IEDS: Exploring an Intelli-Embodied Design Space Combining Designer, AR, and GAI to Support Industrial Conceptual Design

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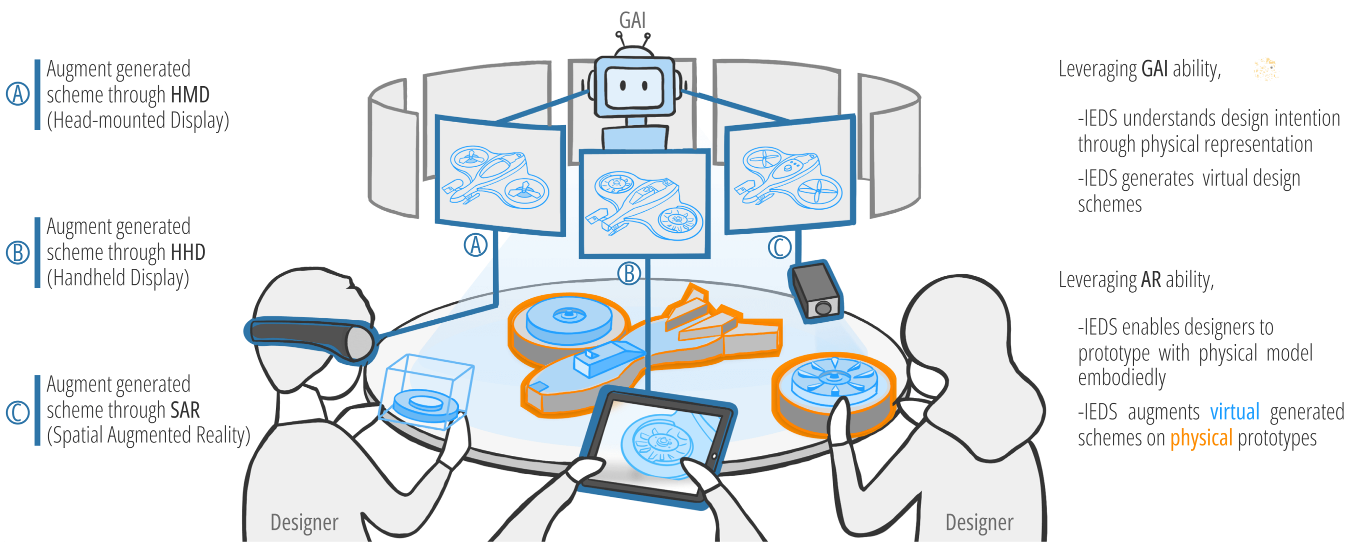

Figure 1: The introduction of Intelli-Embodied Design Space (IEDS). In IEDS, designers can simultaneously view and interact with both physical and virtual prototypes in a natural and intuitive manner. By leveraging GAI, IEDS first interprets design intentions from designers' physical design representations and textual requirements, then refines them into virtual forms. By integrating AR, IEDS can embed these generated visual forms into the physical world.

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Abstract

Conceptual design is an important stage in industrial product development, influenced by the design space and materials available to designers. Advancements in human-computer interaction (HCI) and artificial intelligence (AI) technologies have broadened these aspects considerably. On the one hand, augmented reality (AR) technologies merge physical and virtual representations to enhance intuitive interaction and embodied cognition. On the other hand, generative artificial intelligence (GAI) serves as a novel design material, boosting creativity and productivity. Inspired by these technological strides, we proposed an Intelli-Embodied Design Space (IEDS), which integrates designers, AR, and GAI to support industrial conceptual design by combining embodied interaction with generative variability. Within IEDS, designers can interact with the physical prototypes intuitively, while GAI refines these into virtual forms that can be embedded in the physical world through AR technology. In this study, we established the theoretical framework and interaction modes of IEDS through literature reviews and expert interviews. Subsequently, we designed and implemented three GAI+AR tools, GAI + Head-mounted Display (HMD), GAI + Handheld Display (HHD), and GAI + Spatial Augmented Reality (SAR), based on three AR approaches in IEDS to practically examine the benefits and challenges of these interaction modes across industrial conceptual design tasks. We discussed IEDS's influence on industrial conceptual design and released its application guidelines to the HCI community.

CCS Concepts

• **Human-centered computing → Interactive systems and tools**; **Mixed / augmented reality**.

Keywords

conceptual design, augmented reality, generative AI

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1 Introduction

Conceptual design is one of the most critical stages in industrial product development, typically responsible for 60-80% of development costs [37, 51]. It is crucial for design success because designers explore, evaluate, and select an overall product concept to pursue [9, 47]. In conceptual design, the design space, including the design representation display and external environment, affects designers' cognition and perception [68]. The visual and spatial design representation shapes how designers perceive and interpret design problems and solutions they face. Besides, the design materials, containing the design tools and prototypes, influence designers' creative modes and production efficiency [29]. The availability of these design materials can impact how effectively designers can create, test, and iterate on their ideas. In this sense, designers' thinking can be significantly enhanced if the expanded design space provides a more intuitive design representation and the innovative design materials optimize the traditional creative flow.

The expanded design space containing both physical and virtual objects is considered an interactive environment, which can enhance intuitive perception and promote embodied cognition [121]. As findings in cognitive science and psychology show that body movement can be part of thinking, the physical form of design information can augment the way designers think and create through body-based cognition — beyond the graphical display [69, 151]. This is because the physical design representation enables a richer and more intuitive way of exploring, manipulating, testing, and sharing ideas through bodies and physical space, which has the potential to enhance creativity during conceptual design [133]. Motivated by these theoretical foundations, the HCI community has paid attention to expanding the virtual interface and integrating computational media with the physical environment [134]. Among them, utilizing augmented reality (AR) technology is a mainstream method to tightly combine physical and virtual design representations, superposing the inherent strengths of both physical and virtual design space [121].

Artificial intelligence (AI) is now a fairly established technology, serving as the new design material for design practitioners [29, 162]. Especially with the recent advances in generative artificial intelligence (GAI), its integration within design tools and design space is burgeoning. As a novel design material, GAI has transformed the designer-centered paradigm of industrial conceptual design. First, GAI has shown proficiency in generating high-quality design schemes indistinguishable from human-created artifacts [145]. It has changed the traditional creation mode and allowed designers to create design schemes through natural language instead of complex manipulation, improving the efficiency of idea exploration. Second, GAI provides design inspiration or insights based on the capability of understanding commonsense, as well as offers unpredictable design schemes based on generative variability [126]. In this sense, GAI can act as a design partner, leveraging knowledge and offering multi-perspective connections, while the human designer acts as a design manager, providing direction to the conceptual design. The diverse and decentralized design roles might enrich the ideation process.

As integrating physical representation in design space and utilizing GAI as a new design material brought new possibilities for design, we aim to explore a novel design space based on designers' embodied cognition and GAI's generative ability. By combining the rich expressivity of physical representation with the generative variability, designers might think and design within the novel design space in unprecedented ways — just as computers and graphic displays have changed the way designers create in the past [133]. In this sense, we proposed an Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support conceptual design. In such a design space, designers can see physical prototypes and interact with the physical environment naturally and intuitively. GAI can first understand design intention through concrete physical design representation and textual requirements, then refine them into virtual forms that can be embedded in the physical world through AR technology. IEDS not only reduces designers' cognitive load and augments their thinking through an embodied design space but also enriches the ideation process and opens up an imaginary space through GAI generation.

2 Scope, Methodology, and Contribution

2.1 Scope and Definition

The topic covered by this study is IEDS combining designer, AR, and GAI to support industrial conceptual design. In this section, we narrow our concrete scope and definition.

2.1.1 Industrial Conceptual Design. The focus stage in this paper is regarded as the process of identifying the design problem and exploring potential design solutions in industrial product development, in which designers need to deepen the design problem, specify main functions, establish basic structures, and select appropriate principles to evaluate and implement [25]. Therefore, we focus on the exploration process, which proposes potentially feasible design concepts.

2.1.2 AR Scope. The definition of AR can vary according to context [124]. Azuma et al. [8] defined that AR has to satisfy three conditions: a combination of reality and virtuality, real-time interaction, and a 3D real world. In this study, referring to Suzuki et al. [134], we take AR as a broader scope and include any system that augments physical objects or surrounding environments in the real world regardless of the technology used.

2.1.3 GAI Scope. This paper examines GAI as computational techniques capable of generating novel and plausible media, distinguishing them from methods that primarily rely on data for labeling and classification [92]. Specifically, this study focuses on neural network-based generative techniques, such as generative adversarial networks [64] and diffusion models [112], which are characterized by a large number of parameters that enable them to capture intricate features within datasets. In addition, to better integrate a hybrid design space, we pay more attention to visual generative methods instead of language-based generative techniques.

2.2 Workflow and Methodology

We proposed and explored an IEDS by combining theoretical and practical work (Figure 2). Initially, we conducted a systematic review of 113 papers, combining a comprehensive search with expert evaluation to extract the common principles of AR and GAI applications in industrial design. From this review, we identified key interaction methods, implementation principles, and application values of both AR and GAI in the industrial design process. We then conducted semi-structured interviews with four experts possessing extensive experience in AR and GAI to gather their insights on the combination of designer, AR, and GAI in a design space. Building upon these theoretical proposals, we designed and implemented three GAI+AR tools in IEDS. We also conducted an open-ended design workshop with 27 participants under IEDS's support. We asked designers to complete various industrial design tasks under the IEDS support and collected their feedback related to IEDS opportunities and challenges. Eventually, we proposed application guidelines for IEDS, outlining its potential vision and future applications of GAI and AR integration.

2.3 Contribution

We provided the following contributions. First, we proposed the novel concept of Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support industrial conceptual design. IEDS allows industrial designers to leverage embodied interaction with the physical environment while gaining creativity from generated artifacts. Second, we designed and developed IEDS systems that combine AR and GAI. Third, we conducted a practical user study and proposed new insights into IEDS application guidelines, especially the opportunities and challenges of the AR and GAI combination in conceptual design.

3 Theoretical Background

As we drew inspiration from both embodied design representation and generative ability, we introduced the influence of design space containing physical representation and the influence of design materials with GAI on conceptual design.

3.1 Design Space Containing Physical Design Representation

In addition to verbal and textual expression for design, the industrial conceptual design process involves the manipulation and modification of external representations, also referred to as design representation [101]. It plays an important role in conceptual design because it allows designers to encode information to easily handle complex problems and serve as a long-term memory, as well as free their cognitive memory and facilitate ideation [14]. These design representations assist designers in representing their ideas and provide examples as stimuli for inspiration [6]. As Kirsh indicated cognitive processes flow to wherever it is cheaper to perform them, the information representation modes are a way of changing the cognition domain and range [68].

The physical design representations, such as foam prototypes, paper shell models, and clay molds, offer distinct advantages in facilitating industrial design ideation. First, these physical prototypes promote design exploration. Physical forms of information increase the number of sensorial stimuli, such as touch, sight, and smell, compared to paper containing texts and images [42]. Therefore, there is a surge in the available design information for analogy, which is beneficial for spatial relationship reasoning, hidden features perception, and unexpected insights discovery [43]. Second, the physical form supports design analysis. The physical environment allows designers to perceive and analyze design concepts in a tangible form instead of processing steps in their minds. It supports faster decision-making in the cognitive process because the more rules are distributed in the external representation, the easier it is to solve the problem [54]. Third, the physical object enhances design communication and collaboration. The tangible prototype provides a concrete anchor for discussion to occur [70]. It allows more seamless collaboration among designers since all people can manipulate the artifact and see the action result immediately and simultaneously [28]. These physical artifacts can serve as shared objects of thought and an essential medium for collaboration [68].

