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كلية الفنون الجميلة - جامعة المنصورة

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المؤتمر العلمي الدولي الأول

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كلية الفنون الجميلة - جامعة المنصورة

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ملخص البحث:

شهد مجال العمارة في العقود الأخيرة اهتماما ملحوظًا بتصميم البيئات المرتكزه على الاستجابات السلوكية للمستخدم، و هذا يعكس الوعي المتنامي بتأثير الفضاءات المبنية على مشاعر الأفراد وسلوكهم وحالتهم الإدراكية. وفي ظل هذا السياق المتطور، برز دمج التقنيات الذكية كمنهج تحويلي يمكّن المعماريين من تجاوز الاعتبارات المادية التقليدية نحو استراتيجيات تصميم تفاعلية قابلة للقياس.

يستكشف هذا البحث كيف يمكن للمواد الذكية أن تعيد صياغة أنظمة التوجه الحيزي بوصفها أنظمة إدراكية سلوكية متقدمة، حيث يرتكز تصميم أنظمة التوجه الحيزي المعاصرة على مفاهيم مستمدة من التصميم البيئي النفسي، والذي يتميز باعتماده على أدوات تحليلية متقدمة مثل تتبّع السلوك الحركي للمستخدم. وتُعد أنظمة الاستشعار الذكية والمواد التفاعلية من أبرز هذه الأدوات. وتُسهم هذه التقنيات في إعادة ضبط الخصائص البيئية كالإضاءة، والمسارات، والإشارات البصرية بشكل ديناميكي، بما يعزز من كفاءة التوجه الحيزي .

يُعالج هذا البحث قضية مركزية في تصميم الفضاءات المعمارية العامة، وهي ضعف فاعلية أنظمة التوجيه داخل المباني المعقدة مثل المتاحف، وخاصة تلك ذات الطابع التاريخي. تنبع المشكلة من عدم قدرة الزائرين على إدراك العلاقات المكانية والتوجيه الذاتي، مما يؤدي إلى ارتباك معرفي وتراجع جودة التجربة الثقافية. ومن هنا، يقترح البحث مقاربة مبتكرة تعتمد على دمج المواد الذكية والتقنيات التفاعلية في تطوير أنظمة توجيه متكاملة تُعزز الإدراك الحسي والبصري للمستخدم.

يهدف هذا البحث إلى استكشاف وتقييم إمكانات التقنيات الحديثة المستندة إلى المواد الذكية في تطوير أنظمة التوجه الحيزي (Way-Finding) داخل الفضاءات المعمارية المعقدة خاصة المتاحف ، وذلك من خلال تحليل دور هذه المواد كوسائط تفاعلية تسهم في تعزيز الإدراك المكاني، وتيسير التنقل الذاتي، وتحسين جودة التجربة الحسية للمستخدم.

يستخدم البحث منهجًا وصفيًا تحليليًا مدعومًا بمحاكاة رقمية لنماذج واقعية لتحديد مناطق التعقيد البصري أو التشويش الإدراكي داخل الفضاء. يرتكز الإطار الوصفي النظري للدراسة على مفاهيم التوجه الحيزي ونظرية التركيب الفراغي(Space Syntax) باعتبارها أداة تحليلية تربط بين التكوين المعماري وسلوك المستخدم. يتمثل المنهج التحليلي في تحليل التكوين الفراغي للمبنى باستخدام أدوات Space Syntax. وتهدف هذه المرحلة إلى تشخيص المشكلات التوجيهية التي يواجهها المستخدم، وتحديد نوع المادة الذكية المناسبة لمعالجتها وفقًا لطبيعة الاستخدام والسياق المكاني.تم تطبيق هذه المنهجية على حالة دراسية واقعية هي متحف Palazzo dei Diamanti في مدينة فيرارا الإيطالية، وهو أحد أبرز الأمثلة على العمارة النهضوية. ويتميز هذا المتحف ببنية فراغية معقدة ذات رمزية تاريخية، ما يجعله بيئة مثالية لاختبار جدوى المواد الذكية في دعم التوجيه.

تُظهر نتائج الدراسة أن استخدام المواد الذكية يمثل تحولًا في مفهوم التوجيه من كونه مجرد نظام لافتات ثابتة إلى كونه نظامًا ديناميكيًا حيًا يتفاعل مع المستخدم ويُعيد تشكيل تجربته مع المكان.تشمل الحلول المقترحة توظيف المواد الفوتولومينسنتية (المضيئة ذاتيًا) لتحديد المسارات، واستخدام أسطح حسية تفاعلية كالخرائط اللمسية، ونظم الإضاءة الذكية المتكيفة بحسب كثافة الاستخدام. تسهم هذه العناصر في بناء بيئة توجهية متعددة الحواس تدعم اتخاذ القرار اللحظي وتقلل الاعتماد على اللافتات التقليدية. ويوصي البحث بضرورة إعادة النظر في تصميم أنظمة التوجيه من منظور شمولي يجمع بين المعرفة السلوكية، والذكاء البيئي، والتكنولوجيا الحسية، بما يضمن بيئات أكثر قابلية للفهم والاندماج والإدراك.

وفي الختام ، يمثل هذا البحث مساهمة نوعية في المجال المعماري حيث يدمج بين المبادئ النظرية لعلم النفس البيئي وأدوات التكنولوجيا الحديثة، مما يتيح للمصمم المعماري أدوات أكثر دقة وفعالية في استشراف استجابات المستخدمين وتكييف التصميم بما يعزز الأداء الوظيفي والنفسي للمبنى، كما يوفر البحث إطاراً معرفياً لتطوير معايير تصميمية قادرة جعل البيئات الثقافية أكثر توافقاً مع الحاجات البشرية المعقدة.

الكلمات المفتاحية : أنظمة التوجه الحيزي – نظرية التركيب الفراغي – أنظمة الاستشعار الذكية – المحاكاة البيئية الافتراضية

Research Summary

In recent decades, architecture has increasingly embraced behavior-based design, recognizing the impact of built environments on users’ emotions and cognition. Within this context, smart technologies have emerged as transformative tools, enabling architects to adopt interactive and measurable design strategies beyond traditional material approaches.

This research examines how smart materials can transform wayfinding systems into advanced cognitive-behavioral tools by dynamically adjusting environmental elements like lighting and circulation. Grounded in environmental psychological principles, it emphasizes the role of smart sensors and responsive materials in improving users’ spatial orientation and navigation.

This research addresses a central issue in the design of public architectural spaces: the limited effectiveness of wayfinding systems in complex buildings, particularly museums and historically significant structures. The problem stems from visitors' inability to perceive spatial relationships and navigate autonomously, which results in cognitive confusion and a diminished quality of the cultural experience. In response, the study proposes an innovative approach that integrates smart materials and interactive technologies to develop comprehensive wayfinding systems that enhance users’ sensory and visual perception of space.

This research aims to explore and evaluate the potential of emerging technologies based on smart materials in the development of wayfinding systems within complex architectural environments particularly museums. It does so by analyzing the role of these materials as interactive mediums that contribute to enhancing spatial cognition, facilitating autonomous navigation, and improving the overall sensory experience of the user.

The research employs a descriptive-analytical methodology supported by digital simulation of real-world models to identify zones of visual complexity or perceptual confusion within the architectural space. The theoretical framework of the study is grounded in the concepts of spatial wayfinding and Space Syntax theory, which serves as an analytical tool linking architectural configuration with user behavior.

The analytical component involves examining the spatial layout of the building using Space Syntax techniques, aiming to diagnose the way-finding challenges encountered by users and to determine the appropriate type of smart material to address these issues based on functional requirements and spatial context.

This methodology was applied to a real case study the Palazzo dei Diamanti Museum in Ferrara, Italy, one of the most notable examples of Renaissance architecture. The museum is characterized by a complex spatial structure and strong historical symbolism, making it an ideal environment for testing the effectiveness of smart materials in enhancing wayfinding performance.

The study highlights a shift in wayfinding design from static signage to dynamic, interactive systems using smart materials. Solutions like photoluminescent paths, tactile maps, and adaptive lighting create multisensory environments that support real-time navigation. The research calls for rethinking wayfinding by integrating behavioral insights, environmental intelligence, and sensory technologies to enhance spatial clarity and inclusivity.

This research contributes to architecture by combining environmental psychology with modern technology, enabling more effective, user-centered design. It also proposes a framework for creating culturally responsive environments that address users' functional and psychological needs.

Keywords: Way-finding Systems – Space Syntax – Smart Sensing Systems – Virtual Environmental Simulation.

1. Theoretical Framework

1.1. Introduction

The past decades have witnessed a growing interest in the knowledge acquisition of smart materials and their applications in different fields, especially in the field of architecture and building technology. The field of smart materials has witnessed great development in the twentieth century, and this development became more rapid with the start of the new millennium. This paved the way towards the development of architecture itself and reshaped the way designers and construction specialists think.Recent definition of smart materials describes it as: ‘‘A material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short appropriate time and reverting to its original state as soon as the stimulus is removed”.

