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Fused Twins: A Cognitive Approach to Augmented Reality Media Architecture

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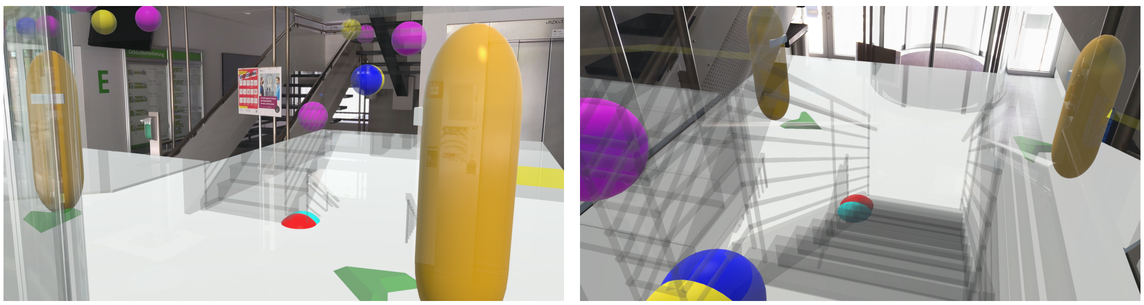

(a) Entering the augmented lobby in the Fused Twins.

(b) Coming down the stairs into the augmented lobby.

Fig. 1. The Fused Twins are used to augment the building's lobby with visualizations of sensors and agents through a HoloLens 2.

Recent advances in Augmented Reality (AR), the Internet of Things (IoT), cloud computing, and Digital Twins transform the types, rates, and volume of information generated in buildings as well as the mediums through which they can be perceived by users. These advances push the standard approach of media architecture to embed screens in the built environment to its limits because screens lack the immersive capacity that newer media afford. To bridge this gap, we propose a novel AR approach to media architecture that uses a Digital Twin as a platform for structuring and accessing data from various sources, including IoT and simulations. Our technical contribution to media architecture is threefold. First, we extend the possibilities of media architecture beyond embedded screens to three dimensions by presenting a Digital Twin using AR with a head-mounted display. This approach results in a shared and consistent augmented experience across large architectural spaces. Second, we use the Digital Twin to integrate and visualize real physical sensor information. Third, we make artificial occupancy simulations accessible to everyday users by presenting them within their natural context in the Digital Twin. Observing the Digital Twin *in situ* of the Physical Twin also has applications beyond media architecture. Fusing the two twins using AR can reduce the cognitive load of users from consuming big and complex information sources and enhance their experience. We present two use cases of the proposed *Fused Twins* in a university building at ETH Zürich. In the first use case, we visualize a dense indoor sensor network (DISN) with 390 IoT sensors that collected data from March 2020 to May 2021. In the second use case, we immerse visitors in agent-based simulations to enable insights into the real and projected uses of space. This

*All three authors contributed equally to this research.

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work brings forward an ambitious vision for media architecture beyond traditional flat screens, and showcases its potential through fusing state of the art simulations, sensor data integration and augmented reality, finally making the jump from fiction to reality.

CCS Concepts: • **Human-centered computing** → **Visualization systems and tools**; **Mixed / augmented reality**; **Ubiquitous and mobile computing systems and tools**; • **Applied computing** → **Computer-aided design**; • **Computing methodologies** → **Mixed / augmented reality**.

Additional Key Words and Phrases: Fused Twins, Augmented Reality, Digital Twin, Physical Twin, Agent-Based Modeling, Dense Indoor Sensor Networks, Data-Driven Design

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1 INTRODUCTION

In the era of big data, media architecture is limited by its focus on the medium of 2D screens and 2D projections. Whereas media architecture has extended beyond aesthetically pleasing art installations to interactive façade mapping [13], place-making and participation [8, 16, 18, 23], health [41], and design [42], it remains unprepared to address the underlying abundance of raw spatio-temporal data. In contrast, Augmented Reality (AR) technologies enable the consumption of big data in its spatio-temporal context, allowing for the entire world to be a screen [28, 33]. Modern works of science fiction (e.g., Minority Report, Ghost in the Shell, and Blade Runner) have explored artistically the manner in which AR could impact society as part of media architecture. However, the challenge of whether AR media architecture is feasible beyond science fiction remains to be addressed.

