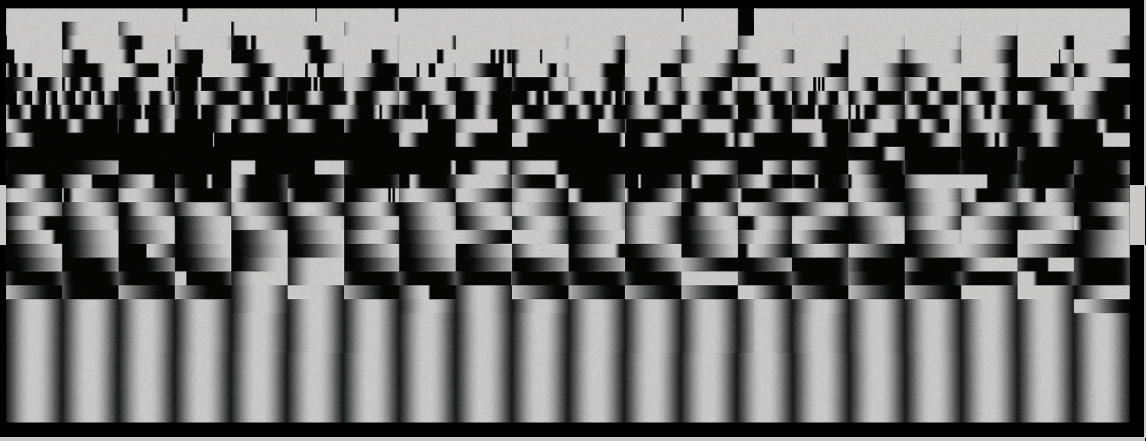

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ACCELERATED DESIGN

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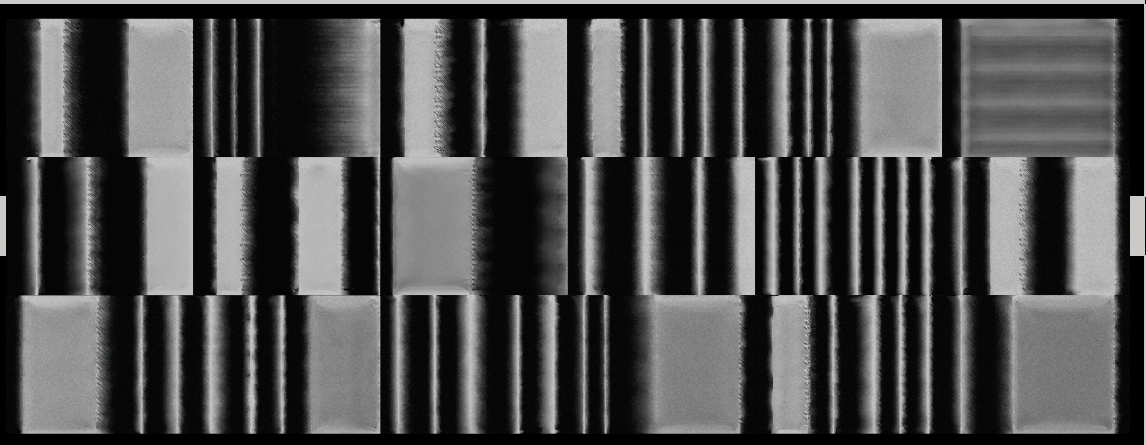

ACCELERATED DESIGN

Proceedings of the 29th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2024)

Volume 2

Edited by

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University of New South Wales, Australia

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Accelerated Design
29th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2024)

20-26 April 2024

Hosted By:

Singapore University of Technology and Design,
SINGAPORE

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Foreword

The annual Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) conference provides an international community of researchers and practitioners with a venue to exchange, to discuss and to publish their latest ideas and accomplishments. These proceedings, consisting of three volumes, contain the research papers that were accepted for presentation at the 29th International CAADRIA Conference, organised by Singapore University of Technology and Design, Singapore. The papers are also available online at the open access cumulative database *CumInCAD* (http://papers.cumincad.org).

The proceedings are the outcome of an extensive collaborative and voluntary effort between the International Reviewing Committee and Paper Selection Committee, with the former consisting of 203 reviewers from 33 different countries working across the globe. It marks another year of growth and strength in the history of CAADRIA. The papers in this publication have been selected through a two-stage double-blind peer review process. Calls for papers in July of 2023 resulted in a record high stage 1 submission of 541 abstracts from 37 countries, of which 397 were invited for further development as full paper submissions. For the stage 2 double-blind review, at least 2 international reviewers were assigned to each of the submitted full papers. In February of 2024, following the reviewers' recommendations and the Paper Selection Committee's evaluation, 159 papers were accepted for inclusion in the publication and presentation at the conference.