1.2. Previous Studies

-Villani, T. (2018) ‘Materiali e soluzioni tecniche per il wayfinding nei musei’, TECHNE - Journal of Technology for Architecture and Environment, 16, pp. 289–298.

Explored smart material solutions for museum wayfinding, focusing on tactile, visual, and interactive elements. Proposed a three-level intervention model based on cost, reversibility, and sensory impact.

-Romagnoli, F., Villani, T., & Oddi, A. (2018). The Environmental Contribution to Wayfinding in Museums. Advances in Intelligent Systems and Computing, DOI:10.1007/978-3-319-96068-5_64
Applied Space Syntax analysis to optimize visitor circulation in heritage buildings. Identified spatial bottlenecks and proposed design strategies to enhance wayfinding efficiency.

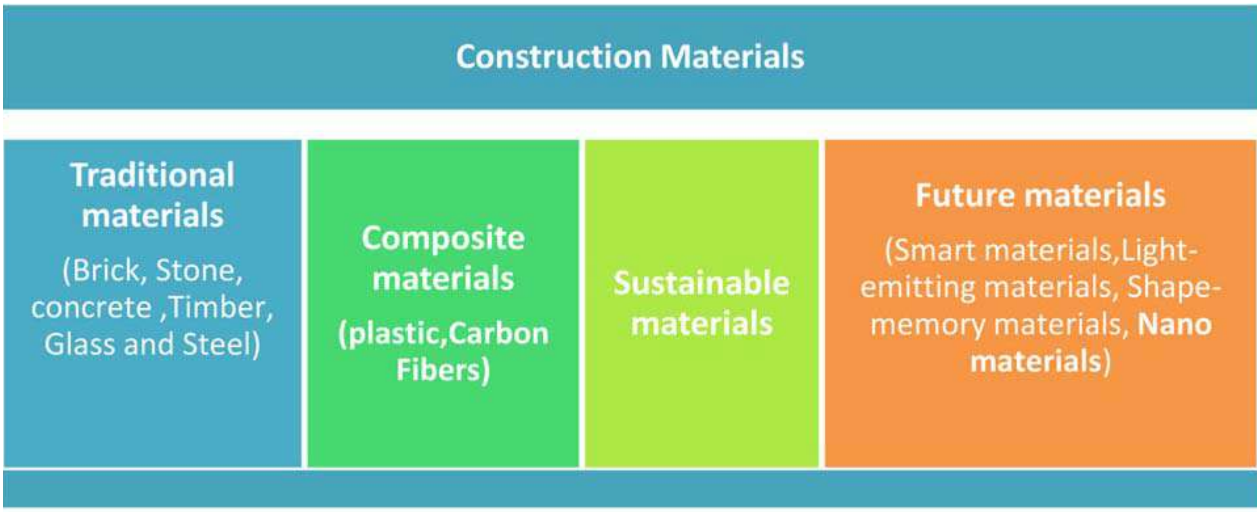
-Abdullah, Y. S., & Al-Alwan, H. A. S. (2019). Smart material systems and adaptiveness in architecture. Ain Shams Engineering Journal, DOI:10.1016/j.asej.2019.02.002

Classified smart materials in architecture into property-changing, energy-exchanging, and integrated smart systems. Highlighted their adaptive potential to improve spatial and user experience.

2. Concept of Materials Technology

The key to 21st-century competitive advantage is smart materials technology. The utility of a structure can be greatly enhanced by using various building materials. "Smart Materials" will play an important role in the evolution of building technology; these materials are components of a smart structural system that can detect its surroundings and function like living systems (Mohamed, 2017, p. 139).

On both a professional and academic level, the study of material structure and its function in creative design has become a popular topic. Material function in design study and understanding has become an important part of the architectural knowledge base and one of its research topics. Techniques for modifying representations of material structures are also included in these study fields. Lorraine Farrelly lays up a global layout in her book "building materials"



to illustrate how materials have been utilized historically in architecture and to raise awareness of new material applications **(Figure 1)** (Mohamed, 2017, p. 141).

Figure 1: Construction materials layout.
Source: *(Mohamed, 2017, p. 141).*

2.1. Definition of smart materials

Smart materials are engineered materials that can produce a one-of-a-kind advantageous response when a specific change in their surrounding environment occurs (Sharp & Clemeña, 2004). NASA defines smart materials as "materials that (remember) configurations and can conform to them when given a specific stimulus", the third definition refers to materials as a series of actions, according to the Encyclopedia of Chemical Technology. Smart materials and structures are those objects that sense environmental events, process sensory information, and then act on the environment (Mohamed, 2017, p. 142).

Smart materials, according to architectural definition, are high-tech materials that, when installed in a building, intelligently respond to seasonal climatic variations (summer, winter, etc.) To comfort or meet human requirements, the environment is either hot or cold. The term "smart materials" refers to materials and systems that, through material characteristics or material synthesis, may respond to changing interior environments (Mohamed, 2017, p. 142).

3. Smart Materials Classification System

Because of advancements in the field of material technology, it is no longer possible to classify materials according to previous systems. As a result, in 2005, Addington and Shodek (D Michelle Addington & Schodek, 2006) created a new classification system that divides materials into categories based on how they perform (Abdullah & Al-Alwan, 2019) (Figure 2):

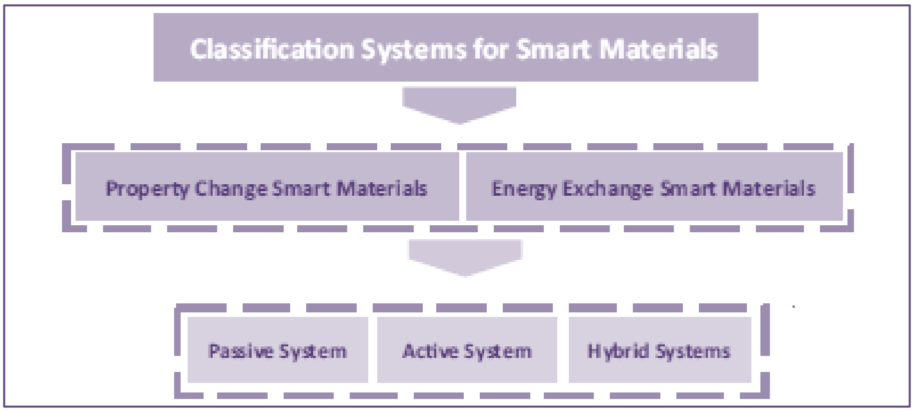


Figure 2: Classification for smart materials.

Source: (Abdullah & Al-Alwan, 2019, p. 624), and re-visualized by the Researcher.

3.1. Type 1 – Property Change Material

These are smart materials that respond to a direct external stimuli by changing one or more of their properties. These are immediate and reversible adjustments that do not require the use of an external control system. A photochromic substance, which changes colour when exposed to ultraviolet radiation, is an example of this. Thermochromic materials, phototropic materials, Thermotropic materials, shape memory materials, Mechanochromic materials, Chemochromic materials, Electrocgromic materials, and phase changing materials are the most prevalent property change materials (Abdullah & Al-Alwan, 2019, p.624).

3.2. Type 2 – Energy Exchange Materials

This category contains smart materials that have the ability to transfer energy from one form to another form's output energy. It is also capable of performing its function in a direct and reversible manner. Electro-restrictive materials, for example, convert electrical energy into mechanical energy, resulting in a change in shape. In the same way, it can be simply reversed to its original shape. Light-emitting materials, Piezoelectrics, Thermoelectrics, Photovoltaics, Light Emitting Diodes (LEDs), and Shape Memory Alloys are some of the most prevalent forms of energy-exchange materials (Abdullah & Al-Alwan, 2019, p.624).

3.3. Smart material systems

A smart material can only perform one function; however, a system can be formed by combining materials. The system can do a variety of tasks in addition to detecting the change that causes the actuation. The system's response to stimuli is used to classify smart material systems. They are divided into three categories: passive, active, and hybrid. **(Figure 3)** Shows the types of smart material systems (Abdullah & Al-Alwan, 2019, p.6240)