3.2 Design Material Integrating GAI

As GAI has become an increasingly established technology, designers now serve it as a novel design material to think and create [29, 162]. Recent advances in deep generative models have enabled the rapid production of high-quality multimodal content that is indistinguishable from human-generated work, thereby driving significant progress in the integration of GAI into conceptual design. Previous studies have shown that GAI excels in supporting ideation [139], assisting prototype [41], stimulating inspiration [20], facilitating design reasoning [126], and advising iteration [76].

Based on the GAI's strong abilities, its participation is poised to fundamentally change traditional design materials. First, the interactive way of creation can be changed. The chat-like interfaces provided by GAI platforms like Bard [84] or ChatGPT [98] allow

STEPS	METHODS	OUTCOMES
■ IEDS Proposal *Section 4*	**Literature Review** Conducting systematic search and expertise review related to "GAI+Design" and "AR + Design".	**Common Principles** A corpus of 113 papers and common interaction methods of both AR and GAI in design.
	Expert Interview Communicating with experts possessing extensive experience with both AR and GAI.	**Experts' Insights** Insights on combination of AR and GAI in a hybrid design space.
□ IEDS Design & Implementation *Section 5*	**-** Designing and implementing three GAI+AR tools based on three AR approaches and extracted theoretical findings.	**Design Systems** Practical hybrid design systems combining AR and GAI.
□ IEDS Open-ended Exploration *Section 6*	**Design Workshop** Inviting participants to design under the IEDS support, collecting their design experience feedback through interview.	**Application Guidelines** Clarification of strengths, limitations, and practical guidelines in IEDS.

■ theoretical work □ practical work

Figure 2: Workflow, methodology, and outcome in this study.

designers to create design schemes through their natural language, often in their mother tongue. This significantly reduces the design threshold, allowing design members without hand-drawing and modeling skills to participate in design innovation. Second, the modalities that designers perceive in design space can be richer. In traditional design platforms or tools, the perceptible design modalities are often constrained by the capabilities and formatting parameters inherent to the platform. For instance, designers cannot create 3D representations within 2D sketch software. However, with the generative ability of GAI, designers can utilize various generative models to effortlessly obtain multi-modal design information [79]. It enables a richer and more effective way of exploring, expressing, and manipulating ideas in design space. Third, the design roles in the design space become more diverse. GAI's variability allows it to contribute insights and suggestions that might not be immediately apparent to human designers [126]. In addition, it supports designers in efficiently gathering knowledge from fields outside their personal experience through data-enabled generation, enriching the ideation process [126].

4 IEDS Proposal

4.1 The Scope of IEDS

Based on the above theoretical viewpoints, we aimed to propose initial IEDS features. We expect the IEDS to have the following capabilities:

- allowing designers to interact directly with physical representations, including the physical environment, objects, materials, and prototypes.
- enabling GAI to understand designers' intentions according to physical representations and provide generated artifacts.
- coupling the GAI-generated artifacts with the physical design representation tightly in a hybrid design space through AR techniques.

To complete this concept, we first conducted a literature review to collect common interaction guidelines on how to utilize AR and GAI in supporting industrial conceptual design. Second, based on these common principles, we organized expert interviews to summarize expertise insights on the combination of AR and GAI in a hybrid design space.

4.2 Part I: Survey of Literature Review

We initiated a comprehensive review of existing literature on AR+ Design and GAI+Design respectively. For the dataset and inclusion criteria, we completed a systematic search and an expertise review. Initially, we conducted a systematic search in the ACM Digital Library, IEEE Xplore, Springer, Elsevier, and Taylor & Francis. For the AR+Design, our search terms included the combination of "*augment reality*" AND "*design*" in the title AND/OR author keywords since 2010. For the GAI+Design, our search terms included the combination of "*generative artificial intelligence*" AND "*design*" in the title AND/OR author keywords. As GAI was a relatively new research field, the publishing time started in 2020. This gave us a total of 800 articles related to GAI+Design and 582 articles related to AR+Design. Then, four authors individually looked at each paper to select papers strongly related to our topic and excluded out-of-scope papers. First, papers unrelated to design fields were excluded. For instance, in many paper titles, 'design' is used as a verb (e.g., 'to design a XXX'), rather than referring to the design domain. Second, we focused on research articles, the reviews and comments were not considered. Third, as we focused on the technology application from the HCI lens, some technology-oriented papers were withdrawn. For example, some AR papers related to augmenting techniques, such as optics and reconstruction algorithms, instead of the interaction perspectives. All withdrawn papers were browsed by four authors, and the disputes were settled and unified. After this process, we obtained 11 strongly related papers for GAI+Design and 16 for AR+Design.

Additionally, we conducted an expertise review to complement the systematic search. Specifically, four authors reviewed several top-tier journals and conferences in both design and HCI fields, including *CHI*, *UIST*, *TOCHI*, *IJHCS*, *HCI*, *Design Studies*, and *The Design Journal*, to avoid ignoring papers whose titles do not contain the above keywords, but whose contents are strongly related to our topic. Consistent with the systematic search, in the expertise review, the scope of consideration for AR-related papers began in 2010, and GAI-related papers began in 2020. After four authors discussed and cleared up their differences, we supplemented 55 GAI+Design papers and 35 AR+Design papers. Eventually, by merging these papers and removing duplicates, we finally selected a corpus of 113 papers (Appendix A), including 64 for GAI+Design and 49 for AR+Design, for our further analysis.

For the analysis and synthesis, four authors conducted open coding on a small subset of our sample to identify the dimensions and categories of the application of AR and GAI in the design space. All authors reflected upon the initial code classification to discuss the consistency and comprehensiveness of the categorization methods, and then categories were merged, expanded, and removed. Next, all authors performed the coding process and completed classification after discussion and disagreement elimination. We focused more on the industrial design or product design domain to narrow our focus. Therefore, although we reviewed papers related to all design domains for comprehensive understanding, we only showed codes tightly related to industrial design in this paper. We visualize the coding results of the literature review in Figure 3 and 4 and elaborate details in the following section.

4.2.1 Potential GAI interaction in industrial conceptual design . In related articles, we focused on the AI Application Purpose (AP), Human-to-AI Communication Mode (HM), AI-to-Human Communication Mode (AM), Participation Style (PS), Task Distribution (TD), and AI Role (RO).

- For the AI application purpose, most of the studies integrated the generation ability in order to *stimulate creativity* (AP1) [23, 88], *customization* (AP2) [30, 44], *automate tasks* (AP3) [20, 148], *improve efficiency & optimize processes* (AP4) [116, 122], and *facilitate collaboration & improve team synergy* (AP5) [39, 71].
- For the Human-to-AI Communication Modes (HM): We coded human users' input information and interaction modes to GAI here. Undoubtedly, the most common human-to-AI interaction is to directly input design requirements through *text* (HM1) [35, 146], part of which supports *voice input* (HM2) [67, 77]. *Sketch and graffiti* (HM3) [81, 160] are also one of the common input methods. Some systems supported to specify the design requirement in the *structured relationship* (HM4), such as the semantic map [161], bounding box [50], and graph-based network [3]. In addition, for some systems that support complex design requirements and fine editing, the functions of *direct editing and manipulation* (HM5) are developed, mainly including direct mouse drag and drop [44] and graphical panel control [22]. Other human-to-AI communication modes also exist but are rarely involved in our corpus, including *3D model* (HM6) [36, 97], *3D sketch* (HM7) [115], *image* (HM8) [13, 20] and *body movement data* (HM9) [34, 173].
- For the AI-to-Human Communication Modes (AM): The modalities for AI-initiated communication are mainly supported or limited by the ability of the generative models in systems. Based on our coding, the textual and visual are the most common modalities in GAI's output. The textual information can be further divided into *text* (AM1) [119, 171] and *voice* (AM2) [34, 79], while the visual information can be divided into *image* (AM4) [122, 136] and *animation* (AM5) [3, 158]. With the development of the ability to generate models, the AI-to-human communication mode involved the multimodal outputs, such as *3D model* (AM3) [79, 173] and *stereo image* (AM6) [48, 115].
- For the Participation Style (PS): As defined in Rezwana and Maher [111], the participation style refers to whether the collaborators can participate and contribute simultaneously or one collaborator has to wait until the partner finishes a turn. We classified the participation style into *parallel-tasking* (PS1) [34, 168] and *turn-tasking* (PS2) [30, 117]. In parallel-tasking participation, continuous parallel participation from the human designers and GAI occurs, while in *turn-tasking* interaction, they take turns to create and contribute. In our corpus, the *turn-tasking* style is more common because designers often need to correct the next iterative direction and adjust the human-to-AI communication according to GAI's response and feedback.
- For the Task Distribution (TD): We paid attention to the distribution of tasks among the human designers and GAI. We coded two types of task distribution. First, when it is the *same task* (TD1) [12, 27], human designers and GAI take part in the same task without work division. This mode was usually utilized in painting or sketching systems, human designers and GAI create in the same canvas space. However, more systems adopted the *divided task* (TD2) mode. Designers usually put forward design requirements and constraints. GAI completes and executes subtasks, including reasoning tasks (e.g., brainstorming and divergent reasoning [144]) and implementing tasks (e.g., generating image schemes based on requirements [122]).
- For the AI Role (RO): We investigated the GAI contribution form and its influence on the design process, classifying GAI into several roles. First, the GAI can be a *stimulator* (RO1) in ideation, in which GAI provides multi-perspective and interdisciplinary knowledge, assisting design reasoning and enriching ideation. When GAI is a stimulator, the generated artifacts were mostly text [104], as well as a few visual modes, such as conceptual image [50] and style image [136]. Third, GAI can be an *analyzer or evaluator* (RO4) [36, 159] to perform in-depth analysis and evaluation of design schemes, helping designers identify potential flaws and highlight ignored issues. It is worth mentioning that we find that the AI role in a generative system is not unique, and diverse roles are switching based on design tasks and designers' demands.