We thank all authors for their research contributions and congratulate them on their publication achievement. We extend our sincere thanks to the International Review Committee members who volunteered their valuable time and expertise. We also thank the hosts at the Singapore University of Technology and Design for organising the 2024 CAADRIA Conference and developing a thought-provoking, creative, and engaging theme and schedule of events. Special thanks are offered to Gabriel Wurzer for his patient, generous, and expert contribution to the CAADRIA proceedings production. Finally, we thank the CAADRIA organisation for providing the opportunity and honour to serve on the Paper Selection Committee for the CAADRIA 2024 conference.

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Theme: ***'Accelerated Design'***

Can and should design be accelerated? To what extent and to what end? Or perhaps, design must decelerate instead? Accelerated Design is an urgent call for a critical reflection of and creative action by architecture during this challenging time of accelerating climate crisis, unrestricted data surveillances, generative AI copyright infringements, global geopolitical conflicts, hyperconcentration of digital power, post-pandemic mental health deterioration, and widespread disinformation attacks.

CAADRIA2024 seeks contributions in addressing the conference theme by discussing and debating the role of design and designers in the midst of accelerated changes brought about by and on technology, economy, environment, and governance, to construct new ways of thinking, teaching, researching and practising architecture in the age of artificial intelligence and climate change.

The 29th Annual Conference for Computer-Aided Architectural Design Research in Asia (CAADRIA) brings together academics, researchers, and practitioners to contribute to the fields of computational design methods, instruments, and processes towards an inclusive future for humans and non-humans. Contributions focusing on the Asia / Pacific context are particularly encouraged.

CAADRIA 2024 invited contributions including but not limited to the following topics:

- Artificial intelligence and machine learning in design
- Building Information Modelling
- Climate change and sustainability
- Collective, collaborative & interdisciplinary design
- Creativity, design thinking and human-computer interaction
- Digital Heritage
- Digital representation and visualization
- Generative, algorithmic & evolutionary design
- Interactive environments
- Bio-designs
- Pedagogical shifts in computational design
- Structural performance-based design and optimization
- Robotics, digital fabrication and construction
- Innovative material systems and manufacturing methods
- Theory, philosophy & methodology of computational design research
- Urban analytics, big data analysis and smart cities
- Urban modelling and simulation
- VR/AR/XR

Conference Organisers & Hosts,

Immanuel Koh	*Singapore University of Technology and Design (Chair)*
Jianxi Luo	*Singapore University of Technology and Design*
Jeffrey Chan	*Singapore University of Technology and Design*
Sumbul Ahmad Khan	*Singapore University of Technology and Design*
Elissa Hartanto	*Singapore University of Technology and Design*

{https://caadria2024.org}

About CAADRIA

CAADRIA - The *Association for Computer-Aided Architectural Design Research in Asia* promotes teaching, research and innovative practices in Computer-Aided Architectural Design (CAAD) and beyond, spanning across the larger Austral-Asian and Pacific regions with a global membership across six continents.

CAADRIA was founded in 1996 with the following key objectives:

- To facilitate the dissemination of information about CAAD among Asian schools of architecture, planning, engineering, and building sciences.
- To encourage the exchange of staff, students, experience, courseware, and software among schools.
- To identify research and develop needs in CAAD education and to initiate collaboration to satisfy them.
- To promote research and teaching in CAAD that enhances creativity rather than production.

Among other initiatives, CAADRIA organises an annual conference. The first of which was held in 1996 in Hong Kong, where the association is registered to date. Since then, 28 conferences have been held in India, Australia, China, Hong Kong, Japan, Korea, Malaysia, New Zealand, Singapore, Taiwan, and Thailand. The annual CAADRIA conferences provide an opportunity to meet each other and learn about the latest research in the field. CAADRIA is a growing community with many motivated volunteers who generously give their time and energy to support the organisation in various roles. One of CAADRIA's missions is to engage with emerging researchers (especially PhD students), supporting and expanding such initiatives as our Postgraduate Consortium and the World CAAD PhD workshop.

