DigiTouch: Haptic Guidance for Learning Construction Engineering Tasks in Virtual Reality

Prof. Ivan A Mutis, Illinois Institute of Technology
Ms. Marina Oberemok, Illinois Institute of Technology

Marina Oberemok is a Ph.D. student in Civil Engineering (Construction Management) at Illinois Institute of Technology, Chicago, and a Fulbright alumna. Her research focuses on computational and immersive learning systems for construction planning and coordination, including VR- and haptics-enabled training environments and data-driven methods to support engineering learners.

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ABSTRACT: Construction engineering and management (CEM) learning often requires students to interpret complex spatial-temporal information from two-dimensional drawings — spatial (how design components or resources relate to one another in 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task). This process imposes a high cognitive load as learners must mentally transform static representations into dynamic construction sequences.

The DigiTouch project introduces an immersive, multisensory framework that integrates virtual reality (VR) and vibro-tactile haptic feedback to improve learning. The framework aims to explore how CEM students learn by engaging with and interpreting the meanings of engineering designs through immersive and haptic technologies. This will be achieved by examining how multisensory interaction can reduce cognitive load, enhance engagement, and strengthen perceptual reasoning during spatial problem-solving tasks. These technologies offer opportunities to engage with the complex realities of physical space, such as CEM problem-solving tasks on construction job sites.

Using DigiTouch technology, learners explore a virtual construction space where visual and tactile cues are synchronized to represent task dependencies, spatial constraints, and sequencing logic for construction management tasks. Haptic cues guide the conveyance of contextual information that parallels the logic of construction assembly, enabling learners to perceive relationships typically abstract in traditional instruction. Grounded in cognitive load theory, this approach distributes cognitive effort across sensory modalities, thereby promoting more efficient reasoning and deeper conceptual understanding through embodied interaction.

A subsequent controlled pre/post experiment will be used to compare the haptic-guided VR with a traditional 2D task environment on sequencing construction deliverables to quantify effects on learning performance, workload, and engagement. Outcomes will include sequencing accuracy, completion time, working memory capacity, perceived cognitive load, and post-activity engagement/reflection, providing empirical evidence of instructional impact relative to conventional training.

As a result, DigiTouch will be proposed for integration into a construction scheduling course as a lab activity aligned with early units on basic planning and scheduling techniques and building network models. After instruction, students will complete a short onboarding and a 20-minute haptic-guided VR construction-planning exercise, selecting BIM-derived deliverables from a WBS inventory and placing them in the correct order and location. Haptic cues will flag precedence-constraint violations and reinforce the component category and WBS hierarchy at decision points. The resulting performance and implementation data will clarify how DigiTouch strengthens early scheduling competencies and define the practical conditions for adopting haptic-guided VR as a repeatable instructional module.

Conceptually, DigiTouch extends immersive learning research by showing how human–technology interaction can strengthen engineering cognition and spatial reasoning. By coupling vibrotactile feedback with construction logic, the platform supports embodied understanding of spatial–temporal processes and bridges digital visualization with physical intuition. This work aligns construction engineering pedagogy with Industry 4.0 priorities, such as digital twins, automation, and human–machine collaboration, and advances STEM education goals by demonstrating the potential of multisensory XR to improve cognitive efficiency, engagement, and concept transfer. The findings lay the groundwork for scalable multisensory learning frameworks that prepare future engineers for digitally augmented construction practice.

KEYWORDS: haptic cues, human-computer-interaction, design interpretations.

1. INTRODUCTION

Construction engineering and management (CEM) education relies on learners' ability to derive meaning from design and planning representations. Yet many foundational CEM tasks, such as interpreting drawings, understanding precedence constraints, and producing Work Breakdown Structure (WBS) sequences, require students to coordinate spatial relations with the logic time dimension (spatio-temporal information) [1]. The learners' abilities to effectively manage and comprehend significant amounts of spatial (how design components or resources relate to one another in 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information are the spatial cognitive ability [2]. For novices, this coordination often demands extensive mental transformation: translating static 2D representations into dynamic 3D/4D reasoning while tracking constraints and dependencies in working memory. Cognitive Load Theory (CLT) suggests that this translation increases extraneous cognitive load and reduces the resources available for schema construction and higher-level conceptual reasoning [3-5]. Meta-analytic evidence indicates that cueing in multimedia materials can reduce subjective cognitive load and improve retention and transfer [6].

Immersive and interactive environments have been used to offload spatial interpretation demands by allowing learners to inspect geometry and spatial relations directly, rather than inferring them from static views [7]. In AEC education, prior work suggests that BIM-enabled visualization and VR can improve learners' comprehension and performance relative to 2D-only instruction, particularly for spatial understanding [8]. However, much of the instructional burden in construction planning remains visually dominated, even though learners' difficulties often stem from interpreting planning semantics, particularly process sequencing across trades and the precedence logic needed to coordinate activities during decision-making [9].

Introducing an additional modality, such as haptics, provides a complementary channel for conveying compact, time-sensitive cues while preserving visual attention for the task. Research on tactile message design demonstrates that vibrotactile parameters, such as rhythm, duration, amplitude/intensity, and spatial location, can be organized into discriminable cue sets [10], and research on wearable haptics indicates the feasibility of delivering informative tactile feedback in applied settings [11]. There is a need in CEM-oriented VR applications to use haptic cues beyond simple confirmation or alerting. This need leaves an open design problem: how to encode semantics (e.g., hierarchy and precedence) as a stable, learnable tactile code that supports decision-making during task execution?

This paper addresses this research gap by advancing a multisensory learning approach in which vibrotactile feedback is designed as a learnable cue system with VR-based interaction. The contribution is to understanding haptic affordances that support representational competence and spatiotemporal reasoning in planning-oriented CEM learning tasks. This work positions multisensory Human Computer Interaction (HCI) as an instructional strategy to reduce extraneous load and strengthen learners' ability to interpret and act on representations used in the engineering and architectural designs—capabilities that are increasingly relevant as construction workflows move toward digitally augmented and human–technology-integrated practice.

2. BACKGROUND

STEM education research has steadily moved haptics from a niche interface topic to an instructional modality. When instruction relies almost exclusively on vision, learners must infer key properties, such as shape, resistance, alignment, and change over time, from visual cues alone. Early studies focused on device development and the use of haptics to support spatial visualization and object manipulation, aiming to make geometry and interaction more perceptible [12, 13]. Later work shifted from device feasibility to instructional value, showing that tactile feedback can improve interaction quality and spatial guidance when cues are salient and timed to the learner's actions [14, 15]. More recent investigations in immersive environments report that adding haptics to VR can yield measurable performance gains and increase perceived presence, particularly when tactile feedback is synchronized with task-relevant events [16, 17].

