [25] indicate that under high-traffic conditions, robotic agents often fail to resolve path planning conflicts, remaining stationary for extended periods and effectively “getting stuck,” which necessitates external human intervention to restore navigation. From a computational standpoint, Kottuppallil [17] identifies “planner synchronization errors” as a primary technical determinant of such interruptions, observing that high computational loads often result in only partial path completion. The clinical ramifications of such latency are severe; Yoo et al. [29] report that during emergency situations or after structural layout changes, immobilized robots can inadvertently transform from logistical facilitators into physical obstructions, thereby introducing new safety hazards into already congested workflows. Collectively, these findings indicate that navigation performance in hospitals cannot be reliably assessed through kinematic smoothness or average velocity alone, but must be evaluated in terms of sustained task execution under dynamic uncertainty. Consequently, the validation of robotic platforms must transcend kinematic metrics such as average speed to prioritize operational reliability. Rondoni et al. [20] argue that in hospital settings, “safety and task success are of greater importance than smoothness metrics,” proposing a rigorous evaluation framework anchored in Success Rate (SR), quantified as $SR = (N_{succ} / N_{tot}) \cdot 100$, where task failure is strictly defined by collisions or distance errors (DE) exceeding safety tolerances rather than velocity profiles.

5.1.3 Mechanical Design and Sample Integrity

While holonomic architectures utilizing Mecanum wheels facilitate omnidirectional maneuverability within constrained hospital environments, experimental assessments identify a critical mechanical limitation regarding their compatibility with sensitive payloads. Acosta Calderon et al. [14] established that the discontinuous roller contact inherent to Mecanum designs generates persistent vertical vibrations, thereby creating a kinetically unstable platform that is contraindicated for the transport of laboratory specimens. From a clinical fidelity perspective, such mechanical agitation is a known determinant of pre-analytical errors; Moulana et al. [36] report that excessive acceleration forces and motion-induced instability significantly elevate the risk of hemolysis, leading to systematic distortion of sensitive biochemical markers such as lactate dehydrogenase (LDH) and potassium (K^+). Taken together, these findings underscore that mechanical design choices directly propagate into diagnostic reliability, necessitating a validation paradigm in which robotic transport systems are assessed not only as mobile platforms but as integral components of the clinical diagnostic chain. Consequently, the validation of robotic logistics platforms must extend beyond kinematic efficiency to encompass biological integrity, ensuring—analogous to the validation protocols required for pneumatic tube systems [36]—that mobility solutions do not compromise diagnostic accuracy.

5.2 Multi-Layered Security: From Physical Safety to Cyber Resilience

In clinical robotics, security is not an "option" but a fundamental architectural requirement that covers a broad spectrum from medication/sample security to patient data privacy.

5.2.1 Chain of Custody and Authorization

While autonomous transport architectures significantly enhance logistical throughput, the unsecured conveyance of sensitive medical payloads introduces unacceptable risks regarding unauthorized access and medication mix-ups [14], [16]. To mitigate these vulnerabilities, Thamrongaphichartkul et al. [12] establish that the implementation of locking mechanisms for individual dispensing slots serves as a prerequisite design requirement to prevent mechanical dispensing errors. Furthermore, strengthening the chain of custody necessitates advanced authentication layers; Yiğit and Kara [37] demonstrate that integrating biometric verification, such as fingerprint recognition or password protocols, is essential for securing high-risk narcotics, thereby restricting access solely to authorized personnel and precluding theft. The clinical imperative for such verification layers is further underscored by Yoo et al. [29], who reported that in multi-bed isolation rooms, systems lacking patient identification mechanisms (e.g., RFID) harbor a high risk of erroneous delivery—specifically citing the danger of dispensing medication to "Patient B instead of Patient A" This evidence collectively indicates that chain-of-custody mechanisms must be conceptualized not as optional security enhancements, but as core clinical safety functions that directly govern error propagation within hospital workflows.