CAADRIA fosters long-standing bonds with its sister organisations: CAAD Future Foundation (CAAD Futures), Education and Research in Computer Aided Architectural Design in Europe (eCAADe), Sociedade Ibero-Americana de Gr áfica Digital (SIGraDi), Association for Computer-Aided Design in Architecture (ACADIA), and Arab Society for Computer-Aided Architectural Design (ASCAAD).

The 29th conference, in 2024, is hosted by the Singapore University of Technology and Design, Singapore. CAADRIA 2024 is held as a face-to-face conference, continuing the Association’s mission to bring together researchers, practitioners, and schools of the Asia-Pacific region. CAADRIA 2024 is themed ‘Accelerated Design’ and aims to bring together academics, researchers, and practitioners to contribute to the fields of computational design methods, instruments, and processes towards an inclusive future for humans and non-humans.

All CAADRIA conference proceedings are indexed in CumInCAD - a Cumulative Index of Publications About Computer-Aided Architectural Design. The proceedings are available both online and in research libraries around the world. CAADRIA is one of the four founding organizations of the *International Journal of Architectural Computing* (IJAC) and supervises one issue each year. IJAC is published by Sage Publications in both paper and electronic versions.

Anastasia Globa
President, CAADRIA

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Xi'an Jiaotong-Liverpool University

Werner Lonsing
Independent researcher

Guest of Honour (Conference Event)
Chong Tow Chong
President, Singapore University of Technology and Design (SUTD)

Professor Chong Tow Chong was appointed President of the Singapore University of Technology and Design (SUTD) in April 2018. He had been SUTD's founding Provost since 2010, where he played an instrumental role in steering the strategic development and operationalisation of SUTD. As President, he provides leadership and guidance in the next phase of the University's growth and development, as well as ensuring continuity in the pursuit of SUTD's vision, mission and strategic goals. Prior to joining SUTD, Prof Chong had been the Executive Director of A*STAR's Science and Engineering Research Council and Data Storage Institute for 15 years. He also had a 30-year academic career with the National University of Singapore as Professor of Electrical and Computer Engineering.

Keynote 1

Akihisa Hirata

Architect, Professor at Kyoto University
Akihisa Hirata Architecture Office

Born in Osaka, Japan in 1971. Graduated from the Department of Architecture in the Faculty of Engineering at Kyoto University in 1994. Received a master's degree from the Kyoto University Graduate School of Engineering in 1997. After working at Toyo Ito & Associates, Architects, he established "akihisa hirata architecture office" in 2005. Currently, He is Professor at Kyoto University. His important works include showroom "Masuya" (2006), apartment "Alp" (2010), "Bloomberg Pavilion" (2011), "Art Museum & Library, OTA" (2017) and "Center of Yatsushiro Folk Performing Arts" (2021). He was awarded 19th Japan Institute of Architects Newcomer Prize (2008), Golden Lion at the Venice Biennale with Toyo Ito, Naoya Hatakeyama and other 2 architects (2012), Colored Concrete Works Award at Berlin (2015) and The Murano Togo Prize (2018) etc. His publications include "Tangling" (LIXIL, 2011), "Discovering New"(TOTO, 2018)etc. He has lectured at Bauhaus Dessau (Germany), Harvard University (U.S.A), University of British Colombia (Canada) and currently lectured at Architecture Foundation (U.K.), etc. He has done personal exhibitions in Tokyo, U.K. and Belgium, etc. And he sent his works to variety of Art fair such as Art Basel, Frieze Art Fair and Milano salone.

"Tangling" and "Resonance"

I have been wishing to create architecture that resonates with the world of life. I would like to see human activities including architecture as an integral part of the world of life, not as something special. It means that keeping away from 'human.' It is at such boundaries that define what it is to be human - at the water's edge of the human - that a new architecture for the age of the environment and life will be appeared.

"Tangling" and "Resonance" are two complementary clues to explore the water's edge of the human. "Tangling" corresponds to proximity, while "Resonance" corresponds to remoteness.

In this lecture, I will introduce some geometric challenges to create the "Tangling" where various things can be intertwined – "Karamarishiro." Additionally, I will talk about architecture that is intertwined with the datistical = 'resonance', like a swarm of thoughts from different people, and creating "Resonances of Resonances," to resonate "Resonance" of the single horizon each other.