4.2.2 Potential AR interaction in industrial conceptual design. In related articles, we focused on the AR Application Purpose (AP),

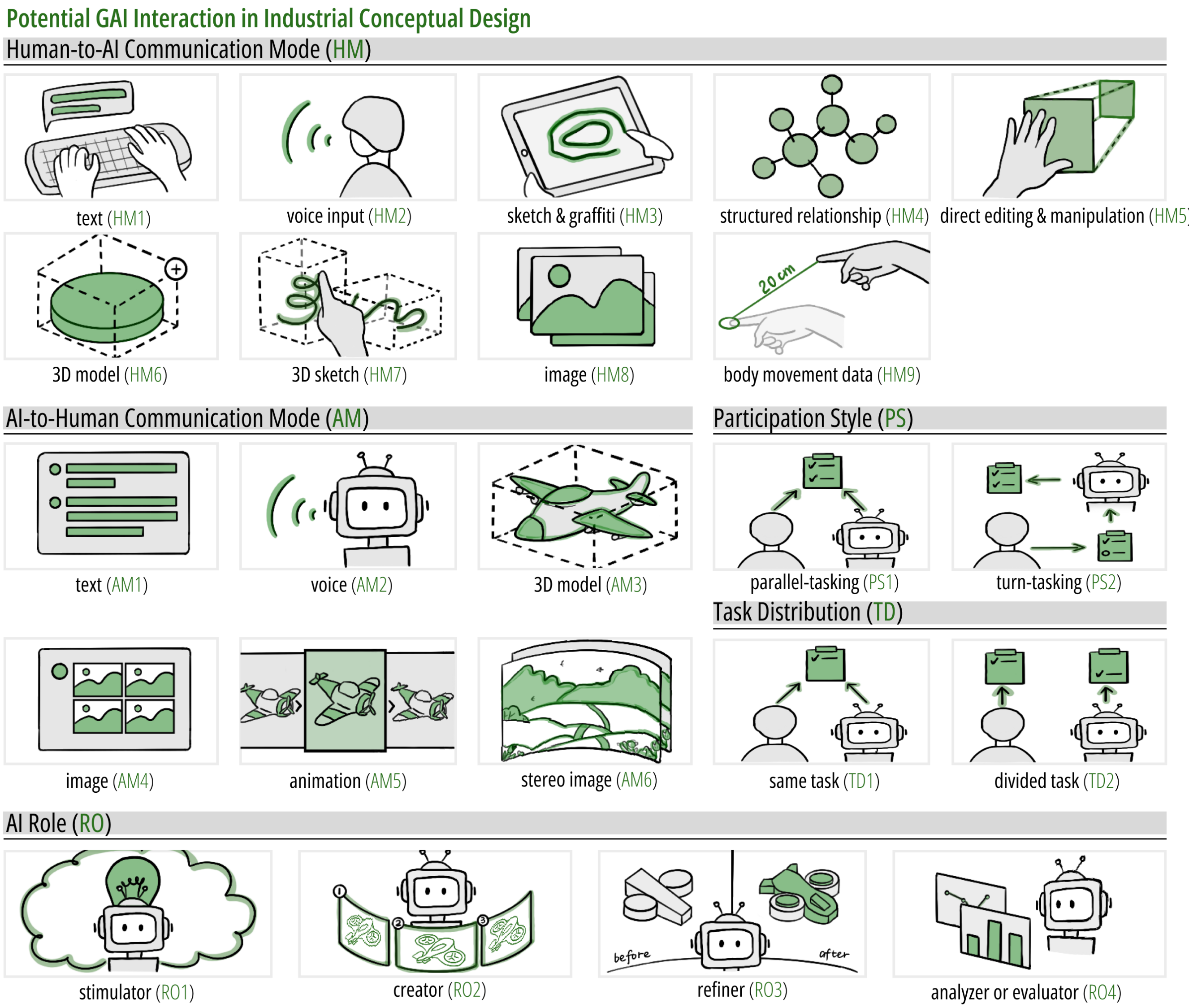


Figure 3: Extracted codes through literature review, which related to potential GAI interaction in industrial conceptual design.

Augment Information (IN), Augment Approach (AA), and Interaction Modality (IM).

- For the AR Application Purpose (AP): The AR application purpose mainly focused on *presenting rich information* (AP1) [66, 141], *supporting intuitive interaction and simulation* (AP2) [95, 127], *enhancing surrounding immersion* (AP3) [11, 66], *strengthening cooperation* (AP4) [53, 85], and *promoting rapid information access* (AP5) [93, 141].
- For the Augment Information (IN): We summarized the types of information presented through AR interfaces in the design process. The categories we identified include *design prototype and scheme* (IN1), *design simulation and plan* (IN2), *design environment information* (IN3), and *design supplementary information* (IN4). Specifically, most design systems using AR techniques augmented the design scheme information, including digital design schemes [72, 163], structural design [95, 106], and detail display [102, 143]. These augmented schemes ranged from low-fidelity to high-fidelity, as well as from 2D to 3D form. These virtual prototypes and schemes were coupled with physical objects or environments to represent rich design. Besides, some studies presented the *design simulation and plan*, emphasizing the simulation and visualization of dynamic motion [62, 147] or interactive simulation based on physical design [61, 89]. The *design environment information* presented supporting components or surroundings related to the physical design, such as

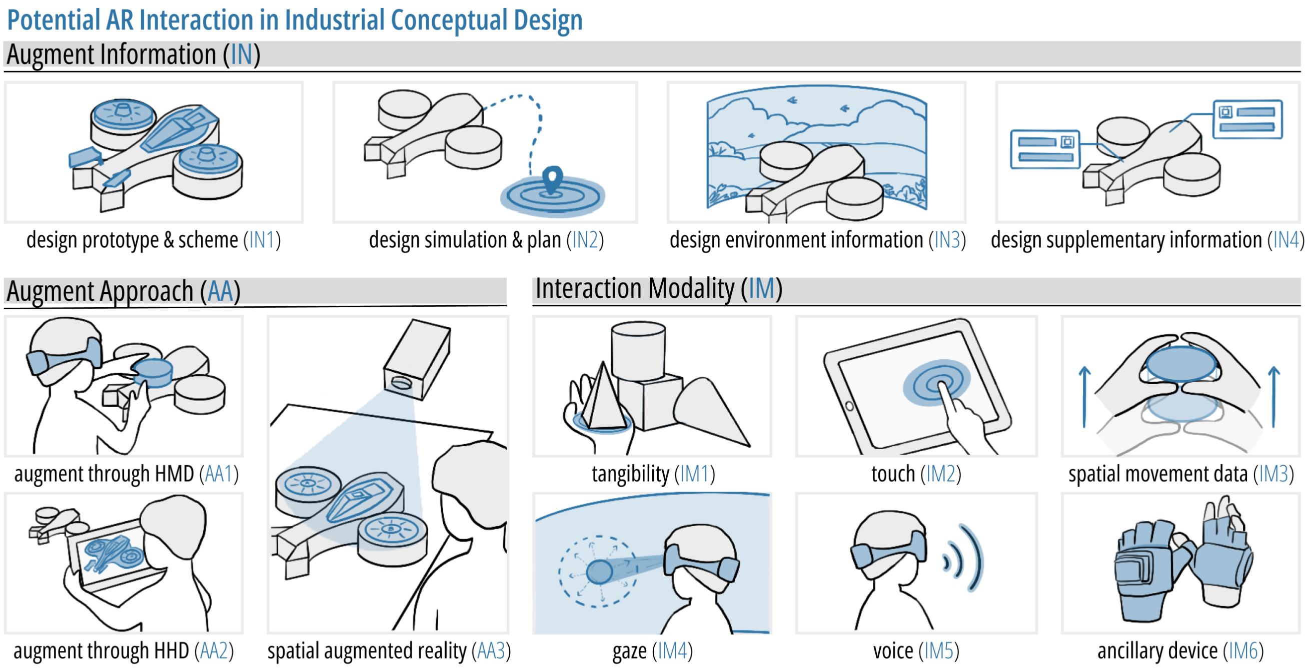


Figure 4: Extracted codes through literature review, which related to potential AR interaction in industrial conceptual design.

the reconstruction of the 3D environment and virtual background [11, 165]. The *design supplementary information* was mainly used to explain and clarify the additional information of the current design scheme, such as design notes [53] and comments [66, 141].

- For the Augment Approach (AA): We paid attention to how virtual information was enhanced in design space, that is, how physical and virtual information are coupled. First, the most widely used AR method is through head-mounted display devices (HMD), which can overlay virtual information directly onto the user's field of view, creating an immersive experience where virtual elements appear as part of the real world. We summarized that method as *augment through HMD* (AA1) [127, 129]. In addition, some studies utilized hand-held devices (HHD) to augment reality. These tools relied on the shooting capabilities of mobile devices, such as tablets or mobile phones, to capture the physical environment and overlay virtual information onto the live camera feed [137, 141]. We marked this method as *augment through HHD* (AA2). The third method was *spatial augmented reality* (AA3). Raskar et al. defined it as the projection of virtual content onto a physical object directly [109]. This method employed fixed or portable projectors to attach the virtual information onto the physical objects or environments [15, 174].
- For the Interaction Modality (IM): We investigated the interaction modality in AR studies in the design field. First, designers can interact with AR space through *tangibility* (IM1), in which they change the shape or physically deform the tangible object, such as tangible objects [128, 175] or physical prototypes [123, 143], which can be shaped or edited directly in the physical world. Second, in some AR systems augmented through HHD equipment, designers can interact with tablets or mobiles through *touch* interaction (IM2) [61, 91]. Third, the *spatial movement data* (IM3) was a common interaction modality for HMD-based interfaces, such as spatial gesture [106, 132, 175]. Designers can model and edit design schemes through gesture movement and interact with virtual menus. Other interactive modes were also involved, such as *gaze* (IM4) [4, 114] and *voice* [4] (IM5). These auxiliary input methods enabled designers to fully use their bodies, making the interaction more direct and immersive. Some studies also utilized ancillary devices to interact in AR space, such as smart gloves [21] and smart pens [5].

4.3 Part II: Expert Interview

Based on the extracted codes, we further organized a semi-structured interview with four experts. Our interview aimed to summarize more focused insights on the combination of AR and GAI in a hybrid design space.

4.3.1 Expert Background. Each of the four experts (E1-E4) has over 10 years of professional experience in AR interface research or development. They also have basic knowledge and rich experience using GAI in their design work. E1 is an AR interaction researcher at a famous mobile hardware research and development company currently working on intelligent HMD development. E2 is an AR interface design leader at an internet company. E2 is currently engaged in the combination of GAI ability and HoloLens application to support creative work. E3 is an assistant professor in the computer science college of a university. E3's research focuses on AR

STEPS	OUTLINES & QUESTIONS
S1: IEDS Proposal Introduction	Introduce IEDS concept and scope; Clarify IEDS features.
S2: Codes Introduction and Screen	Introduce a code and provide examples; Asking expert's attitudes towards the code: -Q1: "*Do you think this item is valuable for our proposed hybrid design space?*" -Q2: "*Where do you think its value lies, and what role does it play in that design space?*" -Q3: "*Do you think the lack of it will affect the design space?*" (repeat for all codes)
S3: Codes Review	Confirm all screening codes with the expert.
S4: IEDS Attitudes Collection	Ask expert for the attitudes and suggestions on the concept of IEDS: -Q1: "*Do you have any comments or suggestions on our concept of IEDS?*" -Q2: "*From your experience, what do you think we should pay attention to in integrating AI and AR in design?*" -Q3: "*What do you think are the challenges and difficulties in integrating AR and GAI in IEDS?*"

Figure 5: The procedure and outline of the expert semi-structured interview.

and its application in HCI. E4 is a co-founder of an AR technology company specializing in utilizing spatial augmented reality techniques to support product design.

4.3.2 Method. We invited all experts to participate in remote interviews with authors one by one. One of the authors was responsible for communication, and the other two were responsible for recording and summarizing the interview contents. During the interview, we initially introduced our theoretical background, research scope, and research vision to experts. Then we presented and explained our extracted codes from the literature review one by one. Experts were asked to discuss each code and evaluate its potential value or positive influence for a hybrid design space combining AR and GAI based on their knowledge and experience. We asked experts to critically discuss from the necessity perspective to help us screen each code effectively. The procedure and outline of the expert interview are presented in Figure 5.

For the code screen, two authors counted the code screening results of four experts. For experts' view summarization, the recordings of the interview were transcribed into text, and the two authors repeatedly read the transcripts to acquaint themselves with the interview data. Two authors extracted views strictly pertained to the semantic content of the interview data. For example, the statement "*the tangibility in IEDS might provide multi-sensory stimulation*" was summarized as "*enrich stimulation*". Two authors discussed and resolved disagreements for the final results.

4.3.3 Results and Findings. **Positive Attitudes to IEDS.** All four experts expressed their strong interest and positive attitude towards our IEDS vision. We summarized the potential strengths of IEDS mentioned by experts, which include *enriching stimulation* (E1-4), *increasing available design information* (E2, 4), *expanding imagination* (E1, 3, 4), *deepening ideation* (E1, E4), *making creation more free* (E1-3), *improving prototype efficiency* (E2-4), *making design immersive and intuitive* (E2-4), *breaking away from data modal constraints* (E2, 3), *enhancing GAI usability and friendliness* (E3), *promoting cooperation and communication* (E1, 2, 4). These positive feedback findings corroborate experts' favorable views on IEDS concept, thereby providing a foundation for further research.