5.2.2 Cyber-Physical Threats and Network Architecture

As edge nodes within the Internet of Medical Things (IoMT) ecosystem, autonomous robots significantly expand the institutional cyber-attack surface. Empirical findings by Lee et al. [9] indicate that the potential exposure of personal information constitutes the primary user concern regarding medical service robots, thereby positioning data privacy as a critical determinant of clinical adoption. Beyond data confidentiality, Soriano et al. [38] emphasize inherent vulnerabilities regarding sensory fidelity, warning that the susceptibility to remote hacking and system subversion directly threatens the precision and safety of healthcare delivery. Addressing these systemic risks, Khalid et al. [39] contend that reliance on standard wireless encryption is inadequate for interconnected autonomous systems; instead, they advocate for a dedicated security layer to guarantee data integrity against malicious exploitation. Therefore, architectural countermeasures such as end-to-end encryption and network segmentation (e.g., dedicated lines or VLANs) must be adopted as fundamental components of cyber-physical security, isolating critical robotic traffic to preclude localized breaches from cascading into systemic failures.

5.3 Integration and Socio-technical Acceptance: the 'Digital Island' and Invisible Workload

A technically competent robot struggles to generate clinical value when it cannot integrate with the hospital's operational and digital ecosystem.

5.3.1 The "Digital Island" Problem (HIS Integration)

A significant portion of robotic prototypes in clinical logistics remain characterized as "digital islands" due to a lack of standardized interoperability frameworks, such as HL7 and FHIR, with Hospital Information Systems (HIS) [40]. Thamrongaphichartkul et al. [12] provide empirical evidence of this systemic isolation, noting that in the absence of direct HIS integration, mission scheduling often necessitates manual CSV imports—a process that introduces operational latency and requires persistent human intervention. Furthermore, the functional efficacy of autonomous platforms is critically constrained by legacy infrastructure; Zachariae et al. [10] emphasize that hospital environments are frequently not "robot-ready," identifying inadequate elevator and door interfaces as primary architectural barriers to multi-story navigation. The inability to digitally orchestrate tasks or synchronize with facility automation necessitates manual job creation and physical coordination by clinical staff, such as facilitating elevator access [10]. Consequently, as underscored by the literature [41], [42], the lack of systemic interoperability transforms autonomous agents into isolated prototypes, where the expected gains in throughput are offset by the increased burden of manual data entry and infrastructure management.

5.3.2 "Invisible workload" and Acceptance Dynamics

The primary objective of clinical automation is the mitigation of personnel workload; however, ethnographic assessments by Søraa and Fostervold [41] demonstrate that robotic systems characterized by frequent operational disruptions—such as connectivity losses, docking failures, or suboptimal elevator prioritization—paradoxically generate a significant "invisible" cognitive and operational burden on nursing staff. These disruptions necessitate "junction work," an undocumented form of labor where clinicians must engage in continuous monitoring and perform ad hoc interventions to compensate for the system's inability to maintain autonomous workflow continuity. This additional workload is typically not reflected in conventional performance metrics, which explains why short-term evaluations may overestimate the net benefit of automation. Consequently, user acceptance in high-acuity environments is shaped not merely by conventional aesthetic or perceptual factors [18], but more critically by the degree of functional reliability and seamless alignment with everyday clinical workflows. As Mutlu and Forlizzi [25] report, while logistics units may embrace robotic platforms for their throughput benefits, clinical staff often exhibit resistance when the system fails to integrate into daily routines, effectively relegating nurses to the role of robotic assistants rather than alleviating their professional burden.

5.4 Economic Realism: ROI, TCO, and Scalability Constraints

In transitioning robotic applications from the pilot phase to clinical scale, the realism of the economic model is as decisive as technical competence.

5.4.1 ROI and Hidden Costs (CAPEX–OPEX–TCO)

While initial investment appraisals frequently project return on investment (ROI) periods within a 2–3.3 year range, longitudinal evidence suggests these calculations often assume ideal conditions [42]. Berdot et al. [33] demonstrate that actual payback periods can escalate to 6 years—a 50% increase over projections—due to unplanned technological upgrades and regulatory transitions. Although selecting low-cost hardware [12] reduces initial capital expenditure (CAPEX), it introduces a critical trade-off regarding long-term reliability [10]. Sub-optimal hardware integrity increases maintenance frequency and operational interruptions, thereby inflating the total cost of ownership (TCO) and operational expenses (OPEX).