Keynote 2

Jinjoon Lee FRSA

Professor of Graduate School of Culture Technology in KAIST (Korea Advanced Institute of Science and Technology)

Founding director of KAIST Art & Technology Center (KATEC)

Distinguished Professor of New Contents Academy (NCA), Korea Creative Content Agency (KOCCA)

FRSA, Life Fellow of Royal Society of Arts, UK

MRSS, Member of Royal Society of Sculptors, UK

Dr. Jinjoon Lee FRSA is a celebrated new media artist, renowned for his groundbreaking research and artistic creations that leverage cutting-edge technologies to examine East-Asia utopian vision and liminoid experiences. His unique artistic journey was initiated in 2007, with his solo exhibition Art Theatre – Role Play held at the Arko Museum of Korea Art Council. Since then, his body of work has graced over 50 global exhibitions and recently he successfully held the solo exhibition Audible Garden (2023) in Korea Cultural Centre UK, London, UK. At present, Dr. Lee shares his wealth of knowledge as an assistant professor at KAIST and as a distinguished professor at New Contents Academy (NCA), Korea Creative Content Agency (KOCCA). After acquiring a B.B.A. in Business School from Seoul National University in 2001, he proceeded to secure a B.F.A and an M.F.A. from same institution. He quests for knowledge led him to Royal College of Art (RCA) for an M.A., and finally, the Ruskin School of Art at the University of Oxford, where He obtained a DPhil. As a Fellow of the historic 270-year-old Royal Society of Arts (FRSA) and a full member of the Royal Society of Sculptors (MRSS), he delves into the study of data-driven art and design, sound art, and the intriguing concept of XR performance for future opera through the use of virtual reality (VR) and artificial intelligence (AI). Lee has invited as a guest artist by the ZKM Center for Art and Media at Germany in 2023 and by Vermont Studio Center (VSC) with full-fellowship at USA in 2024.

Total Experience in Liminal Spaces with VR, AR, and MR Inspired by East Asian Garden Philosophy

This keynote speech delves into the fusion of East Asian garden philosophy with Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies to craft transformative liminal spaces. The talk will commence by outlining the core tenets of East Asian garden philosophy, spotlighting the themes of natural harmony and the artistic representation of landscapes. It will then progress to discussing the notion of liminoid experiences, which are environments that facilitate transformative encounters beyond the commonplace. The primary focus will be on leveraging VR, AR, and MR technologies to actualize these philosophical concepts, thereby engendering a Total Experience that engrosses

users within an amalgamation of virtual and tangible realms. This presentation will underscore the significance of an integrated and synesthetic approach that synergizes technology, design, psychological insights, and cultural legacy. The conclusion will speculate on the future role of these technologies in altering our perception and understanding of space and reality. The objective of this keynote is to inspire a profound appreciation of how enduring aesthetic principles can augment contemporary technological experiences.

Keynote 3

Philip F. Yuan

Professor and Associate Dean, College of Architecture and Urban Planning at Tongji University

Philip F. Yuan is a professor and associate dean of the College of Architecture and Urban Planning at Tongji University, Honorary Fellow of American Institute of Architecture (Hon. FAIA). He is also the co-founder of DigitalFUTURES Association, a global educational initiative with a particular emphasis on the latest computational design and fabrication technologies, Editor-in-Chief of Architectural Intelligence journal, and founding partner of Archi-Union Architects & Fab-Union Technology. Yuan has served as Thomas Jefferson professor at University of Virginia (2019), the visiting professor at Massachusetts Institute of Technology (2019), and Royal Melbourne Institute of Technology (2021). He has also served as council member of UIA Professional Practice Commission (PPC). Yuan was attributed with UIA 2023 The Auguste Perret Prize for Technology in Architecture. His work has been recognized with notable awards, including 2022 AIA Open International | Architecture Honor Award, 2022 Dezeen Award Best Civic Building, 2020 ACADIA Innovative Academic Program Award of Excellence and etc. Yuan has participated in Venice biennale, Chicago biennale, Milan triennial, Tallin biennale, etc. His works have been collected by MOMA New York City, M+ Hong Kong and Centre National d'art et de Culture Georges Pompidou.