The educational value of haptics extends beyond enhancing the realism of VR. Studies in haptic-enhanced immersive learning report improvements in outcomes such as conceptual understanding and retention [18]. Work evaluating haptic gloves in training settings also highlights practical instructional implications, including what the hardware consistently delivers, what learners reliably perceive, and how these constraints shape training design [19]. In parallel, multimodal Industry 4.0 learning platforms that integrate visual, haptic, and auditory channels emphasize adaptive feedback and analytics, positioning multisensory support as a pathway to scalable deployment in engineering education [20]. These contributions suggest that haptic feedback becomes educationally consequential when it functions as a representation that carries interpretable information.

In AEC, haptics has been applied most often in contexts where learning is demonstrated through doing, including virtual assembly, vocational simulations, and craft-oriented training [21-24]. Another line of AEC research extends haptics into mixed reality and teleoperation, where touch cues can support remote manipulation and help operators infer object or material properties during interaction [25, 26]. These applications demonstrate feasibility and value, but they also reveal a design challenge.

Across the broader haptics literature, cue design is repeatedly identified as the hinge point. Tactile message design research shows that vibrotactile parameters such as rhythm, duration, intensity, and location can be organized into cue sets that users can learn and differentiate [10]. Recent work on body-vibrotactile patterns reinforces this requirement. When the goal is interpretation rather than sensation, cues must be discriminable, and mappings must remain consistent [27]. Educational studies that pair robotics and haptic interfaces likewise suggest that higher-level learning goals, including computational thinking, can be supported when tactile feedback is coupled to interpretable task states and learner actions [28]. The critical design question is therefore not whether to add haptics, but rather what information haptics should convey and how that information should be encoded so that learners can use it.

This question becomes especially consequential in CEM, where instructional difficulty in planning often lies in explaining reasoning rather than in demonstrating the states and sequences of motion. In planning, students must identify dependencies, understand hierarchy, and justify why a step is appropriate at a given time within a work package [29]. Existing haptic guidance approaches rarely externalize these planning meanings or help learners build a coherent spatial-temporal representation. This limitation motivates the present study's focus on integrating visual and haptic stimuli to strengthen spatial-temporal reasoning and representational competence in planning concepts in CEM, consistent with recent conceptualizations of haptic interaction as a structured learning mechanism in engineering education [21].

Research questions

By using perception-rich enhanced virtual reality (VR) with haptic affordances for CEM learners, this study addresses the following questions:

1. *Multisensory cue representation*: How can visual and vibrotactile cues be represented in a complementary fashion in an immersive learning environment to support the reasoning skills and reduce cognitive demand?
2. *Haptic code as a semantic layer*: How can vibrotactile cues be structured as a semantic representation mechanism to convey the meaning of the concepts in CEM learning tasks?
3. *Scalable, learnable vibrotactile cue design*: What design principles support a scalable and learnable vibrotactile cue system to remain consistent across different task contexts, object sets, and levels of model detail?

This paper presents the design and implementation of the learning platform to address these questions in the initial phase. The design includes a platform architecture using a BIM/IFC-derived WBS object model and a vibrotactile cue strategy for category-to-pattern mapping. In the next experimental phase, this research will present the effects of learning with the presented design and evaluate learning performance, engagement, and cognitive load using controlled pre- and post-testing. In a subsequent phase, we will propose integrating the platform into a Construction Planning and Scheduling course as VR lab activities on WBS sequencing and precedence-logic constraints, thereby allowing us to assess learning gains and classroom feasibility and to define the practical conditions for adopting DigiTouch as a repeatable instructional module.

Haptic feedback

Many digital interfaces pair visual and auditory cues with vibrotactile feedback, using touch as a lightweight channel to signal events and support engagement [30]. Its instructional value depends on how users perceive and assign meaning to tactile events. Human touch is supported by dense cutaneous receptors that enable discrimination of pressure, texture, and other surface properties, and it is inherently active, as people explore surfaces through contact rather than passively receiving touch [31]. For this reason, effective haptic design requires more than generating sensation. It requires a principled mapping between tactile cues and the information they convey.

Haptic technology interaction incorporates multiple haptic modalities, including force feedback, vibrotactile, ultrasonic, and thermal actuation [32]. Prior surveys commonly organize haptic applications around three primary functions: simulation, teleoperation, and guidance [33]. In *simulation*, haptics approximates physical interaction to support more realistic contact and manipulation. In *teleoperation*, haptics enables a bidirectional loop in which an operator can perceive remote contact while controlling a robotic or remote device [34]. In *guidance*, tactile patterns deliver actionable cues that shape behavior during interaction, such as directional or corrective information [35]. In addition, a substantial body of work treats vibrotactile feedback as a *signal code*: tactile signals are designed as discrete, learnable symbols ("tactons" or haptic icons) that stand for specific meanings, in the same way an icon or short tone can represent a message [10, 36]. In learning contexts, both guidance and communication functions can be implemented as well-scaffolded cues that can reduce errors and improve performance [37-40].

When a signal code system is implemented through a structured haptic code, tactile symbols can efficiently convey information through variations in rhythm, intensity, duration, and location [32, 41]. For a code to be meaningful, cues must be differentiable, identifiable, and learnable [41]. At a basic level, such cues support notifications and action feedback, providing guidance. With more deliberate design, they can encode higher-level meaning, including object classes, hierarchy, and dependencies, enabling users to infer relationships and sequencing logic. In this sense, systematic vibrotactile design can operate as a compact representational layer and, in advanced implementations, as a learnable haptic language for communicating abstract structure.

3. METHODOLOGY

This work develops the DigiTouch VR training platform to support CEM learners in interpreting spatial–temporal information of CEM designs. The platform integrates (1) a BIM-derived virtual environment that externalizes spatial structure, (2) a WBS panel that makes sequencing logic and hierarchy explicit through deliverables and milestones, and (3) a vibrotactile code that provides synchronized tactile cues for both interaction state and planning meaning. The methodology below describes the platform built and the WBS-to-haptic mapping used to study multisensory interaction.