Consequently, economic evaluations must shift from static acquisition costs to a life-cycle perspective that accounts for battery degradation, software maintenance, and the complexities of integrating autonomous units into legacy infrastructures.

5.4.2 Fleet-Scale Deadlocks and Infrastructure Bottlenecks

The success of a single robot does not automatically replicate at the fleet scale. As the number of robots increases, charging station queues, deadlocks at corridor intersections, and network bandwidth issues can grow. Therefore, coordination problems that are not apparent in the pilot phase can turn into major bottlenecks that limit clinical performance as the scale increases.

VI. DISCUSSION AND FUTURE RESEARCH AGENDA

The synthesis of this review indicates that the value of autonomous mobile robots (AMR) in hospital logistics cannot be reduced to a single technological component; rather, it represents a complex optimization problem managed among competing multi-dimensional performance criteria. A viable clinical value proposition necessitates the balanced management of (i) logistical performance, (ii) safety and traceability, (iii) digital integration with HIS and medication management systems, and (iv) economic sustainability encompassing total cost of ownership (TCO) [11], [42], [6]. Current literature attributes the lack of widespread clinical adoption to a structural "misalignment" between robotic design decisions and organizational workflows. As Rasmussen et al. [11] highlight, future research must transcend debates on isolated technological limits to address the institutional dynamics and organizational barriers of healthcare innovation. Ultimately, transitioning the field toward maturity necessitates a shift from proof-of-concept demonstrations to a rigorous analysis of operational trade-offs, ensuring that autonomous units evolve from intermittent "gimmick hurdles" into stable, integrated components within legacy healthcare infrastructures [11], [43].

6.1 Critical Design Trade-Offs

The hospital environment is not a deterministic factory floor; therefore, design decisions produce a set of trade-offs that must be optimized according to clinical priorities.

- While holonomic systems utilizing Mecanum wheels facilitate superior maneuverability within confined patient rooms, their operational viability is compromised by mechanical limitations; specifically, the discontinuous surface contact inherent to these wheel designs [30] generates vibrations explicitly contraindicated for the transport of sensitive laboratory samples [14] and leads to trajectory accuracy degradation during diagonal displacements [27]. In contrast, four-wheeled adaptive drive architectures provide enhanced high-speed stability [30], yet the kinematic requirement to reorient the chassis prior to translation [14] restricts agility in narrow spaces, a geometric constraint that increases the probability of entrapment [30] and necessitates dynamic path re-planning, which has been quantified to negatively impact task completion times [20].

- While SLAM-based strategies facilitate flexible, infrastructure-independent deployment, their operational stability is frequently compromised in dynamic clinical environments. High densities of moving obstacles have been reported to induce false feature identification [46] and positioning errors [23], thereby triggering critical failure modes such as the robot "freezing" or getting stuck [25]. Moreover, although ROS-based architectures offer modular versatility, they impose a significant computational burden that often exceeds the capacity of standard embedded processors [30], [17]; this complexity adversely impacts energy efficiency, transforming the power supply into a critical vulnerability for operational continuity [14].

• Security and Efficiency Balance: Authentication modules such as NFC [10] or fingerprint/password combinations [37] enhance clinical accountability and data security by preventing unauthorized access [18]. However, each added authentication layer creates a time cost in the workflow, leading to critical drug access delays, especially in emergencies [42]. These interruptions in the workflow and the perceived cost-benefit mismatch are key factors triggering staff resistance [25]. Therefore, security architectures should strike a balance between clinical risk management and process fluidity, rather than being purely protection-focused [24].

• Individual Optimization and Fleet Scalability: The route and usage method designed for a single robot lose their scalability as the fleet grows. Navigation disruptions that can be tolerated at the individual level cause systemic congestion, equipment discrepancies, and critical interruptions in the distribution of work efficiency in high-volume clinical traffic [25]. The literature emphasizes that scalable logistics situations are not sustainable without a dynamically managed central controller structure for task planning [14]. In this context, Fleet Management Systems (FMS) are an inevitable necessity for the coordination of multiple robot fleets and task diversity [10].

