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A review for analyzing critical factors affecting indoor robot operation: Evidence-based design approaches

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Abstract: This study addresses the growing need for architectural environments that support stable navigation and perception performance of service robots as their deployment expands. Based on the principles of Evidence-Based Design (EBD), the research investigates correlations between robotic performance and the physical properties of architectural finishing materials. While conventional EBD has focused on human responses, evidence concerning environmental factors that influence robotic sensors and locomotion remains limited. This study examines service robot performance indicators, perception accuracy, path stability, and collision rate and relates them to material properties such as reflectance, coefficient of friction, surface roughness, illuminance uniformity, and transparency. The findings indicate that reflectance and lighting uniformity are critical determinants of sensor recognition, while friction and surface roughness strongly affect navigation stability. In addition, transparent obstacles and lighting conditions act as moderating factors that impact both perception and mobility. As a foundational investigation, this study provides baseline evidence for a correlation-based evaluation framework that can inform future design, construction, and operational guidelines for robot-friendly built environments.
Keywords: *Evidence-based design (EBD), Human-robot-environment interaction, Robot-friendly buildings, Service robot.*

1. Introduction

Labor shortages caused by low birth rates and an aging population, along with the growing reluctance to work in the construction sector, have exacerbated the structural crisis of the domestic construction industry. Consequently, the demand for improving operational efficiency and ensuring safety in building management through the utilization of service robots has been rapidly expanding [1]. In public and commercial facilities such as hospitals, airports, logistics centers, hotels, and large office complexes, the commercialization of service robots capable of performing diverse functions such as guidance, cleaning, transportation, and security has been steadily increasing [2]. The NAVER 1784 headquarters serves as a representative example of a robot-friendly building, equipped with robot-dedicated elevators, a centralized robotic operation management system, and high-performance network infrastructure, realizing an architectural environment in which dozens of robots operate continuously [2].

However, most existing buildings reveal critical limitations in robotic operation due to designs that did not account for robotic functionality, where physical environmental factors such as flooring, wall surfaces, and lighting conditions adversely affect robotic perception and navigational performance. For instance, highly reflective floor finishes or transparent glass partitions can induce recognition errors in LiDAR and vision-based sensors, while uneven illuminance and shadow patterns degrade the accuracy of robotic autonomous navigation and obstacle avoidance algorithms [3, 4]. Such issues negatively influence not only the robot's locomotion stability but also its interactive performance with human occupants.

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Previous studies have primarily focused on the behavioral aspects of service robots, including social acceptability, user trust, and safety; however, evidence-based analyses examining the correlation between robotic performance and the physical properties of architectural finishing materials remain highly limited [5]. In contrast, Evidence-Based Design (EBD), which has evolved within the field of architecture, provides a methodological framework for empirically identifying the relationships between physical environmental factors and user responses, thereby serving as a promising approach to address these challenges.

EBD has evolved into a systematic design framework that objectively verifies spatial performance by incorporating scientific evidence into the architectural decision-making process [6-8].

Ulrich [6] provided empirical evidence demonstrating that natural views through patient room windows positively influence recovery rates, and subsequently, Hamilton and Watkins [7] established a systematic process consisting of problem definition, evidence collection, application, and evaluation [6, 7].

Furthermore, Zimring et al. [8] proposed a transition from a procedural approach to an outcome-oriented design system that enables the prediction and evaluation of design results based on scientific evidence [8].

This concept has recently expanded into a data-driven design framework capable of predicting and optimizing spatial performance through the integration of technologies such as BIM, IoT, AI, and Digital Twin [9]. Meanwhile, robot-friendly architectural environments require a new design paradigm that extends beyond human-centered approaches, recognizing robots as active agents that interact with the physical properties of space. Mohan et al. [10] introduced the concept of Robot-Inclusive Space, emphasizing the mutual influence between robotic navigation characteristics and spatial configuration, and reported that surface reflectance, illuminance, and texture irregularity directly affect robotic perception performance [10]. Similarly, Farkas et al. [11] provided experimental evidence demonstrating that surface reflectance, transparency, and illumination significantly influence the robotic perceptibility of architectural environments [11].

Therefore, it is necessary to conduct evidence-based research that links the sensing and navigation performance of robots with the physical properties of architectural finishing materials. In other words, the conventional human-centered concept of EBD should be extended to derive correlation factors between robots and building materials, thereby establishing empirical evidence for the development of robot-friendly architectural environments.

Accordingly, this study analyzes the correlation between service robot performance indicators, such as perception accuracy and navigational stability, and the physical properties of architectural finishing materials, including reflectance, friction coefficient, illuminance, and transparency, based on previous EBD-related research associated with robot-friendly architecture. Through this analysis, the study aims to identify key evidence-based factors applicable to the design, construction, and operation phases of robot-friendly buildings, and to provide foundational data for developing a future evaluation system that assesses the correlation between robotic performance and material characteristics.