3.1 Platform development overview

The platform was designed to help learners recognize the meaning of planning representations by coupling WBS-based task structure with tactile cues in VR. Learners interact with deliverables represented as VR objects, navigate a workflow organized by a WBS, and receive synchronized visual and vibrotactile cues during selection and placement (Figure 1). The cue system separates two complementary roles: *operational haptics* and *functional haptics*. *Operational haptics* provides real-time guidance and feedback for users' actions in the VR environment by informing the current state of their actions, including assessing them (e.g., confirming correct placement, flagging misplacement, or indicating updates). *Functional haptics* informs the user about the semantic meaning of the user's interacting objects (i.e., the VR objects the user is interacting with at the current time) in the VR environment (e.g., providing information on manipulated and observed object categories, hierarchies, and relationships) to support decision-making.

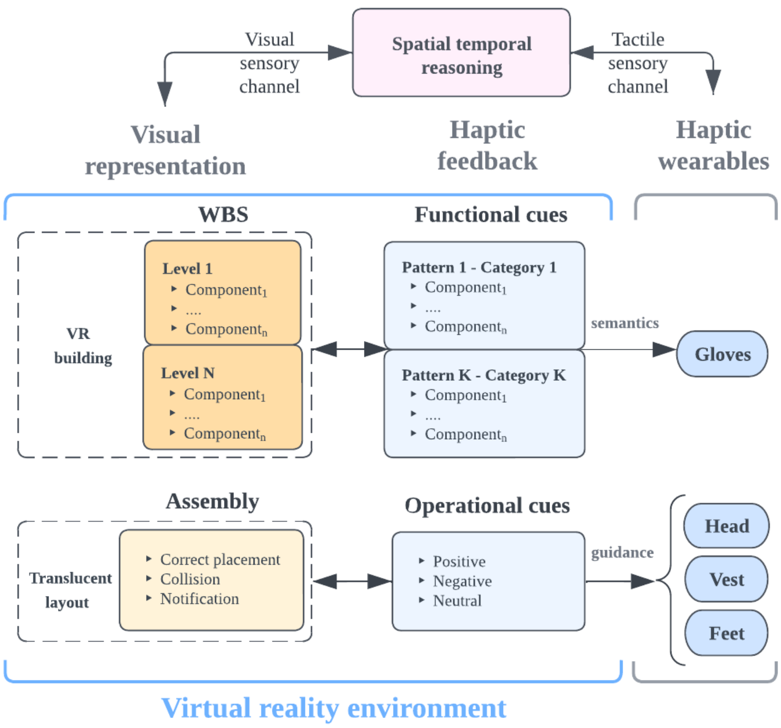


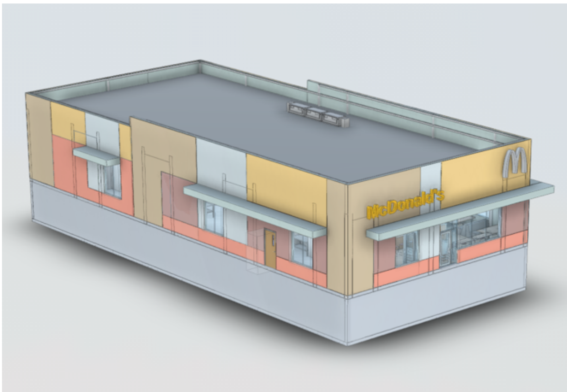
Figure 1. System architecture and information flow

3.2 VR environment and WBS object model

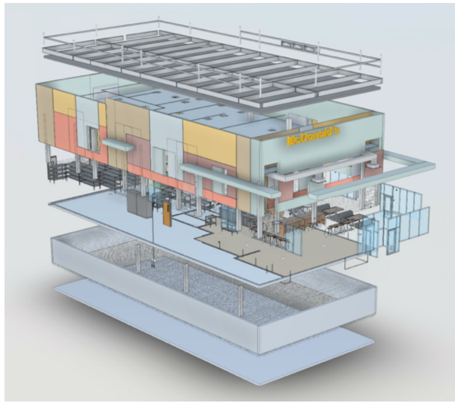
A design of a typical commercial facility was represented as a Building Information Model at approximately Level of Development 300. The model was exported as an Industry Foundation Classes (IFC) file to preserve object identity, then imported into a VR game engine for creation. The outcome is a VR model with the following features. First, it is presented as a translucent reference layout to support spatial orientation and accurate placement. Second, it is decomposed into interactive game objects representing deliverables for the WBS sequencing task.

Each deliverable object in the VR system is instantiated with planning metadata, including its WBS classification and the corresponding functional haptic assignment (Table 1, Appendix). Figure 2 summarizes the BIM-to-VR workflow. Figure 2a shows the source BIM model of the commercial facility. Figure 2b depicts the WBS-oriented decomposition of the building, in which components are grouped into level-based milestones (e.g., Substructure and

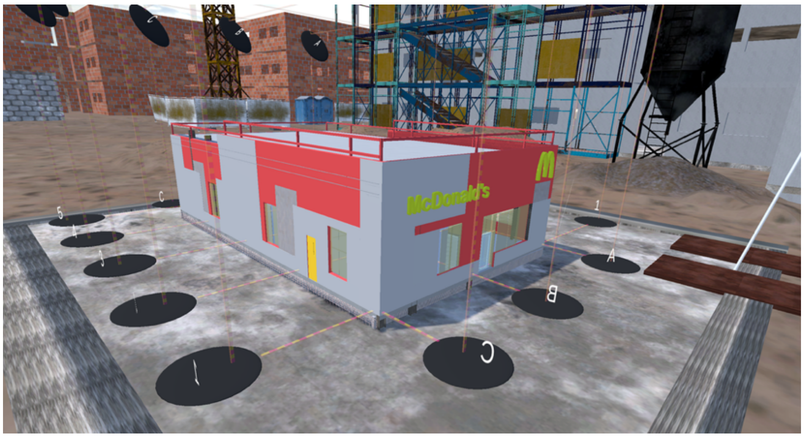
Superstructure) to align with the sequencing logic used in the planning task. The model is then imported into Unity, producing the interactive VR scene shown in Figure 2c, where decomposed deliverables are represented as manipulable game objects for placement and sequencing. This WBS structure operationalizes planning as a spatial–temporal task by linking each deliverable to both a target location in the 3D layout and an ordered position within the sequencing hierarchy. For use in constrained physical spaces, the VR environment can be uniformly scaled while preserving proportions to maintain perceptual coherence during interaction.



