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Digital Twin in Architectural Design Process: Foetal Twin Design Test Kit

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Abstract: Digital twin technology is often overlooked in early architectural design stages, with most studies focusing on final applications and performance evaluation. Our research bridges this gap by exploring hybrid prototypes, combining digital and physical models enriched with sensors by a "foetal" digital twin during conceptual design, representing the eventual "adult" version. Physical twins collect data, while digital twins simulate and optimize within these prototypes. We utilize a foetal physical twin collecting and transmitting data for a more sustainable architectural design process.

Keywords: Design Process, Prototyping, Architectural Design, Digital Twin, Foetal

1 Introduction

The latest Digital Twin (DT) technology has significantly influenced the role of Computer-Aided Architectural Design (CAAD) as a digital design tool in architectural practice. This virtual spatial information technology acts as a mirror image of the real information of the Physical Twin (PT) and relies on synchronised real-time data updates (Grieves and Vickers, 2017, p. 92).

The DT system comprises integral components, including a DT in the virtual space, a PT in the real space, and a bi-directional data-information connection (Grieves and Vickers, 2017, p. 93). The DT in the virtual environment corresponds to its PT in the real environment (Singh et al., 2021, p. 1). PTs can represent both living objects (animals, people, plants, etc.) and non-living objects (built environments, buildings, etc.) (Pylianidis et al., 2021, p. 4). PTs provide data from sensors—sensed, actuated, and monitored—while DTs generate simulated, optimised, and predicted data (Boje et al., 2020, p. 10) within the hybrid prototypes. Furthermore, Sacks et al. (2020, p. 13) describe the transitions of data, information, and knowledge using the DT to make design decisions through generation, derivation, storage, and manipulation.

Following the conceptual definition of the DT, studies on this technology have been extensively investigated in academia and industry (Jones et al., 2020, p. 36). Naqvi et al. (2022) state that DT can encompass the lifecycle of elements, from design and production to manufacturing and maintenance. Notably, there is a gap in studies indicating that DTs are not implemented in the design phase before the final design is reached (Jones et al., 2019, p. 2558). The current state of DT primarily involves its application in designing real-world objects or evaluating their performance; there is limited consensus on building designs from the ground up using DT for new objects (Liu et al., 2021, p. 356).

Sacks et al. (2020) propose developmental stages of DT, categorised as foetal, child, and adult DT. Emir Isik and Achten (2023c, p. 3826) incorporate these notions and hypothesise that they correspond to progressive stages of the design process linked to DT. To explore this, they define so-called hybrid prototypes, which combine digital and physical models using DT technology. Consequently, they also focus on enhancing these hybrid prototypes with sensor technologies in the context of DTs in the architectural discourse. They present an architectural design catalogue that incorporates sensors during prototyping to guide designers. The DT connects models to simulate the response of sensors attached to the PT using precise sensor data (Wright and Davidson, 2020, p. 7). The aim of this work is to contribute to the knowledge about these progressive DT stages. Therefore, we aim to fit into the gap of these progressive states, as this has not yet been established in the studies.

Creating a foetal twin of a physical-scale model coupled with sensors is feasible from the early stages of conceptual design. We argue that the architectural design process can be characterised by foetal and child DTs as precursors to adult twins. In this study, we propose an experimental design using the Foetal Twin Design Test Kit, a small-scale model of a house equipped with sensors, as a key component of our argument. Initially, data acquisition is performed during data transmission using Arduino, and the data is transmitted using the developed C# programming language integrated with Unity3D. Subsequently, the system is monitored for functionality. Ultimately, this research aims to lead architects to explore the integration of DT in digital architecture to create more sustainable designs.

1.1 Objectives

Instead of aiming to develop a universally applicable design test kit, we focus on supporting the creation of experimental architectural design. This approach acknowledges the complexities and specificities of architectural design, potentially leading to nuanced insights and innovations tailored to specific design challenges. By focusing on the foetal stage of DTs, we explore how their early integration can influence the design process, potentially leading to more informed and optimised design decisions. This investigation could significantly contribute to the field by demonstrating the benefits of early-stage DT integration in enhancing design efficiency and effectiveness. By offering a methodological framework based on preliminary experimental design, we introduce a tangible approach to implementing and assessing DTs in architecture. This objective is particularly valuable as it transcends theoretical discussion to provide a structured method for applying DT technology in real-world design scenarios. It serves as a guide for other researchers and practitioners interested in exploring the potential of digital twins in their work.

