ENHANCING INTERACTIONS IN AUGMENTED REALITY FOR CONSTRUCTION SITES: INTRODUCING THE ARCHI ONTOLOGY

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ABSTRACT: *Augmented reality (AR) systems offer new possibilities for enhancing how people interact with information and their environment in the construction sector. However, traditional software-driven approaches to AR system design have limitations in creating intuitive user experiences. This research presents a new user-centric framework and ontology for BIM-AR system development focused on human needs and perspectives. The BIM-AR Framework consists of a 5-step circular hybrid process with the user at the center. To enable knowledge sharing, the Augmented Reality Computer-Human Interaction (ARCHI) ontology was developed using Protégé based on established design principles. Initial validation indicates the framework's potential for improved AR system design, but further expert review and case studies are needed. The ontology also requires additional refinement and linkage to open data. This pioneering research lays the groundwork for next-generation AR systems that emphasize usability by taking a human-focused approach. With rigorous validation and evolution, the framework and ontology could transform AR technology development to create more purpose-driven and adopted solutions. This research represents a paradigm shift to user-centric AR system design that has significant potential to improve how augmented reality enhances construction project management.*

KEYWORDS: *Augmented Reality, Building Information Modeling, BIM, Linked Data, Ontology, Human Computer Interaction.*

1. INTRODUCTION

Augmented reality (AR) refers to technology that overlays digital information and objects onto the real-world environment in real-time (Azuma et al., 2001). This is achieved by supplementing the user's view with computer-generated input such as text, images, video, audio, and GPS data. In recent years, AR has emerged as a transformative technology with a diverse range of applications across industries like healthcare, education, manufacturing, and construction. Within the construction industry, AR is being explored as a means to enhance on-site work processes and information visualization. By overlaying 3D models, assembly instructions, or other data directly onto physical construction sites, AR enables workers to intuitively interact with digital information in context (Rankohi & Waugh, 2013). Specific applications include visualizing building designs and underground infrastructure, annotating issues for repair, remotely guiding workers through assembly tasks, and detecting risks or errors in construction (Behzadan & Kamat, 2009). AR and Building Information Modelling (BIM) can reduce workspace clutter, improve information communication, and integrate digital tools directly into the work environment (Um et al., 2023).

However, there are several challenges to widespread AR adoption in construction. Current AR solutions are often provider-specific proprietary platforms that lack interoperability (Um et al., 2023; X. Wang et al., 2013). This makes integrating AR into existing construction workflows difficult, as data may not transfer seamlessly between different vendor tools. Additionally, much AR research has focused on novel visualization techniques rather than task-based, user-centric design (Amin, Mills, & Wilson, 2023; Behzadan & Kamat, 2009). As a result, usability and practical utility for on-site workers requires further improvement. To drive end-user acceptance, AR solutions need to tie tightly to actual construction tasks and processes, with UX design centered around user needs (Rankohi & Waugh, 2013). Realizing AR's full potential in construction will require developing flexible and standardized AR platforms that can be tailored to diverse use cases. Rather than one-size-fits-all vendor products, open AR ecosystems are needed where components can be mixed and matched (K. Wang et al., 2023; X. Wang et al., 2013). Tying these tools directly to construction workflows and end-user requirements will be key. With improved integration and usability, AR can transition from isolated proofs-of-concept to transformative mainstream applications in construction.

2. BACKGROUND

In recent years, AR has emerged as a potentially transformative technology for the architecture, engineering, and construction (AEC) industry. By superimposing digital models, data, and instructions directly onto physical

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construction sites and assets, AR enables more intuitive visualization and interaction with information in context. Researchers have explored AR applications across the construction lifecycle, including design visualization, construction planning, progress monitoring, quality inspection, maintenance, and safety training (K. Wang et al., 2023). One major area of research has been integrating AR with Building Information Modeling (BIM) to extend the utility of virtual BIM models to physical construction settings. BIM refers to digital 3D models of buildings containing rich parametric data on components and systems. Linking geo-located BIM models with AR allows contextually relevant on-site visualization and interaction with model data (Amin, Mills, & Wilson, 2023). This has been posited to improve communication, decision-making, work planning, quality control, and collaboration between on-site and off-site teams during construction and operations (Elshafey et al., 2020).