2. Concept of Evidence-Based Design

Evidence-Based Design (EBD) is a design approach that supports architectural decision-making based on scientific evidence, emphasizing the quantitative and qualitative verification of user experience and environmental performance. As illustrated in the framework shown in Figure 1, the EBD process proceeds sequentially through the stages of Pre-Design, Design, Construction, Occupancy, and Organizational Readiness.

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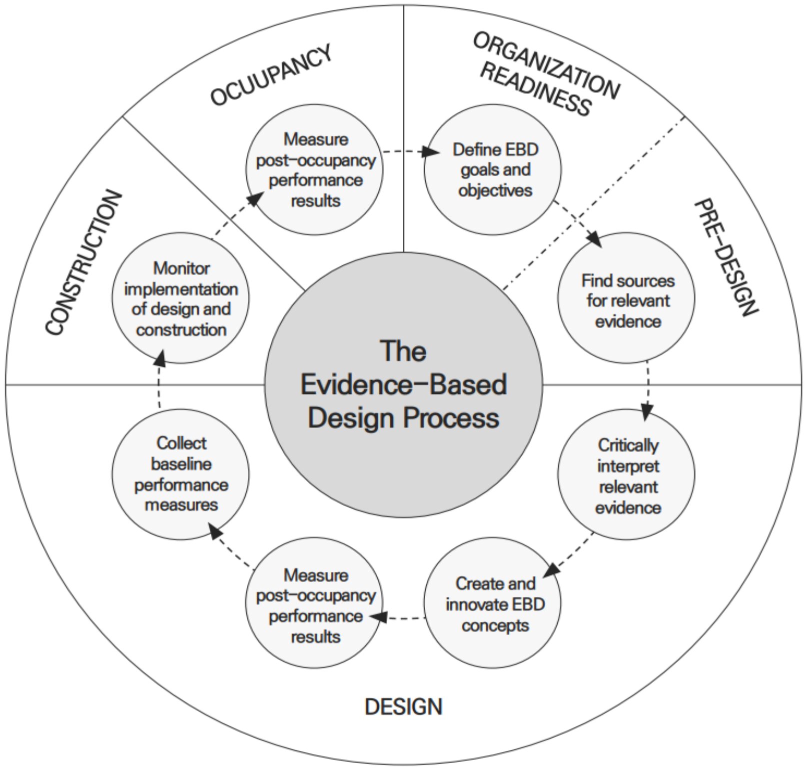

Figure 1.
Evidence-Based Design Framework.

In the field of architecture, the concept of EBD was actively introduced through studies investigating the effects of environmental factors in healthcare facilities on patients' health and psychological well-being [6]. The conceptual development of EBD in this context has been summarized in Table 1.

Table 1.
Evolution of Evidence-Based Design (EBD).

Generation	Key Focus	Main Contributions	Reference
1st Gen – Empirical Foundation	Empirical verification of environmental effects on human health and recovery	Demonstrated that natural views from hospital windows positively influence patient recovery speed, providing the first evidence-based linkage between architectural design and medical outcomes.	Ulrich [6]
2nd Gen – Procedural Structuring	Establishment of a systematic design process integrating evidence into decision-making	Defined the four-stage EBD procedure: problem definition, evidence gathering, application, and evaluation to guide evidence-driven design practice.	Hamilton and Watkins [7]
3rd Gen – Outcome-Oriented Approach	Transition from procedural to outcome-based validation	Proposed that EBD should aim to predict and evaluate measurable outcomes (user satisfaction, safety, efficiency) through scientific evidence, expanding EBD from process-based to results-driven design.	Zimring et al. [8]
4th Gen – Data-Driven and Technological Integration	Integration of digital and intelligent technologies into evidence-based design	Emphasized convergence of BIM, IoT, AI, and Digital Twin technologies to enable real-time performance prediction, optimization, and feedback within the design process.	Andrade et al. [12]

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Representative studies include Ulrich [6], who demonstrated that exposure to natural scenery through patient room windows positively influences recovery speed and stress reduction, thereby introducing a new paradigm of design grounded in empirical rather than intuitive evidence [6]. Subsequently, Hamilton and Watkins [7] expanded this concept into a comprehensive design process, proposing an evidence-based decision-making framework in which designers define problems, collect, interpret, apply, and evaluate evidence throughout the entire design cycle [7]. As a result, EBD evolved beyond a reference-based approach into a systematic methodology that transforms measurable evidence into data and validates the legitimacy of design outcomes. Zimring et al. [8] further developed an EBD performance evaluation framework linking objective data derived from experimental studies to actual building outcomes. while Andrade et al. [12] empirically examined the relationships among user satisfaction, safety, and healing effects in hospital architecture, demonstrating that EBD can function as an effective tool for evaluating architectural quality [8, 12].

Recently, the integration of digital technologies such as AI, IoT, sensor networks, and BIM has led to the automation and intelligence of EBD's data collection and analysis processes. Through this convergence, environmental performance data of buildings and user response metrics can be analyzed in real time, enabling the prediction and optimization of spatial performance during the design phase. Consequently, EBD is evolving into an *Evidence–Data Loop Design* framework that continuously links evidence-based reasoning with data-driven decision-making [9, 13].