Experts Insights for GAI Interaction in IEDS. On the GAI integration in IEDS. The *text* (HM1), *3D model* (HM6), and *image* (HM8) were regarded as necessary Human-to-AI communication modes. E1-4 all considered the textual information the most basic way to convey design requirements and restrictions. E1-3 believed that the 3D model was an effective way to convey design intention. Both the virtual model and physical model contained rich information, helping GAI to understand detailed intentions. Similarly, the *text* (AM1), *image* (AM4), and *3D model* (AM7) were regarded as important AI-to-human communication modes. The *turn-tasking* (PS2) and *divided task* (TD2) were extracted to the preferred participation style and task distribution mode respectively by all experts. Experts indicated that it helped designers enhance their control over GAI, dominated the ideation process, and controlled its rhythm. For the AI participation role, experts demonstrated that all kinds of roles were meaningful in design, especially the *stimulator* (RO1), *creator* (RO2), and *refiner* (RO3). Experts indicated that it would be best to switch roles according to the design tasks and stages.

Experts Insights for AR Interaction in IEDS. First, experts agreed on the augment information, in which they considered the *design prototype and scheme* (IN1) as the most basic and necessary information in conceptual design. In addition, although experts mentioned that the more interactive modes in an AR environment, the more natural and immersive the interaction, experts commonly thought that *tangibility* (IM1), *spatial movement data* (IM3), and *voice* (IM5) were the most indispensable interactive modes in IEDS. For the augmented approach, there are differences among experts, and they argue that various augmented approaches should coexist in IEDS. Specifically, E1 considered *augmenting through HMD* (AA1) was the most suitable approach because it was the mainstream AR mode at present and achieved immersion to the greatest extent. However, E3 indicated that the HMD equipment weight might reduce the friendliness in the practical design process. And E3

Table 1: Expert (E1-4) feedback on codes extracted through literature review. A check indicates that the expert assesses that the given item would be useful for IEDS.

		GAI+Design				
Category	Code	Description	E1	E2	E3	E4
Human-to-AI Communication Modes (HM)	HM1	text	•	•	•	•
	HM2	voice input	•		•	
	HM3	sketch and graffiti		•		
	HM4	structured relationship				
	HM5	direct editing & manipulation				
	HM6	3D model	•	•	•	
	HM7	3D sketch				
	HM8	image	•		•	•
	HM9	body movement data	•	•		
AI-to-Human Communication Modes (AM)	AM1	text	•	•	•	•
	AM2	voice				
	AM3	3D model	•		•	•
	AM4	image	•	•	•	•
	AM5	animation	•			
	AM6	stereo image		•		
Participation Style (PS)	PS1	parallel-tasking				
	PS2	turn-tasking	•	•	•	•
Task Distribution (TD)	TD1	same task				
	TD2	divided task	•	•	•	•
AI Role (RO)	RO1	stimulator	•	•	•	•
	RO2	creator	•		•	•
	RO3	refiner	•	•	•	•
	RO4	analyzer or evaluator			•	
		AR+Design				
Category	Code	Description	E1	E2	E3	E4
Augment Information(IN)	IN1	prototype and scheme	•	•	•	•
	IN2	simulation and plan	•			•
	IN3	environment information		•		•
	IN4	supplementary information				
Augment Approach (AA)	AA1	augment through HMD	•	•		
	AA2	augment through HHD		•	•	
	AA3	spatial augmented reality		•		•
Interaction Modality (IM)	IM1	tangibility	•	•	•	•
	IM2	touch				
	IM3	spatial movement data	•	•		•
	IM4	gaze		•		•
	IM5	voice	•	•	•	•
	IM6	ancillary device				

pointed out that *augment through HHD* (AA2) was the closest augment approach to the practical design work, which most naturally supported the conceptual design process. E4 argued that *spatial augmented reality* (AA3) was the most real interaction mode because designers could get what they see, while E2 acknowledged the value and benefits of three augment approaches. All experts agreed that different augment approaches had their application scope and they should all be supported in IEDS.

4.4 Brief Summary for IEDS Concept Proposal

Following the theoretical findings, we clarified the IEDS concept and defined its interaction mechanism. Specifically, designers can input textual design intention through text and voice, as well as convey concrete requirements through physical objects embodied. The GAI will participate in the cooperation in the form of turn-tasking. GAI first understands designers' intentions through textual description and captured physical prototypes. Then GAI becomes the content creator and generates virtual schemes. The generated virtual artifacts can be embedded in the physical world through AR techniques. The augmented approaches should involve multiple AR approaches, including HMD, HHD, and SAR. The AR space containing physical and virtual prototypes provides rich spatial stimulation to designers.

5 IEDS Design and Implementation

In addition to the theoretical understanding, we aim to conduct practical user study to understand and explore IEDS. Therefore, we design and implement IEDS to support further user study. As summarized in Section 4.4, various augment approaches are valuable in IEDS. So far as we know, no existing AR system support the combination of SAR and other two AR approaches together. Therefore, we have developed three independent design tools based on the three AR approaches (i.e., augment through HMD, HHD, and SAR) in IEDS.

5.1 Interaction Flow in IEDS

We provide an interaction flow in IEDS to introduce its capabilities. There are three supported tools (GAI+HMD, GAI+HHD, and GAI+SAR) in IEDS. In IEDS, designers start from prototyping with physical design material. They can ideate and test through embodied interaction with tangible prototypes. With AR support, designers can conduct virtual editions based on the physical prototype for hybrid creation. The interaction modes of virtual editing depend on the different features of augment approaches. Specifically, designers can conduct mid-air sketching and modeling with the HMD support or add 2D sketch based on the screen with the HHD support. Designers can use cameras of different augment devices to capture the mixed vision including virtual editing and physical prototype, and input it to GAI with textual design requirements and limitations. GAI understands the design intention according to prototype images and texts and then generates candidate schemes that meet the design requirement. All the generated schemes will be augmented in the physical design space through three augment approaches for hybrid presentation. In this linear workflow, designers can move forward and backward freely according to their own needs to repeatedly iterate the design scheme.

5.2 GAI Role, Function, and Implementation in IEDS

According to the theoretical guidance in Section 4, GAI mainly plays the role of *creator*, *refiner*, and *stimulator* in IEDS. Therefore, we integrated the image generation model in IEDS. The input of the generation model involves the captured view and textual description while the output is various product renderings. We expect GAI participation to have two main effects on prototype workflow. On the one hand, its participation can greatly improve prototype efficiency. On the other hand, its participation can transform the low-fidelity physical prototype into high-fidelity rendering.

For the GAI implementation in IEDS, we employed the pre-trained image-to-image diffusion model, Stable Diffusion XL 1.0 [125] to achieve image generation in the back-end server. The input involves the textual design description and captured image of the physical prototype. In order to improve the generation quality, we integrated the Rembg [40] plug-in to remove the background and fed the physical prototype image without background to the image-to-image generation model. Designers can interact with IEDS systems to adjust prompts through voice input. We utilized the default

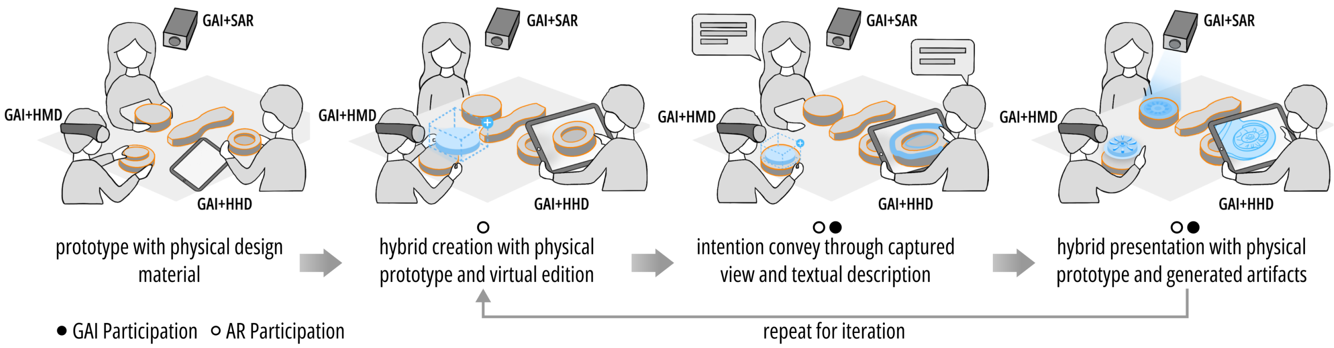


Figure 6: The user interaction flow in IEDS, in which shows how designers use IEDS to interact with GAI and AR. Orange represents physical prototype, while blue represents virtual prototype, including user-created mid-air model (through HMD), 2D sketch (through HHD) and the GAI generated virtual content.

recommended values for parameters, which did not support user perception and modification. The back-end server is hosted on a local server equipped with a GTX 3090 GPU.

5.3 AR Feature, Configuration, and Implementation in IEDS

Based on the same GAI capability in the back end, we designed and developed three tools in IEDS, which led to different virtual editing and presentation interactions. We compare three developed tools and introduce their AR features in Figure 7, specifically:

- We achieved the GAI+HMD through the HoloLens. The built-in camera of HoloLens will capture the designer's current vision and combine the textual requirements to understand the designer's intention. The virtual generated artifacts will be embedded in a hybrid space through the HMD. Due to the HMD's distinct characteristic that supports spatial editing, we integrated the 3D modeling functions in GAI+HMD to support aerial modeling and manipulation.
- We achieved the GAI+HHD through a tablet computer (iPad). Unlike GAI+HMD, designers will digitally browse generated artifacts on the iPad screen. Based on the characteristics of HHD, we developed the sketching function for GAI+HHD. Designers can draw on the captured image of the physical model through the touchscreen, which serves as input information to GAI.
- We achieved the GAI+SAR through an independent camera and a projector. The virtual artifacts will be attached to the surfaces of the physical prototype through a projector. We follow the characteristics of SAR with strong expressiveness but weak operation, developing the GAI+SAR that does not support virtual editing.

5.3.1 GAI+HMD Configuration and Implementation in IEDS. The configuration of GAI+HMD comprises three main hardware components: a HoloLens device, a router, and a computer for Unity's operation. During the conceptual design, designers wear the HoloLens, connecting to the host computer through a local area network. The wireless connection facilitates real-time data transmission between the HoloLens and Unity on the computer.

The implementation of GAI+HMD encompasses two main works. The first involves supporting designers in creating and editing 3D virtual models in the air through gesture-based interactions. We utilized Unity (version 2020.3.26) [138] and MRTK (version 2.8) [105] to implement GAI+HMD. To support the real-time modeling, we integrated two Rhino packages into Unity: *Rhino3dm* [87] and *compute-Rhino3d* [86], which enable the invocation of modeling functions directly from Unity and operate based on the local Rhino servers. Our integration allows for real-time conversion of mid-air sketches created via HoloLens into 3D models by the Rhino server, with the processed data swiftly relayed back to the HoloLens for visual rendering. Through this way, we developed and implemented the basic mid-air modeling function: *Revolve*, *Sweep*, *Extrude*, and the basic editing function: *Move*, *Copy*, *Rotate*. Second, we achieved the scheme generation and presentation. Designers can input the textual requirements via voice and capture their current vision (including the physical prototype and created virtual model). The input information via Unity will be sent to the back-end server of the system, which is then relayed back to Unity and presented in designers' vision through HoloLens.

