Blurring the Line between AI and Architecture: Developing AI-powered Data-Driven Panels for Interactive Architectural Features

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Abstract. The integration of artificial intelligence (AI) into architecture heralds a new era of innovation. This paper investigates the convergence of AI and interactive architecture through data-driven mechanical panels. Building on prior experimental research inspired by Daniel Rozin's mechanical mirror installations, this study integrates AI to elevate human-machine interaction (HMI). Machine learning (ML) is utilized to recognize images, body gestures, and speech, triggering the display of animations. A four-stage design-led methodology results in real-time simulation via 3D graphics software and integrated ML features. This investigation extends precedent work, using advanced 3D simulations to experiment with higher unit-density installations and various designs. The findings demonstrate the panels' dynamic and responsive capability, showcasing the potential for more adaptive and engaging architectural features. This paper underscores AI's transformative impact on static architectural elements, promoting the development of intelligent, interactive systems that enhance human experience, occupant comfort, and contact with the built environment.

Keywords: Interactive Architecture, Responsive Architecture, Human-machine Interaction, Visual abstraction, Artificial Intelligence

1 Introduction

The rapid evolution of artificial intelligence (AI) has an exponentially growing effect on spatial design. Data-driven design methods in relation to interactive architecture and human-machine interaction have started to come to fore regarding this acceleration. While many related studies focus on adaptation of these technologies through the digital realm (Sarirete, Balfagih, Brahimi, 2022), the integration to spatial contexts through hybrid mediums is recently gaining more interest in terms of understanding the human-machine-space interaction trio in depth (Sharafi Rohani and Akçay Kavakoglu, 2023). Hybrid mediums refer to a broad range of media that blend various technologies within digital and physical environments. Interactive, kinetic spaces, and responsive, dynamic environments stand out within this context in which AI and data-driven processes enhance diverse human experiences. The evolution of architecture has always been moving in parallel to the availability of resources and technology (Costa Maia & Meyboom, 2015). Thus, as AI continues to advance, developments within the domain of interactive, responsive architecture become increasingly pertinent. Smart, adaptive spaces would be more attainable by incorporating AI into architectural design. This shift in design thinking would push society into a new era of technological sync, revolutionizing the way architecture looks (Bryson, 2021).

In prior research, image perception was the main tackled issue starting from theory up to the built prototype. Pixels are the fundamental visual units of image composition and are the core elements of the discussed digital realm. They offer not only a flexible ground for digital design, but also an underrated opportunity for interpretation within the physical world. Understanding pixels requires in-depth examination of how they are perceived by the human eye and mind. Although typically a pixel conveys visual information through color and intensity, its recognition also relies on visual cues such as spatial arrangement and composition. These cues can be consolidated in physical objects such as patterns and scenes within the domain of architecture.

1.1 Overview of Previous Research

Previous research experimented with designing and building a mechanical data-driven paneling system that reflects the image of the person interacting with it. The study involved the development of a 36-pixel unit prototype inspired by Daniel Rozin's weave mirror installation, specifically focusing on capturing and processing image data using a depth sensor and translating this data into mechanical movements through servo motors. The prototype demonstrated the capability of transforming visual input into dynamic interactive displays that respond to environmental stimuli, such as movement and sound (Figure 1). Each singular unit in the prototype is hemicylindrical in shape featuring a gradient surface degrading from white to black. White denotes negative visual values representing the background while black denotes positive visual values representing the foreground. This procedure provided foundational insights into the design, construction, and application of data-driven panels, highlighting their potential to transform static architectural elements such as tiles into responsive, interactive surfaces. Building on previous findings, the current study aims to further explore the integration of artificial intelligence to enhance the interactivity and adaptability of these panels (Figure 2), thereby advancing the scope of human-machine interaction in architectural design.

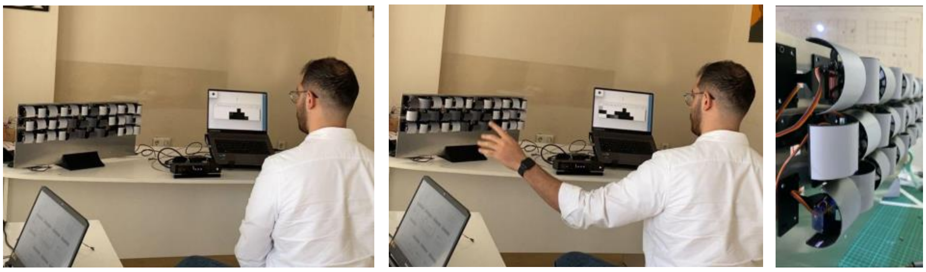

Figure 1. Left and Middle Show image reflecting feature of Data-driven panel prototype, right shows close-up of data-driven panels (Source: Authors, 2024)