Crafting Robotics for Architectural Intelligence

This lecture navigates the intersectional study of AI for architectural design and robotic fabrication, a union encounting the future of architecture in the post-humanistic era. Amidst global challenges, it urges a re-evaluation of the relationship between globalization and locality, advocating for the integration of globalized technologies into localized practices. The production paradigm and knowledge landscape of architecture are being reshaped by crafting robotics for architectural intelligence. As the field of design and practice transits into a new era of flourishing development of intelligent and autonomous technologies, it becomes imperative for architectural academia to redefine the symbiotic relationships between humans and technology. We'll delve into the 'symbiotic' intelligence, aiming to rethinking on the global warming and new paradigm shift under the influence of future technologies. Based on research and practice, the discussion will illustrate how this symbiotic relationship can drive innovative, sustainable solutions, transform the socio-cultural, industrial economics, and environmental resiliency. We are aiming to inspire architects to blur the lines among architects, artifacts, and social processes, contributing to a new understanding of architecture in the post-humanistic era.

Sister Special Roundtable

Accelerated Research

Sherif Abdelmohsen
President | ASCAAD
Professor and Chair, Department of Architecture, American University in Cairo, Egypt

Sherif Abelmohsen is Professor of Digital Media and Design Computing, Chair of the Department of Architecture, Director of the Robotic Fabrication Laboratory, and co-founder of the Educational Virtual Environments Lab at the American University in Cairo, Egypt. He is also President of ASCAAD, and Co-Founder and Managing Partner at UDAAR.

Anastasia Globa
President | CAADRIA
BAE Program Director The University of Sydney

Anastasia is a researcher, academic and designer working in the field of architecture, with strong research interests in algorithmic design, interactive systems, and simulations. Anastasia is based at The University of Sydney. She closely collaborates with the Computer Aided Architectural Design in Asia community, being elected CAADRIA President in 2022.

Christiane M. Herr
Vice-Chair | CAADFutures Foundations
Professor, School of Design
Southern University of Science and Technology, Shenzhen, China
Past President, CAADRIA

Christiane M. Herr is an architectural researcher and educator focusing on cross-disciplinary innovation in engineered ecosystems on buildings as well as digitally supported design. She is currently Professor at the School of Design, Southern University of Science and Technology. Christiane is Past President of CAADRIA as well as board member and vice chair of the CAADFutures Foundation.

Rudi Stouffs
Vice-President (Emeritus) | eCAADe
Dean's Chair Associate Professor

Rudi Stouffs is Dean's Chair Associate Professor in Architecture and Assistant Dean (Research) in the College of Design and Engineering, NUS. He is Vice-

President (Emeritus) of the association for Education and research in Computer Aided Architectural Design in Europe (eCAADe). He has held previous appointments at Carnegie Mellon University, ETH Zurich, and TU Delft.

Paula Gómez Zamora
Vice-President | SIGraDi
Senior Research Engineer with the Georgia Tech Research Institute, USA.

Dr. Paula Gómez, a senior research engineer at GTRI, earned her Ph.D. in Computational Design from Georgia Tech. She leads several projects in systems modeling, emphasizing the built environment, energy, sustainability, and human well-being. Recognition of her work includes international awards, service on scientific committees, and IJAC editorials. She currently serves as Vice-President of SIGraDi.

CAADRIA Fringe City Events

AI-NITE Guest of Honour

Chee Su Eing

President, Design Business Chamber Singapore (DBCS)

Chee Su Eing, a pioneering figure in Singapore's design landscape, notably serves as the first female President of Design Business Chamber Singapore (DBCS) in its 36-year history. As Founder and Director of D'Perception Pte Ltd and Managing Director of D'Perception Ritz Pte Ltd, she spearheads full-suite interior design ventures across Singapore and Asia, acclaimed for their excellence in residential, social, and hospitality interior architecture. With over two decades of expertise, she champions innovative design solutions and has served as a juror for various prestigious design awards. Su Eing is deeply committed to leveraging design for societal and business impact, exemplified through her leadership at DBCS. Under her guidance, DBCS actively fosters partnerships and collaborations with major design players, positioning itself at the forefront of discussions on cutting-edge topics such as AI and sustainability. Through these initiatives, Su Eing and DBCS drive forward the dialogue on how design can shape a more sustainable and technologically advanced future.