2 Digital Twin in Architectural Design

This section presents the digital twin in architecture by looking at subsections as follows: progressive states of a digital twin, digital twins in the architectural design process and hybrid prototypes versus digital twin and physical twin, and integration of sensor technologies in architectural design.

2.1 Progressive states of a digital twin

Sacks et al. (2020, pp. 16–19) illustrate the lifecycle of digital and physical twins through three progressive states: foetal, child, and adult twins. Since Sacks et al. do not further detail the functionalities of these states, our research aims to establish a theoretical framework named Digital Twin in Design Process (DTDP). Subsequent investigations have been conducted to explore the progressive states of DTs and their implementation at various maturity stages in the design process (Emir Isik and Achten, 2023c).

Sacks et al. (2020, pp. 12–17) describe the foetal DT as representing project intent information, encompassing both the planned process and the designed product. The foetal DT marks the initial stage of DT during the design phase (Drobnyi et al., 2023, p. 2). It captures both product and process information, primarily referring to Building Information Modelling (BIM) as designed. Designers start with a conceptual plan, potentially proposing multiple BIM models. However, only the final design approved by the client remains, serving dual purposes as an indicator for future construction assessments and a maintenance guide (Pan et al., 2023, p. 86). For instance, a foetal DT can exemplify a door within a BIM, designed by an architect and approved by the owner for construction, as mentioned by Sacks et al. (2020, p. 19).

The child DT, as defined by Sacks et al. (2020, pp. 12–17), symbolises project status information, the performed process, and the built product. It emerges during the construction phase, building on the foundation set by the foetal DT (Drobnyi et al., 2023, p. 2). This state contains the built product information and performs process data, mirroring the asset's physical status during construction. As construction progresses, this DT continuously accumulates product and process details, adapting to changes in real-time to aid in progress monitoring and quality control (Pan et al., 2023, p. 86). The child DT could represent a door within a BIM used and procured by the contractor, as Sacks et al. (2020, p. 19) suggest.

Sacks et al. (2020, pp. 12–17) describe the adult DT as managing asset information, with the adult PT being the actual constructed design. The adult DT comes into play during the operation phase (Drobnyi et al., 2023, p. 2), primarily supporting performance analyses for aspects like energy consumption and component maintenance. Once construction concludes, data collected during the operation phase enhances the as-maintained product, thus augmenting the adult DT (Pan et al., 2023, p.86). Continuing the analogy, the adult DT could represent an installed door, evaluated, and approved either by an inspector or a software agent, as drawn from the example given by Sacks et al. (2020, p. 19).

Using hybrid prototyping, the conceptual design begins with a foetal digital and physical twin, representing an incomplete model or an ongoing twin-related process. The preliminary design phase incorporates child PTs and DTs through hybrid prototyping, signifying an incomplete model or an evolving DT process. Finally, operation is achieved with the adult PT and DT, indicating a comprehensive model or a finalised DT process (Emir Isik and Achten, 2023a; 2023c). The foetal versions are primarily rooted in simulations or simple volumetric representations.

2.2 Digital twin in architectural design process

In the era of the digital revolution and the advancements in CAAD, there is an increasing emphasis on exploring early architectural design (Hannibal et al., 2005, p. 109). Architects of this century, as pioneers in CAAD research and creators of digital design culture, play a more important role than ever in the development of information architecture (Schmitt, 2004, p. 33). Modelling methods, as noted by Oxman (2006, p. 245), offer powerful tools to comprehensively explore the vast potential of digital design models. They facilitate a deep understanding of the diverse relationships between designers, conceptual elements, applied design processes, and the design objects themselves.

Digital Twin Technology Development (DTTD) represents a significant advancement, enabling the creation of DT at building and city levels in five-layered approach (*data acquisition layer, transmission layer, digital modelling layer, data/model integration layer*, and *service layer*) (Lu et al., 2020, p. 5). In the DTTD digital modelling layer, digital models are constructed using CAD software (Segovia and Garcia-Alfaro, 2022, p. 13). Many CAAD programs, such as Revit, Rhino3D, SketchUp, and more are widely employed in architectural modelling. These digital models are then used to simulate the behaviour of the physical twin under various scenarios (Grieves and Vickers, 2017, p. 96).