2 Methodology

Drawing inspiration from design-led approaches discussed by Menges (2015) in "Fusing the Computational and the Physical: Towards a Novel Material Culture", this paper involves an experimental research methodology comprising four stages: (1) Integration of visual development platform, (2) Utilizing machine learning techniques to trigger actions, (3) Pixel animations as action outcomes, (4) Workflow of creating real-time simulations. This approach demonstrates the feasibility and explores the potentials of using AI within the realm of interactive architecture such as in the data-driven panels. The primary outcome of this research is the development of a more sophisticated data-driven panel capable of recognizing objects, body gestures and spoken words performed in front of it, with the ability to respond with different displayed animations to each triggered action. These developments can contribute to enhancing the element of human-machine interaction by allowing a more intuitive and dynamic engagement. Finally, this research introduces a workflow customized to capture the processing data responsible for the panel's functionality and transfer it to 3D graphics software in which real-time simulation takes place. This facilitates experimenting with various designs and approaches before constructing physical installations. By integrating these tools, the research not only offers space for creativity within interactive design but also provides a practical framework for testing and refining interactive systems within the virtual environment.

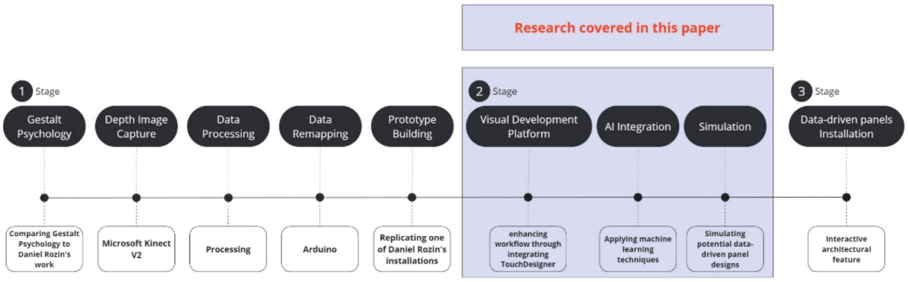

Figure 2. shows flowchart of research progress and stages of development (Source: Authors, 2024)

2.1 Integration of Visual Development Platform

In the development of data-driven panels, TouchDesigner is selected as the primary tool to initiate the workflow due to its advanced capabilities that enhance the creative and technical aspects of the project. Additionally, it integrates seamlessly with various hardware components, including Microsoft Kinect, which is responsible for capturing depth images in the data-driven panels. Moreover, TouchDesigner excels in handling multi-channel outputs, thereby enabling the simultaneous execution of multiple tasks without heavy computing power. The initial setup of the TouchDesigner environment involved migrating features previously implemented in Processing. This process begins by utilizing the depth sensor of Microsoft Kinect as the primary input unit. The captured live image is then processed into a channel that pixelates the input into 529 pixels in black and white, each assigned a value between 0 and 1 in which white is 0 and black is 1. These pixel values are updated with each frame by Kinect and are compiled into a list of numerical values and transmitted to Processing via the Open Sound Control (OSC) protocol, which is a network that helps transferring data in real-time between two channels from different software or computers. Once the data reaches Processing, the list of numbers are remapped to be from 0 to 90, which represents the rotation movement of the stepper motors that will be generated once the data-driven panels are in action. After that, Processing sends the remapped data to Arduino programming software, which distributes every number in the list with its corresponding motor.

2.2 Utilizing Machine Learning Techniques to Trigger Actions

By employing machine learning techniques through Google's web-based tool, Teachable Machine, and integrating it with TouchDesigner using the Teachable Machine plugin, three primary recognition features are achieved: (1) Image recognition, which identifies various objects in front of the camera, such as a vase, mouse, or shelf (2) Body gesture recognition, which uses camera input to map an illustration of a human stick figure, analyzing main body parts in a simplified manner. The AI is trained to recognize gestures like raising both hands, waving one hand, and crossing hands. (3) Speech recognition, which captures the user's voice through a microphone, identifying distinct words or short phrases, such as "apple" "action" and "water bottle" (Figure 3). The AI is also trained to filter out background noise, focusing on relevant commands. The machine learning algorithms capture images and voice to use them to learn target recognition and generate percentage-based confidence scores for each target contained within separate channels in TouchDesigner. Each channel's output is connected to a video file that activates corresponding animations when the confidence score meets the determined thresholds. Integrating these features enhances the capabilities and enables dynamic and intuitive responses in the data-driven panels, overall improving their functionality and interactivity.