(a) Source BIM model of a commercial facility



(b) WBS-oriented decomposition of the building



(c) Imported and interactive VR model in Unity

Figure 2. BIM-to-VR workflow for the VR training environment

3.3 Hardware and interface implementation

The platform was implemented in Unity and deployed on a Meta Quest 3 head-mounted display. Vibrotactile feedback was delivered using a set of bHaptics wearables (Fig. 3): TactGlove DK2 (hands), TactSuit (torso vest), Tactosy for Feet (ankles/feet), and a head-mounted facial haptics module (TactVisor) integrated with the headset. This hardware configuration constrains haptic development by limiting output to the actuator layouts and intensity/frequency ranges supported by each device. In the interaction design, the gloves deliver functional vibrotactile patterns associated with selected deliverables, while the vest, feet modules, and facial haptics provide operational cues (e.g., system events, boundary conditions, and action evaluation). The interface includes a WBS panel that exposes deliverables as selectable tiles, and the translucent reference model remains visible throughout interaction as a continuous spatial scaffold.

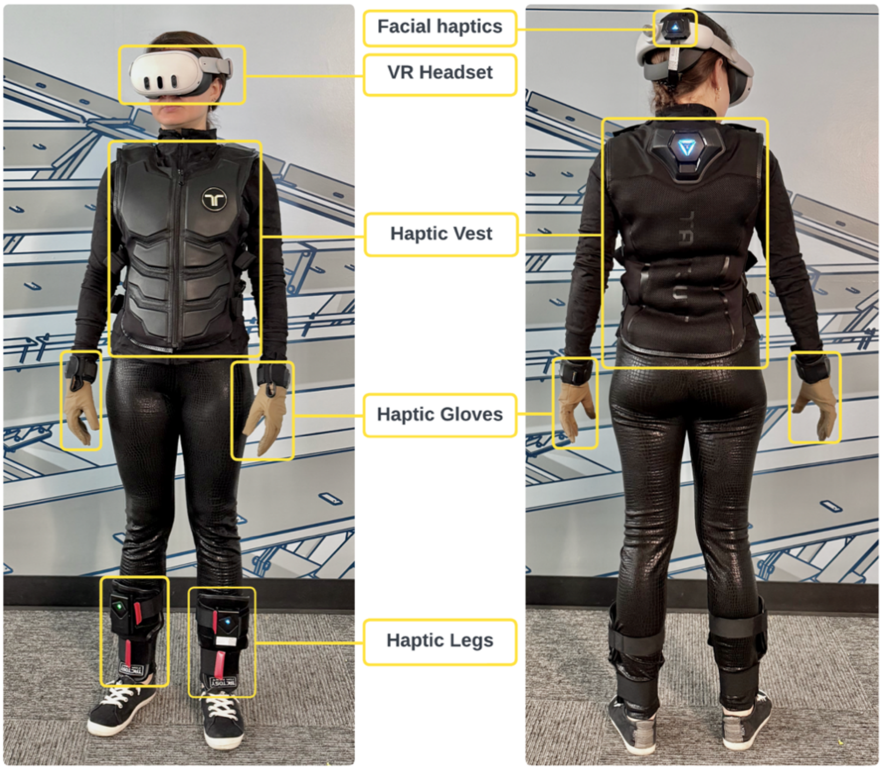


Figure 3. VR and haptic hardware configuration

3.4 Vibrotactile code design

The platform implements a vibrotactile code to provide a compact tactile representation during VR interaction. The code is expressed as a set of repeatable patterns functioning as haptic icons, meaning brief tactile signals associated with consistent interpretations [10, 36]. Pattern behavior is parameterized using four perceptual features, such as intensity, sharpness, duration, and granularity, enabling systematic variation while preserving each pattern's identity.

In the learning task, *operational haptics* communicates interaction state and action evaluation (e.g., success, error, notifications), and *functional haptics* encodes planning meaning by mapping WBS categories to vibrotactile patterns, allowing learners to recognize the semantic class of a selected deliverable.

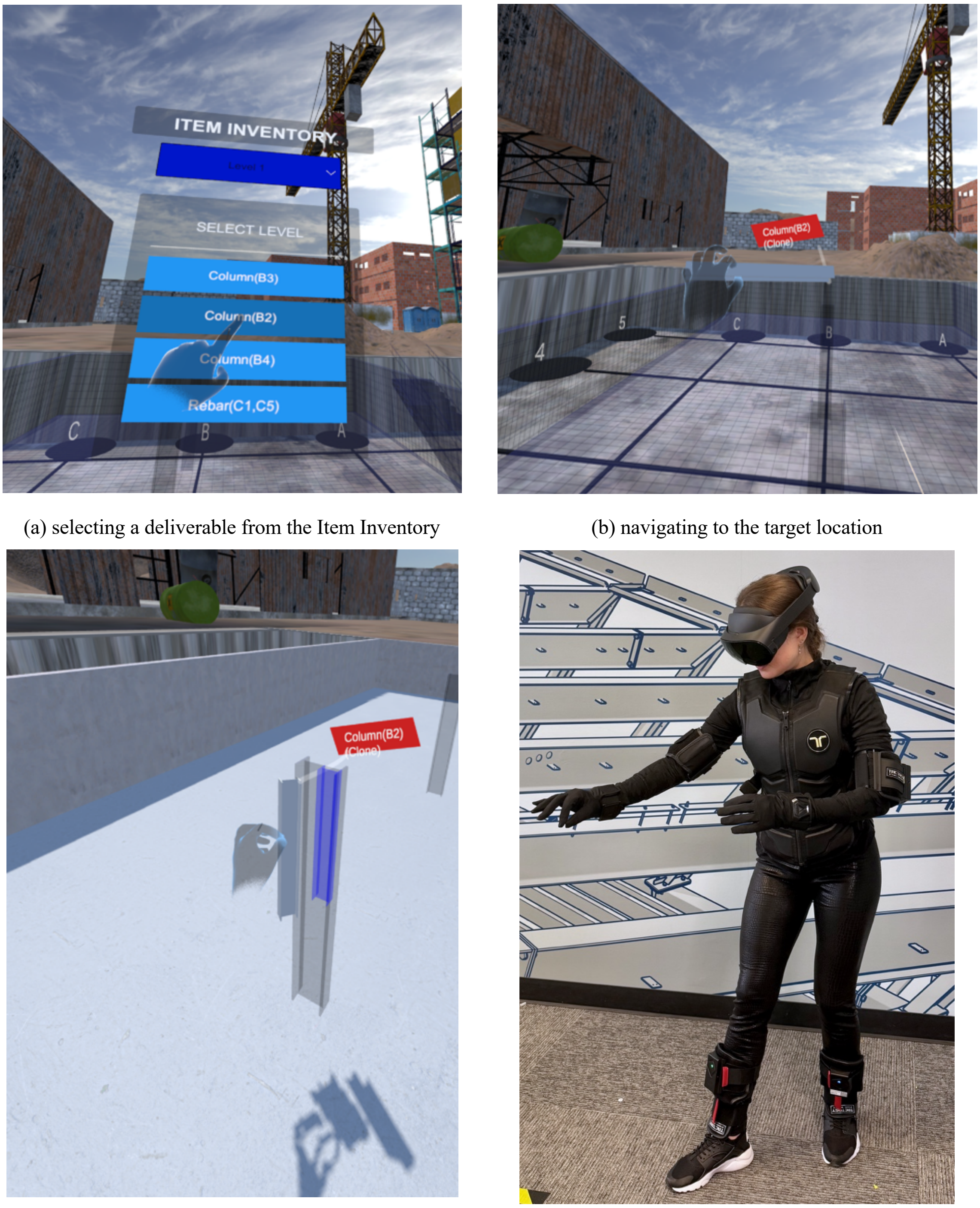
Operational cues are designed to be brief and easily discriminable, so they do not compete with functional cues that carry planning meaning. Operational feedback is delivered via the wearable to reinforce situational awareness, whereas functional cues remain primarily hand-based to support rapid interpretation during selection and placement. *Operational haptics* provides immediate feedback on the outcomes of user actions and the system's state, independent of the planning category.