Despite the availability of AR since the early 2010s [2], it has not yet been established in the field of media architecture. Whereas small scale AR experiences have been developed, they are not yet broadly implemented at the architectural scale. Most early AR focused on viewing 3D content without a persistent spatial or temporal reference to the real world [35]. For this technology to become comparable to classical media architecture [18], it is necessary to anchor AR persistently in the physical environment to support a fully immersive and shareable experience. Here, advances in edge computing and computer vision have produced persistent traces of users' activity that are anchored in the real world and can be accessed remotely by others [39]. Advances in computer vision of real-time environment scanning have made it possible to interact more accurately with AR objects (e.g., the iPad with LIDAR-sensors, the HoloLens) by keeping track of the entire space with, for example, world-locking [12]. With these technologies in place it becomes possible to systematically explore the ways in which AR could extend the notion of media architecture to an augmented space [28].

Another challenge for implementing AR in media architecture is placing virtual data in the physical space. Here, it is necessary to retrieve only meaningful information from the raw data, which we will achieve using the concept of a Digital Twin from industrial research [19, 38]. Digital Twins represent physical objects, processes, or systems by generating a virtual representation of a physical component to model, simulate, and predict its behavior [25]. This enables users to explore past, present, and future activity by modeling higher order processes [25] including social processes [5]. Because a Digital Twin consists of a physical component, a digital component, and the data exchanged between them [19], it lends itself naturally as the backbone of AR media architecture.

To understand the relation between AR media architecture and classical media architecture, we evaluate screen use along the Reality-Virtuality-Continuum [31] (see Fig. 2). Classical media architecture has remained on the reality end of the continuum, foregoing the benefit of 3D visualizations. Technological limitations such as hardware costs and the ruggedness of devices have limited media architecture to the 2D world of a screen. Recent work in media architecture has focused on low-cost screens [23] as ubiquitous dashboards to access data [4, 26]. Consequently, there is an increase in the number of screens, which can lead to issues such as light pollution [45]. These issues have led proponents of media architecture to question its purpose beyond art installations and to strive towards reinventing it [15].