6.2 Evidence Gaps in the Literature

A critical evaluation of the existing literature points to four fundamental methodological weaknesses that complicate the translation from laboratory to clinic:

• A fundamental structural barrier in current robotics research is the lack of standardized reporting protocols, which precludes rigorous meta-analysis and comparative benchmarking. While success is frequently reported, the absence of consistent definitions for sample size, follow-up duration, and environmental dynamic density results in significant data heterogeneity [11], [20]. Rondoni et al. [20] emphasize that navigation evaluations in clinical settings remain largely preliminary, lacking well-established performance and safety requirements. This lack of standardization prevents hospital administrators from making evidence-based technology choices; as Cresswell et al. [44] argue, strategic purchasing decisions require an accessible, empirical evidence base of functional metrics that current literature fails to provide. Furthermore, the absence of a common format for error profiles—specifically when comparing LiDAR-visual fusion to LiDAR-only architectures—leaves technical superiority open to subjective interpretation [17], [20]. Consequently, the inherent lack of transparency in reporting multimodal fusion outcomes complicates the establishment of quantitative benchmarks necessary for the safe adoption of autonomous agents in complex clinical infrastructures [17], [23].

• A significant methodological deficiency persists in current research, where evaluations frequently prioritize instantaneous workability—defined as the isolated capacity to perform a task—over operational sustainability, which entails long-term, repeatable reliability within clinical environments. Rondoni et al. [20] demonstrate that hospital-based navigation tests remain largely preliminary and non-standardized, often reporting success rates while neglecting systematic performance benchmarks. Sustainability metrics critical for clinical integration, such as Mean Time Between Failures (MTBF) and intervention rates, are rarely reported [11], [43]. Zachariae et al. [12] emphasize that clinical efficacy must be validated through comprehensive longitudinal evaluations, such as 30- to 90-day trials, rather than brief proof-of-concept demonstrations. Especially in high-acuity tasks like patient monitoring, operational continuity exceeding a 100-hour failure-free threshold is more decisive than instantaneous success [45], [10], [32]. Consequently, the literature suggests that achieving clinical maturity necessitates a methodological shift from measuring immediate task completion to quantifying resilience and mission continuity within complex, real-world infrastructures.

• Current literature exhibits significant deficiencies in the quantitative reporting of clinical and ergonomic risks, particularly regarding the physical impact of robotic hardware on sensitive specimens. Acosta Calderon et al. [14] demonstrate that specific kinematic architectures, such as Omni and Mecanum drive systems, generate vibration profiles that are contra-indicated for laboratory samples due to discontinuous floor contact. This mechanical agitation, compounded by rapid acceleration and directional changes, facilitates fluid mobility stress and increases the risk of hemolysis [36]. Furthermore, the inherent trade-off between safety protocols and operational efficiency remains under-analyzed; Rondoni et al. [20] identify a negative correlation where dynamic obstacle avoidance increases completion time (CT) and path length (PL), while Najim et al. [24] report direct throughput losses through motor voltage reductions during obstruction detection. Finally, data security risks [9] and ergonomic deficiencies [25] persist as critical "invisible" barriers to clinical compliance. Concerns regarding personal information exposure [9] and perceived disrespect toward established workflows [40] frequently lead to staff resistance, compelling clinicians to revert to manual processes [29] and neutralizing the intended advantages of robotic automation.

• Economic validation and scalability problem: While Return on Investment (ROI) analyses often appear favorable within controlled pilot environments, their generalizability is severely constrained by factors such as "premature obsolescence" driven by technological and regulatory shifts, which can extend actual payback periods significantly beyond initial projections [33]. The consequent low rate of successful transition to clinical deployment indicates that the impediment lies not merely in technical competence but in organizational adaptation barriers, specifically the low tolerance for workflow interruptions and insufficient process engineering [25], [20]. This economic ambiguity is further exacerbated by hardware selection strategies; although low-cost architectures (e.g., Raspberry Pi) effectively reduce initial Capital Expenditure (CAPEX) [17], the prioritization of development ease over industrial robustness [30]—evidenced by synchronization delays under high computational loads [17]—introduces significant unpredictability regarding long-term Operational Expenditure (OPEX), rendering the overall economic validation incomplete.