DTDP can be divided into the following stages, as outlined (Emir Isik and Achten, 2023b; 2023c). *Defining goals and data needs:* In the first stage, designers pose crucial questions such as: What are the objectives of using DT? What aspects should DT monitor, track, or record? What types of data are required? Sensor technologies play a fundamental role in addressing questions related to environmental comfort, as demonstrated in the provided case study. A list of sensors is provided, along with methods for acquiring and transmitting data to the system using the Arduino board. *Creating the model:* In the second stage, designers ask the question of what kind of model is needed to build. They also can use the XR tools for synthesis of the design process. *Implementing actions*: The third stage investigates the actions that DT should undertake. Designers can have simulations in this part to explore potential actions. *Analysing results:* In the fourth stage, designers evaluate the outcomes achieved with DT. This typically involves creating necessary dashboards and providing data visualisation. *Assessing goal achievement:* The final stage prompts the designer to reflect on whether the desired DT objectives have been met. This stage represents the realisation of design goals through DT.

2.3 Hybrid prototypes versus digital twin and physical twin

The integration of hybrid prototyping, complemented by DTs in the design process, holds the potential to enrich the understanding of these DT progressive states. Achieving this integration is made feasible through the application of various tools such as parametric design, simulation, BIM coupled with digital prototyping, as well as sensors, actuators, and processors with physical prototyping (Kim, 2019, pp. 7–10). Prototyping variables encompass aspects like appearance, data, functionality, interactivity, and spatial structure (Lim et al., 2008, p. 11), which serve to characterise these progressive states.

Hybrid prototypes extend the traditional concept of the prototypes, typically static and disconnected objects, into the realm of digital modelling. They place an even greater emphasis on real-time monitoring and simulation during the design process. The presented approach underscores that the progressive states of the DT, described as foetal, child, and adult twins, can be equivalently understood as physical models, prototypes, mock-ups, or prefabrications (Emir Isik and Achten, 2023a, p. 56; 2023c, p. 2829).

The prototype examples from Burry and Burry's (2016) show that many designers routinely use models, prototypes, mock-ups, or prefabrications in their architectural design processes. In line with the designer's ideas, prototyping serves as a comprehensive method for testing the performance of designs, abstractions, things (especially in digital environments where calculation or simulation can be challenging), ideas, emotions, materials, assemblies, manufacturing techniques, technologies, and environmental design facts; integrated passive and active technologies; adaptation to different conditions; informing designers about design processes, and reassuring the project owners (Emir Isik and Achten 2023a, p. 51).

2.4 Integration of sensor technologies in architectural design

Hybrid prototypes that combine physical and digital models can be complemented in architectural discourse with digital design tools by sensor technologies related to DTs. This integration offers various ways to establish a bidirectional connection between the digital and physical realms.

Arduino is a compact and cost-effective computer that easily fits in the palm of your hand. It is commonly used to sense or control things in the physical world. Arduino´s popularity stems from its seamless integration with everyday household appliances, digital devices, and computer code. It serves as a hardware replicator, allowing communication with and reconfiguration of standard everyday electronics (Hertz, 2011, pp. 45–46).

The Arduino board (http://arduino.cc) functions as a single-chip microcomputer that executes programmes generated in processing programming languages. Using sensors or actuators, lighting, daylighting, renewable energy, and ventilation can be controlled based on the knowledge of environmental data (Kensek, 2014, p. 2). Designers can use open-source platforms such as Arduino, which provide direct access to the electronics world (Adamantidis et al., 2013, p. 356). As a hardware component, an Arduino board microprocessor is managed through programming in the Arduino language facilitated by a written code (Sanchez, 2010, p. 290).

Arduino environmental sensors enable the recording of actual values for various comfort parameters. Emir Isik and Achten (2023b, pp. 76-77) provide a systematic list of important aspects for foetal, child, and adult DTs by offering a design catalogue and sensor network to analyse the design environment in terms of required data types: acoustic comfort (*sound* *level sensors*); air quality (*air-gas, pressure, wind sensors*); soil quality (*conductivity, pH sensors*); spatial use (*occupancy sensors*); structural (*acceleration, displacement, force, gyroscopic, strain, vibration sensors*); tactile comfort (*touch sensors*); thermal comfort (*humidity, temperature sensors*); visual comfort (*colour, contact, daylight, passive infrared, proximity sensors);* water (*pH, rain, soil moisture sensors*) (Figure 1).