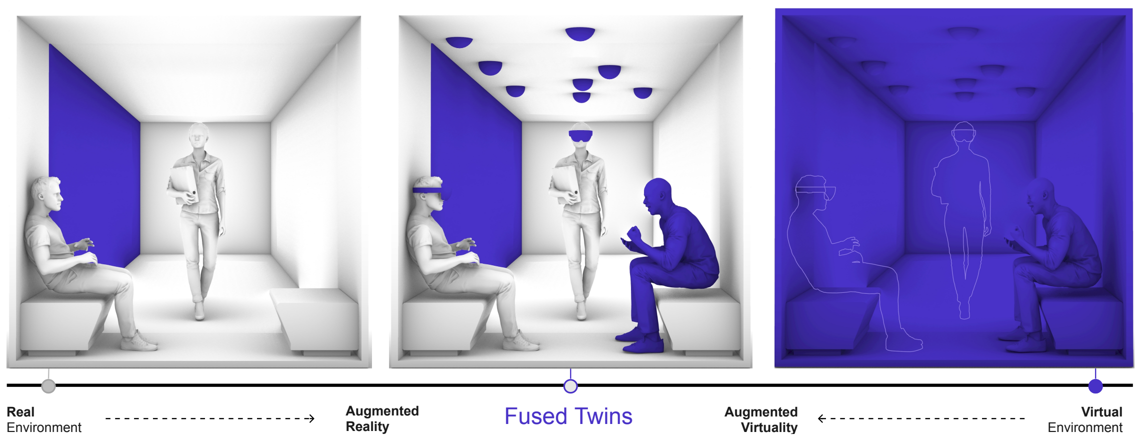


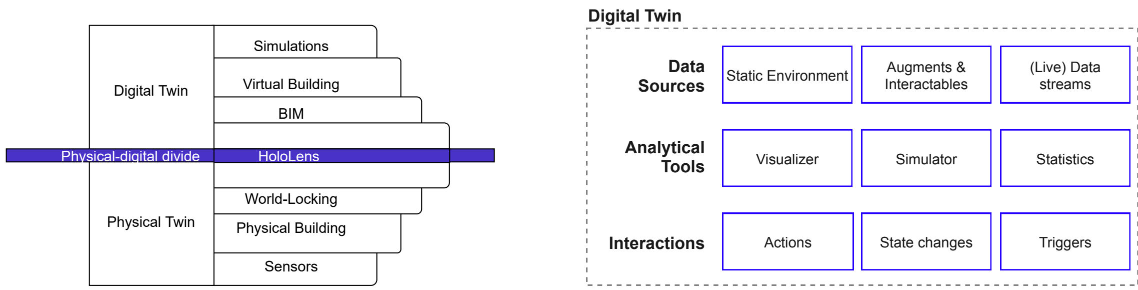
Fig. 2. Media architecture shown across the Reality-Virtuality-Continuum [31]. The media architecture content is displayed in **blue** and the physical world in white. A progression along the continuum shifts the display in media architecture from external screens to augmentable user screens. The Fused Twins allow an optimal mix of adding virtual content from the Digital Twin and remaining present in the environment.

Offering a novel alternative, AR Digital Twins have been a popular topic since 2018 [7, 10, 24, 27]. Although there are some commonalities with classical media architecture, AR Digital Twins have so far been focused on remote miniaturized viewing of an environment and its processes. This focus of AR Digital Twins differs fundamentally from that of classical media architecture because, with AR, digital information can be embedded *in situ* in the physical environment. To extend AR Digital Twins to media architecture, it is necessary to fuse the Digital Twin with its Physical Twin. This approach also offers cognitive benefits as it could overcome the limitations of screens to convey spatio-temporal big data. The externalization of cognitive processes into the augmented space allows for the reduction of perceptual and cognitive load when reasoning about data by removing the need for keeping the context in mind [37]. Using AR enables *immersive analytics* [9], has been shown to reduce task completion time in manufacturing [29, 44], and can help to logically organize the information [32]. Viewed through a Fused Twins, data can be provided in a more natural context, allowing non-experts to engage more easily with the data in an augmented space.

In this late-breaking paper, we describe our first prototype of an AR media architecture that fuses the Digital Twin of a building with its Physical Twin. Beyond the technical proof-of-concept of Fused Twins, we make the data from IoT sensors and occupancy simulations visible for the public promoting the engagement of building occupants and participatory design. Our work demonstrates the potential of AR for media architecture, marking an important step towards fulfilling a societal role beyond the imaginations of science fiction.

2 SYSTEM DESIGN & PROTOTYPE

We present a first version of the Fused Twins platform that is used as a backbone for AR media architecture (see Fig. 3a). We fuse the Physical Twin in the real world and the Digital Twin in the virtual world using a wide stack of technologies. In the digital realm, we combine a Building Information Model (BIM) [3, 11], virtual environment management [20, 21], and simulations software [17]. In the physical realm, we use computer vision [12, 39], a real building, and 390 IoT sensors [20]. The divide between the physical and the digital is bridged by augmentation through a head-mounted see-through display. Specifically, we employ Microsoft HoloLens 2 (See-through holographic lenses/52°FOV,8 cameras, 6DOF tracking, Qualcomm Snapdragon 850/8 cores/2960MHz, 4GB RAM) [30].



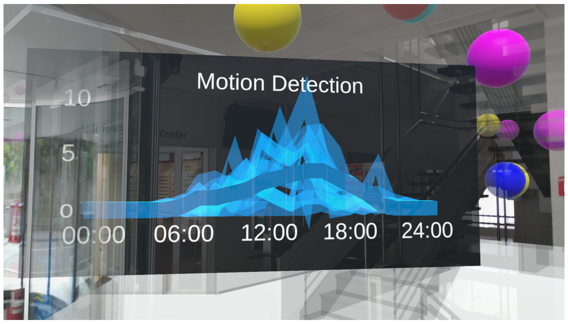
(a) The Fused Twins technology stack.