In domestic research, Lee and Noh [14] emphasized the need to promote the activation of EBD and to introduce the Evidence-Based Design Accreditation and Certification (EDAC) system, proposing the establishment of an institutional framework to certify the expertise of designers, researchers, and facility managers, particularly in healthcare architecture [14]. EDAC is an international qualification system administered by The Center for Health Design (CHD) in the United States, which formally verifies a designer's competency in evidence collection, application, and evaluation [14]. Such institutional expansion indicates that EBD has evolved beyond a mere design methodology into a data-driven design paradigm grounded in quantitative evidence.

The application scope of EBD, which initially focused on healthcare facilities, has expanded to include schools, offices, residential buildings, and public facilities. Along with the integration of environmental psychology, user experience (UX), and human–robot interaction (HRI), EBD has evolved into a user-centered, performance-based design approach [6-9, 12-14]. This expansion provides the theoretical foundation for research on robot-friendly architecture that incorporates robots as new agents within the built environment, further emphasizing the need for an evidence-based framework capable of quantitatively and qualitatively verifying interactions between architectural environments and robotic systems.

Ultimately, EBD has evolved from a traditional design approach based on experience and intuition into a rational decision-making tool grounded in scientific evidence and data. This transformation provides a theoretical foundation for evaluating and optimizing the safety, perceptibility, and accessibility of indoor environments in which robots operate.

3. Research Methodology

This study aims to identify key evidence factors for establishing robot-friendly architectural environments by examining architectural and material parameters that influence the operational performance of service robots within the theoretical framework of Evidence-Based Design (EBD). The main research procedure is structured as illustrated in Figure 2.

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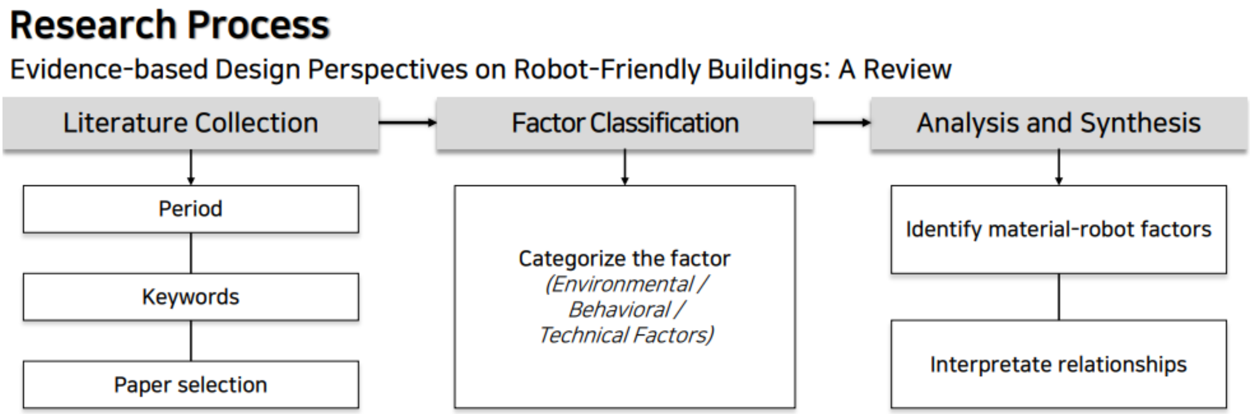

Figure 2.
Research Process.

First, this study aims to identify environmental factors among the architectural variables addressed in previous EBD studies that may influence the perception (sensing) and navigation performance of service robots. Subsequently, a literature search is conducted using major academic databases such as Scopus, Web of Science, KCI, and ScienceDirect, focusing on papers published between 2000 and 2024. The search employs a combination of keywords, including *Evidence-Based Design (EBD)*, *Robot-Friendly*, *Service Robot*, *Material Properties*, and *Indoor Environment*. After removing duplicate records, the abstracts and full texts are reviewed to select studies related to the physical characteristics of finishing materials and the operational environments of robots.

The inclusion criteria for the literature selection are as follows:

(1) Studies that investigate how architectural environments affect the perception and navigation performance of robots;

(2) studies examining how the properties of finishing materials, such as reflectance, friction coefficient, illuminance, surface roughness, and transparency, impact the sensing accuracy or navigational stability of indoor service robots; and

(3) studies that apply EBD or data-driven approaches to analyze environmental factors.

Papers that do not meet these criteria, such as those focusing solely on robotic control or algorithmic optimization, or those dealing primarily with outdoor environments, are excluded from the analysis.

The selected literature is analyzed through a qualitative data charting process. The key variables identified in each study are categorized into Environmental Factors and Performance Indicators. The former includes characteristics of finishing materials such as reflectance, friction coefficient, illuminance, transparency, and surface roughness, as well as spatial conditions, while the latter encompasses performance metrics such as sensor detection rate, perception accuracy, navigational stability, and collision rate of robots. The frequency and directional relationships between these variables are examined to identify patterns of correlation, and recurring elements are synthesized to derive EBD-based Evidence Factors relevant to robot-friendly architectural environments.