5.3.2 GAI+HHD Configuration and Implementation. The configuration of GAI+HHD only comprises one hardware component: a tablet computer (iPad). Designers hold the iPad or put it on the table to capture their physical design representation.

The implementation of GAI+HHD involves supporting designers in capturing physical representations and sketching on the screen. Accordingly, we developed a web application for accessibility on mobile devices. The built-in rear camera of the iPad facilitates direct capture of physical environments or objects. The user interface of the GAI+HHD system was developed based on Stable Diffusion Web UI [7] and a Gradio library-based browser interface, which has a canvas to support image presentation and sketch.

5.3.3 GAI+SAR Configuration and Implementation. The configuration of GAI+SAR comprises three hardware components: an independent portable camera (GoPro Hero 10), a projector (EPSON

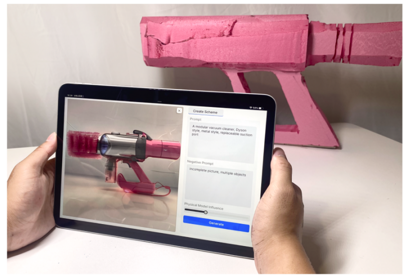
	GAI+HMD	GAI+HHD	GAI+SAR
AR Approach	augment through HMD	augment through HHD	augment through SAR
System			
Equipment	a HMD (HoloLens)	a HHD (iPad)	a camera; a projector
Information Capture Channel	the built-in camera of HoloLens	the built-in camera of iPad	an independent camera
Information Embedding Mode	digital artifacts generated by GAI are embedded in a hybrid space through a HMD equipment	digital artifacts generated by GAI are displayed on the screen of a HHD equipment	digital artifacts generated by GAI are attached on the surface of the physical prototype through a projector equipment
Physical Operation	physical prototype editing	physical prototype editing	physical prototype editing
Virtual Operation	virtual modeling in air	sketching on screen	n/a
Interaction Mechanism	1. physically prototype 2. digitally model in air based on physical prototype 3. capture HMD vision to image 4. image to image generation 5. embed generated scheme to hybrid space	1. physically prototype 2. capture 3D model to image 3. sketch on the captured image 4. image to image generation 5. display generated scheme on the screen	1. physically prototype 2. capture 3D model to image 3. image to image generation 4. attach generated scheme on the surface of physical prototype through projector

Figure 7: Introduction and comparison of three developed IEDS systems.

CB-X49), and a computer for information transmission. Designers can hold or wear the portable camera on heads or chests to capture physical prototype. The projector is used to attach the virtual design scheme to the surface of physical models. The connection of multi-devices and information transmission is achieved through a local area network.

As we follow the characteristics of SAR with strong expressiveness but weak operation, we did not develop the virtual editing functions like the other two systems. We only achieved the generation function in GAI+SAR. Specifically, the captured image of physical prototype through the individual portable camera will be sent to the host computer. The host computer can collect designers' voice-input textual requirements, transmitting them with the captured image to the back-end server. The visual generated scheme will be stuck on the surface of physical prototype via a projector.

5.4 IEDS Environment Implementation

We constructed an IEDS environment for implementation (Figure 8). There are two main work areas: the physical prototype building area (Figure 8 Ⓐ) and the prototype augmentation area (Figure 8 Ⓑ). We divided those two areas, considering that the GAI input in IEDS relies on the quality of captured images. Therefore, we enable designers to ideate and discuss their design in a relatively clean space, keeping the background of captured images as clean as possible. Common physical materials were provided, such as the plastic foam and paper shell model, and basic tools, such as electric knife and hot melt adhesive. In our implemented IEDS environment, the tablet computer (Figure 8 Ⓓ), head-mounted display equipment (Figure 8 Ⓔ), projector (Figure 8 Ⓕ) were provided and connected to local host (Figure 8 Ⓖ) and back-end sever.

Figure 8: The constructed IEDS environment. Ⓐ physical prototype building area: providing physical prototype materials and common tools; Ⓑ prototype augmentation area: in which a blank table is provided for virtual editing and prototype discussion; Ⓒ current version of the built physical prototype for discussion; Ⓓ the tablet computer (for GAI+HHD); Ⓔ the HMD equipment (for GAI+HMD); Ⓕ the projector (for GAI+SAR); Ⓖ the computer for connecting the projector, head mounted display equipment, and back-end server. *Note*: IEDS supports multi-person collaboration, with more than one tablet computer and head-mounted display equipment in the design space. Only one piece of equipment is shown as an example.

6 IEDS Open-ended Exploration Study

Building upon the implemented IEDS systems, we conducted a design workshop and invited designers to complete industrial design tasks with IEDS support for the open-ended exploration. We aim to collect designers' attitudes towards IEDS, the experience of IEDS interaction, and the influence of IEDS on conceptual design.

6.1 Participant

We recruited 27 designers (16 males and 11 females, with an average age of 25.04). We mainly recruited professional industrial designers with more than three years of design experience. All participants have the basic knowledge and practical experience of GAI tools, which was determined via a registration questionnaire. During the workshop, every three designers performed the design tasks together. Therefore, we organized a total of nine design workshops during the open-ended exploration study. During grouping, the gender, age, and design experience have been balanced to eliminate individual differences. All participants signed a consent form approved by our institution. There were no other ethical or privacy impacts in this experiment.

6.2 Design Task

To explore the design diversity with the IEDS support, we set two design task types during the design workshop: the appearance-oriented design task and the structure-oriented design task. They are products with relatively fixed structures but different appearances and styles and those with dynamic and changeable structures, respectively. We chose an *electric oven* as an appearance-oriented task while a *modularized cleaner* as a structure-oriented task. These two tasks were carefully selected. They are electric industrial products, which have enough innovation space in their function at the conceptual design stage. Besides, they are universally known and commonly used, which can facilitate using prior knowledge and experience to develop design ideas [65]. To enable designers to have a similar ability to explore and complete design as they usually do in actual design activities, we provided a design problem card to specify the design task before the start of the design workshop [59].

6.3 Procedure

During the design workshop, participants have completed the informed consent confirmation and ice breaking, and then are instructed to familiarize themselves with the IEDS environment and tool. In the design task stage, designers are required to complete two design tasks (i.e., appearance-oriented design & structure-oriented design). Each design task lasted 30 minutes. To avoid the influence of the experimental order on the results, the design tasks are balanced among participants. Designers can freely switch between virtual and physical domain during design tasks, and they can also freely utilize the generation function. At the end of each task, designers were asked to introduce design outcomes, which were translated into text for record. Eventually, there was a phase to engage in a semi-structured interview. The interviews were conducted one-on-one after the design collaboration. The entire experiment took approximately 100 minutes.

6.4 Interview Outline and Thematic Analysis

We aim to collect designers' attitudes towards IEDS, the experience of IEDS interaction, and the influence of IEDS on conceptual design. Therefore, the semi-structured interview content focused on six key issues, including the *attitude to IEDS*, *interaction experience*, *comparison with traditional tools*, *GAI cooperation*, *AR influence*, and *creativity*. The outline of semi-structured interview is presented in Table 2.

Table 2: The structure and outline of the semi-structured interview in the open-ended exploration study.

Key Issue (K)	Outline and Question (Q)
K0: Ice Breaker	Q1: "*Could you introduce your design?*" Q2: "*Which design are you most satisfied with?*"
K1: Attitude to IEDS	Q1: "*Would you like to use IEDS for your conceptual design work?*" Q2: "*Which design task and stage do you prefer to use IEDS?*"
K2: Interaction Experience	Q1: "*How is your overall experience when you used IEDS to complete the conceptual design?*" Q2: "*What do you think is the biggest challenge in using IEDS during design?*"
K3: Comparison with Traditional Design Tool	Q1: "*What do you think is different from the design tools you commonly used before?*" Q2: "*What do you think are the advantages and disadvantages compared with traditional design tools?*"
K4: GAI Cooperation	Q1: "*How is your cooperation experience with GAI during the design process?*" Q2: "*When and where do you think GAI is helpful for your design process?*"
K5: AR Influence	Q1: "*What kind of design content do you augment through AR in your design?*" Q2: "*What effect do you think AR's participation has on your conceptual design?*"
K6: Creativity	Q1: "*Do you think IEDS can affect your creativity?*" Q2: "*How does your interaction with AR or GAI affect and iterate your design concept?*"

Qualitative analysis emphasizes deriving meaning from data, often through the identification of themes [2]. In this study, we employed thematic analysis to examine the raw interview data [135]. Our analysis began with familiarization, which involved transcribing the audio recordings from each case study. In the second step, two researchers independently coded and assigned labels to all statements, focusing on the semantic content of the interview data rather than interpreting it based on assumptions. Subsequently, the two researchers collaboratively reviewed and compared the codes using a mind map. They discussed discrepancies, resolved disagreements, and merged similar codes until reaching a consensus.

6.5 The Showcase of Design Workflow and Outcome

We present some workflow showcases (Figure 9) to show the prototype process with IEDS support in practical industrial conceptual design. All data in the showcases was extracted from the back-end log and experimental video record, which mainly included the captured image and generated artifacts. We highlight how designers switched between physical and virtual domains to advance their design process. Designers usually start with the rough physical prototypes and add virtual editing based on the physical form (i.e., screen sketching in GAI+HHD and mid-air modeling in GAI+HMD). Designers can also iterate their physical prototypes after getting inspiration from the generated schemes. They can freely switch between physical and virtual editing according to their design stages and requirements.

6.6 Results of Semi-Structured Interview

Building upon our semi-structured interview, we extracted some codes in six key issues and showed corresponding quotes.

Attitude to IEDS (K1): We collected participants feedback on their attitude to IEDS. Almost all participants admitted the "*novelty of integrating GAI and AR in IEDS*". In addition, four participants pointed out the "*IEDS strength for design communication and cooperation*". P1 reported that "*AI enhances my expressiveness, while AR intuitively visualizes highly expressive schemes, enabling me to communicate my ideas with partners more efficiently*". Besides, four participants mentioned "*weak editability and operability in AR interaction*", especially the participants using the GAI+SAR. P18 indicated that "*Although SAR enhances expressiveness, I can't further modify and iteratively generate my scheme. I need more refined operations, such as local editing or replacement*". Similarly, P5 also reported that "*While mid-air modeling with HMD support is intuitive, operating in mid-air is more complex and challenging compared to 2D interactions. I hope IEDS can provide diverse interaction modes to enhance its operability and usability. For instance, supporting both 3D and 2D editing might offer greater flexibility*".

Interaction Experience (K2): We collected on designers' interaction experience under IEDS support, focusing on the strengths and challenges in their interaction experience. With the support of GAI+HMD, five participants reported "*physical discomfort*": P5 indicated that "*Working for a long time makes my neck ache and dizzy*". Four participants mentioned "*parallax*" and "*collaborating challenge*": P11 reported that "*HMD's camera is different in height from my eyes, and seems to have parallax with what I see*" and "*Partners had different horizons and are prone to misoperation*". Additionally, with the support of GAI+HHD, seven participants mentioned "*conforming to habit*". For example, P6 reported that "*The usage and operation are in line with my usual cognition and habits during design*". Five participants mentioned "*indirect editing*". P9 said "*I can only modify and edit 3D on the screen, and I need to imagine the perspective relationship, which is not direct and intuitive enough*". Besides, with the support of GAI+SAR, nine participants mentioned "*high expressiveness*" during the interaction: P18 elaborated that "*Expressiveness surprises me, just like a real oven*" and P4 reported that "*SAR enhances my immersion in design, especially during my evaluation*". Six participants thought the SAR has the "*small use range*": P20 reported that "*It seems that it can only be used for products with square dimensions with flat surfaces*".