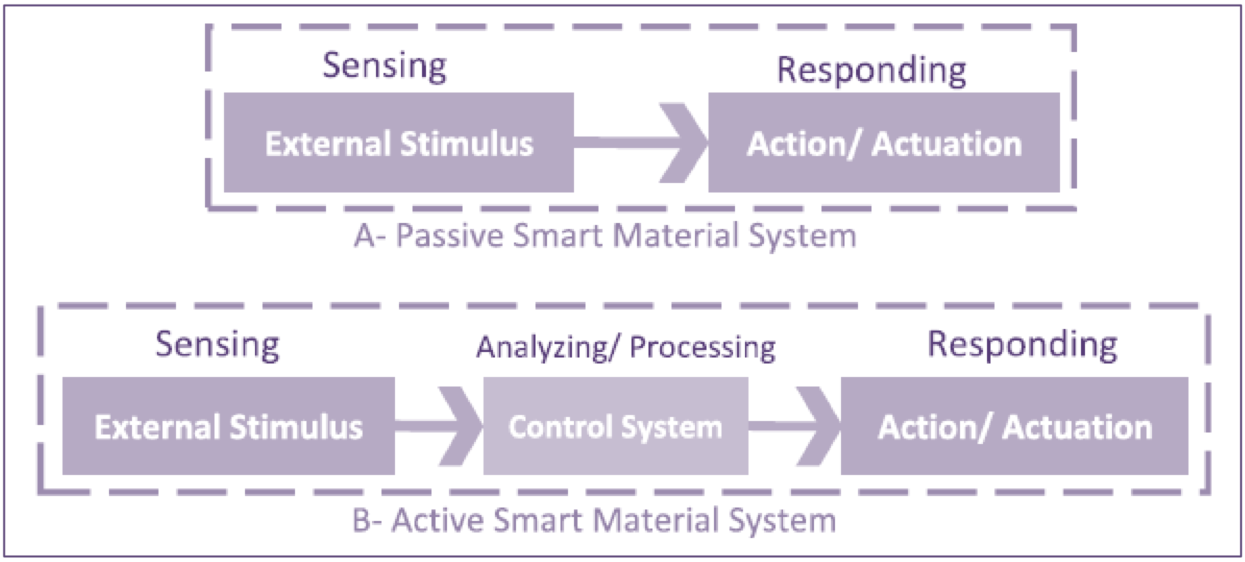


Figure 3: *A–Passive smart material system, B – Active smart material system*

Source: (Abdullah & Al-Alwan, 2019, p. 625), and re-visualized by the Researcher.

3.3.1. Passive smart material systems

When a materials system detects a change in stimulus and responds directly with an action or actuation, it is considered a passive system. The energy required by the system to trigger this activation is derived from the environment's resources. This type is a closed-loop system that can’t be disrupted (Abdullah & Al-Alwan, 2019, p.624).

3.3.2. Active smart material systems

This system has a sensor that can detect changes in the stimulus and provides a signal to the control unit, which then responds by activating the material system. When needed, the system's performance can be fine-tuned. For the system to work, it needs an energy source (Lelieveld, 2013).

3.3.3. Hybrid smart material systems

A hybrid system combines active and passive elements. Although the material can function as a passive system, an active system can monitor and manage its performance. The active shading system is a good example (Lelieveld, 2013). It shades the glass on hot summer days when the sun shines through it, but its functions are managed by an active system in the winter to prevent shading and enable the essential heat to pass through. Hybrid systems can achieve higher levels of performance and complexity than conventional systems (Abdullah & Al-Alwan, 2019, p.625).

4. Concept of Way-finding

When person moving from point (a) to point (b), or moving from the current place to another place during a period of time, this process is called "spatial orientation or Way-finding",Way-finding was formally defined by Lynch (1960) as the consistent use and organization of sensory cues from the external environment. This definition guided the idea of way-finding being the concept of spatial orientation (Arthur& Passini, 1992; Jesus, 1994).

5. Applications for Smart Materials in Way-Finding Systems Design

It is a severe omission to pay little attention to the material characteristics of space during design. This feature is not incidental; it serves both a communicative and a functional purpose, making it 'collaborative' between people and space. Surface treatment and material installation have an impact on how they are viewed, and they frequently play an active and persuasive role. Because of the positive impact it can have on usability. As a result, materials play a crucial role: they not only express shape, but also convey a variety of information through their physical quality, and they also influence the emotional response (Villani, 2018, p. 289).

Signs and maps have traditionally been the primary instruments for guiding people around an environment, and the importance of signage in way-finding is discussed in more detail later in this Guide. Visitors employ many indications and instruments to locate their destination, from spatial relationships exhibited by architecture to lighting and interior finishes, according to an enlarged meaning of the word way-finding (U.S Department of veterans affairs, 2012, p 2).Lights, tactile objects, acoustic messages, and computer-based technologies, including virtual environments and augmented reality, are all examples of active and passive means of communication (Paskoff, Weed, Corbett, & Mclean, 2015, p. i). Below is a review of some examples of these articles and regulations:

5.1. Active System: Incandescent lamps and Light Emitting Diodes (LEDs) (for emergency egress) **(Figure 4)** - Directional Indicators – Electroluminescence **(Figure 5)** (Paskoff, Weed, Corbett, & Mclean, 2015, p. 2,3).

Figure 4 (Right): *An electroluminescent exit sign, easy to operate on low power and very long lamp life.*

Source: https://edisontechcenter.org/electroluminescent.html.

Figure 5 (Left): *High brightness LED way guidance lighting.*

Source: https://es.aliexpress.com/item/32348692477.html.

5.2. Passive System: Escape path marking systems rely primarily on **photoluminescent** technology **(Figure 6) - tactile path marking systems (Figure 7), (Figure 8)** (Paskoff, Weed, Corbett, & Mclean, 2015, p. 3-5).

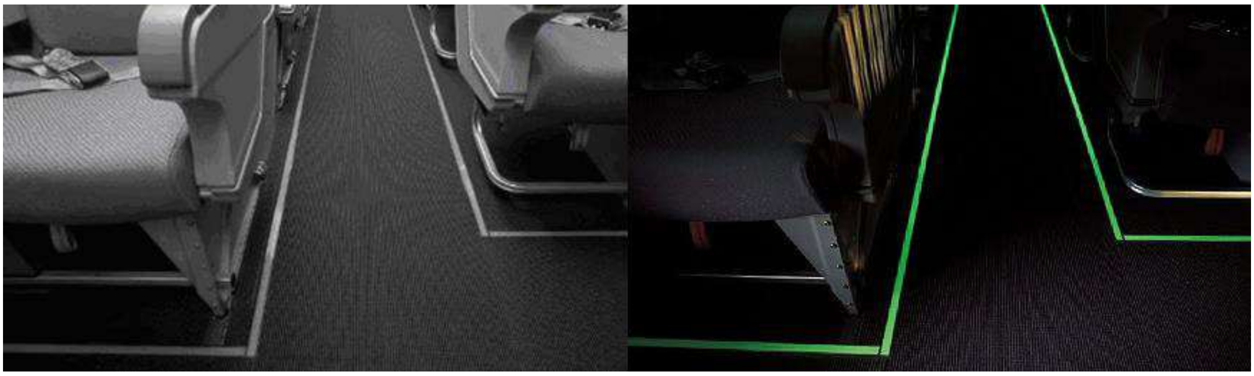
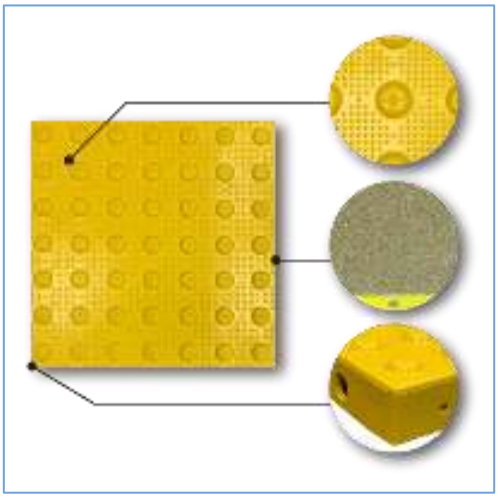


Figure 6: *Photoluminescent path marking in lighted and darkened conditions.*
Source: (Paskoff, Weed, Corbett, & Mclean, 2015, p. 4).



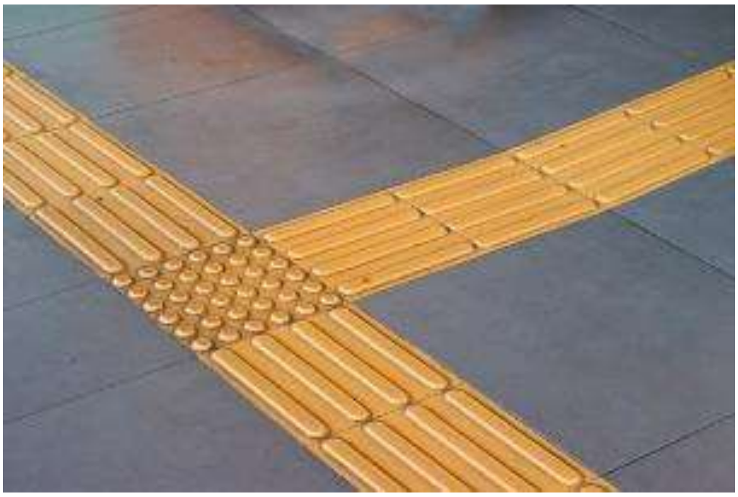


Figure 7 (Right): *The tiles are generally installed with raised lines and/or dots that let visually impaired pedestrians know that they are able to walk on safely.*

Source: https://www.arabnews.jp/en/features/article_6980/.

Figure 8 (Left): *Tactile detectable warning pavers can be easily installed directly into fresh concrete.*

Source: https://armor-tile.com/products/.

5.3. Light Amplification by Stimulated Emission of (LASER) Technology

Lasers can produce a ceiling-to-floor corridor of sequencing laser light columns, or "projected" arrow indicators, graphics, or alpha-numeric indicators to show the path and direction to an exit **(Figure 9)** (Paskoff, Weed, Corbett, & Mclean, 2015, p. 9).