6.2.1 Open Issues and Future Research Agenda

Although the field appears to have largely surpassed the "working prototype" threshold, a research direction focused on standardization and verification engineering is needed for the technology to mature. In this context, seven critical orientations stand out:

1. Methodological heterogeneity in the literature does not prevents universal dimension comparison (benchmarking) of the effectiveness of autonomous hospital robots. To overcome this problem in technical evaluations, standardized test protocols based on quantitative metrics such as Success Rate (SR), Completion Time (CT) and Minimum Distance from Obstacles (MDO) should be used [20]. For technical performance to be translated into clinical validity, a regime of high standard analysis methods with high retention power, reporting large sample sizes (n) and sustainable workload changes, should be used [6].

2. Quantifying the "Invisible Workload": The assumption that robots reduce nursing workload has not yet been empirically confirmed in the literature due to the lack of quantitative data on specific task substitutions [6]. Contrary to the expected efficiency, the effort expended by personnel to overcome system limitations is described as "invisible work" or "junction work" [41]. This situation, embodied in physical interventions to resolve robot navigation errors [25]. As a result, robotic deployment may inadvertently shift workload rather than eliminate it, redistributing effort from primary clinical care to system supervision and recovery tasks. Empirical observations indicate that this redistribution not only erodes the anticipated efficiency gains but may also elevate operational complexity and error exposure under real-world conditions [11].

3. Multicenter and Long-Term Field Studies: The lack of standardization and preliminary nature of navigation tests in the current literature masks the true clinical robustness of robotic systems [20]. To fill this methodological gap, priority should be given to multicenter and longitudinal field studies covering periods of up to 15 months, instead of short, single-center pilot trials [25]. Long-term data flow is critical for detecting unpredictable battery cycle life losses in the laboratory environment [14] and mechanical structural deformations that develop under load [21]. Similarly, the "novelty effect" [11], which is dampened by user adaptation, and the evolving human-robot trust dynamics [41] can only be reliably analyzed within these extended time windows.

4. System reliability in hospital logistics robots cannot be inferred solely from nominal task success rates and must instead be verified through structured, reproducible benchmarking protocols explicitly aligned with international safety standards, most notably ISO 13482:2014 [20]. However, a critical limitation of the current literature is that compliance is often asserted descriptively rather than demonstrated through scenario-based validation.

Accordingly, reliability assessment must incorporate explicit stress-test scenarios that evaluate system behavior under realistically degraded operating conditions. These scenarios should include autonomous communication redundancy switching during network outages—such as controlled transitions from Wi-Fi to cellular (3G/4G/LTE) links [12]—as well as sensor-failure contingencies that trigger deterministic safe-stop behaviors or graded auditory/visual alerts.

Crucially, ensuring safety under graceful degradation requires the formal enumeration and verification of all plausible failure paths within the control architecture, rather than ad hoc recovery logic [10]. Without such exhaustive failure-mode coverage, reported reliability metrics remain optimistic abstractions that do not reflect the operational risk profile encountered in real clinical environments.

5. Digital integration transcends mere API connectivity, necessitating a holistic alignment of robotic operations with existing clinical workflows [12]. This approach mandates a comprehensive data management framework where manual scheduling processes are digitized and directly assimilated into the system architecture [12]. Consequently, robots should not be treated as passive network endpoints but rather positioned as integrated "edge computing nodes" [32] that proactively stream sensor data and status analytics to the central server [12]. Without this architectural repositioning, autonomous robots remain functionally decoupled from clinical workflows, limiting their role to mechanized transport units rather than active participants in hospital logistics optimization.

6. User acceptance should be conceptualized not as a retrospective metric assessed post-implementation, but as a foundational design input managed from the project's inception. Achieving widespread adoption necessitates a development methodology that prioritizes active user involvement to guarantee interface usability [10]. Within this framework, design elements such as form factor and interaction language must be optimized to simultaneously accommodate the time-critical demands of clinical workflows and the distinct social requisites of healthcare staff [45]. Furthermore, given that the risk of personal information exposure constitutes a primary determinant of user resistance, data privacy protocols must be intrinsically integrated into the design objectives [9].