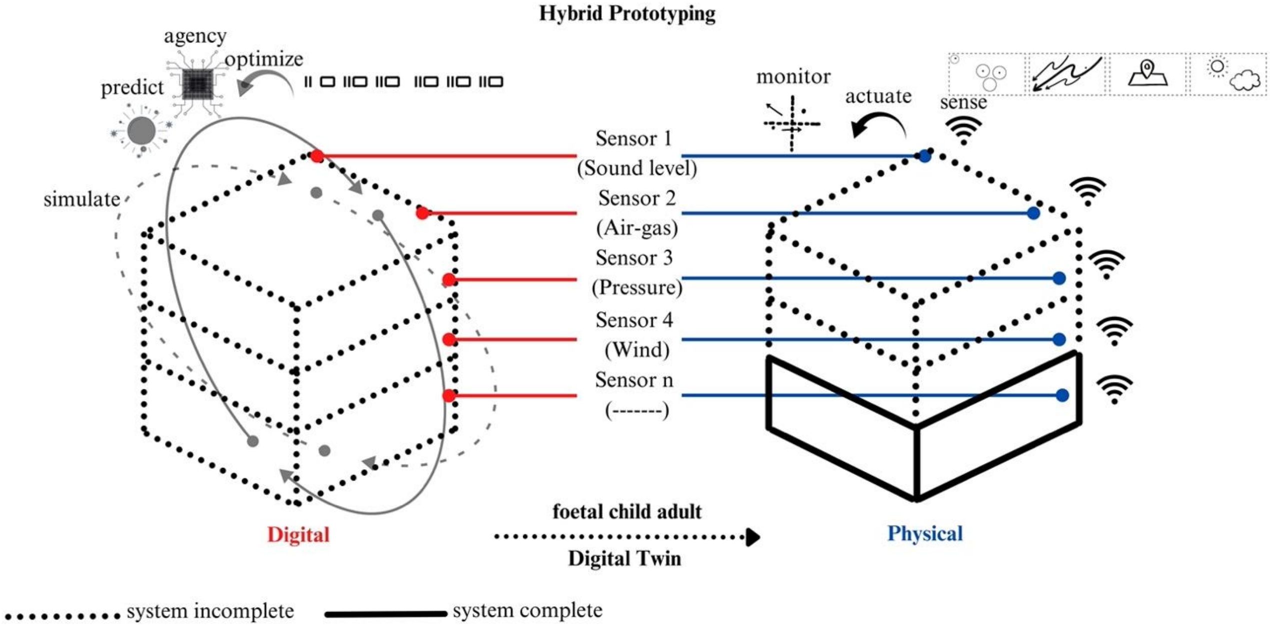

Figure 1. Sensor networks for foetal, child and adult digital twins

Sensor networks closely align with the comfort parameters of the design process. Further exploration and utilization of sensor technology can enhance environmental adaptability and occupant comfort in architectural design. By embedding sensors in the early stages of design, architects can obtain data in real-time and with greater precision, making designs more responsive to microclimate conditions. This precision can lead to buildings better adapting to their environments, reducing energy consumption, and increasing comfort.

Monitored sensor data feeds into the DT, allowing architects and engineers to simulate and optimize building performance before the final design. As a result, the final structure is more likely to provide a comfortable living or working environment tailored to the specific needs of its occupants. With the data collected from sensors, architects can design spaces that are not only environmentally adaptive but also customizable to individual preferences in real-time. For instance, lighting and climate systems can adjust automatically based on the presence and activities of occupants, thus personalizing the environment according to user preferences and patterns.

3 Methodology

This research adopts an experimental design focusing on the integration of DT in architectural design. For this research, we have introduced a Foetal Twin design test kit. This kit comprises a small-scale model of a house embedded with a range of sensors. Our initial step was to build a physical prototype, which serves as our Foetal PT using an Arduino-based board. The Foetal PT is then combined with the modern programming language C#, building upon the foundational DTDP stages. The emphasis is on simultaneous interaction of digital and physical twins.