AI-NITE Keynote

Immanuel Koh

Assistant Professor, Singapore University of Technology and Design (SUTD)
Director, Artificial-Architecture

Immanuel Koh is the founder and director of Artificial-Architecture. He is an Assistant Professor in Architecture & Sustainable Design (ASD) and Design & Artificial Intelligence (DAI) at the Singapore University of Technology & Design (SUTD) where he leads research and teaching at the intersection of AI and Architecture. Trained at the Architectural Association (AA) in London and holds a PhD from the School of Computer Sciences and Institute of Architecture at the École polytechnique fédérale de Lausanne (EPFL), he is a pioneer in AI x Architecture who operates in an original and trans-disciplinary way. He is the Principal Investigator for several funded AI research projects with support from, among others, the National Research Foundation (NRF), Ministry of Defence (MINDEF), National Arts Council (NAC), AI Singapore (AISG), DesignSingapore Council (DSG), Urban Redevelopment Authority (URA), DSO National Laboratories, Temasek Laboratories, Hokkien Foundation, Sunray Woodcraft Construction, and National Supercomputing Centre (NSCC). Immanuel is an expert consultant at the ZJU-BOSIDENG Joint Research Centre on AI Design and currently conducts research for high-profile architecture

practices such as Zaha Hadid Architects (London) and MVRDV (Rotterdam) in developing custom state-of-the-art deep learning models. He has also published and exhibited widely, ranging from AAAI, ICCV, CVPR, NeurIPS and AD to Singapore's Arts House, Venice Architecture Biennale, and V&A Museum; and taught internationally such as at UCL, RCA, Bauhaus Dessau, Harvard GSD, and Strelka. Immanuel co-founded Neural Architecture Group, directs DesignerlyAI, and is the author of the book 'Artificial & Architectural Intelligence in Design' published in 2020.

AI-NITE Roundtable

Accelerated Practice

Marios Tsiliakos
Partner | Applied R+D, Foster+Partners
Lecturer | Bartlett School of Architecture, UCL

Marios is a Design Systems Analyst and Partner at the Applied R+D team at Foster+Partners, expanding the boundaries of applied computation and problem solving for AEC industry. Specializing in complex geometry, performance driven design, and interoperability, he leads the development of F+P's in-house interoperability tool.

Hui Min Chan
Director and the Head of Green Well Tech at DP Architects

Green-Well-Tech (GWT) is DP Architects' strategic initiative to drive growth and excellence throughout its business thrusts and unify its actions and capabilities toward innovative and sustainable solutions. As part of her role, she also oversees DPA's Smart Sustainability Unit, which extends the core business into tech-related business lines.

Vignesh Kaushik
Principal & Regional Design Technology Director at Gensler

Vignesh leverages his passion for people empowerment, process development and technological innovation to lead the digital transformation of the Gensler practice, which covers multiple typologies, complexities and scales across different sectors in the APME and GC regions. He has taught advanced computational design in many institutions in Southeast Asia.

Eva Castro
Professor of Practice at SUTD ASD
Co-founder & Director GroundLab / Plasma studio / formAxioms

Eva Castro currently is the coordinator of core studio 2 and co-leads the advanced option studio on speculative futures and oceanic inhabitations at SUTD. Castro is co-founder of form_axioms lab, a territorial agency for academic research purposes operating from within Singapore. As a practitioner, Castro is cofounder of Plasma Studio and GroundLab.

Pia Fricker
Professor of Practice in Computational Methodologies in Landscape Architecture and Urbanism, Vice Head of Department, Aalto University Finland, School of Arts, Design and Architecture.

Prof. Dr. Pia Fricker, is a leading expert in computational methodologies for landscape architecture and urbanism. Her pioneering work utilizes diverse AI-driven computational methods to tackle pressing challenges in urban design amidst the accelerating climate crisis and technological advancements. With a focus extending beyond the human-centered paradigm, Fricker's internationally showcased research redefines trajectories for architecture in the era of artificial intelligence and environmental transformation.

AI-NITE Exhibition
Neural MONOBLOC Black: Artificial Intelligence and its Aesthetic Subversion
By Immanuel Koh | Artificial-Architecture

The white stackable plastic Monobloc chair is the world's most widely/cheaply/quickly produced and disposed chair. Most people would have at some point in their lives sat on a Monobloc chair without even noticing it. The Monobloc chair is also the most common chair imagery on the internet, thus automatically finding its way into any datasets used to train today's most powerful foundation AI models such as ChatGPT and Stable Diffusion. The Monobloc is a blanket term and therefore it is one and many chairs at the same time. It doesn't really have a name(s) nor an acknowledged designer(s). However, its physical and digital ubiquity makes it the perfect baseline artefact to discuss design with anyone, from anywhere, and at any time. In fact, the Monobloc is closer to a design concept than a designed object.