(b) An overview of the features of the Digital Twin.

Fig. 3. (a) The bridge between the digital realm and the physical realm is fused by combining world-locking with a BIM to co-locate the virtual and physical space in a holographic device. (b) The components of the Digital Twin. The data sources provide the information, the analytical tools process the information, and the actions enable users to interact with the data.

The prototype of the Digital Twin is based on Unity3D, extending the Experiments in Virtual Environments (EVE) platform [20, 21]. The twin is organized into three types of components: data sources, analytical tools, and interactions (See Fig. 3b). The data sources provide all the information such as the static environment based on a BIM and augments interactables for users (e.g., representations of sensors and agents). The static representation is further expanded with live data streams (e.g., IoT sensor data). The analytical tools provide users with information processing capabilities to visualize the data streams, run simulations, and apply statistics to engage with the data. Finally, the interactions define how users can dynamically communicate with the Fused Twins. Actions allow users to directly manipulate the state of the Fused Twins (e.g., starting a simulation, enabling a visualization). State changes and triggers are similar in that they automatically provide new augmented content. State changes rely on the internal state of the Fused Twins (e.g., the end of a simulation, the display of statistics) whereas triggers are caused by users (e.g., users enter a room and a display is opened). This prototype is limited to demonstrating basic visualizations of sensors and agents.

Integration of Dense Indoor Sensor Networks. Previous research in the building deployed a sensor array of 390 sensors to test a dense indoor sensor network (DISN) [20] with the goal of passively sensing human activity. We reuse this infrastructure to create a live data stream of sensor data for the Digital Twin. The sensor sends the data via LoRaWAN to the EVEREST data server [20], and the physical locations and raw sensor data are streamed from the EVEREST data server via its Representational State Transfer Hypertext Application Language (REST-HAL) interface [34]. The resulting visualization in the Fused Twins (see Fig. 4) enables users to perceive the sensors and their data in the environment. Whereas this initial integration offers limited interaction, it forms the basis for greater participatory opportunities, making the data collection and data itself visible and accessible in a natural way.

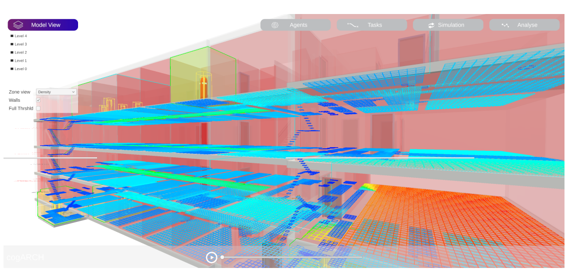


(a) Daily data from a motion sensor at the entrance.

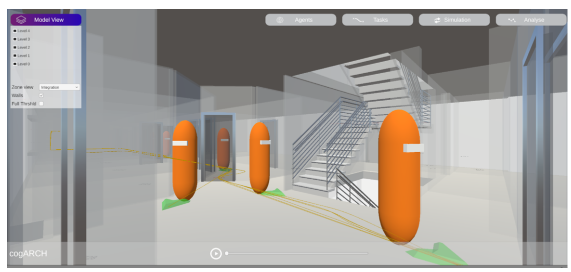
(b) Increased visibility of the many sensors through AR.

Fig. 4. Two snapshots taken live from the HoloLens 2. The IoT sensors are installed in the ceiling and out of sight for the users. The colored spheres reveal the locations of sensors in the building (noise: blue; CO_2: red; VOC: cyan; PIR: yellow and magenta; gateway: green). (a) A motion sensor is gaze-activated to display a summary of the collected data.