4 Design Test Kit of a Foetal Twin

The components of the Foetal PT revolve around a control board akin to the Arduino UNO, on which various sensors have been implemented. The essential components include a sensor shield, the Arduino control board, an LCD 1602 display, a Bluetooth module, dupont lines, and a selection of sensors. These sensors are closely aligned to the comfort parameters of the design process: air quality (*incorporating a passive buzzer module and an MQ-2 gas sensor); soil quality (utilising soil humidity sensor);* spatial use (*comprising a passive infrared (PIR) sensor*); thermal comfort (*employing a fan module*); visual comfort (*utilising a PIR sensor, photocell sensor, white LED, yellow LED*); and water-related parameters (*including steam sensor*). In addition, the system features two button sensor modules that offer manual control of the system in a physical environment. Two actuators are incorporated to control the system based on the data collected by the sensors.

In the DTDP framework, the first layer includes the functional and analytical aspects of the design process, along with the technological part involving data collection and data transmission, which is mainly achieved using Internet of Things (IoT) tools (Emir Isik and Achten 2023b). It is essential to select sensors thoughtfully for the early design phase, as DT data is collected and recorded via sensor technology (Lo et al., 2021, pp. 8-11; Emir Isik and Achten 2023b). Our process commences with the careful determination of sensor replacement and the requisite electrical connections, followed by the installation of the IoT sensors (Figure 2).

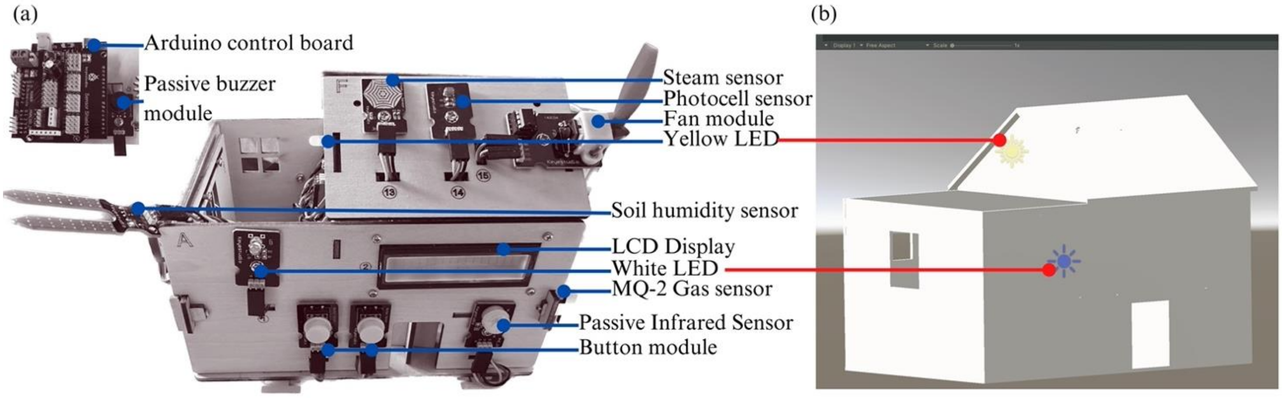

Figure 2. Foetal digital twin (a) sensors applied (b) Unity game view

5 Results and Discussion

This case study, being part of an ongoing research project, inherently has several limitations that prevent us from making broad generalisations at this stage. One significant limitation pertains to addressing scale effects and methodological constraints. The design kit may not fully replicate the real environmental conditions experienced by full-scale buildings, presenting challenges in accurately simulating such environments.

Collecting detailed data from full-scale buildings is challenging, a problem also found in simulation models. Additionally, when using scaled models like a 1:10, 1:20 etc. scale building, there are further complications. For example, the scaled model has much less surface area and even less air volume compared to the original building. This difference in scale makes it nearly impossible to accurately replicate temperature and other environmental factors without using a complicated, non-linear mapping function (Burns et al., 2021, p. 5). The concept of non-linear scaling in architecture can help us understand the limitations of physical models. This idea has been explored from the time of Galileo up to modern research.