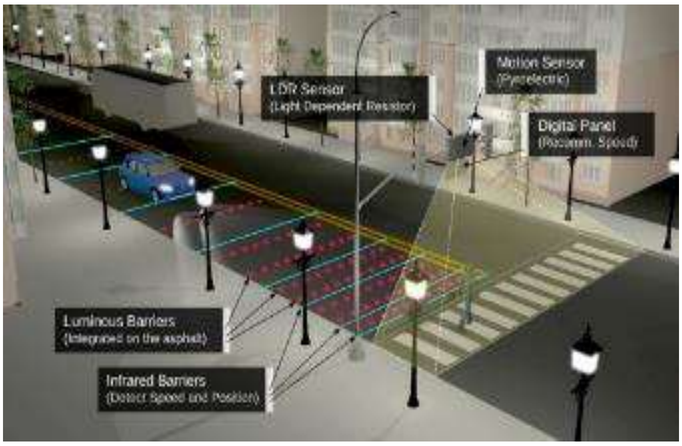


Figure 9: *Laser "virtual wall" across pedestrian crossing zone.*
Source: (Albusac, Vallejo, Castro-Schez, & Gzlez-Morcillo, 2018 p. 4).

5.4. Auditory Systems:

The ability of the human binaural auditory system to localise sounds is generally focused on when using directional sound technology (i.e., identify the spatial location of a sound source) (Paskoff, Weed, Corbett, & Mclean, 2015, p. 9).

5.5. Electronic Information Technology:

5.5.1. Virtual Environments

The animation guide displayed a floating view of the route, which began at the same spot as the participant, rose above the environment, and finally descended to the participant's route's finish point (Paskoff, Weed, Corbett, & Mclean, 2015, p. 10).

5.5.2. Augmented Reality

AR integrates the actual and virtual worlds, interacts with the user in real time and provides feedback, and is recorded in three dimensions **(Figure 10) (Figure 11)** (Paskoff, Weed, Corbett, & Mclean, 2015, p. 11).

Figure 10 (Right), Figure 11 (Left): HUD/HMD design of constantly seeing the real world with a digital graphics overlay showing an integrated world of digital and physical information,

Source Fig. 10: https://www.forbes.com/sites/theyec/2019/02/06/augmented-reality-in-business-how-ar-may-change-the-way-we-work/?sh=5fe8a3ce51e5.

Source Fig. 11: https://www.information-age.com/augmented-reality-transforming-e-commerce-123465096/

5.5.3. Persuasive Technology

People's attitudes and behavior are influenced by this technique. Typical way-finding systems produce noticeable sensory cues that can improve an individual's physical capability. (Paskoff, Weed, Corbett, & Mclean, 2015, p. 12).

5.5.4. Serious Games

"A mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic objectives, thus increasing exposure to specific information and making its retention more likely" was added to the definition (Paskoff, Weed, Corbett, & Mclean, 2015, p. 12).

6. Example of Study: Palazzo dei Diamanti Museum

Palazzo dei Diamanti is a renowned Renaissance palace known for its unique façade of about 8,500 diamond-shaped marble blocks. Located in the historic "Addizione Erculea" urban plan, it was heavily damaged during WWII and by a 2012 earthquake but was restored

Figure 12: Palazzo dei Diamanti Museum.

Source: https://commons.wikimedia.org/wiki/File:OtCABB_Ferrara_-_Palazzo_dei_Diamanti.jpg both times. It remains home to the National Art Gallery of Ferrara and the Civic Gallery of Modern and Contemporary Art.

Between 2016 and 2017, there were more than 50 million visits, with an increasing trend, thanks to changes in the services provided (repair points, conference rooms, bookshops), as well as initiatives adopted after the reform of museums and funding programs for them. With a growing and articulated presence of services to support social and cultural inclusion, participation, engagement, and a more active fruition, overcrowding issues have arisen (Villani, Materiali e soluzioni tecniche per il wayfinding nei musei., 2018).

6.1. Analytical Study

Several case studies were examined throughout the investigation phase, where this technique, which presented various levels of modification and design solutions, promoted visitor interaction. These examples include the British Museum and Barbican Arts Centre in London, the Children's Museum in Denver, the Museum of Byzantine Culture in Thessaloniki, and the Stedelijk Museum in Amsterdam, among others. Other types of facilities (such as airports and hospitals) were also included in the analysis to transfer their expertise and establish determining criteria to be included in project inputs (Villani, 2018, p. 292).

By examining traditional materials and some innovative trends, the detailed discussion presented below relates to the description of the main components of the methodological approach to way-finding, as well as the structuring of selection criteria for materials and technical solutions for surfaces favoring sensory perception and communication (Ibid).

6.2. Architectural Analysis of the Museum

There are four functional areas in the building **(Figure 13)**:

• An entrance area from the garden, which is required to ensure the building's independence from the rest of the building (3ti Progetti Italia Ingegneria Integrata Spa, 2017).

• The exhibition area: a large open space with movable walls that may be reconfigured according to the demands (Ibid).

• There are two technical areas: one for restrooms and one for storage (Ibid).

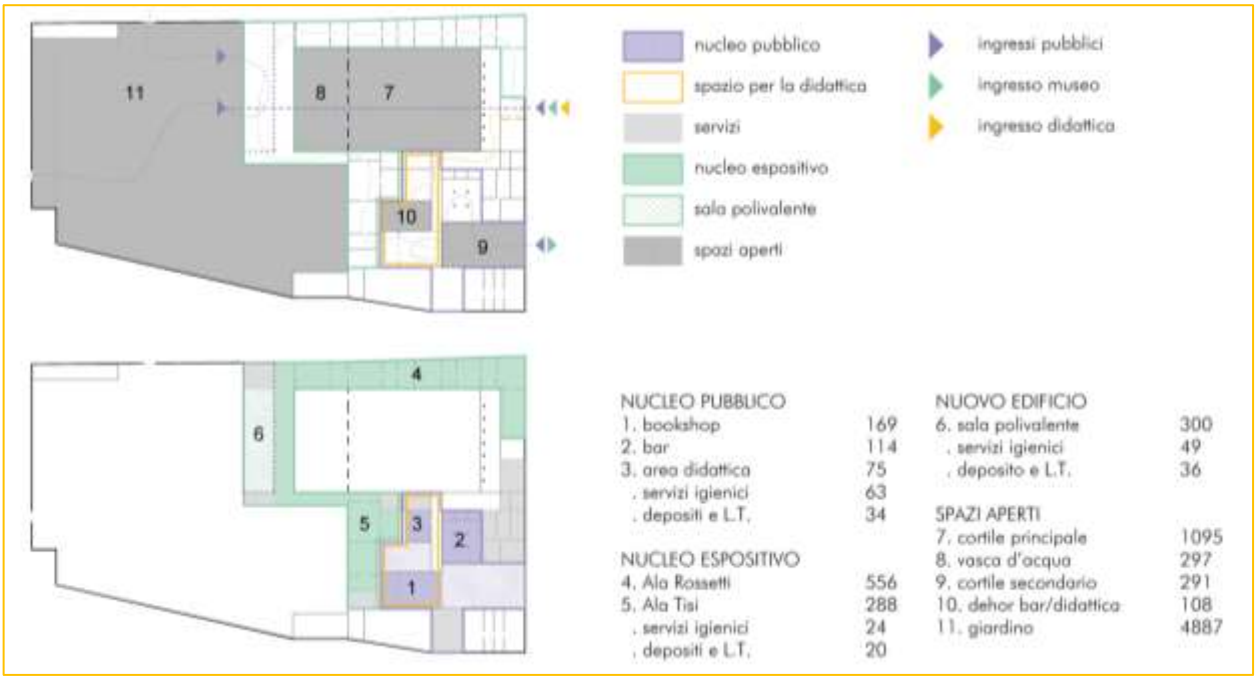


Figure 13: Zoning Analysis for ground floor plan (above), first floor plan (below) for Palazzo dei Diamanti Museum.