Comparison with Traditional Design Tools (K3): When compared to traditional design tools and workflow, eight participants mentioned "*rapid creation and iteration*". P7 reported that "*IEDS could let me see the feedback that conforms to my modification intention immediately, which greatly speeds up the time and cycle of prototype iteration*". Besides, four participants mentioned "*utilization of design information in early stage*". For example, P23 indicated that "*In the traditional design process, it is often difficult to use existing low-fidelity information when making high-fidelity prototypes, which need to be modeled from scratch. IEDS can fully use this early design information and gradually refine it*".

GAI Cooperation (K4): When talking about the human-AI collaboration, more than half of participants mentioned "*expressiveness enhancement*", which is considered by many designers as one of

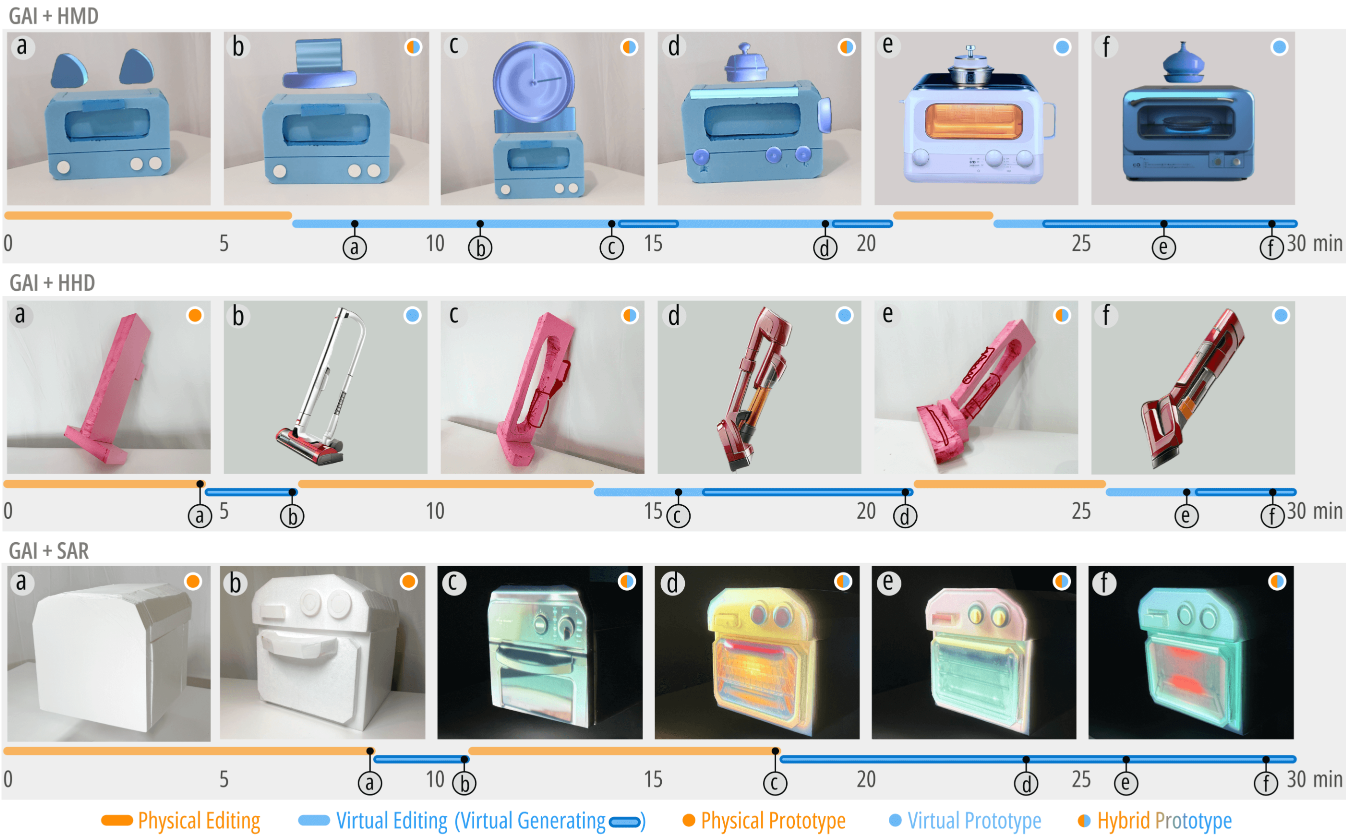


Figure 9: The showcase of design workflow and outcome. The yellow part indicates the physical editing process while the blue part indicates the virtual editing process. Lowercase letters indicate the design output at each time point.

GAI's greatest contributions to IEDS. Besides, seven participants mentioned "*lack of structure and engineering knowledge*". For example, P15 reported that "*GAI can only 'add skin' when refining my prototype, but GAI can't understand the structure of my physical prototype, let alone optimize my structural details reasonably*". P20 also reported that "*GAI can only meet my design intention on the whole but cannot understand and generate all details correctly. When my physical prototype is unusual, GAI cannot understand my abstract elements and cannot even distinguish its front and back*". In addition, four participants mentioned "*Disruption of design rhythm*". P23 indicated that "*Sometimes, the GAI's variability makes me lose my current design goal and fall into randomness*".

AR Influence (K5): More than half participants mentioned the "*immersive presentation*", especially the participants who utilized the GAI+SAR. Five participants mentioned the "diversified inputs". P9 reported that "*With the AR support, I can build basic scale and structures with physical materials, and add details by sketching. This hybrid prototype reduces my time to externalize ideas*". Similarly, four participants mentioned "*intention conveyed to GAI*", which indicates that the design intention could be conveyed more intuitively and efficiently due to the mixed input with diversified inputs. For example, P11 said "*It is difficult for me to clearly convey my design intention to GAI through pure text prompts, but in IEDS, I can use both physical materials and mid-air modeling to convey abstract intentions*". P27 reported that "*When I use GAI in HMD, just like GAI and I share our vision, I can convey my ideas more efficiently*".

Creativity (K6): We paid special attention to the influence of IEDS on creativity support and fixation. Eleven participants mentioned "*expand imagination space*" during creation. P13 reported that "*GAI generates various details and opens an imaginary space*". Besides the concrete generated artifacts, P21 indicated that "*The abstract content generated by GAI serves as a source of inspiration for me, allowing me to assign different semantics and functions to these abstract ideas*". However, four participants mentioned "*fixed ideas brought by concrete generated artifacts*". Specifically, P26 indicated that "*GAI tends to generate a significant amount of concrete content. These high-fidelity details may be unnecessary at the early stage, and they can interfere with my natural thought process or cause idea fixation. Such premature details might even become deeply ingrained in my mind, potentially influencing my final design outcome*".

7 Discussion

According to the interview codes extracted from the open-ended exploration study, we summarized and released the IEDS application guideline based on our findings (Figure 10). We divided it into two parts: *understanding the contribution of AR and GAI in IEDS* and *understanding the IEDS influence on industrial conceptual design*. We critically discuss our findings and highlight their implications for future applications.

7.1 Contribution of GAI, AR, and Their Integration in IEDS

We summarized GAI's contribution to IEDS, including *enriching details and improving fidelity*, *supporting rapid creation and iteration*, and *providing creativity*. We also summarized AR's contribution to IEDS, involving *supporting diversified information input* and *allowing immersive design outcome presentation*. Additionally, we paid special attention to the integration of AR and GAI, which is the most valuable feature of IEDS. First, GAI participation in AR enables real-time augmentation, presentation, and iteration. While some HCI studies have employed AR technology for mixed prototypes, most virtual content is typically retrieved from databases [55, 89]. This reliance on preset artifacts restricts designers' freedom of conception during on-site modeling. However, with the support of IEDS, designers can interact with physical prototypes in an embodied manner while simultaneously viewing high-fidelity virtual feedback in real-time. Second, AR participation allows GAI to capture designers' intentions more concretely. Converting ambiguous design intentions into precise text remains challenging, as simple text prompts often fail to fully capture what designers envision [170]. However, in IEDS, designers can leverage physical prototypes, mid-air modeling, and screen sketches to express design details more naturally and concretely, promoting communication between human designers and GAI.

We clarified how to combine GAI with different AR approaches for the best practice. Specifically, our user study indicated that the GAI+HMD provided the free creation beyond physical limitations (e.g., the limitation of gravity) while showing challenges of cooperation and physical load. Besides, the interaction in GAI+HHD conformed to designers' creation and operation habits but provided indirect and non-intuitive 2D editing. Additionally, GAI+SAR offered the most immersive creation space due to the real presence but showed drawbacks in structure-oriented design and single view. Considering the advantages and disadvantages of these combinations comprehensively, we suggested designers avoid using GAI+SAR to complete structure-oriented design tasks and short-term efficient tasks in conceptual design, and also avoid using GAI+HMD for team cooperation and long-duration tasks. Besides, the GAI+HMD was suggested to be given priority for better immersion and structural tests. The GAI+HHD was recommended when faced with an efficiency-oriented design task without high requirements for immersion and intuition. The GAI+SAR was given priority to use for better expressiveness and communication.

7.2 IEDS's Influence on the Industrial Conceptual Design

We discuss IEDS's influence on industrial conceptual design from the design workflow, design creativity, and design collaboration perspectives.

First, from the design workflow perspective, IEDS enhanced the efficiency and accelerated the design iteration with its generation ability. It also took over the repetitive and tedious expression tasks, allowing designers to focus on creative work. This reflects IEDS can lower friction in design work by simplifying or speeding up this manual process [60, 139]. In addition, the combination of AR and GAI enabled the direct utilization of the low-fidelity prototype into high-fidelity renderings immediately. Designers usually have difficulty or need to spend a lot of time and labor to effectively translate low-fidelity physical information into high-fidelity virtual formats [32]. For instance, although designers often externalize ideas by low-fidelity physical prototypes efficiently before transitioning to virtual modeling, they have to commence virtual modeling from scratch as they generally cannot leverage the prior design information [32]. In this context, IEDS allowed the transformation of low-fidelity design information in the early stages, facilitating a seamless design workflow between low- to high-fidelity.

However, although the generative variability and uncertainty of GAI can provide creativity stimulation, they can also potentially disrupt the workflow and rhythm [150]. Previous studies elaborated that the end-to-end generation might provide irrelevant and unpredictable inspiration, which breaks designers' original thinking and disturbs their rhythm [169, 170]. Besides, the rapid generation and iteration made designers obtain and see design solutions immediately, which limited designers' reflection process. For example, participants reported that "*I always hope to see a more detailed solution as soon as possible. It makes it challenging to patiently utilize physical prototypes to ideate*". Similarly, previous studies indicated that designers might fall into a narrow view due to the rapid and straightforward visualization enabled by AI [139]. To address these problems, we recommend maintaining a clear understanding of the design methodology and objectives and keeping reflection within IEDS to avoid falling into randomness and disorder caused by GAI.

Second, from the design creativity perspective, IEDS was particularly effective for gaining insights into design problems and extensively exploring ideas in the initial stages of conceptual design. Designers reported that IEDS allowed them to generate diverse design schemes by simply adjusting prompts, which stimulated creativity and expanded their imaginative space [150]. As noted by [10], generative design can lead to creativity since every new generation brings opportunities to look for new emergent properties. Additionally, the tangible ideation with real-time feedback contributed to the structural consideration in industrial design [43]. For example, designers used physical models to represent the vacuum cleaner body. They used mid-air models or screen sketches to explore diverse modular suction nozzles. The tangible prototype allowed designers to quickly assess the feasibility of their ideas, while AI-generated feedback provided immediate suggestions for potential improvements or alternative design directions, enhancing the decision-making process.