4. Review of EBD-Based Approaches to Robot-Friendly Buildings

4.1. Overview of EBD Review Results

Based on the theoretical framework of Evidence-Based Design (EBD), this study aims to identify the correlation factors between the physical properties of architectural finishing materials and the perception and navigation performance of service robots. Previous EBD research has primarily focused on verifying how physical parameters such as lighting, color, reflectance, texture, friction coefficient, noise, and thermal conditions affect users' cognitive, behavioral, and safety-related responses within

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architectural spaces [6-9, 12]. However, as robots emerge as autonomous agents capable of perceiving and navigating within built environments, similar physical factors are increasingly recognized as influencing robotic sensing, navigational stability, and perception accuracy [11, 15].

From this perspective, the present study extends the conventional human-centered EBD approach into a robot-centered framework, reinterpreting the key factors identified in previous studies, as summarized in Table 2.

Table 2.
Key Factors Affecting Robot Perception Performance.

Category	Material Characteristics	Effect on Robot Perception	Observed Influence in Previous Studies	Reference
Illuminance	Light intensity, uniformity, directionality	Influences camera and LiDAR recognition; low or uneven lighting causes false detection and SLAM drift.	Imbalanced lighting reduces object detection accuracy	Ng et al. [3]; Farkas et al. [11], Wang et al. [16] and Ezhilarasu et al. [15]
Reflectance	Surface gloss, specular reflection, and material finish type	Alters LiDAR return rate and vision-based distance estimation; high reflectance or transparency leads to misdetection.	Reflective surfaces cause recognition instability and distance estimation errors	Mohan et al. [4] and Farkas et al. [11]
Texture & Friction	Surface roughness, pattern density, and friction coefficient	Affects both perception and motion stability; low-friction surfaces cause localization drift and wheel slip.	Surfaces with higher roughness improve traction and mapping accuracy	Andrade et al. [12]; Farkas et al. [11]; Wang et al. [16] and Ezhilarasu et al. [15]
Color & Contrast	Color tone, saturation, contrast ratio	Influences visual feature extraction and boundary recognition; low contrast reduces perception reliability.	Balanced contrast enhances visual marker recognition and spatial distinction	Ng et al. [3]; Wang et al. [16] and Ezhilarasu et al. [15]

Luminance is one of the most representative visual factors and is known to directly affect human visual fatigue and cognitive accuracy. Ulrich [6] and Andrade et al. [12] reported that the ratio of natural to artificial light, color temperature, and luminance contrast significantly influence user satisfaction and concentration [6, 12]. These lighting conditions similarly affect the optical sensors of robots, such as vision and LiDAR systems. Farkas et al. [11] demonstrated that an imbalance in luminance can reduce LiDAR distance measurement accuracy by more than 15% while Ezhilarasu et al. [15] experimentally verified that differences in light intensity directly impact object detection confidence in vision sensor–based recognition tasks [11, 15]. In other words, luminance imbalance that induces cognitive fatigue in humans translates into perception errors in robots, and this effect becomes more complex when combined with the reflective properties of surface finishing materials.

Reflectance is another critical factor. Zimring et al. [8] experimentally demonstrated that high-reflectance materials in indoor environments can cause visual discomfort and potentially compromise safety [8]. This finding is directly related to robotic optical sensing performance. Mohan et al. [4] using a Roomba-based experimental setup, it was reported that increased floor reflectance led to higher detection errors in infrared sensors and reduced accuracy in path-tracking algorithms [4]. Furthermore, Farkas et al. [11] observed that LiDAR detection errors increased by an average of 0.18 m on surfaces with reflectance exceeding 70%, identifying this as a key design constraint in developing robot-friendly environments [11].

Texture and friction coefficient are also critical physical factors that affect both humans and robots. Chen et al. [9] analyzed the influence of surface roughness and texture on walking stability and fatigue, reporting that the risk of slipping increases sharply when the friction coefficient falls below 0.4 [9]. In a similar context, Ezhilarasu et al. [15] found that variations in the friction coefficient caused trajectory

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error rates to increase by 8–12% during robot navigation [15]. These findings indicate that differences in surface roughness or texture of finishing materials substantially influence motor torque fluctuation, locomotion efficiency, and control stability in robotic operations.

Color and contrast are also critical factors directly related to vision-based perception. Andrade et al. [12] demonstrated that color contrast influences spatial recognition and psychological comfort in humans, while Ruo et al. [5] reported that color contrast affects the emotional inference accuracy of vision-based classifiers in their study on the social acceptability of robots [5, 12]. These findings suggest that the color and reflective properties of architectural finishing materials can indirectly influence the performance of robotic object detection algorithms such as CNN and YOLO.