6.2.1. Materials

A database of materials used for internal finishes of all Palazzo dei Diamanti Museum spaces has been established

– analysis of the environment setting of affected units, with specific attention to requirements of usability, visual integration and transformability based on highly-valued elements pavements, high-quality claddings, wooden ceilings, mouldings and frames) (Villani, 2018, p. 292)

– Analysis of the existing technical solutions for surfaces **(Figure 14) (Figure 15)**:

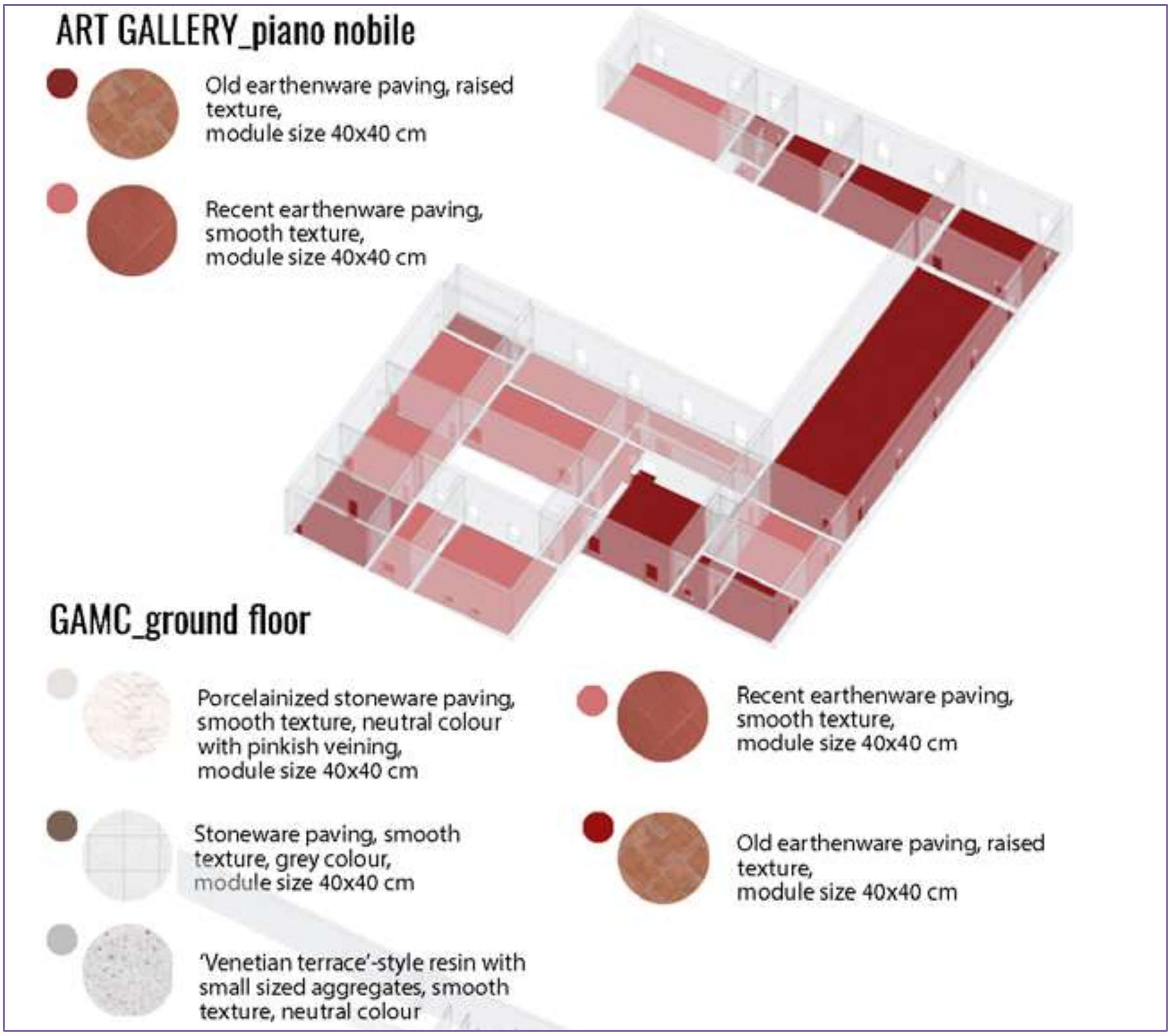


Figure 14: Palazzo dei Diamanti in Ferrara: graphical representation of the analysis of existing materials.

***Source**: (Villani, 2018, p. 294)*

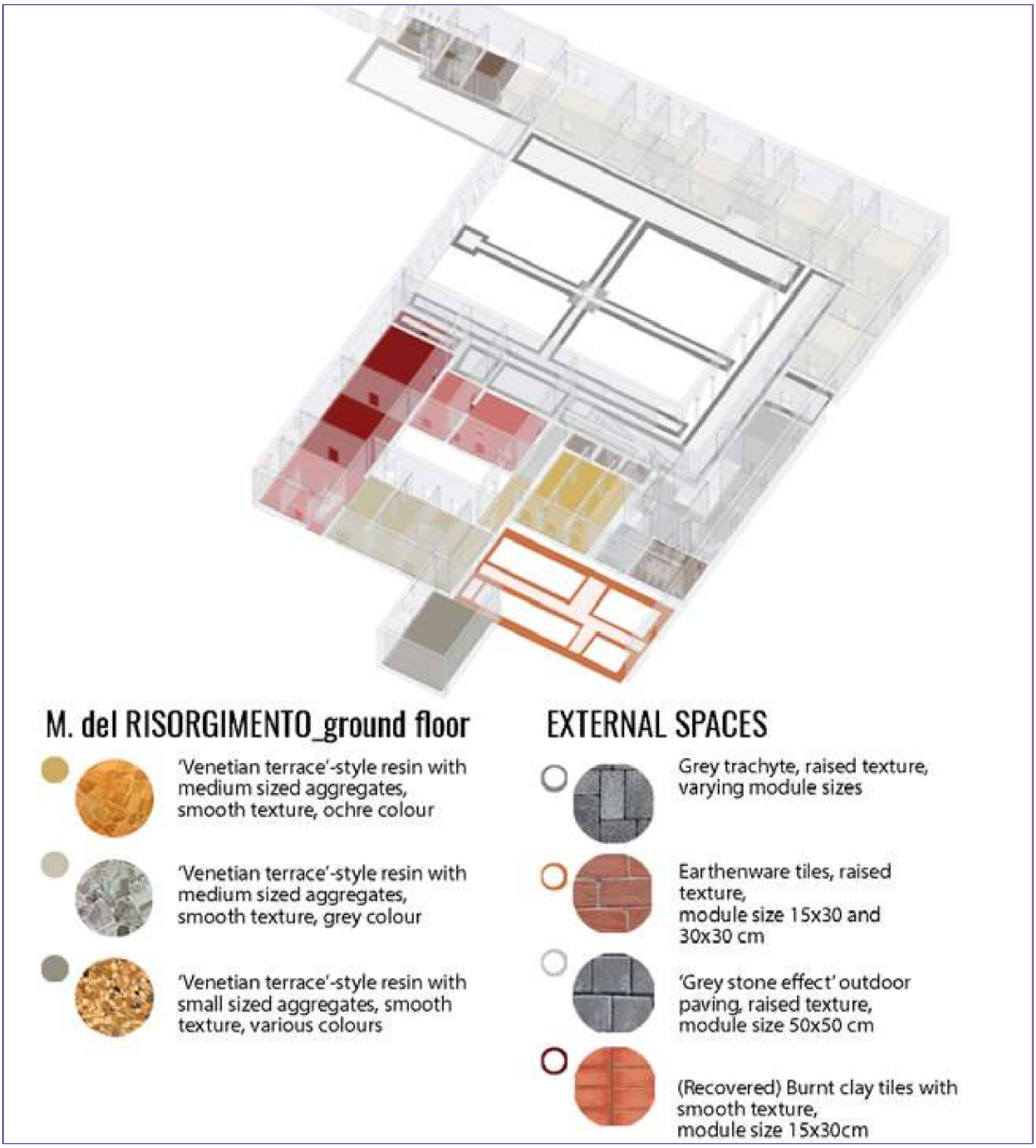


Figure 15: Palazzo dei Diamanti in Ferrara: graphical representation of the analysis of existing materials.

Source: *(Villani, 2018, p. 294).*

6.3. Users of Museum

A series of preliminary conversations with a variety of multidisciplinary organizations (cultural heritage authorities, museum directors, designers, exhibition curators, and visitors) were held with the goal of gathering information for the creation of a database and subsequently proposing design guidelines (Villani, 2018, p. 292).

– Investigations of the museum's history and evolution, as well as the context and the quantity and type of visitors (Ibid).

On the samples, an operational series of studies and preliminary inspections were undertaken, including:

- Museum partitioning into functional regions and related environment components (Ibid).
- Flows and pathways are analyzed, and important concerns are identified through configuration analysis (Ibid).
- Determination of environment units that need to be changed in order to improve space communicability (Ibid).