Functional haptics encodes planning meaning by mapping WBS categories to vibrotactile patterns, enabling learners to perceive hierarchy and component class while reasoning about sequence and dependency relationships. Functional cues are assigned at the WBS category level: each deliverable inherits the pattern associated with its category, ensuring a consistent tactile "label" across the VR model. Pattern assignment follows a perceived-heaviness principle: lower-level categories (e.g., substructure) are mapped to more rigid and salient patterns, whereas higher-level categories (e.g., superstructure) are mapped to softer patterns, creating a learnable hierarchy signal.

Functional patterns were implemented as a compact set of canonical vibrotactile waveform families (Table 1, Appendix) parameterized by carrier frequency, envelope, and temporal structure, and rendered on the bHaptics actuators as time-varying intensity commands. The pattern families were synthesized from standard "Tacton" design primitives, such as rhythm/temporal profile, envelope/amplitude modulation, and waveform/texture, rather than device-specific presets [42]. Accordingly, family names (e.g., amplitude-modulated carrier, band-limited noise) refer to the signal-generation method. Candidate patterns were selected to be perceptually distinct, prioritizing differences in rhythm/granularity and spectral content; FFT-based characterization was used as a design check to verify separability across pattern classes [43, 44].

3.5 Case Example

The DigiTouch training platform presents an interactive assembly task on a virtual construction site. Learners are required to assemble a group of WBS virtual objects in order (sequence) to understand the logic of planning architecture, structural, and mechanical systems. Learners review a commercial building design, including its structural and architectural solutions, to understand the planning and associated reasoning for construction products and the construction sequence. The activity can be viewed as a WBS-based sequencing planning exercise conducted in VR. Learners select deliverables from the WBS as a collection or group of objects to be in a virtual space that represents a virtual construction site (i.e., 3D design objects, such as architectural and structural system design objects, placed in a VR environment). The group of objects is represented in a list akin to an "Item Inventory" and presented in a panel for easy selection by the user. Once selected, the user can drag them from the panel and place them into the virtual building layout, using a translucent reference model as a placement scaffold. Planning milestones align with the building levels shown in the panel (Basement, Floor 1, and Roof). After selecting a deliverable (Fig. 4a), the learner navigates the environment during a virtual walkthrough to reach the target location (Fig. 4b) and then places the deliverable at its designated position (Fig. 4c). The task is completed by repeating this select–navigate–place loop until all work packages are closed. Each deliverable is associated with a WBS position and a spatial target; progress requires correct sequencing and correct placement.



(a) selecting a deliverable from the Item Inventory

(b) navigating to the target location

(c) placing the deliverable at the correct location

(d) the learner placing the deliverable

Figure 1. Interactive planning task in VR

During placement, the system enforces Finish-to-Start constraints and location validity. If a learner attempts to place a deliverable out of sequence or at an invalid location, the system rejects the action, and the object remains unplaced. This forces precedence- and location-consistent decisions, keeping the sequence aligned with constructability rather than trial-and-error. Valid placements lock the object into the layout and trigger a brief confirmation cue. Milestone completion is indicated by an operational notification when the learner closes work packages in the WBS panel. The meanings of object categories and hierarchies follow the cue mappings defined in Table 1 in the Appendix.

The case example implements a WBS sequencing exercise as a VR planning task that requires learners to coordinate spatial placement with temporal precedence. The WBS defines the work packages by dividing them into explicit deliverables and milestones, while the translucent reference model provides a consistent spatial scaffold for locating each deliverable in the 3D layout. Vibrotactile cues confirm selection and placement and provide distinct haptic patterns for component category and hierarchy during decision-making. The platform enforces precedence and location constraints by rejecting invalid placements and withholding confirmation when conditions are not met, encouraging logic-driven sequencing and constructability. This design yields a standardized, instrumental training workflow suitable for subsequent evaluation of effects on performance and perceived workload.

3.6 Experiment design

A subsequent phase will rigorously evaluate the proposed haptic-guided VR training approach by quantifying its effects on learning performance, engagement, and cognitive load in a construction education context. Using a controlled pre-/post-test, engineering students will be randomly assigned (1:1) to either a VR + haptics environment or a traditional 2D annotated-drawings condition and will complete the same WBS-based sequencing task. Prior to the intervention, participants will complete baseline measures, including demographics and background information, prior VR exposure, a spatial ability assessment, and a VR-specific motion-sickness screening. During the task, learning performance will be captured via sequencing accuracy and task completion time. After the task, participants will complete post-task assessments, including working memory capacity test, perceived workload (NASA-TLX), perceived usability, and engagement with VR/haptics-specific items. These measures will generate empirical evidence of instructional impact and provide a direct benchmark of the haptic-VR approach against conventional sequencing instruction used in construction engineering education.