In summary, previous studies indicate that physical environmental factors validated through EBD, such as luminance, reflectance, color, texture, and friction coefficient, mutually influence robotic perception accuracy, navigational stability, and response efficiency. In other words, the factors that define users' cognitive and behavioral responses in human-centered EBD correspond to sensor detection rate, navigation stability, and data recognition confidence in robot-centered analyses. Therefore, this study redefines EBD environmental factors from the perspective of robotic operational performance and presents correlation analysis results for each factor accordingly.

4.2. Critical Factors Affecting Robot Operation in Buildings

By integrating previous studies on Evidence-Based Design (EBD) and robotic operation, this study identified architectural environmental factors that influence the perception and navigation performance of service robots. As summarized in Table 3, the derived factors are categorized into three domains: Environmental, Behavioral, and Technological.

Table 3.
Factors Affecting Robot Performance by 3 Domains.

Domains	Material Factors	Effect on Robot	Observed Influence in Prior Studies	Reference
Environmental Factors	Lighting condition, surface reflectance, friction coefficient, texture	Physical properties influencing sensor accuracy and motion stability	High reflectance or low friction decreases wheel traction and path consistency	Andrade et al. [12]; Farkas et al. [11]; Wang et al. [16] and Ezhilarasu et al. [15]
Behavioral Factors	Corridor width, turning radius, visibility of markers, path continuity	Spatial configuration affecting movement efficiency and collision frequency	Narrow passages and poor visual continuity increase deviation and collision rate	Lee [1] and Ruo et al. [5]
Technological Factors	Illumination uniformity, signal interference, and sensor calibration	Hardware–environmental consistency, determining control precision, and navigation reliability	Proper calibration reduces SLAM drift and sensor misdetection under high reflectance	Farkas et al. [11]; Wang et al. [16] and Ezhilarasu et al. [15]

This classification extends the core principle of EBD, linking physical environments, behavioral responses, and performance outcomes into a robot-centered analytical framework [7, 8, 12]. While conventional human-centered EBD derives design factors from users' cognitive and behavioral responses within a space, the present study reinterprets environmental variables through the lens of robotic perception, navigation, and interaction processes, focusing on the corresponding physical and technological responses.

Environmental factors refer to the physical attributes of space, such as lighting, reflectance, friction coefficient, and material texture, that directly affect the sensing accuracy and navigational stability of robots [9, 11, 15]. Behavioral factors describe the response characteristics observed as robots plan paths, avoid obstacles, and interact with humans or other robots within a space. For example, corridor

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width, turning radius, and visibility of markings act as determinants of mobility efficiency and interaction stability [1, 5]. Technological factors represent environmental requirements closely related to robotic hardware and sensor characteristics, including luminance uniformity, surface reflectance thresholds, and potential signal interference [11, 15]. The classification of these three domains is not merely intended for categorization but rather serves as a multilayered analytical framework for understanding how robots perceive and adapt to their built environments.

According to the literature review, the factors most strongly correlated with robotic performance can be broadly categorized into three groups: visual perception–related factors, surface and locomotion–related factors, and spatial configuration and interaction factors. The visual perception–related variables include luminance, reflectance, color contrast, and transparency, all of which directly affect the sensing accuracy of vision and LiDAR sensors in robots. Farkas et al. [11] and Ezhilarasu et al. [15] reported that luminance imbalance and surface reflectance influence the accuracy of distance measurement and object detection while Mohan et al. [4] and Ng et al. [3] experimentally verified that variations in reflectance and transparency serve as major causes of obstacle detection failures and path planning errors [3, 4, 11, 15].

Surface and locomotion-related factors include friction coefficient, roughness, flatness, and slope. Chen et al. [9] reported that when the friction coefficient of finishing materials falls below 0.4, human walking stability decreases significantly, while Ezhilarasu et al. [15] demonstrated that the same factor directly affects the trajectory deviation rate and locomotion efficiency of robot navigation [9, 15] [9,15]. In addition, Farkas et al. [11] analyzed that surface flatness and obstacle height exhibit proportional correlations with the accuracy of autonomous path tracking and travel time in robotic operations [11].

Spatial configuration and interaction factors include corridor width, turning radius, obstacle placement, and visibility of markings. Ruo et al. [5] emphasized that both spatial visibility and corridor configuration must be considered simultaneously to ensure social acceptability in indoor environments shared by humans and robots [5]. Similar findings were consistently reported by [2] in a study on automated logistics centers and by Lee [1] in research on human–robot collaborative spaces, Lee [1] and Jo [2]. Jo [2] highlights that simplifying floor layouts, securing sufficient turning radii, and maintaining surface flatness are essential for improving the mobility efficiency of robots in logistics environments. Lee [1] further identified that ensuring luminance uniformity, controlling surface reflectance, and enhancing the visibility of spatial markings are key design factors that reduce recognition errors in collaborative human–robot spaces [1, 2]. Both studies underscore that the integrated consideration of spatial configuration and visual marking factors is a critical condition for improving robotic navigational stability, thereby supporting the notion that the physical factors derived from EBD have tangible effects on robotic perception, navigation, and interaction performance.