However, studies note that widespread field adoption of BIM-AR remains limited, especially in developing countries, due to technical and organizational challenges (Sidani et al., 2021). Major technical barriers include issues with accurate and stable registration of virtual content with the physical environment. This is impacted by factors like lighting, network connectivity, and occlusion (X. Wang et al., 2013). Developing flexible AR platforms that can leverage different positioning techniques based on context has been identified as important. Organizational challenges also exist around integrating AR into construction workflows and aligning it with user requirements (Amin, Mills, Wilson, et al., 2023). In particular, research gaps remain around understanding user needs and perspectives for on-site AR applications. As Amin, Mills & Wilson (2023) discuss, much AR research has focused on novel visualization techniques rather than task-based, user-centric design. However, usability and practical utility requires aligning AR tightly with actual construction tasks and end-user workflows. Wang & Dunston (2006) and K. Wang et al. (2023) similarly argue there has been insufficient investigation of user-centered factors that influence the effectiveness of AR for on-site construction tasks. These include aspects like UI design, functionality, and ergonomics based on workers' processes and needs.

Overall, studies emphasize that realizing the potential of BIM-AR in construction requires moving from proofs-of-concept to solutions tailored to end-users' requirements and field workflows. This entails research on AR applications within the context of specific construction tasks, roles, and information needs. A user-driven approach can help identify high-impact areas where AR adds value for field personnel and integrate AR seamlessly into existing construction practices and project delivery processes. Bridging these research gaps around user-centered design and task-based workflows will be key to driving user acceptance and widespread adoption of BIM-AR on construction projects. In the following section we will discuss the current practice of the implementation of BIM-AR solutions.

3. BIM-AR CURRENT PRACTICE

The typical process of developing and implementing BIM-AR solutions tends to follow a linear path (Figure 1), rather than a circular user-centric approach. Researchers/Project Managers often identify a potential construction application area for BIM-AR visualization, such as design review or progress tracking, based on technical feasibility rather than validated user needs (Amin, Mills, & Wilson, 2023). Developers then select AR hardware and software components to prototype, focusing on demonstrating novel visualization capabilities more than usability (X. Wang & Dunston, 2006). A pilot study is conducted to test the BIM-AR prototype in a lab or limited field setting, with evaluation criteria tending to be technical performance metrics rather than workflow integration or user-centered design (Sepasgozar et al., 2016). If feasible, the prototype may be deployed in a real construction project to showcase a “proof of concept”, but these deployments often function as stand-alone tools disconnected from broader workflows and BIM processes. User feedback is collected informally, if at all, and BIM-AR solutions are not co-designed with end users or iteratively refined based on their input and task needs. Outcomes focus on the technical aspects and visualization capabilities, rather than productivity, quality, or other construction industry benefits. Consequently, BIM-AR prototypes frequently stall at the proof-of-concept stage without translation into commercial solutions or best practices (K. Wang et al., 2023). In summary, the current linear BIM-AR development process does not start with identifying user requirements or aligning systems tightly to construction workflows. Collaboration with industry stakeholders occurs late, if at all, which limits the real-world utility and adoption of BIM-AR innovations. A more circular, participatory design approach is needed, where end user perspectives drive the development and evaluation of BIM-AR solutions for construction.

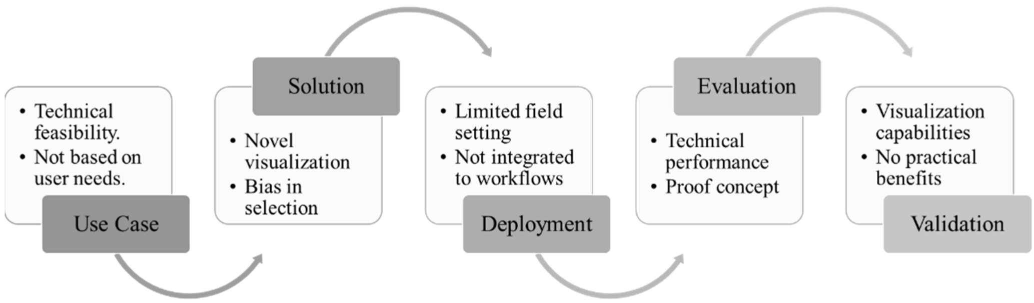

Figure 1: The current practice of BIM-AR solutions and research

4. PLUG&PLAY BIM-AR SOLUTION

A more circular approach for the effective implementation of BIM-AR solutions in the construction industry is proposed. As mentioned before, the current linear process of BIM-AR development has limitations, as it does not sufficiently incorporate end user requirements or align solutions with real-world workflows. To address this, we suggest a participatory, iterative process, Augmented Reality Computer-Human Interaction (ARCHI), that centers end user perspectives for (Figure 2):