7. Future economic analyses must transcend the exclusive focus on initial acquisition costs by adopting a comprehensive Total Cost of Ownership (TCO) framework. This perspective is essential to account for the substantial resources required during the initial integration phase [11], as well as the long-term cumulative expenditures associated with maintenance, repairs, and unplanned upgrades [33]. Furthermore, ensuring the sustainability and return on investment of these systems necessitates dedicated resource allocation for periodic software updates and continuous staff training [42].

VII. CONCLUSION

This systematic review has synthesized the literature on autonomous mobile robots (AMR) used in hospital logistics within a structured framework that connects technical design decisions with clinical/operational outcomes. The primary conclusion of the review is this: Although technological capacity has increased, three obstacles, commonly seen in most studies, stand in the way of transitioning from the prototype stage to a sustainable clinical infrastructure: the lack of comparable performance metrics, the lack of deep integration with HIS, and insufficient evidence regarding long-term operational sustainability. This picture shows that the barriers to widespread clinical adoption are concentrated not in a single engineering component but in the trio of standardization–integration–verification.

The reviewed studies reveal that a "one-size-fits-all" approach is not valid for hospital logistics robots; success depends on the management of architectural trade-offs specific to the clinical context. The trade-offs become prominent on three axes: (i) in navigation, the balance between the deterministic predictability of infrastructure-dependent AGVs and the flexibility of AMRs in dynamic environments, (ii) in motion architecture, the choice between the payload stability of differential drive and the maneuverability advantage of holonomic drive in tight spaces, and (iii) in payload security, the operational speed of passive transport versus the traceability and security gains provided by identity verification/locked module approaches. Therefore, design decisions should be optimized based on measurable objectives according to scenario requirements, rather than with a claim of being "generally better."

Two structural problems revealed by the review directly limit clinical scalability. First, weak integration with HIS can turn robots into "digital islands" disconnected from the hospital's digital workflow, generating additional workloads such as manual task assignment and verification. Second, the heterogeneity in performance metrics and test conditions makes it difficult for institutions to make evidence-based choices between systems and slows the cumulative progress of scientific knowledge. Therefore, clinical value is determined not only by "how fast/autonomous" a system is, but by its predictability, reliability, and low need for intervention. Systems that reguire high intervention, exhibit "freezing “behavior ,or experience frequent interruptions can create additional cognitive/operational load on staff in practice, even if they aim to reduce workload; thus, it seems critical for the design focus to shift from "maximum performance" to the goal of "continuity with minimum intervention."

The original contribution of this review is its structuring of findings scattered in the literature into a "classification → architecture → performance" chain, establishing a systematic link between engineering choices and clinical value. For decision-makers, this framework necessitates shifting evaluation criteria from singular technical features to holistic indicators like workflow compatibility, integration capacity, and TCO; for developers, it requires prioritizing operational resilience (fail-safe/degraded operation), standard integration interfaces, and transparent Key Performance Indicator KPI reporting beyond raw performance.
The primary limitation of the study is that quantitative meta-analysis was not feasible due to the reporting heterogeneity in the literature, leading to the preference for qualitative synthesis. Additionally, the date the search was completed limits the temporal scope of the study. However, these limitations provide a direct indication of which verification and standardization steps are a priority for the maturation of the field.

The priorities for future research are clear: (i) the creation of a minimum reporting package and standard test scenarios for comparability, (ii) the systematic measurement of metrics like intervention rate and "invisible workload" for operational resilience, (iii) the design of degraded operation behaviors for network/sensor outages, and (iv) multi-center, long-term field validations to reveal true clinical value and TCO. In conclusion, the success of AMRs in hospital logistics depends not on improving isolated capabilities, but on building an ecosystem based on standard reporting, deep digital integration, and evidence-based operational verification that will enable the transition to reliable, sustainable, and accountable infrastructures at a clinical scale.

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