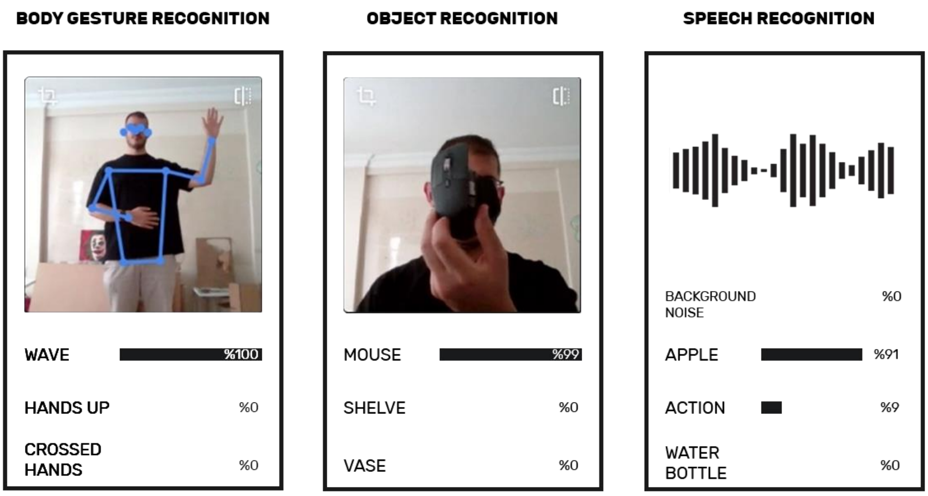

Figure 3. Left shows body gesture recognition, middle shows image recognition and right shows speech recognition features (Source: Authors, 2024)

2.3 Pixel Animations as Action Outcomes

The series of animations were drawn manually frame by frame in AutoCAD (Figure 4). These animations comprised 529 pixels arranged in a 23x23 grid, corresponding to the pixel units in the planned installation. The first set of animations is designed for the image recognition feature, representing objects such as a mouse, a vase, and a shelf with the animation illustrating the object's movement from left to right. The second set focuses on body gesture recognition, featuring emotes that represent specific body movements, including one waving hand, two hands raised, and crossed arms, each with distinct animation sequences. The third set was dedicated to the speech recognition feature, where written words of the spoken phrases were animated, with each letter or phrase moving from left to right.

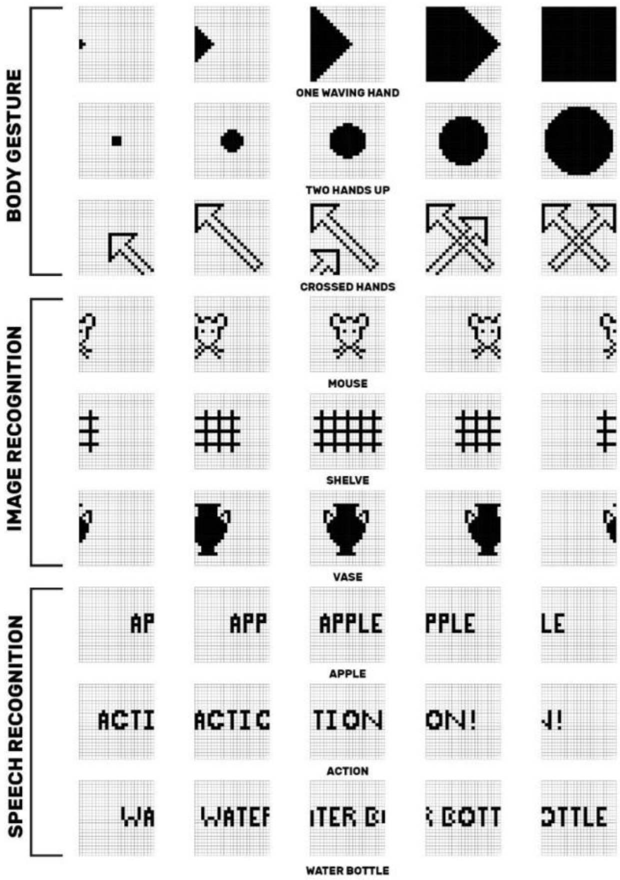

Figure 4. shows frames of animation designs to be assigned to each action trigger (Source: Authors, 2024)

2.4 Workflow of Creating Real-time Simulations

Following the completion of the workflow in TouchDesigner (Figure 6), the same list that is used to represent the gray numerical value of each pixel is transferred in real-time. Utilizing geometry nodes in Blender, an array of shapes - such as spheres, cubes, or any object that can serve as a medium to reflect an image - is generated. The channel of each unit within this array is individually connected to Blender using the Open Sound Control (OSC) feature, which facilitates direct data transfer from TouchDesigner. Each number in the transferred data gets assigned to a different unit within the array, determining its rotation angle, scale factor, or movement necessary to compose an image. Subsequently, each frame of the unit's movement is rendered, resulting in the production of an animation corresponding to the final data-driven panel's design (Figure 5).