- Cultivate Use Case - The starting point should be identifying a practical use case cultivated by end users. This includes details on the application area, project phase, location, and key stakeholders who would benefit from the BIM-AR implementation. Example use cases could be design coordination, construction planning, or facilities maintenance.
- Identify Requirements - With a target use case, multidisciplinary workshops with stakeholders are held to determine functional and information requirements. User requirements capture necessary features and workflows to efficiently accomplish tasks using BIM-AR. This entails understanding objectives, processes, pain points, and needs. Information requirements outline graphical and non-graphical data inputs from integrated systems like BIM to achieve the user requirements.
- Map to Key Functions - The user and information requirements are then mapped to key BIM-AR functions needed to fulfill the use case. As Amin, Mills & Wilson (2023) proposed, these functions include positioning, visualization, interaction, collaboration, automation, and integration. Not all functions are necessary; the focus is on those critical for the specific use.
- Select Solution - With key functions defined, the project team surveys potential AR devices, software platforms, and components to meet the requirements. Table 1 provides an overview of current BIM-AR solutions and capabilities. The goal is finding flexible tools to fulfill the required key functions.
- Implement with Users - BIM-AR experts collaborate with end users to implement the selected solution in the construction project context. Workshop sessions ensure it aligns properly with real-world workflows while addressing information needs. Agile development principles can help adapt the system based on user feedback.
- Assess Against Use case and Requirements - Once deployed, structured assessments evaluate the BIM-AR solution against the original functional and information requirements. Metrics quantify performance, usability, and impact on productivity, quality, safety, etc. User surveys also provide qualitative feedback on enhancements.

By applying this circular approach, BIM-AR solutions are driven by end user and project requirements rather than technical novelty. The focus is on integrating AR seamlessly into existing construction practices to solve real problems. Continuous assessment and improvement further refine the system over time and across projects. With BIM-AR tools tightly aligned to use cases and stakeholder needs, user adoption and benefits can expand markedly. This practical, participatory implementation process is key to unlocking the true potential of BIM-AR in construction.

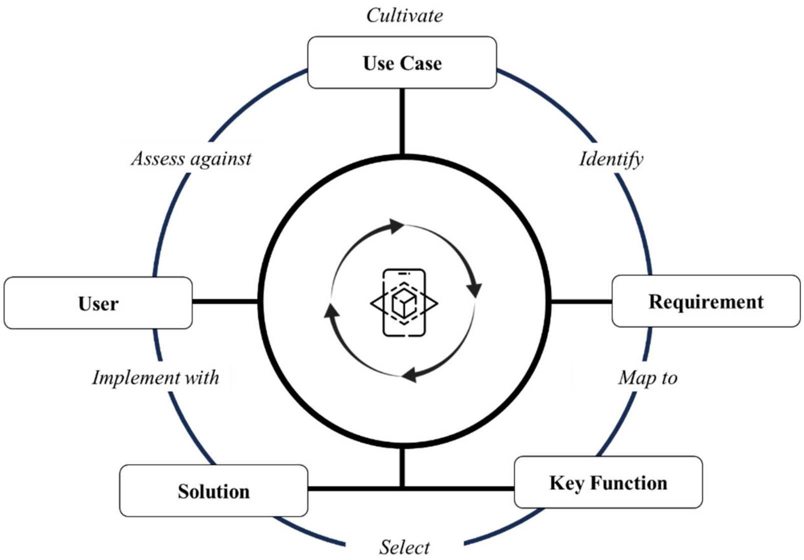

Figure 2: ARCHI proposed framework

Table 1: The existing solutions of BIM-AR (available in the construction market in 2023).