3.6 Course integration

As a final outcome, DigiTouch will be proposed for integration into the *Construction Planning and Scheduling* course as a lecture–lab module aligned with the first-month units: (1) Introduction and setting up a schedule, (2) activity types and logic (durations, floats, lags, relationship types), and (3) scheduling computations (WBS, forward/backward pass, critical path method (CPM)). This integration supports core scheduling objectives: constructing a WBS, defining precedence relationships, generating an executable sequence, and validating network and CPM logic through spatially grounded constructability reasoning.

DigiTouch will be deployed after core instruction to help students operationalize spatiotemporal relationships among building elements and to test sequencing logic through embodied interaction. Training is intentionally brief to fit within class time: a 5-minute orientation (task goals, safety, and problem statement) followed by a 10-minute guided VR tutorial covering the select–navigate–place workflow and interpretation of operational (confirm/notify) and functional (category/hierarchy) haptic cues. The practice consists of a 20-minute VR lab exercise delivered at the end of the first-month module. Students apply course content by translating activity relationships into an executable WBS-driven sequence (see 3.5 Case example). The VR activity serves as a validation step for precedence logic: operational haptics indicate Finish-to-Start violations, and functional haptics reinforce component category and hierarchy at key decision points, while the system logs each action to generate a sequence trace. Performance outputs, such as sequencing accuracy and completion time, and feasibility measures (training time, throughput given one to two users per setup, and instructor support requirements) will be documented to inform discussion of instructional value and practical trade-offs for curriculum adoption.

4. CONCLUSION

This paper presents DigiTouch, a VR training platform that frames construction planning as an interactive, multisensory learning task. The platform addresses a persistent challenge in CEM education: interpreting spatial–temporal meaning from design representations when defining activity sequences, constraints, and hierarchies. DigiTouch addresses this challenge by coupling a BIM-derived virtual environment with WBS categories and a vibrotactile code, enabling learners to receive synchronized visual and tactile information while acting on planning deliverables.

The contribution of this phase is a concrete method for embedding planning semantics into interaction. BIM/IFC data are decomposed into deliverable-level VR objects that carry WBS attributes, creating a direct correspondence between what learners manipulate in VR and how deliverables are represented in planning practice. Visual and vibrotactile cues are designed to complement each other. Visual scaffolds support spatial inspection and decision-making through the translucent reference model and the deliverable-based WBS panel. Vibrotactile cues are delivered at key interaction points (selection, interpretation, navigation, and placement) to support reasoning and reduce the need for additional visual search. Accordingly, the vibrotactile code functions as a guidance and semantic layer rather than a generic alerting mechanism. Operational cues provide real-time guidance by indicating system state and assessing user actions (e.g., confirmation, correction, or notification), whereas functional cues encode planning meaning by mapping each deliverable's WBS category, hierarchy level, and sequence position to a fixed set of vibrotactile patterns.

To remain scalable and learnable, the mapping uses a perceived-heaviness ordering and a canonical pattern set, normalized and parameterized to reduce masking as the number of elements grows. The task logic further enforces precedence and location constraints, ensuring progress depends on reasoning about sequencing and hierarchy. A typical commercial facility case example illustrates how these elements combine into a repeatable training workflow.

The immediate outcome of this work is a validated platform architecture, a WBS-to-haptic assignment scheme (Table 1), and a training task structure suitable for controlled evaluation. The next phase will deploy the platform in a pre- and post-test study to assess how haptic-guided VR training improves sequencing accuracy and efficiency, reduces perceived workload relative to traditional 2D planning tasks, and captures engagement and learner reflections.

Looking ahead, we will extend DigiTouch beyond a lab prototype by proposing its integration into a Construction Planning and Scheduling course as supportive VR-based lab activities. These modules will reinforce early scheduling topics, such as WBS sequencing and network and precedence logic, by having students apply course concepts in an interactive VR environment with visual and haptic cues. This classroom deployment will allow us to evaluate instructional impact and practical feasibility in an educational setting.

Key limitations should be acknowledged before classroom integration. First, immersive VR can trigger motion sickness, eye strain, or fatigue for some learners, which may affect performance and limit participation. Second, the current prototype is not yet plug-and-play; it requires specialized expertise to implement and maintain, including BIM/IFC preprocessing, Unity development, and haptic integration. Third, scalability is constrained by the small-lab setup, typically supporting only one or two students at a time, and by equipment costs (VR headsets and wearable haptics), which may hinder broader classroom adoption.

DigiTouch positions multisensory HCI as a practical instructional mechanism for strengthening representational competence in CEM—specifically, the ability to connect WBS semantics, precedence constraints, and spatial constructability into an executable plan. By embedding planning meaning directly into learner interaction through synchronized visual scaffolds and a structured vibrotactile code, the platform moves beyond “technology novelty” toward a repeatable training approach grounded in how sequencing decisions are actually made. As construction practice continues to shift toward model-centric delivery and digital-twin workflows, such multimodal guidance may help learners develop faster, more reliable intuition for spatial–temporal constraints. The next phases—controlled evaluation and course deployment—will determine the magnitude of learning benefits and define the practical conditions required for scalable adoption in construction engineering education.