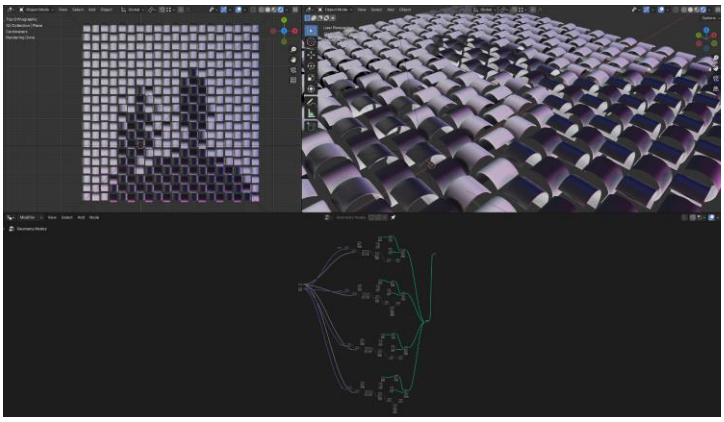

Figure 5. shows viewport of Blender's interface while simulating a data-driven panel design (Source: Authors, 2024)

Figure 6. shows viewport of TouchDesigner with the used components (Source: Authors, 2024)

3 Results

Both the simulation of data-driven panels and the integration of AI have further broadened the scope of this research in terms of human-machine interaction, particularly within architectural contexts. The developed simulation, consisting of 529-pixel units, successfully demonstrates the capacity for dynamic and responsive interaction. TouchDesigner, Blender, Processing and Arduino are used for visual development and data handling. This custom setup processes depth sensor inputs and converts them into movements through Blender, achieving real-time feedback from environmental stimuli such as movement and sound. The inclusion of machine learning via Google's Teachable Machine enhanced the functionality further, enabling the recognition of objects, body gestures, and spoken words. The recognition triggered specific pixel animations (Figure 7), thus showcasing the system's potential for diverse interactions. The integration of a real-time simulation workflow using Blender facilitated experimenting with various design approaches, ensuring efficient testing before physical construction of denser installations. This progress in interactive architecture presents a framework for future possibilities of AI-enhanced architectural designs, highlighting the potential for creating smarter, more adaptive, and more engaging architectural environments.

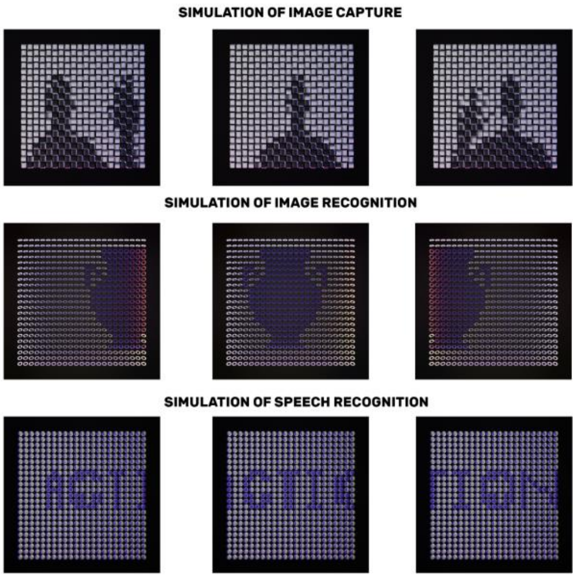

Figure 7. shows outcomes of data-driven panel experimental designs (Source: Authors, 2024)

4 Discussion & Conclusion

The relationship between humans and AI is evolving, in which it's increasingly becoming integrated into daily life. The primary goal of developing data-driven mechanical panels is to augment the interplay between humans and architecture. These panels can transform static barriers, like walls, to receptive, dynamic elements. Future unfolding of these potentials could enormously impact the field of interactive design by improving occupant comfort and environmental control, such as regulating temperature and ventilation through adaptive openings. Moreover, such a system could be implemented as kinetic acoustic panels for concert halls and auditoriums to enhance the audio experience. This research aims to elevate spatial interaction by embedding AI within architectural elements. The vision is for buildings to become dynamic, responsive entities that adapt to human needs. Along with current progress in mechanical engineering and AI, this vision is increasingly attainable. Future buildings with data-driven panels will offer new spatial experiences, blurring the lines between architecture and machines.

The potential applications of data-driven panels extend beyond aesthetics. They could revolutionize industries such as retail, advertising, healthcare, and education. For example, shopping experiences could be tailored to individual preferences, and educational settings could use dynamic visual data for immersive learning. Integrating AI with these panels allows for real-time, personalized user experiences by analyzing and responding to user data. In smart homes, for example, IoT technology could work with these panels to optimize energy use and comfort by adjusting temperature and lighting based on user routines and preferences.

In summary, this research explores the development and potential of data-driven mechanical panels to enhance interaction in architecture. By integrating information-centric systems into the built environment, the boundaries of what is possible with AI and interactive architecture remain in constant expansion, offering new applications in this interdisciplinary field.

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