Solution	Hardware	Software	Type	User Interface
HoloLens-Kognitiv Spark	HoloLens	Kognitiv Spark	Headset	Gestural-based
Varjo XR-3	Varjo XR-3	-	Headset	Gestural-based
ATOM-XYZ Cloud Platform	ATOM	XYZ Cloud Platform	Headset	Tangible User Interface
iPad Pro-Gamma AR	iPad Pro	Gamma AR	Tablet	Touch-based
iPad Pro-GenieVision	iPad Pro	GenieVision	Tablet	Touch-based
iPad Pro-Augmentecture	iPad Pro	Augmentecture	Tablet	Touch-based
iPad Pro-ARKI	iPad Pro	ARKI	Tablet	Touch-based
iPhone -Gamma AR	iPhone	Gamma AR	Smart Phone	Touch-based
iPhone -GenieVision	iPhone	GenieVision	Smart Phone	Touch-based
iPhone -Augmentecture	iPhone	Augmentecture	Smart Phone	Touch-based
iPhone -ARKI	iPhone	ARKI	Smart Phone	Touch-based

5. ARCHI ONTOLOGY

To achieve the proposed framework, it is crucial to identify and capture all the key information needed for effective implementation. In this section, we introduce the ARCHI ontology which identifies all the important aspects to be captured. For developing a domain or upper ontology, it is essential to follow a set of defined recommendations and ordered steps (Farghaly et al., 2023). The process of the development of an ontology consists of seven main steps (Noy & McGuinness, 2001). The first step is to define the covered domain and the scope. As mentioned before, this research concentrates on the aspects related to BIM-AR solution implementation and presents the different tasks needed for that. The second step is to consider reusing existing ontologies. Several classifications and taxonomies have been taken in consideration as ontologies in this research such as PVICAT (Amin, Mills, & Wilson, 2023) for the key functions, Human Computer Interaction (HCI) ontology (Costa et al., 2022) for the user and solution classes. The third step is to enumerate important terms in the ontology. In this step, terms are extracted to form a list of concepts (classes, relationships, and slots) from the data schema regardless of any overlap between the concepts they represent. The names of the selected terms have to follow a specific strategy as specified in define resources-naming strategy task. In this stage, all the classes and their related instances are identified. The fourth step is to define the classes and develop the class hierarchy. Several approaches can be used for developing a class hierarchy: namely, top-down, bottom-up and combination. Most of the ontologies are developed based on the top-down approach, which starts from an abstraction of a domain and continues to a concrete level. However, it has been argued that the bottom-up approach is more effective as domain modeling is based on raw and evidential data instead of theoretical conceptualization. In this research, the top-down approach is used for the reusable ontologies and concepts, while the bottom-up approach is selected for the development of the new ontologies. For example, the PVICAT was utilized to identify the classes of the key function classes. The researchers used that to develop instances for each class (Table 2). The instances were identified through the engagement of the researchers in two projects where BIM-AR are implemented. The fifth step is to define the properties of classes (slots); while the sixth step is to define the facets of the slots. The values of slots are described in different facets such as: value type, allowed values, cardinality, and other facet features. The value type facet can be described in different value types, such as string, number, Boolean and enumerated. The allowed value facets define the range of slot, and the cardinality facets define how many values the slot can have. In this research, the string value type is used for defining most of the slots for the classes' properties. Finally, the seventh step is to create the instance of classes in the hierarchy. The last three steps are ongoing part of this research. Several interviews and workshops will be conducted with end users to identify the instances especially for both the use case and requirement ontology.

The ARCHI ontology was initially modelled collaboratively using diagram.net, enabling researchers to visualize and connect classes and relationships. The resulting UML diagram was exported and converted to an OWL ontology using the Chowlk tool. This OWL file was then imported into Protégé for further refinement. Protégé provides a platform to construct domain models and knowledge-based systems by enabling the creation of classes, properties, and individuals. To develop a robust ontology of knowledge for the BIM-AR framework, certain design principles and best practices were followed. As highlighted by Hlomani and Stacey (2014), the ontology requires precise conceptualization of the domain knowledge through iterative refinement of definitions. Furthermore, Gruber's (1995) criteria of clarity, coherence, extendibility, minimal encoding bias, and minimal ontological commitment were adhered to ensure a well-founded ontology. By leveraging Protégé and adhering to established guidelines, the ARCHI ontology codifies the concepts and semantics required to represent the knowledge and relationships underlying the BIM-AR framework.