5. ACKNOWLEDGEMENTS

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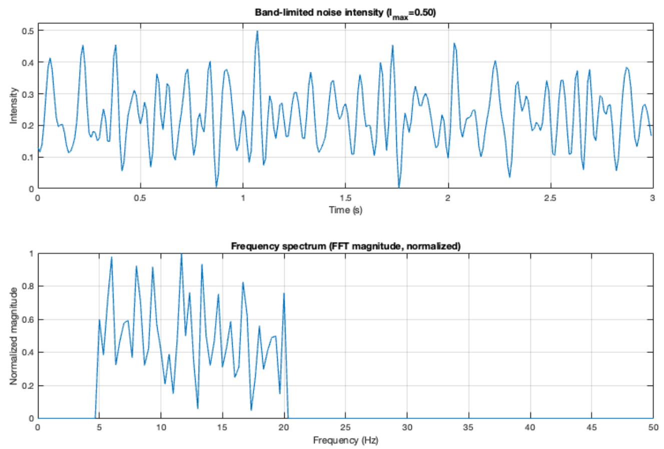
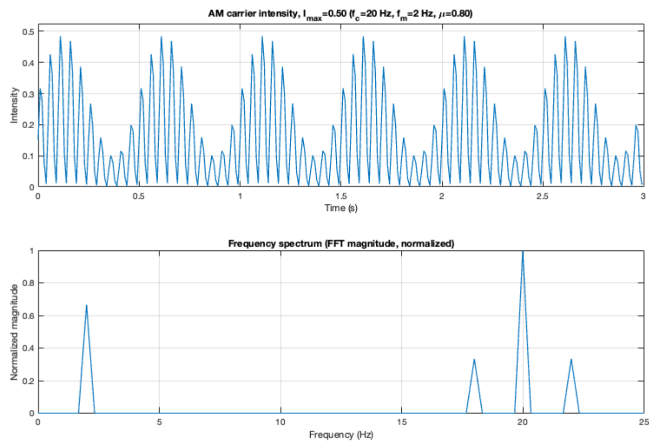
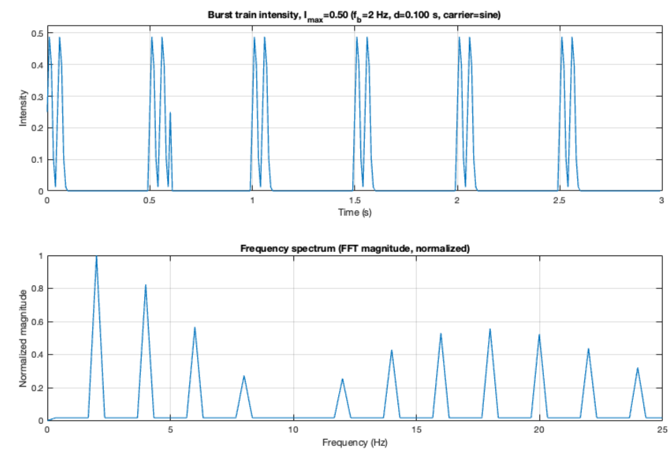
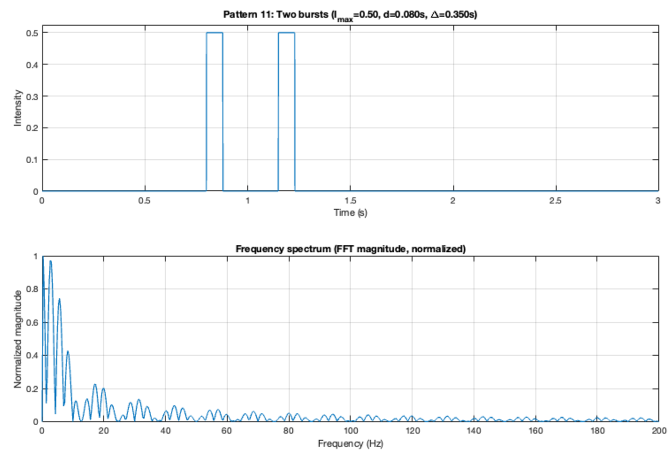
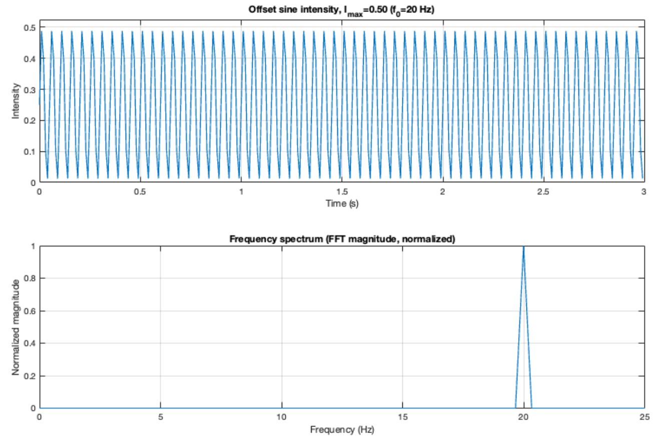
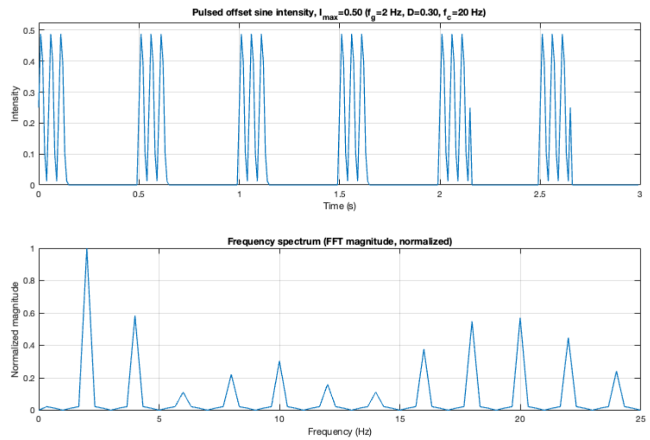
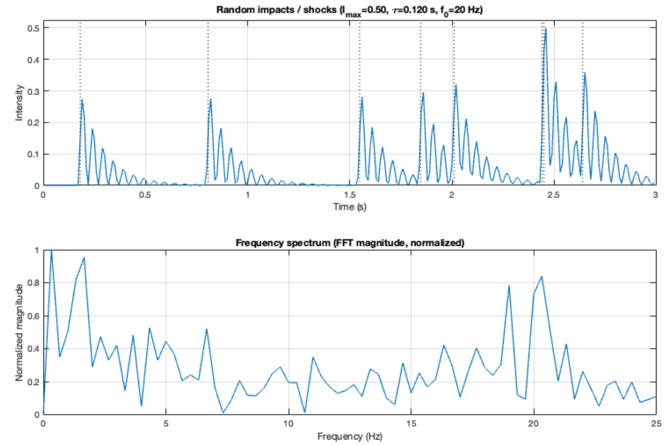
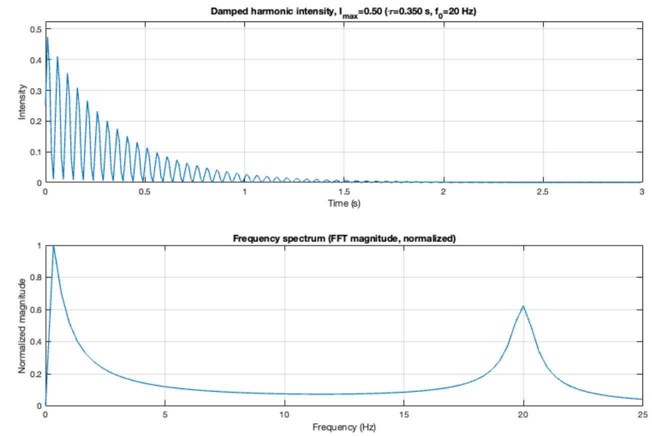
Appendix A