The focus of the case study is on integrating architectural and engineering tools with digital computing technology to meet specific design criteria. An example of this integration is demonstrated through the foetal DT, where sensor pin signals from a photocell sensor are connected to the Arduino control board to monitor data outputs. This sensor, which adjusts its resistance in response to changes in light levels, is used to measure illuminance—a critical parameter for visual comfort. This measurement provides practical insights into the application of sensor technology in architectural design to enhance environmental adaptability and occupant comfort (Lynch et al., 2015) (Figure 3).

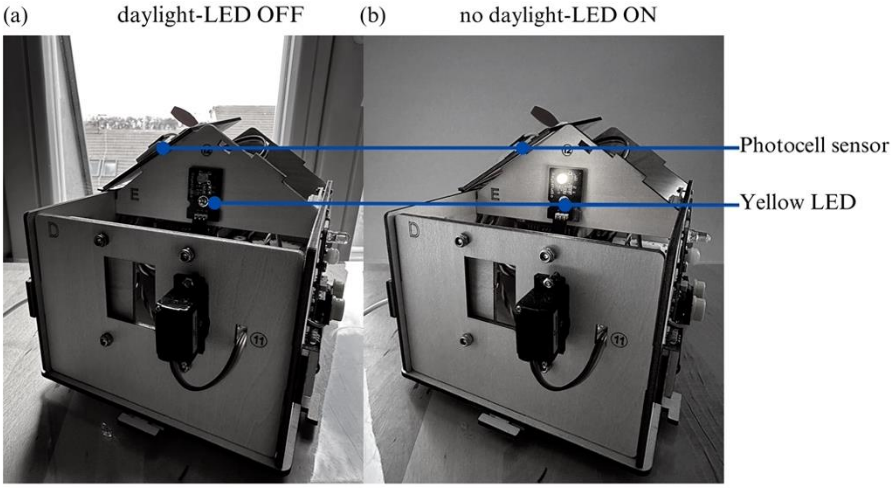

Figure 3. Foetal digital twin photocell sensor (a) day light-Led off (b) no daylight-Led on

We use the analog pin A1 to read values from the photocell sensor. Once the code is developed and uploaded to the Arduino control board, the sensors begin the measurement process. The code for installing and operating the sensors is designed to measure specified comfort parameters. The collected data is then displayed on the serial monitor, with the outputs from the photocell sensors—indicating lighting levels—presented in lux (lx).

The outputs from the Arduino sensors are integrated with the C# programming language, and MySQL is used in conjunction with Unity for storing, managing, and utilising the sensor data. This integration ensures that data collected from Arduino sensors can be effectively incorporated into the Unity application via C#, thereby enhancing the project's capacity for future studies and applications. The key to success lies in secure and efficient data transfer between the Arduino, the MySQL server, and Unity, facilitated by a local server. This data is then utilised for a local web dashboard to monitor the collected data.

Using insights from the foetal DT, designers can make crucial design decisions to enhance the performance, functionality, and user experience. Designers can iteratively refine design solutions by analyzing data on various spatial conditions such as daylight levels, acoustic quality, air quality, and odor, collected by sensors embedded in the scale model. For instance, based on insights from light sensors, designers may choose to relocate windows or adjust their size and orientation to optimize natural light penetration while minimizing glare. Similarly, data from sound sensors could prompt designers to reconfigure room layouts or select different surface materials to improve acoustic comfort. Additionally, data from odor sensors could prompt designers to reconsider room layouts or adjust the height and volume of spaces to mitigate unpleasant odors and improve indoor air quality. This insight may lead designers to relocate rooms or introduce ventilation strategies to ensure optimal air circulation and a more comfortable indoor environment. By integrating these insights, architects can develop adaptive design solutions that prioritize environmental performance and user well-being, contributing to more responsive and sustainable built environments.

6 Conclusion

This study presents a method for building a DT using hybrid prototypes in the architectural realm. The Foetal DT is equipped with IoT sensors related to the design comfort parameters to read the real-time data. This research represents an initial step in the creation of the DTs encompassing the progressive states called foetal, child, and adult. It serves as a pivotal precursor for future DTs developed in the form of hybrid prototypes. These endeavours are poised to support designers in their adoption of DT approaches within the design process. The collected data will play a pivotal role in informing design decisions based on real-world conditions and processes. This data is systematically stored in a MySQL database, facilitating its analysis for future purposes. Additionally, real-time data and historical data are monitored in dashboards both Unity3D and web dashboards.

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