The ARCHI ontology consists of 5 key classes that characterize the problem space from different perspectives: Use Case, Requirements, Key Functions, Solutions, and Users (Figure 3). The Use Case class captures details about the context and goals of implementing AR into a BIM workflow. This includes the phase of integration such as design, construction planning, active construction, handover, or operations. It also covers specific applications and objectives, such as visualizing design models on-site, evaluating construction progress, or providing digital overlays for facility maintenance. Additionally, it describes the physical environment where AR will be utilized, for example a construction site or design office. The Requirements class contains the functional and non-functional needs that emerge based on parameters defined in the Use Case. For instance, a construction site application may require ruggedized hardware to withstand harsh conditions. Or an operations use case may require integration with existing facility management software platforms. Also, it covers the information requirements related to the information needed for the 3D models provided by the BIM systems. Based on each use case, we can define a Model View Definitions (MVD). Requirements provide a link between goals and necessary capabilities. The Key Functions class draws from the taxonomy of augmented reality capabilities synthesized by Amin et al (2023). It contains main categories of AR functionality. Each class also has associated instances as shown in Table 2. This provides a standardized vocabulary to describe AR features. The Solutions class characterizes the software, hardware, and other technological components of existing AR platforms. This includes parameters like software packages and versions, types of display hardware, interface modalities, tracking methods, input devices, and capabilities for data output or export. Lastly, the User class models the human users of the AR system. Both solution and user classes leverage existing ontologies related to human-computer interaction to fully define user-solution side factors. These 5 classes provide a structured foundation for evaluating and selecting optimal AR solutions. Use Cases define goals, Requirements outline needed capabilities, Key Functions provide a vocabulary of AR features, Solutions characterize technologies, and Users represent the human perspective. By mapping Use Cases to Requirements and Key Functions, then matching those to candidate Solutions while considering Users, the ontology enables principled assessment of how well a given AR platform suits a particular BIM use case need. This facilitates both targeted selection of existing tools and identification of areas requiring new solutions.

In summary, ontology-based modeling of the BIM-AR solution space can enable richer representations of end user perspectives, workflows, requirements, and project contexts. This knowledge base can then drive the circular participatory framework by connecting BIM-AR capabilities directly to construction practices and stakeholder needs. Additional research is underway on ARCHI's formal ontology development and its applications for guiding successful BIM-AR adoption.