6.4. Simulated Study: Configurationally analysis by Space Syntax technique

Configurational analysis is a helpful tool for making planning decisions. The plan metric and spatial configuration was checked by considering and prioritizing the systems of flows inside the building, starting with a careful analysis of the current state of affairs from both an environmental and technological standpoint to understand the potentialities of the spaces and the feasible intervention levels **(Figure 16) (Figure 17)**. Following that, various interventions were proposed to describe the places from a material standpoint by focusing on the perceptual and sensory aspects of architectural features (finishing materials, furnishing, devices). The utilization of approaches from a number of international examples of renovations and upgrades to very complicated museum spaces based on scientific and objective assistance for project verification was also utilized **(Figure 18)**. The software utilized was

Figure 16: Space syntax analysis (with depthmapX) of ground floor of Palazzo dei Diamanti, current state. (a) Connectivity (b) Integration HH (c) Visual integration (d) Agent analysis. (Color figure online)

Source: *(Romagnoli, Villani, & Oddi, 2018, p. 583).*

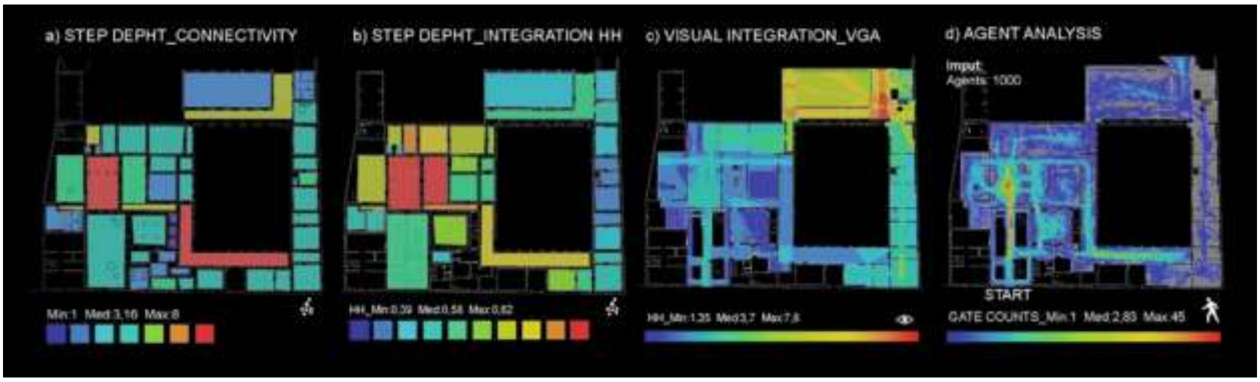


Figure 17: Space syntax analysis of ground floor of Palazzo dei Diamanti.

Source: *(Romagnoli, Villani, & Oddi, 2018, p. 586).*

dephtmapX, which can evaluate the spatial configuration and was useful for doing an early verification of the project selections and was made available by the University College (Romagnoli, Villani, & Oddi, 2018, p. 581).

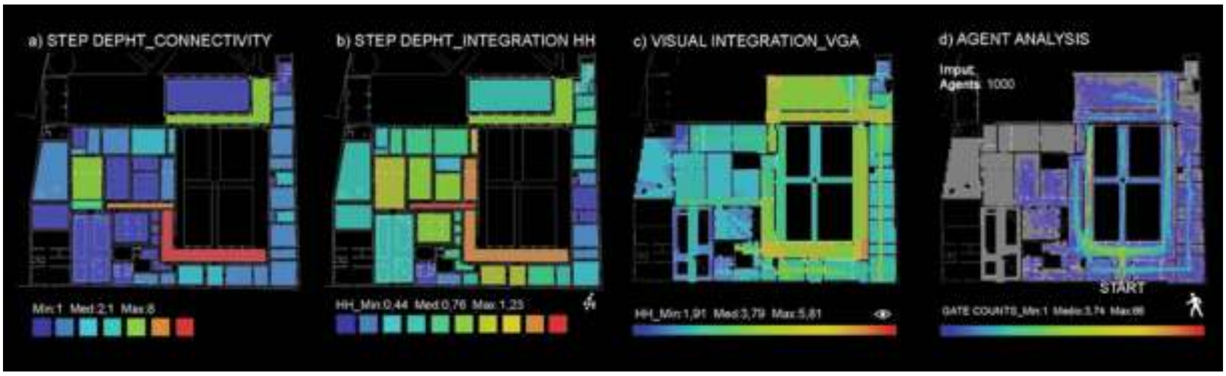


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Figure 18: Meta-project of alternative sub-lots and checks with depthmapX..

Source: *(Romagnoli, Villani, & Oddi, 2018, p. 587).*

6.5. Define the Problem

Figure 19: Palazzo dei Diamanti in Ferrara: graphical representation of the analysis of existing materials.
***Source:** (Villani, 2018, p. 293).*

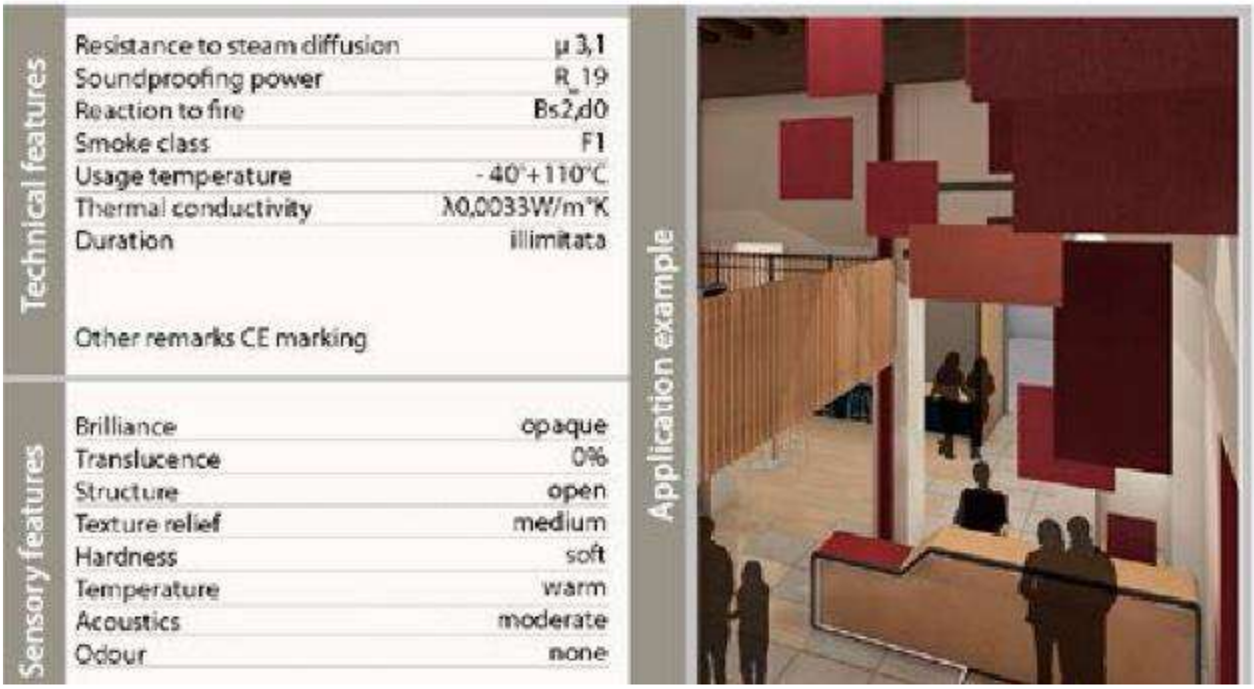
6.6. Proposed Solution

Based on preliminary information, three modification levels were identified:

– Level 1. ‘Minimum change’ solutions and low financial impact: reversibility is favored and traditional materials can be included, by acting on the selection of textures, colours,luminosity, opacity, transparency etc.; alternatively, innovative materials can be used, such as adhesive fluorescent films or materials with embedded fiber optics, particularly useful to mark emergency escape routes (Villani, 2018, p. 292)

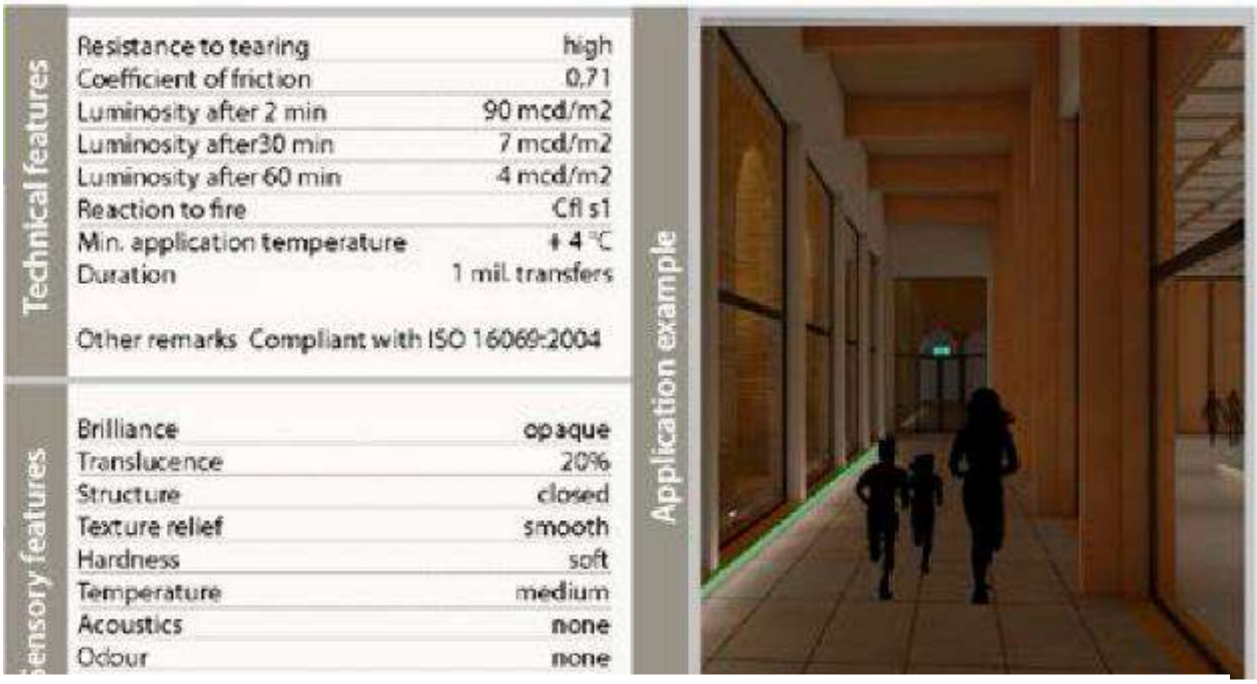
- Level 2. Solutions requiring (partial or total) change of technical elements with medium financial impact. Traditional materials can be chosen, by acting on textures, colors, luminosity, opacity, and transparency. Innovative materials can also be chosen, with high esthetical/ sensory performance, such as ceramics with high optical features, with olfactory features, luminous cloths, etc (Ibid).