In summary, the results indicate that environmental factors exert multilayered influences across the entire process of robotic perception, mobility, and interaction. Visual factors such as luminance, reflectance, color, and transparency affect sensor perception accuracy, while physical factors, including friction coefficient, flatness, and slope, influence navigational stability. Moreover, spatial parameters such as corridor width, visibility, and spatial configuration determine the safety and efficiency of human–robot interactions. Through this analysis, the present study maps these factors to corresponding robotic performance indicators and seeks to structure them into quantitative criteria such as perception accuracy, trajectory deviation, locomotion efficiency, and travel time.

4.3. Correlation between Building Finishes and Robot Performance Indicators

Based on key literature related to indoor robotics, this study analyzed the correlations between architectural finishing and environmental characteristics and the performance of robots in perception, mobility, and interaction. Each reviewed study, from the perspective of Evidence-Based Design (EBD), proposed environmental factors conducive to robot-friendly architecture and specifically discussed how

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material properties such as luminance, reflectance, texture, and friction coefficient influence perception accuracy, navigational stability, and interaction success rate. The findings are summarized in Table 4.

Table 4.
Correlation between Building Finishes and Robot Performance Indicators.

Category	Representative Factors (Finishes)	Effect on Robot Performance	Findings from Prior Studies	Reference
Spatial / Structural Factors	Path width, grid layout, corner radius, dock precision	Determine route stability, turning efficiency, and motion accuracy; inadequate path width or complex layout increases collision and deviation.	Simplified layout and sufficient turning radius improve path tracking and mission efficiency in automated logistics centers.	Jo [2]
Surface / Material Factors	Coefficient of friction (CoF), surface roughness, reflectance ratio, and transparency	Affect sensor detection and driving stability; low friction and high reflectance increase path error and wheel slip.	Uniform illumination and controlled reflectance reduce recognition errors and improve stability on corners and slopes.	Lee [1], Ng et al. [3] and Mohan et al. [4]
Perceptual / Cognitive Factors	Illuminance uniformity, contrast ratio, and pattern visibility	Determine recognition accuracy and SLAM precision; uneven lighting and poor contrast lead to misdetection and deviation.	Bio-inspired sensor systems demonstrate that balanced lighting and texture readability enhance navigation and avoidance performance.	Wang et al. [16]
Behavioral / Interaction Factors	Human proximity, safety distance, motion response time	Affect interaction success rate and social acceptability; delayed responses or unsafe distance reduce trust and usability.	Environmental factors such as lighting and noise influence interaction success and user comfort.	Ruo et al. [5]
Sensor Fusion / Technical Factors	LiDAR–Depth fusion accuracy, HDOL detection ratio, coverage completeness	Determine precision in detecting transparent and slender objects; improve coverage and reduce missed detections through multi-sensor mapping.	Fusion of LiDAR and depth camera increases IoU and reduces route loss in hard-to-detect obstacle mapping.	Jeyabal et al. [17]

Jo [2] analyzed spatial structural changes resulting from the large-scale and vertical expansion of automated logistics centers and identified key design parameters such as pathway width, grid module dimensions, and docking and handover precision to enhance the efficiency of logistics flow [2]. These parameters are directly associated with robotic path stability, repeatability of navigation, and turning efficiency, demonstrating that architectural dimensional elements can be translated into measurable performance indicators for robotic operations.

Lee [1] in a study on Human–Robot Collaboration (HRC) environments, proposed strategies involving dedicated pathways, designated zones, and sectional spatial utilization demonstrate that operational stability can be enhanced by spatially separating robot standby and charging areas from human circulation flows [1]. In particular, the coefficient of friction (CoF) of finishing materials was identified as essential for ensuring stability during inclined or corner navigation, while the legibility of markings and the application of visibility bands on glass surfaces were found to be key factors that improve sensor detection accuracy [1].

Ruo et al. [5] systematically identified the requirements for socially acceptable service robots, presenting safe navigation, obstacle avoidance, perception accuracy, and interaction success rate as the primary performance indicators [5]. The study empirically demonstrated that environmental factors such as lighting, noise, and spatial arrangement significantly affect both robotic sensing stability and the success rate of human–robot interactions [5]. These findings reinforce the necessity of an integrated

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design approach that concurrently considers robotic operational performance and architectural environmental parameters.

Wang et al. [16] analyzed bioinspired perception and navigation systems, emphasizing that luminance uniformity, glare and reflectance control, and the legibility of surface textures and patterns are critical conditions for sensor-based navigation [16]. The study revealed that robots respond sensitively to luminance imbalance, excessive reflectance, and variations in surface texture, with these factors directly affecting SLAM accuracy and obstacle avoidance performance metrics [16]. In addition, the authors recommended interior environmental designs with consistent sound absorption and scattering properties to minimize distortion in acoustic and ultrasonic sensing [16].