We also critically discussed the issue of creativity fixation introduced by IEDS. On the one hand, by generating high-fidelity elements at the early stage of design, IEDS might lead to early fixation in industrial design, discouraging the exploration of alternative solutions [18]. Some studies indicated that some ambiguous artifacts can be re-understood and re-interpreted by self-explanation, which can stimulate creativity when compared to high-fidelity renderings [169]. These generated "well-polished" high-fidelity artifacts seem to have no glitches, defects, or sketchiness, which may

Understanding of AR and GAI in IEDS	Implication & Application
● Contribution of GAI participation - Enrich detail and improve fidelity - Support rapid creation and iteration - Provide creativity stimulation ● GAI Limitation in IEDS - Lack of refined generation control - Lack of engineering & structural knowledge - Lack of design reasoning	- IEDS is best utilized for tasks focused on style and appearance exploration instead of structure-oriented tasks, where IEDS's strengths can be fully leveraged.
● Contribution of AR participation - Support diversified information input - Allow immersive design presentation ● AR Limitation in IEDS - Different AR interactions cannot be mixed - Only augment the prototype visually ● Contribution of AR + GAI integration - GAI participates in AR to realize real-time augmentation, presentation and iteration - AR participates in GAI interaction to enhance concrete intention convey	- GAI+HMD is recommended for better immersion and structural tests. - GAI+HHD is recommended when faced with an efficiency-oriented design task without high requirements for immersion and intuition. - GAI+SAR is recommended for better expressiveness and communication.
GAI combination with various AR approaches Ⓐ GAI + AR **(HMD)** ● beyond physical limitations ● adverse to cooperation ● heavy physical load Ⓑ GAI + AR **(HHD)** ● conform to habit ● indirect virtual editing Ⓒ GAI + AR **(SAR)** ● real and presence ● adverse to structure -orinted design ● more labor and time ● single view	-GAI+SAR is not suitable for structure-oriented design tasks and short-term efficient tasks. -GAI+HMD is not suitable for team cooperation and long-duration tasks.

Understanding of the IEDS influence on industrial conceptual design	Implication & Application
The influence of IEDS on industrial design workflow ● Improve efficiency and optimize design iteration ● Effectively use the low-fidelity design representation in the early stage to realize seamless design workflow ● Disrupt the customary design rhythm ● Limits design reflection	- IEDS can enhance the design efficiency and optimized the design workflow. - It is crucial to maintain clarity about design methodology and objectives to prevent falling into the GAI randomness and disorder.
The influence of IEDS on design creativity ● Open the imagination space based on generative randomness ● Promote structural thinking based on the combination of tangibility and real-time generation ● Premature introduction of high-level design decision ● Premature introduction of high fidelity representation leads to fixed style	- IEDS is particularly effective for gaining insights into design problems and extensively exploring ideas in initial stages. - To mitigate style and creativity fixation, -It is helpful to vary the prompts and iterate version among diverse candidates to mitigate style and creativity fixation.
The influence of IEDS on design collaboration ● Tangible ideation promote design communication (especially in GAI+SAR) ● Lower the threshold of design expression and improve expressiveness ● Spatial positioning of virtual and physical prototypes is challenging, causing parallax between designers in collaboration (especially in GAI+HMD)	- IEDS is well-suited for cross-team design discussions and collaboration, particularly when supported by GAI+SAR.

● Strength Perspective ● Limitation Perspective

Figure 10: IEDS application guideline, which summarized based on our findings of the open-ended exploration study. These findings are classified into strength and limitation perspectives and are marked in green and red respectively.

inadvertently discourage designers from exploring iterative directions and alternative solutions [139]. On the other hand, IEDS's interaction might expose high-level design decisions, such as color and style, prematurely. Designers have to specify the intention style through prompts in advance during IEDS interaction. These prompts often contain high-level mentalistic concepts, such as style, implication, and association [110]. And the color of physical materials can also impact the generated outcome. These interactions might let designers unconsciously pay attention to low-level design decisions early in conceptual design [26]. To mitigate the early design fixation, we recommended that designers iteratively vary the prompts and intentions used in GAI, ensuring a diverse range of candidates.

Third, from the design collaboration perspective, tangible and concrete ideation significantly promoted communication within design teams. On the one hand, the combination of GAI and physical prototype lowered the threshold of design expression. Technical design members without professional expression skills, such as sketching or modeling, can also easily create and express within IEDS, enhancing team collaboration and fostering effective interdisciplinary communication throughout the conceptual design process. On the other hand, the use of tangible prototypes and AR participation facilitated idea externalization and spatial reasoning while the GAI participation supported on-site and real-time iteration. It facilitated dynamic brainstorming sessions, where ideas could be continuously tested, explained, refined, and negotiated in IEDS. Design team members were not only able to evaluate the feasibility of proposed tangible designs but also reframe and recontextualize them based on generated artifacts, imbuing the design schemes with new meanings and perspectives [82]. Besides, the tangible form also enhanced the cooperators' consistent understanding of various ideas, making the communication process of abstract ideas in the early design stage more specific and focused [170].

7.3 IEDS Optimization Space

We critically report GAI and AR limitations in IEDS, which might affect the interaction experience or design process. Then we put forward the optimization space and future vision of IEDS.

First, some participants complained that IEDS can only inspire designers through the visual generation and lack design reasoning like human collaborators. They also indicated that IEDS lacked engineering and structural knowledge. Previous studies also reported that some structures were misunderstood and ignored after the GAI refinement [169]. Building upon these GAI limitations in IEDS, we hope GAI can take on more roles than scheme generation and become a design collaborator in future vision. For example, the multi-modal vision language models, such as GPT-4V [100], Gemini 1.5 [99], and Claude 3 [24] can be integrated with IEDS, thus enabling the GAI to better reason in engineering design and enhance structure feasibility. In the future vision of IEDS, GAI can become the intelligent brain of IEDS, making IEDS a highly available design collaborator in industrial conceptual design.

Second, some participants complained about the problems of AR data transmission and vision synchronization during design collaboration. Besides, the current IEDS consisted of three independent GAI+AR tools according to three AR approaches. However various AR approaches might be not necessarily independent and can be utilized jointly. Both the expert interview and open-ended exploration study indicated that the three IEDS systems showed unique advantages and disadvantages. Therefore, a wider application range and higher usability can be achieved through better AR medium fusion. For example, in the future vision, designers can wear HMD equipment to create prototypes beyond physical limitations through mid-air modeling. At the same time, they can make fine modifications through HHD and finally augment the generated high-fidelity scheme to the physical model directly through SAR. The cross-device joint interaction can give full play to various AR's strengths and make up for each other's limitations.

Third, augmented design information in IEDS can be enriched and expanded for a multi-modal hybrid design space. Currently, due to limitations in the speed and quality of multi-modal generative models, we have completed this study by utilizing the image generation model. With the development of multi-modal generative ability, the design information in IEDS can be enriched. For instance, 3D modality information can be generated and tightly coupled with physical prototypes through AR technology. As our literature review suggested that augmented information need not be limited to prototypes, in the future, IEDS could support the integration of multi-modal design information, such as augmenting images or even videos into the background of physical prototypes or visualizing the interaction paths and movement trajectories of the prototypes. In addition, some participants pointed out that IEDS only augmented prototypes visually and there was no motion logic between virtual and physical prototypes. Building upon that, we also plan to couple the motion relationship between physical and virtual components after integrating the 3D generation ability in IEDS's future vision, rather than just fusing them in presentation.

7.4 Limitation

We discuss the limitations in this study that can be addressed in future studies. First, we only utilized an image-generative model to complete the user study, which may reduce the immersion of the design process. This is the first study to propose and verify the initial concept of IEDS from the HCI perspective. With the development of GAI, more multi-modal generative models can be integrated into IEDS. Second, as IEDS represents a novel integration of AR and GAI, it presents a challenge to identify comparable baselines or existing design tools for comparative analysis. More comparative analysis against existing design tools or traditional design space, as a benchmark, can be conducted to fully explore the underlying factors in IEDS. Third, this is a laboratory study, in which the design duration and participant sample are limited. A more realistic user study can be conducted in a practical design workflow, involving large-scale designers and complex design requirements. We intend to release IEDS to the wild for a broader evaluation.

8 Conclusion

In this study, we proposed an IEDS combining designer, AR, and GAI by integrating theoretical and practical methodologies. We first built a corpus of 113 papers through a literature review, synthesizing methods of constructing design space with AR and GAI, respectively. Besides, we proposed an initial combination of designer, AR, and GAI in a design space after conducting expert interviews based on existing literature and expert insights. We constructed the IEDS environment and developed three GAI+AR tools in IEDS. Based on these implementations, we conducted an open-ended exploration study with 27 designers to practically examine the benefits and challenges of these interaction modes across industrial conceptual design tasks. We discussed the integration contribution of GAI and AR in IEDS and clarified IEDS's influence on the industrial design workflow, design creativity, and design collaboration. Our work propose the preliminary concept for the novel design space combining AR and GAI, providing theoretical guidance and practical suggestions for the HCI community in further constructing the hybrid design space.

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A Collected Corpus in Literature Review

Table 3: Collected corpus related to GAI+Design. 1-55 were collected from expertise review while 56-64 were collected from systematic search.

	GAI+Design								
	Study	Publication Format	Year	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
1	Duan et al. [31]	CHI	2024	AP4	HM3, HM4	AM1	PS2	TD2	RO1, RO4
2	OmniActions [77]	CHI	2024	AP3, AP4	HM2, HM5, HM8	AM1	PS2	TD1	RO1, RO3
3	SimUser [156]	CHI	2024	AP4	HM1	AM1, AM4	PS2	TD2	RO1, RO4
4	Lee et al. [74]	CHI	2024	/	HM2	AM1, AM4	PS2	TD2	RO1, RO2
5	TypeDance [157]	CHI	2024	AP1, AP3, AP4	HM1, HM8	/	PS2	TD1	RO1, RO2, RO4
6	LumiMood [97]	CHI	2024	AP3, AP4	HM6	AM4	PS2	TD1	RO1, RO3
7	C2Ideas [48]	CHI	2024	AP3, AP4	HM1, HM5	AM6	PS2	TD1	RO1, RO2
8	IntentTuner [166]	CHI	2024	AP1, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO3, RO4
9	GenQuery [122]	CHI	2024	AP3, AP4	HM1	AM4	PS2	TD2	RO1, RO3
10	Neural Canvas [115]	CHI	2024	AP3, AP4	HM1, HM7	AM6	PS2	TD1	RO1, RO3
11	CreativeConnect [20]	CHI	2024	AP3, AP4	HM1, HM8	AM1, AM4	PS2	TD2	RO1, RO2, RO4
12	Jigsaw [79]	CHI	2024	AP3, AP4	HM1, HM2, HM6, HM8	AM1, AM2, AM3, AM4	PS2	TD2	RO1, RO2, RO3, RO4
13	From Paper to Card [119]	CHI	2024	AP3, AP4	HM1, HM8	AM1, AM4	PS2	TD1	RO1, RO3
14	PlantoGraphy [50]	CHI	2024	AP3, AP4	HM1, HM4, HM5	AM4	PS2	TD1	RO1, RO2
15	ContextCam [35]	CHI	2024	AP3	HM1	AM1, AM4	PS2	TD1	RO1, RO2
16	StyleMe [152]	CHI	2023	AP3, AP4	HM3, HM8	AM4	PS2	TD1	RO1, RO2, RO3
17	RePrompt [146]	CHI	2023	AP4	HM1	AM1, AM4	PS2	TD1	RO1, RO2, RO3
18	Beyond Skin Deep [173]	CHI	2023	AP3, AP4	HM1, HM2, HM9	AM3	PS2	TD1	RO1, RO2, RO3
19	Magical Brush [46]	CHI	2023	AP3, AP4	HM5	AM4	PS2	TD1	RO2
20	De-Stijl [116]	CHI	2023	AP3, AP4	HM1, HM3	/	PS2	TD2	RO1, RO2
21	Perceptual Pat [120]	CHI	2023	AP1, AP4	HM5, HM8	AM1, AM4	PS2	TD2	RO1, RO4
22	fAIlureNotes [90]	CHI	2023	AP1, AP4	HM8	AM1	PS2	TD2	RO1, RO4
23	Jing et al. [58]	CHI	2023	AP4	HM1, HM8	/	PS2	TD1	RO1, RO2
24	Stylette [67]	CHI	2022	AP2, AP4	HM1, HM2, HM8	/	PS2	TD1	RO1, RO3
25	TaleBrush [23]	CHI	2022	AP1, AP2, AP3, AP4	HM1, HM3	AM1, AM4	PS2	TD1	RO1, RO2
26	FlatMagic [160]	CHI	2022	AP3, AP4	HM3	AM4	PS2	TD2	RO3
27	FashionQ [56]	CHI	2021	AP1, AP2, AP4	HM5, HM8	AM1, AM4	PS2	TD1	RO1, RO4
28	Vinci[44]	CHI	2021	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD1	RO1, RO2, RO3
29	VINS [13]	CHI	2021	AP1, AP3, AP4	HM8	AM4	PS2	TD1	RO1, RO4
30	It Is Your Turn [81]	CHI	2020	AP1, AP4	HM3	AM4	PS2	TD1	RO3
31	EmoG [117]	CHI	2020	AP1, AP3, AP4	HM3, HM5	AM4	PS2	TD1	RO1, RO3
32	VISAR [171]	UIST	2023	AP1, AP3, AP4	HM1, HM5	AM1	PS2	TD1	RO1, RO2, RO3