Table 1. WBS category to vibrotactile pattern mapping with thumbnails

N	WBS category	Example deliverables	Functional pattern name	Pattern thumbnail
1	**Grounding, Foundation**	Footings, mat foundations, pile caps, grade beams, basement walls, foundation slabs, subgrade slabs, foundation waterproofing layers, foundation drainage	**Band-limited noise (texture / roughness)** Noise is generated and band-pass filtered: $x[n] = (h_{BP} * \eta)[n], \eta[n] \sim \mathcal{U}(-1,1).$ Normalized intensity: $I[n] = I_{\max} \frac{x[n] - \min_k x[k]}{\max_k x[k] - \min_k x[k]}.$ Parameters: $(f_L, f_H, \Delta t, N)$ Perceptual descriptor: continuous rough texture.	
2	**Vertical Load-Bearing Structure**	Columns (steel, RC), piers, load-bearing concrete walls, structural cores, column base plates	**Amplitude-modulated carrier (AM texture)** Carrier and envelope: $c(t) = \frac{1 + \sin(2\pi f_c t + \phi_c)}{2}, e(t)$ $= (1-\mu) + \mu \frac{1 + \sin(2\pi f_m t + \phi_m)}{2},$ with $g(t) = 1$. Parameters: $(f_c, f_m, \mu, \phi_c, \phi_m)$ Perceptual descriptor: pulsating / textured vibration.	

3	**Horizontal Structural Framing**	Beams, girders, slabs, metal deck, roof deck, transfer beams, precast planks, structural topping slabs	**Burst train (discrete events)** Gate as periodic bursts of duration d every $T_b = 1/f_b$: $g(t) = \mathbf{1}((t \bmod T_b) < d), e(t) = 1.$ Carrier (either vibrotactile sine or binary carrier): $c(t) = \frac{1 + \sin(2\pi f_c t + \phi)}{2}$ or $c(t) = 1.$ Parameters: (f_b, d, f_c, ϕ) Perceptual descriptor: countable taps / bursts.	
4	**Building Envelope**	Exterior walls, infill walls, CMU backup walls, curtain wall framing, facade panels, parapets, insulation layers, air/vapor barriers	**Two-burst rhythmic signature** Two discrete bursts (binary gate), no carrier needed: $g(t) = \sum_{k=1}^{2} \mathbf{1}(t \in [t_k, t_k + d)), e(t) = 1, c(t) = 1$ Intensity: $I(t) = I_{\max}\, g(t),\ \ I_{\max} = 0.5$ Parameters: (t_1, t_2, d)(or $(t_1, \Delta = t_2 - t_1, d)$) Perceptual descriptor: two countable taps / confirmation cue.	

5	**Openings & Thresholds**	Windows, glazed panels, storefront systems, exterior doors, service doors, louvers, overhead doors, skylights	**Offset sine (steady harmonic)** $$g(t) = 1, e(t) = 1, c(t) = \frac{1 + \sin(2\pi f_0 t + \phi)}{2}.$$ Parameters: (f_0, ϕ) Perceptual descriptor**:** steady vibration.	
6	**Circulation Systems**	Stairs, stair landings, ramps, elevators, lifts, ladders, accessible routes, guardrails	**Pulsed offset sine (ON/OFF gating)** Periodic gating with period $T_g = 1/f_g$ and duty cycle $D \in (0,1]$: $$g(t) = \mathbf{1}\left((t \bmod T_g) < D\,T_g\right),$$ $$c(t) = \frac{1 + \sin(2\pi f_c t + \phi)}{2}, e(t) = 1.$$ Parameters**:** (f_g, D, f_c, ϕ) Perceptual descriptor**:** intermittent vibration.	

7	**Building Services (MEP)**	HVAC units, ducts, diffusers, plumbing pipes, fixtures, electrical conduits, panels, lighting systems, fire protection piping	**Random impacts / shocks (stochastic transients)** Impacts occur at times $\{t_i\}$. Each impact is a decaying oscillatory transient: $$p_i(t) = \mathbf{1}(t \geq t_i)\, e^{-(t-t_i)/\tau}\, \frac{1+\sin\left(2\pi f_0 (t-t_i)+\phi\right)}{2}.$$ Summed and normalized: $$I(t) = I_{\max} \frac{\sum_i p_i(t)}{\max_t \sum_i p_i(t)}.$$ Parameters: (t_i, τ, f_0, ϕ) Perceptual descriptor**:** sporadic impacts / shocks.	
8	**Finishes & Interface Surfaces**	Floor finishes, ceiling systems, wall finishes, paint, tiles, VCT, acoustic panels, facade finishes, trims	**Damped harmonic (free decay)** $$g(t) = 1, e(t) = e^{-\frac{t}{\tau}},$$ $$c(t) = \frac{1+\sin\left(2\pi f_0 t+\phi\right)}{2}.$$ Parameters: (τ, f_0, ϕ) Perceptual descriptor**:** sharp onset with exponential decay.	
	NOTES All functional patterns are generated as a bounded intensity signal and then sampled for playback: $$I(t) = I_{\max} \operatorname{clip}\left(g(t)\, e(t)\, c(t), 0, 1\right), I_{\max} = 0.5.$$ For discrete-time implementation, $t = n\Delta t$and $I[n] = I(n\Delta t),\ n = 0, \ldots, N-1$.			

Parameters:

- $c(t) \in [0,1]$: nonnegative carrier (texture source), e.g., offset sine.
- $g(t) \in [0,1]$: gate / event schedule (continuous, pulsed, bursts, impulses).
- $e(t) \in [0,1]$: envelope (decay, AM modulation, etc.).
- $\mathrm{clip}(\cdot)$: bounds intensity to $[0, 1]$prior to scaling by $I_{\max}$.

All patterns are amplitude-limited via $\mathrm{clip}(\cdot)$and scaled by $I_{\max} = 0.5$ to standardize intensity across categories.

Differences between pattern families are therefore primarily expressed through temporal structure (gating/envelope) and spectral content (carrier/noise).