Ng et al. [3] applied the Failure Mode and Effect Analysis (FMEA) framework to evaluate robot-friendly building environments and identified high-risk elements such as glass and transparent surfaces, slender objects, narrow zones, and exposed cabling using the Risk Priority Number (RPN) method [3]. These elements were found to correlate with failure rates in transparent object detection, docking stability, and path deviation accuracy. Accordingly, the study highlighted that design measures such as controlling surface reflectance, applying visibility bands to transparent materials, and embedding cables within architectural finishes are essential for ensuring robotic perception stability [3].

Mohan et al. [4] proposed spatial design principles for robot-oriented environments through a Roomba-based experimental study, demonstrating that uniform luminance, high color contrast, and clearly defined marking systems enhance robotic perception performance [4]. The study also found that maintaining floor flatness, sufficient corridor width, adequate corner radius, and clearance beneath furniture effectively reduced collision and stop event rates while shortening task completion times [4]. These results indicate that finishing materials and lighting conditions are quantitatively correlated with robotic operational range, collision frequency, and task efficiency.

Jeyabal et al. [17] proposed a High-Difficulty Obstacle Localization (HDOL) technique integrating LiDAR and depth cameras to improve the detection of transparent and slender objects [17]. Experimental results showed enhanced HDOL mapping accuracy (IoU), coverage completeness, and reduced detour occurrence rates, empirically demonstrating that surface reflectance, transparency, and slope conditions of finishing materials are directly correlated with recognition error rates [17].

In summary, the physical properties of architectural finishing materials, such as luminance, reflectance, friction coefficient, texture, and transparency, have a direct influence on the sensor-based perception and path stability of service robots. Specifically, low-reflectance surfaces and uniformly illuminated environments improve the detection accuracy of LiDAR and vision sensors; floors with a friction coefficient above 0.4 and level transitions enhance driving stability and obstacle avoidance performance; and visibility bands or clear markings reduce localization error rates. Therefore, this study confirms the necessity of establishing an EBD-based robot-friendly design indicator system that integratively considers these performance factors during architectural finishing design.

4.4. Implications

Based on the review of previous studies and the analysis of indoor-robot-related literature, this study comprehensively examined architectural factors affecting robotic perception and mobility performance [1-5, 16, 17]. In particular, the performance indicators repeatedly emphasized across multiple studies such as Path Tracking Accuracy, Map Deviation, Detection Range, Time Delay, Speed Reduction Factor, Coverage Completeness, and Detection of Hard-to-Detect Obstacles (HDOL) were identified as the key determinants governing a robot's spatial perception and stable navigation within built environments.

These factors can be interpreted from three perspectives.

First, Path Stability is directly associated with the robot's driving stability along corridors and corner sections, which is significantly affected by the surface friction coefficient, level differences, and curvature of floor finishes.

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Second, obstacle perception and avoidance are closely linked to safe navigation and user acceptability, being influenced by the visual and optical characteristics of materials such as reflectance and transparency.

Third, SLAM and localization accuracy are related to the reliability of environmental recognition algorithms and are strongly affected by environmental conditions, including luminance, color contrast, and acoustic reflectivity.

Meanwhile, Jeyabal et al. [17] proposed a multi-sensor fusion-based approach for mapping hard-to-detect obstacles (HDOL), which improved coverage completeness through integrated sensing data [17]. This finding demonstrates that, beyond enhancing individual sensor precision, the integration of environment–robot interaction data aligned with the evidence-based design (EBD) causal framework is essential for improving robotic operability. Furthermore, Wang et al. [16] employed a bioinspired sensor system to mitigate recognition degradation caused by variations in luminance and surface materials, providing empirical evidence that the physical properties of architectural finishes directly affect the reliability of robotic perception [16].

In summary, the findings indicate that Evidence-Based Design (EBD) should evolve beyond human-centered evaluation of spatial effects to encompass the performance data of non-human agents such as robots. Therefore, future research should establish a Correlation Evaluation Framework that integrates material characteristics such as reflectance, friction coefficient, and color contrast with robotic perception and navigation data, including sensor error rates and path deviation. This framework would provide an empirical, evidence-based foundation for designing and validating robot-friendly architectural environments.

5. Discussion

Based on the results derived above, this section discusses the development direction of a performance correlation evaluation system between robots and architectural finishes, as well as the potential expansion of Evidence-Based Design (EBD) toward robot-integrated built environment research.

First, the primary causes of robotic perception errors and navigation instability arise from mismatches between the physical properties of finishing materials and the sensitivity limits of robotic sensors. Ng et al. [3] analyzed sensor misrecognition (Failure Modes) occurring on transparent glass, slender metal components, and reflective surfaces, identifying material reflectance and transmittance as the major factors influencing detection failures [3]. These findings suggest the necessity of establishing quantitative correlation models between the optical characteristics of materials (e.g., reflectance, transmittance) and the sensitivity of detection sensors. Therefore, future systems should be designed to integrate and analyze material property data, including reflectance, color contrast, surface roughness, and texture, with robotic sensor response data, enabling comprehensive evaluation of perception reliability within architectural environments.