Integration of Simulated Occupancy Analysis. CogARCH is an agent-based simulation framework to simulate occupants' behavior in buildings [17] (see Fig. 5a). The spatial input to perform the simulations is the same BIM that underpins the Digital Twin. By integrating cogARCH into the Digital Twin, it is possible to provide occupancy analytics based on real-world data (e.g., from sensors) or to predict human behavior based on computational models. The fusion of occupancy analytics into Digital Twins and their perception through AR provides a new form of public engagement that could support a range of applications from wayfinding to emergency evacuation [1, 22, 43]. With this approach, occupancy-related (e.g., traces and activities) information may be made available to lay users, enabling participation and informing decision making (see Fig. 5b).



(a) The cogArch framework integration in the Digital Twin.



(b) Agents and their traces in the Digital Twin.

Fig. 5. Screenshot of the Digital Twin implementation [17] fused with an agent-based simulation of occupants' movements in the building. For the Fused Twins, refer to Figure 1.

3 DISCUSSION

Introducing AR as the medium to media architecture extends three recent exchanges: the environmental cost of media architecture, the goals of media architecture beyond aesthetics, and the participation in creation and consumption of media architecture. First, media architecture can have a strong negative impact on the environment through light and noise pollution [15, 45, 46]. The focus of media architecture has thus become the responsibility to design "more than human" media architecture [15] and address the consequences of designing temporary and environmental costly installations. AR media architecture can facilitate these developments because the direct light and noise pollution is limited to the user device. However, the costs of running and maintaining user devices must still be addressed.

Second, media architecture has changed its outlook from aesthetically pleasing art installations to societal issues. As more data is generated, equitable access to the information becomes more challenging. Usually, people will be oblivious the data generation processes [36] around them based on IoT, networks, and building automation. Recent work has therefore focused on regaining accessibility through making the data visible on low-cost screens [23]. We offer another approach through AR that is visually richer and allows people to understand, interact with, and use data in its natural context based on findings in cognitive science. Despite the currently inconclusive evidence on the actual impact of using augmented reality on cognitive load [6, 29, 44], the proposed approach postulates that interactions with the Fused Twins may lower cognitive load by externalizing cognitive processes [37], logically organize the information [32], and enable more participation by a broad range of users (not only experts).

Third, classical media architecture is characterized by its democratic access without a technological barrier from the side of the user [16] but possibly ignores the costs from the side of the creator. In contrast, an AR media architecture approach reverses the burden of these costs. This allows anyone to create augmented content for others to discover but requires physical hardware to access the content. For AR to work, the users have to carry the screens themselves and use them as windows into a virtual world invisible to the naked eye. In this context, AR media design has the potential to inspire more experiences of the data sublime [14]. The latter refers to human awe at the richness of data that can be made accessible through visualizations uncovering the information within the data. As users produce and share their own augmented media architectures, they can strengthen place-making via a pluralistic discourse [14].

The cognitive approach to AR Media Architecture can enable innovative co-creating and co-participation in design processes beyond media architecture. It has been shown that a shared context such a twitter has spawned a thriving ecosystem of co-design tools overcoming the limitations of current software and has enabled innovative applications [40]. Similarly, the Fused Twin could provide a shared spatial context that creates new insights, application, and eventually participation in the use and understanding of the space with regard to environmental and societal questions.

4 CONCLUSION

In this paper, we demonstrate a prototype of a Fused Twins as a first step towards AR media architecture. To our knowledge, we are among the first to effectively lay the foundation for how AR media architecture can work. Our approach goes beyond mirroring the physical in the digital by collapsing the Reality-Virtuality-Continuum [31] and fusing the physical and digital representations *in situ*. The combination of the physical and digital representations allows for a reduction in the cognitive load [37] by providing a natural context for spatio-temporal information. The durable, interactive, and localizable augmentations allow user participation in both the creation and use of AR media architecture. At the same time, we enable engagement with previously invisible data [36] from sources such as DISNs and occupancy simulations. This approach has the potential to increase democratic participation by giving users a better understanding of their surroundings and more equitable access to information. In our future work, we will expand the available interactions for users to explore and arrange the data in its natural context while also enabling the sharing of results with a broader audience. Additionally, we will evaluate the effect of the proposed cognitive approach to AR Media Architecture on the the user's cognitive load by systematically testing user experience.

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