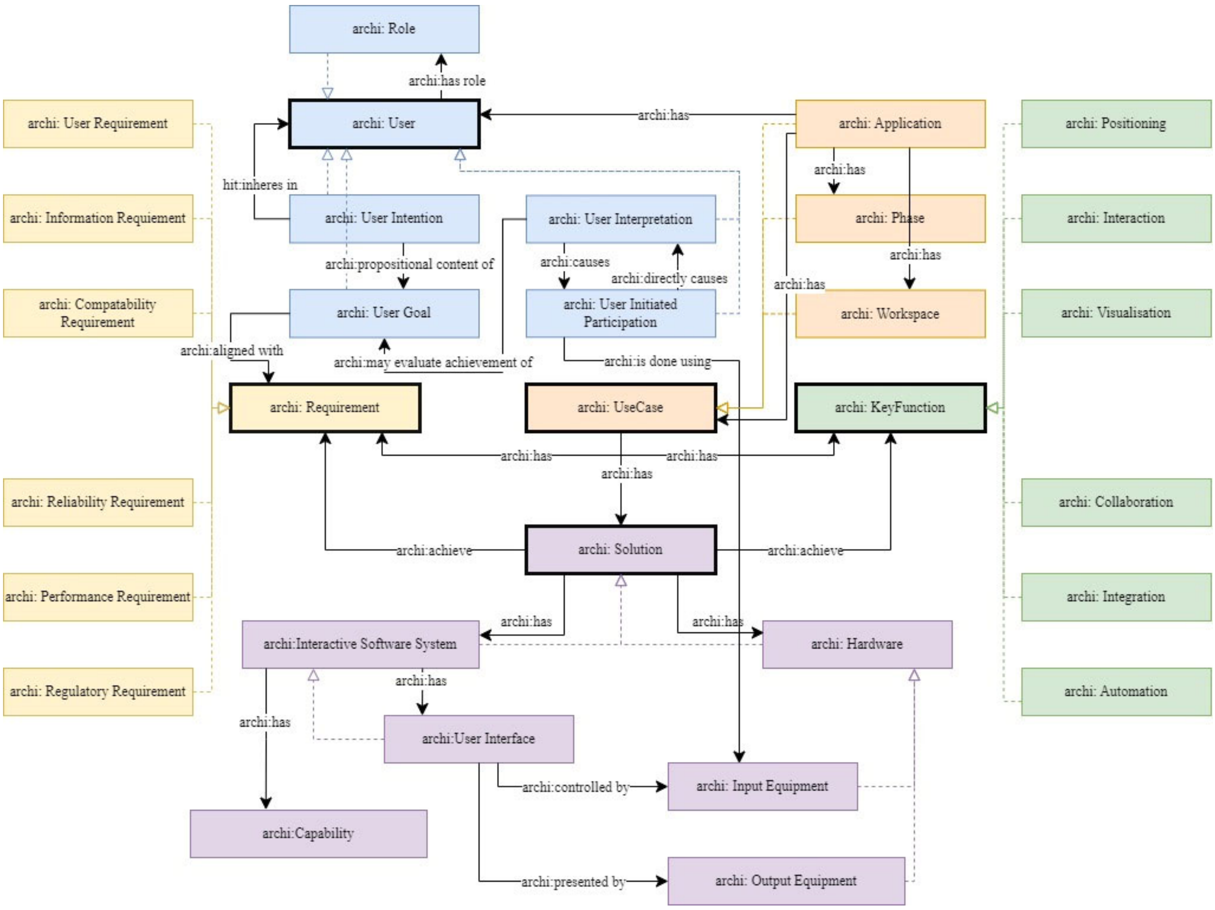

Figure 3: The main classes and relationships of ARCHI ontology.

Table 2: Key function classes and their instances and mapped solution capabilities

Key Function Class	Key Function Instances	Capabilities for the Key Function Instances
Positioning	Marker-based	Scan Marker
Positioning	Natural Feature-based	Scan Natural Feature
Positioning	Object-based	Scan Object
Positioning	Manual Mapping	Map Coordinates
Interaction	Modify	Move, Rotate, Resize, Delete
Interaction	Retrieve Information	Read, Download
Interaction	Store Information	Capture Image, Capture Video
Interaction	Add Information	Comment, Markup
Visualisation	Digital-Digital Inspection	Identify Clash, Identify Defect
Visualisation	Visibility Customization	Show, Change Color, Change Appearance
Collaboration	Issue communication	Upload Image, Upload Video, Stream
Automation	Visual Inspection	Class detection, defect detection
Automation	Report Generation	Progress report, clash report, defect report
Integration	Production and Programme control	Real-time integration with other systems
Integration	Presentation of external datasets	Real-time integration with weather and others
Integration	Improve/Extend existing function	API capabilities to extend functions

6. CONCLUSIONS

The BIM-AR Framework and ontology presented in this research offers a novel user-centric approach for designing and deploying augmented reality systems. Rather than taking a software-driven approach focused on tools like Unity, this framework emphasizes human-centered design with a focus on AR content. The core of this approach is a 5-step circular hybrid process that continuously evolves based on user needs and perspectives. To facilitate the sharing of information between process stages, the ARCHI ontology was developed to capture key data points and relationships. This human-focused approach represents a paradigm shift from traditional AR design methodologies. By putting the user at the center and iterating based on their requirements, the framework enables the development of more intuitive and purpose-driven AR applications. The ARCHI ontology also plays a key role by codifying knowledge to prevent information loss across the design lifecycle. Overall, the framework aims to create a more seamless AR experience by enhancing the symbiotic relationship between user and technology.

While initial expert review and case studies demonstrate the potential of this BIM-AR approach, further validation is required. Future work should concentrate on gathering additional use cases across different domains to refine the framework. More robust testing and evaluation of the ontology is also needed to ensure it adequately captures the necessary design knowledge. Extending the current ontologies with linked open data could also strengthen the knowledge-sharing capabilities. With further development and validation, this human-centric methodology could provide a new paradigm for AR system design that leads to more adopted and usable AR solutions.

This research presents a promising user-focused approach to AR design, moving away from software-centric methodologies. The BIM-AR Framework and ARCHI ontology provide an integrated solution to put human needs at the forefront. While more work is required, this pioneer research lays the foundations for next-generation AR systems that emphasize the human perspective over tools. With rigorous validation and evolution, this framework can enable AR developers to create more intuitive and purpose-driven applications that deliver value in various real-world contexts. The user-centric future envisioned by this research has the potential to transform augmented reality technology and cement its place as an integral part of how people interact with information and their environment.

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