Second, the concept of the Robot-Compatible Environment (RCE) proposed by Farkas et al. [11] emphasizes evaluating the interaction mechanisms between environmental factors and robotic responses, rather than merely controlling the physical environment [11]. This approach aligns with the evaluation system developed in the present study, as it adopts a quantitative mapping framework between environmental parameters and performance indicators rather than a conventional geometry-centered design perspective. In this context, the stability of robotic mobility should be expressed as a functional relationship of surface properties such as friction coefficient, level difference, and smoothness rather than spatial form. Through this relationship, a regression model can be established to quantitatively represent the correlations between material properties and robotic performance outcomes.

Third, Evidence-Based Robot-Friendly Design (EBRFD) extends the human-centered feedback loop of conventional EBD by incorporating robotic operational data (log data) as design evidence [6-8, 12]. Quantitative metrics such as SLAM (Simultaneous Localization and Mapping) error rate, speed

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reduction factor, and avoidance reaction frequency provide empirical datasets that explain the correlations between robotic performance and environmental variables, serving as essential evidence for finish-material evaluation. For instance, when perception error rates increase under uneven illuminance or highly reflective floor conditions, the system can automatically record the corresponding material property values and convert them into a Credibility Index representing sensor reliability.

Fourth, the studies by Jo [2] and Lee [1] quantitatively evaluated path efficiency and recognition error rates in logistics and collaborative environments, respectively, by utilizing robotic operational data [1, 2]. Their approaches are significant in that they go beyond spatial design optimization to reveal the statistical correlations between actual robotic trajectory data and environmental variables. Building upon this direction, the present study aims to develop a Performance–Material Correlation Evaluation System that analyzes the relationship between robotic performance data (e.g., perception accuracy, path stability) and material property data (e.g., reflectance, friction coefficient, surface roughness). This integrated framework ultimately seeks to establish an evidence-based foundation for evaluating and optimizing robot–material interaction within built environments.

This system functions as a Decision Support Tool that statistically links robotic performance indicators such as perception accuracy, path stability, and avoidance frequency with material properties, including reflectance, friction coefficient, and surface smoothness. By establishing these correlations, the system can recommend optimal combinations of robot platforms and finish materials suitable for specific environmental conditions. For example, if an autonomous mobile robot with a particular wheel diameter exhibits recurrent trajectory deviations on a glossy tile floor with a low friction coefficient, the system can interpret this as either a limitation of the robot's drive mechanism or an incompatibility of the surface material, subsequently suggesting alternative material specifications or robot configurations.

Accordingly, the ultimate objective of this study is not merely to evaluate surface materials or accumulate robotic data, but to develop a system capable of learning and modeling quantitative relationships between environmental factors and robotic performance in order to analyze their mutual compatibility. Through this approach, the system aims to propose optimal combinations of robots and finish materials tailored to various indoor service environments such as hospitals, logistics centers, and office buildings and to support rational material robot selection during the early design phase of robot-friendly architecture.

6. Conclusion

This study analyzed the architectural factors and material characteristics that may affect the sensing and navigation performance of service robots, based on an extensive review of existing literature on Evidence-Based Design (EBD). Through this analysis, the research systematically examined the current evidence-based design trends for developing a robot-friendly built environment (RFBE), providing a theoretical foundation for integrating robotic performance data into architectural decision-making.

The literature analysis revealed that most Evidence-Based Design (EBD) studies have traditionally focused on human cognitive and behavioral responses; however, recent research trends indicate emerging attempts to utilize operational data from non-human agents, such as robots, as new forms of design feedback evidence [3, 9, 11, 15]. Within this context, numerous previous studies have demonstrated that the physical properties of finish materials such as luminance, reflectance, friction coefficient, and surface texture can exhibit significant correlations with robotic performance indicators, including perception accuracy, navigation stability, and obstacle avoidance efficiency. Furthermore, studies by Jo [2] and Lee [1] analyzed environmental factors using robotic trajectory log data, demonstrating that the performance interactions between finish materials and robots can be practically assessed and validated in real-world architectural settings [1, 2].

The key implications identified through this review are as follows.

First, to extend the conventional human-centered Evidence-Based Design (EBD) framework to robotic operating environments, it is necessary to establish a systematic correlation analysis between

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material properties (e.g., luminance, friction) and robotic performance indicators (e.g., perception accuracy, mobility efficiency).

Second, the standardization of performance indicators for evaluating robot-operating environments has not yet been established; thus, future studies should develop comparable criteria that account for variations in robot type, sensor characteristics, and surface material properties.

Third, subsequent research should empirically verify the correlations between robotic navigation data and architectural surface characteristics across diverse service environments such as hospitals, logistics facilities, and public buildings to achieve the practical expansion of EBD principles into robot-friendly architectural design.

Consequently, this study serves as a review-based groundwork that extends the conceptual framework of conventional human-centered Evidence-Based Design (EBD) to robotic operating environments, emphasizing the necessity of research on performance interactions between robots and building finish materials. Through this approach, the study is expected to provide a theoretical foundation for establishing evaluation criteria and developing a performance-based correlation assessment system for future robot-friendly architectural design.

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The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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