Level 3. Radical resetting modification, with high financial impact, acting on the reorganization and reconfiguration of spaces and internal pathways. In this case, way-finding (that can include the use of smart and multisensory materials, such as sounds, visual effects etc.) is included in a repurposing programme,thus being integral part of the design (Ibid).The following illustrations **(Figures 20-23)** indicate the characteristics and functions of the proposed materials within the museum to improve the performance of visitors during the spatial orientation.



Technical features	Resistance to steam diffusion	µ 3,1
	Soundproofing power	R_19
	Reaction to fire	Bs2,d0
	Smoke class	F1
	Usage temperature	- 40°+110°C
	Thermal conductivity	λ0,0033W/m°K
	Duration	illimitata
	Other remarks CE marking	
Sensory features	Brilliance	opaque
	Translucence	0%
	Structure	open
	Texture relief	medium
	Hardness	soft
	Temperature	warm
	Acoustics	moderate
	Odour	none

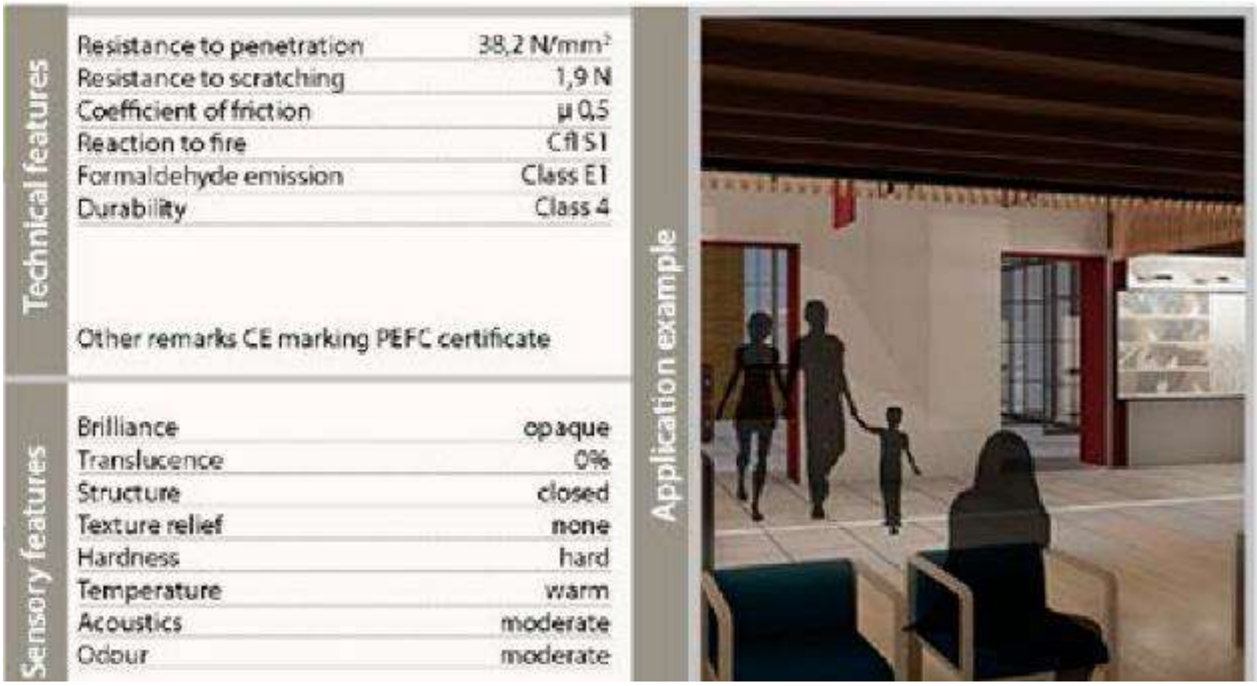
***Figure** 20: The catalogue structure of materials for way-finding in museums **Source:** (Villani, 2018, p. 297)*



Technical features	Resistance to tearing	high
	Coefficient of friction	0,71
	Luminosity after 2 min	90 mcd/m2
	Luminosity after30 min	7 mcd/m2
	Luminosity after 60 min	4 mcd/m2
	Reaction to fire	Cfl s1
	Min. application temperature	+ 4 °C
	Duration	1 mil. transfers
	Other remarks Compliant with ISO 16069:2004	
Sensory features	Brilliance	opaque
	Translucence	20%
	Structure	closed
	Texture relief	smooth
	Hardness	soft
	Temperature	medium
	Acoustics	none
	Odour	none

Figure 21: The catalogue structure of materials for way-finding in museums

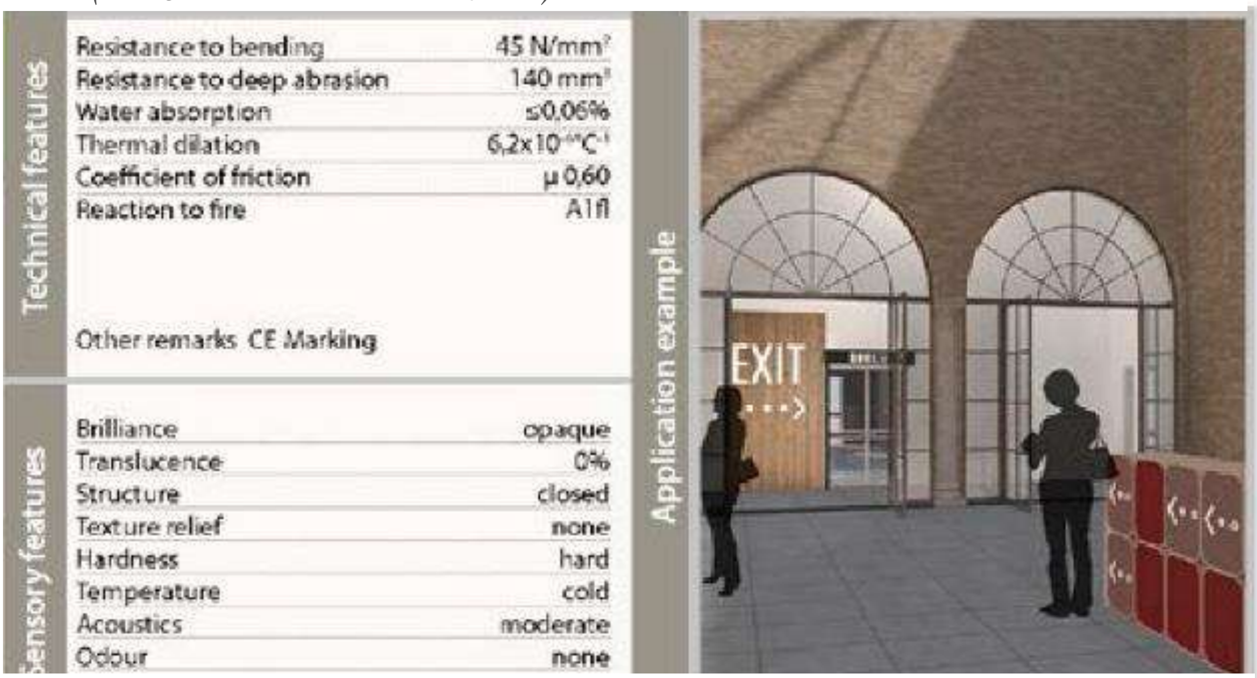
***Source:** (Villani, 2018, p. 297)*



Technical features	Resistance to penetration	38,2 N/mm²
	Resistance to scratching	1,9 N
	Coefficient of friction	µ 0,5
	Reaction to fire	Cfl S1
	Formaldehyde emission	Class E1
	Durability	Class 4
	Other remarks CE marking PEFC certificate	
Sensory features	Brilliance	opaque
	Translucence	0%
	Structure	closed
	Texture relief	none
	Hardness	hard
	Temperature	warm
	Acoustics	moderate
	Odour	moderate

Figure 22: The catalogue structure of materials for way-finding in museums

Source: *(Romagnoli, Villani, & Oddi, 2018, p. 587).*



Technical features	Resistance to bending	45 N/mm²
	Resistance to deep abrasion	140 mm³
	Water absorption	≤0,06%
	Thermal dilation	6,2x10⁻⁶°C⁻¹
	Coefficient of friction	µ 0,60
	Reaction to fire	A1fl
	Other remarks CE Marking	
Sensory features	Brilliance	opaque
	Translucence	0%
	Structure	closed
	Texture relief	none
	Hardness	hard
	Temperature	cold
	Acoustics	moderate
	Odour	none

Figure 23: The catalogue structure of materials for way-finding in museums

Source: *(Villani, 2018, p. 297)*

7. Results:

This section presents the results derived from a comprehensive spatial analysis of the Palazzo dei Diamanti Museum, utilizing Space Syntax techniques with DepthmapX software. These analytical tools were employed to directly address the research objective: to evaluate how smart material-based interventions can improve spatial legibility, navigation efficiency, and user experience within complex architectural environments.The analysis focused on diagnosing key wayfinding challenges, including **low spatial integration zones, visual confusion, and pedestrian bottlenecks**, which were found to significantly hinder users' ability to navigate autonomously within the museum (Table1).