The exhibition "Neural MONOBLOC Black" presents 3 acts of aesthetic subversion through the Monobloc – from the original 'Everyday Normal Monobloc' to the transgressive 'Artist Bricolage Monobloc', and finally to the

AI-hallucinated ‘Neural Monobloc Black’. The ‘Everyday Normal Monobloc’, with its endless machinic production but homogenous design variations, is generally hated and despised by designers, but has continued to exert its usefulness, messiness, and even place-making-ness in public spaces everywhere. This is Act 1. The ‘Artist Bricolage Monobloc’, with its D-I-Y/collage-based formal operations and layered narratives, is a form of design critique by hacking everyday normal monoblocs and showing them as one-off art pieces in esteemed museums. This is Act 2.

The ‘Neural Monobloc Black’ is the Final Act. It is the focus of this exhibition which features eight physical artefacts that are generated and fabricated directly in 3D through a custom fine-tuned text-to-3D AI model developed at Artificial-Architecture. The ‘Neural Monobloc Black’ is the hallucinated result of an AI model’s attempt in deconstructing and reconstructing a hypothetical 3D monobloc from its flatland training set of 2D monobloc imagery. Its appearance of uncanniness suggests an underlying Freudian ‘repetition’ and ‘doubling’. Its appearance of wrongness might be explained by a quote from Mark Fisher -- “The weird thing is not wrong, after all: it is our conceptions that must be inadequate.” The blackbox of artificial intelligence and the charred-black chairs are instrumentalised here to question our all-too-human conception and perception of what design is and can be.

Artificial-Architecture (A-A) is based at the Singapore University of Technology & Design (SUTD) across the academic programmes of Architecture & Sustainable Design (ASD) and Design & Artificial Intelligence (DAI). It is a speculative and experimental design research group that not only explores the technics of the artificial, but also its epistemological, cultural, political, and aesthetic implications through the expanded lens of the architectural, and vice versa. Our team includes architects, designers, urban planners, engineers, programmers, mathematicians, theorists, and computer scientists.

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ENHANCING CULTURAL HERITAGE DIGITALIZATION AND VISITOR ENGAGEMENT THROUGH LIDAR SCANNING AND GAMIFICATION

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Abstract. Cultural heritage assets are valuable, providing important information about humanity's past and conveying it to the future. Unfortunately, conventional documentation is insufficient to preserve them for the next generations. Furthermore, increasing visitor interaction with these assets and raising awareness has been one of the challenges in this field. In this paper, we will examine how mobile LiDAR (Laser Detection and Ranging) technology can be used to precisely scan and document historical sites and how it can be combined with gamification elements to provide visitors with better experiences. It is also important that the texture taken in mobile laser scanning can be used to better visualize 3D mesh models of the scanned objects, so the fastest application that produces 3D models is selected. The study area is Syedra Ancient City in Alanya / Turkey, where the research and excavation process has continued since 2015 and the restoration projects started in 2023. Future work includes the creation of experiences to provide a basis for gamification and revitalizing the story of the heritage for the visitors through digital storytelling and AR (Augmented Reality). Preserving historical sites while providing visitors with a more in-depth, vivid and enjoyable experience are important facts for enhancing cultural heritage and passing it on to future generations.

Keywords. Cultural Heritage, Digitalization, LiDAR, Mobile Laser Scanning, Digital Storytelling, Augmented Reality, Gamification.

1. Introduction

This paper explores how gamification elements can be used to enhance visitor engagement by documenting historical sites using mobile 3D LiDAR (Laser Detection and Ranging) technology. This approach goes beyond traditional preservation and presentation methods, combining the precision of LiDAR with the portability of mobile devices. It also explores the potential of gamification elements to make the site more engaging for visitors. The future work will include presenting the chosen

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archaeological artifacts by analogue and digital presentation materials to different experimental groups and evaluating the effects of different techniques on their memorability. It is aimed to develop a different approach to the presentation of artifacts in archaeological sites, encouraging people who have not yet had the opportunity to visit the archaeological site to experience the artifacts in situ and contribute to cultural tourism by triggering their interest in cultural heritage.