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	Study	Publication Format	Year	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
	GAI+Design								
33	PromptPaint [22]	UIST	2023	AP2, AP3, AP4	HM1, HM5	AM4	PS2	TD1	RO1, RO2, RO3
34	Style2Fab [36]	UIST	2023	AP2, AP3, AP4	HM5, HM6	/	PS2	TD1	RO4
35	GenAssist [52]	UIST	2023	AP1, AP4	HM1, HM8	AM1	PS2	TD1	RO1, RO4
36	XCreation [161]	UIST	2023	AP2, AP3, AP4	HM1, HM3, HM4	AM4	PS2	TD1	RO1, RO2, RO3
37	Warner et al. [148]	UIST	2023	AP2, AP3, AP4	HM5, HM8	AM4	PS2	TD1	RO1, RO3, RO4
38	PColorizor [136]	UIST	2023	AP1, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD2	RO1, RO3, RO4
39	WorldSmith [27]	UIST	2023	AP2, AP3, AP4	HM1, HM5	AM4	PS2	TD1	RO1, RO2, RO3
40	Promptify [12]	UIST	2023	AP1, AP2, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO2, RO3, RO4
41	Wakey-Wakey [158]	UIST	2023	AP2, AP3, AP4	HM1, HM8	AM4, AM5	PS2	TD1	RO2
42	Spellburst [3]	UIST	2023	AP1, AP2, AP4	HM3, HM4, HM5	AM4, AM5	PS2	TD1	RO1, RO2
43	Opal [83]	UIST	2022	AP1, AP2, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO2, RO4
44	We-toon [71]	UIST	2022	AP2, AP3, AP4, AP5	HM5	AM4	PS2	TD1	RO1, RO2, RO3
45	Screen2Words [144]	UIST	2021	AP1, AP4	HM8	AM1	PS2	TD2	RO1, RO4
46	Fosco et al. [38]	UIST	2020	AP1, AP2	HM8	AM4	PS2	TD2	RO1, RO4
47	Design Adjectives [118]	UIST	2020	AP1, AP2, AP3, AP4	HM5, HM8	AM1, AM4	PS2	TD1	RO1, RO2, RO4
48	CoAIcoder [39]	TOCHI	2023	AP4, AP5	HM1, HM5	AM1	PS2	TD1	RO1, RO4
49	Color2Vec [159]	TOCHI	2023	AP1, AP2, AP4	HM1	/	PS2	TD1	RO4
50	Eisbach et al. [33]	TOCHI	2023	AP1, AP4	HM8	AM1	PS2	TD1	RO4
51	DeepThInk [30]	IJHCS	2024	AP2, AP3, AP4	HM3, HM5	AM4	PS2	TD1	RO1, RO2, RO3
52	Karim et al. [63]	IJHCS	2023	AP3, AP4	HM5, HM8	/	PS2	TD1	RO3, RO4
53	CReBot [104]	IJHCS	2022	AP1, AP4	HM1	AM1	PS2	TD1	RO1, RO3, RO4
54	FritzBot [17]	IJHCS	2021	AP3, AP4	HM1, HM5	/	PS2	TD1	RO1, RO2, RO3
55	Michailidou et al. [88]	IJHCS	2021	AP1	HM8	AM4	PS2	TD1	RO4
56	Suessmuth et al. [131]	Conference	2023	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD1	RO1, RO2, RO3
57	OwnDiffusion [154]	Conference	2023	AP1, AP2, AP3, AP4	HM3, HM5, HM8	AM4	PS2	TD2	RO1, RO2, RO3, RO4
58	Zhang et al. [167]	Conference	2023	AP1, AP3, AP4	HM1, HM3, HM5	AM4	PS2	TD1	RO1, RO2, RO3
59	Evaluating ChatGPT [164]	Conference	2023	AP1, AP3, AP4	HM1	AM1	PS2	TD1	RO1, RO2, RO3, RO4
60	Designing with AI [19]	Conference	2023	AP1, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO2
61	AutoPoster [80]	Conference	2023	AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD2	RO1, RO2, RO3
62	Sand Playground [34]	Conference	2022	AP2, AP3, AP4	HM9	AM2	PS1	TD1	RO3
63	Wu et al. [153]	Journal	2024	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM1, AM4	PS2	TD2	RO1, RO2, RO3, RO4
64	Kwieciński and Słyk [73]	Journal	2023	AP2, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD2	RO3, RO4

Table 4: Collected corpus related to AR+Design. 1-33 were collected from expertise review while 34-49 were collected from systematic search.

AR+Design							
	Study	Publication Format	Year	Application Purpose (AP)	Augment Information (IN)	Augment Approach (AA)	Interaction Modality (IM)
1	pARam [127]	CHI	2024	AP2	IN1, IN2	AA1	IM3
2	DungeonMaker [128]	CHI	2024	AP2	IN2	AA2, AA3	IM1, IM2
3	ProObjAR [163]	CHI	2023	AP2	IN1, IN2	AA1	IM3
4	Teachable Reality [89]	CHI	2023	AP2	IN2	AA2	IM3
5	4Doodle [137]	CHI	2023	AP2	IN1, IN2, IN4	AA2	IM3
6	Meta-AR-App [141]	CHI	2020	AP1, AP2, AP4, AP5	IN4	AA2	IM2
7	C-Space [123]	CHI	2020	AP1, AP2, AP4	IN1	AA3	IM1
8	Mix&Match [129]	CHI	2020	AP2	IN1	AA2	IM3
9	Mobi3DSketch [72]	CHI	2019	AP2	IN1	AA2	IM2
10	SymbiosisSketch [5]	CHI	2018	AP2	IN1, IN2	AA1, AA2	IM1, IM6
11	Mobi3DSketch [72]	CHI	2018	AP1, AP2	IN1, IN2	AA2	IM2
12	RoMA [103]	CHI	2018	AP2	IN1	AA1	IM3
13	Pmomo [174]	CHI	2016	AP2	IN1	AA3	IM1
14	MixFab [149]	CHI	2014	AP2	IN1	AA3	IM3
15	TeleAdvisor [45]	CHI	2012	AP2, AP4	IN4	AA3	IM3
16	RealityCanvas [155]	UIST	2023	AP2	IN1, IN2	AA2	IM3
17	Reframe [107]	UIST	2023	AP2	IN1, IN3	AA1, AA2	IM2
18	HoloBots [53]	UIST	2023	AP4	IN4	AA1	IM3
19	Sketched Reality [61]	UIST	2022	AP2	IN2	AA2	IM2
20	MechARspace [175]	UIST	2022	AP1, AP2	IN1, IN2	AA1	IM1, IM3
21	Rapido [75]	UIST	2021	AP2	IN1, IN2	AA2	IM2
22	GesturAR [49]	UIST	2021	AP2	IN2	AA1	IM3
23	WIKA [57]	UIST	2020	AP2	IN2	AA3	IM1, IM3
24	SceneCtrl [165]	UIST	2017	AP2, AP3	IN3	AA1	IM3
25	Oda et al. [96]	UIST	2015	AP2	IN4	AA1	IM3
26	Muresan et al. [93]	TOCHI	2024	AP2, AP5	IN2, IN4	AA1	IM3
27	Strada et al. [130]	IJHCS	2023	AP1, AP2, AP3, AP4	IN2, IN4	AA2	IM2
28	Morosi et al. [91]	IJHCS	2021	AP2	IN1	AA2, AA3	IM1, IM2
29	MorphBenches [15]	IJHCS	2019	AP2	IN2	AA3	IM1
30	Brade et al. [11]	IJHCS	2017	AP3	IN3	AA3	IM3
31	Kang et al. [62]	Design Studies	2023	AP1, AP2, AP3	IN1	AA1	IM3
32	Şen and Şener [113]	The Design Journal	2022	AP1, AP2, AP4	IN1	AA1	IM3
33	Kim and Hong [66]	Design Studies	2020	AP1, AP3, AP5	IN4	AA2	IM2
34	PointShopAR [147]	CHI	2023	AP2	IN1, IN2	AA2	IM2
35	ARCritique [78]	Conference	2022	AP2	IN1, IN4	AA2	IM2
36	ARtect [140]	Conference	2020	AP2	IN1	AA2	IM2
37	Zhao and Ma [172]	Conference	2018	AP2, AP4	IN1	AA2	IM2

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	Study	Publication Format	Year	Application Purpose (AP)	Augment Information (IN)	Augment Approach (AA)	Interaction Modality (IM)
AR+Design							
38	AR Furniture [142]	Conference	2017	AP2	IN1	AA2	IM2
39	Adas et al. [1]	Conference	2013	AP5	IN4	AA1	IM2
40	Nakajima et al. [94]	Conference	2011	AP2	IN4	AA3	IM3
41	Von Itzstein et al. [143]	Conference	2011	AP2	IN1	AA3	IM1
42	Shen et al. [114]	Design Studies	2010	AP1, AP4	IN1	AA1	IM1, IM3, IM4
43	Chen et al. [16]	Journal	2024	AP1, AP5	IN4	AA2	IM2
44	Chu and Liu [21]	Journal	2023	AP4	IN4	AA1	IM1, IM6
45	Radu et al. [106]	Journal	2023	AP2, AP5	IN1, IN2	AA1	IM1, IM3
46	Rajaratnam et al. [108]	Journal	2022	AP2, AP4	IN1	AA1, AA2, AA3	IM2, IM3
47	Ariansyah et al. [4]	Journal	2022	AP2, AP5	IN4	AA1	IM1, IM3, IM4, IM5
48	Masclet et al. [85]	Journal	2021	AP4	IN1	AA2, AA3	IM1, IM2
49	Park et al. [102]	Journal	2015	AP2, AP3	IN1	AA3	IM1