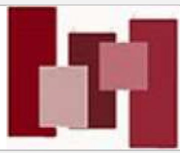
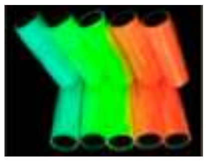
Smart Material Solution	Technical Element/Material	Way-finding Meaning	Picture
Level 1 in Modification: Minimum change in Reception Area Problem: Poor Visibility			
Soundproofing panel	False Ceiling	Function identification	
Level 2 in Modification: Medium change in Additional Services Problem: Disorientation			
Tactile interactive floor maps, Luminous textile elements	Embossed floor textures, luminous ceramics, textile panels	Function identification, Directional guidance, emergency navigation	
Level 3 in Modification: Radical change in Exhibition Hall Problem: Flow Bottlenecks			
Spatial reconfiguration with embedded multisensory signals	Modular walls, digital floor projections, dynamic lighting systems	Directional guidance, emergency navigation	

Table 1: Summary of results
Source: Researcher

While the findings demonstrate measurable benefits reflected in significant improvements in legibility and movement efficiency, it is important to acknowledge that these outcomes are specific to the spatial configuration of the

Palazzo dei Diamanti and may vary in different architectural contexts. Nonetheless, the insights gained provide valuable guidelines for the broader application of smart materials in designing cognitively supportive environments.

7.1. Criteria for using material in museum:

In order to support appropriate options for modification levels, this study proposes some criteria to reuse a catalogue of materials and technical solutions in order to facilitate cognitive and behavioral processes of users while experiencing the museum

The increasing offer of materials on the market, with increasingly updated features, combined with the difficulty in managing the amount of technical data, forces the designer to constant training and requires new decision support tools.

For the specific field of way-finding, a set of criteria was identified in order to select solutions for the different components to be used as finishing for spaces, diversified based on functional areas of the museum and on modification levels (**Table 2**). The purpose was to join technical and financial properties (quantitative analysis) with sensory properties (qualitative analysis), and with the meaning attached to each material in a certain context. The procedure was based on the most common selection processes used in engineering and design.

In the first selection phase, it is necessary to set an initial criterion related to context analysis, whose parameters are:

– Purpose of the selection (based on modification levels and functional areas);

– Technical elements to be modified.

– Conditions of use (natural and artificial lighting, temperature, humidity, wear conditions, etc.).

– The priorities assigned to the features to be investigated (reversibility etc.).

– The level of detail that the selection should achieve (features to be considered contextually).

Criterion	Description	Relevance to Wayfinding
Sensory Impact	Provides visual, tactile, and auditory feedback	Enhances spatial perception
Environmental Adaptability	Reacts to light, humidity, and temperature	Dynamic guidance
Durability	Resists wear in public spaces	Long-term use
Reversibility	Non-invasive on heritage structures	Suitable for historic sites

Table 2: Guidelines for using material in museum
Source: Researcher

7.Conclusion and Recommendations:

This research presents a functional classification of smart materials into three primary categories(Tble3): property-changing materials, which respond to environmental stimuli by altering color, transparency, or form; energy-exchanging materials, capable of converting different energy forms to support functions such as lighting, signaling, or energy generation; and integrated smart systems, which combine sensors, actuators, and control units to enable adaptive and responsive behaviors. This classification forms the foundation for understanding how smart materials contribute to enhancing wayfinding performance by improving spatial legibility, promoting sensory interaction, and enabling dynamic, user-centered guidance within complex architectural environments.

Type	Description	Example Materials
Property Change Smart Materials	React to stimuli by changing properties	Photochromic, Thermochromic, Shape Memory
Energy Exchange Smart Materials	Convert energy from one form to another	Piezoelectric, Photovoltaic, LED

Table 3: Smart Materials Classification

Source: Researcher

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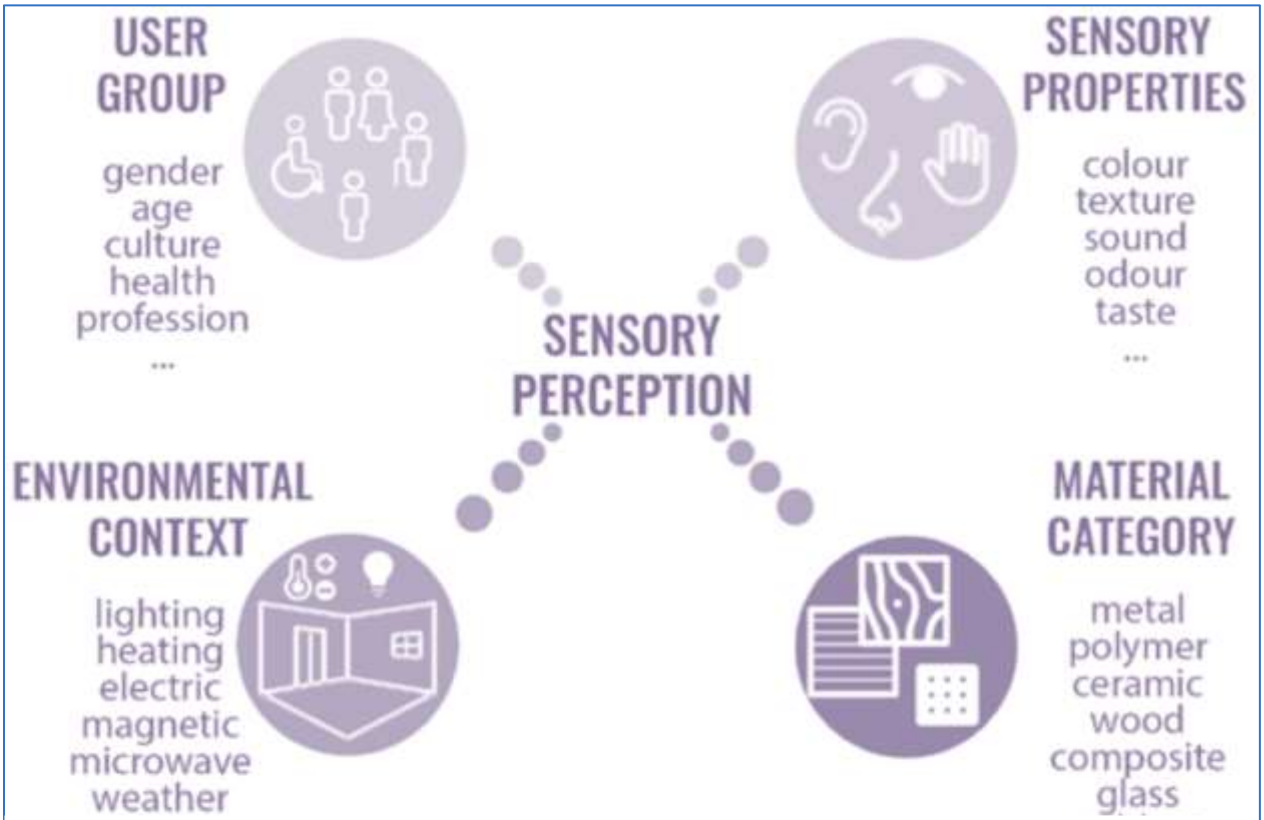
Smart Materials Systems		Combine sensor actuators, and controllers
Passive smart material systems	Responds directly to stimuli without energy	Photoluminescen films
Active smart material systems	Uses sensors and energy to respond	Adaptive lighting,
Hybrid smart material systems	Combines passive and active systems	Hybrid Shading Systems

The study also highlights a paradigm shift from static signage to dynamic, interactive wayfinding systems using smart materials. Integrating behavioral insights, environmental intelligence, and sensory technologies



Outcome Diagram Selection criteria for materials - Factors contributing to sensory perception.

***Source**: (Villani, 2018)*

enhances spatial clarity, usability, and visitor experience. Future research should explore AI-driven adaptive systems to further optimize navigation in complex architectural environments.

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