2. Background Research

2.1. LIDAR SCANNING TECHNOLOGIES WITHIN THE SCOPE OF DIGITALIZATION

This section will concentrate on research methodologies and scanning technologies employed for the digitalization of cultural heritage. It will specifically focus on the utilization of LiDAR scanning technology, highlighting its features, advantages, and limitations while exploring its role in cultural heritage documentation research and investigating the possibilities of using this technology in preparing data for gamification. While traditional documentation in the field of cultural heritage may involve recording details with hand drawings, today, digital documentation research has become more extensive and rapid with modern technological methods. Among these, scanning technologies are crucial elements in transforming the heritage documentation process. Techniques such as laser scanning, photogrammetry, fixed-point LiDAR and aerial LiDAR are used to digitize heritage assets with high precision and speed. LiDAR technology utilizes beams of electromagnetic radiation to gather information about objects (Łabędź et al., 2022). The capability to offer precise measurements and create detailed 3D models positions LiDAR as a valuable tool. The potential of research on scanning technologies includes its integration with fields such as AI (artificial intelligence), big data and AR that can provide greater interaction. This study will discuss potential strategies for more effective documentation of cultural heritage and identify notable areas for future work.

2.1.1. 3D Mobile LiDAR Scanning in Archaeology

LiDAR sensor is found to be a promising instrument compared to photogrammetric techniques, where there are inappropriate lighting conditions, such as harsh shadows or backlighting, that negatively affect the quality of the end results (Bruno et al., 2021). 3D mobile LiDAR technology is a powerful tool for documenting historical sites. An article on the survey of cultural heritage with Apple LiDAR sensor mentions that the instruments in this field have been developed primarily with the aim of optimizing costs and time (Vacca, 2023). It investigates the potential of a 3D mobile LiDAR sensor implemented in Apple devices since 2020 for the production of 3D models of cultural heritage objects in terms of applicability and accuracy. While comparing different apps, they showed different performances in terms of accuracy according to the sizes of the objects. The absence of information regarding its resolution raises questions about whether fine details are accurately captured for larger areas.

2.2. DIGITAL TECHNOLOGIES SUPPORTING VISITOR ENGAGEMENT THROUGH STORYTELLING AND GAMIFICATION STRATEGIES

Emerging digital technologies make powerful contributions to strengthening the perception of heritage and transforming how we experience it (Economou, 2016). It is observed that studies on experiencing cultural heritage artifacts in museums and archaeological sites with techniques such as AR, VR and gamification are effective in increasing cultural heritage awareness. In cases where archaeological sites cannot be visited in-situ, it becomes valuable to promote them through digital media. This can also positively affect people's interest and sensitivity to all world values and cultures.

In order to feed future stages of this paper, studies in which cultural heritage was introduced specifically through storytelling, AR and gamification elements as well as the effects of these techniques on cultural heritage awareness were examined. Analogue or digital completion on 2D images and 3D models, animation and gamification, together with AR technology, emerge as powerful tools. Studies where AR is applied to 3D models to help better perception of archaeological sites constitute practical and effective examples for the presentation and promotion of cultural heritage (Ozer et al. 2016).

One of the pioneering studies in which archaeological cultural heritage is experienced interactively in the museum by visitors with different social qualities through digital storytelling and AR is the project called "CHESS" (Cultural Heritage Experiences through Sociopersonel Interactions and Storytelling) (Pujol et al., 2012). Based on the idea of producing personalized interactive stories, it was stated that the possibility of experiencing a different story during each experience in the virtual environment may trigger a revisit. The study in which digital storytelling is considered as an investible tool for visitor engagement was developed by incorporating mobile AR experiences into personalized storytelling in the museum (Keil et al., 2013). Various techniques, such as voice-over, are used to increase the impact of storytelling. In another study that produced animated graphic narratives on a wooden statue of an important author at the Svevo Literature Museum using audio-visual materials through the Apple ARKit mobile app, the focus was primarily on content, and technology was used to enhance the story (Fenu et al., 2018). It was observed that it attracted the attention of older and various categories of users. In the scope of "The CHATS Project", works using digital storytelling and other tools in the last 10 years were compared in terms of method and content, and the 'personalized' digital story approach stood out in cultural heritage areas (Trichopoulos et al., 2022).

In a recent article investigating the impact of guided storytelling on museum visitors' emotional engagement, imagination and retention, it is emphasized that studies on heritage experiences integrating storytelling with digital technology and multimedia applications should be developed (Campos et al., 2023). Considering the gap in developing the impact of storytelling in heritage experiences, this paper aims to enhance an alternative method that can be applicable for tourists to establish an emotional connection with the heritage site before they even visit the place in-situ. In a similar study that presents the storytelling of a historical settlement in a museum through video projection mapping on a 3D printed model and by AR on large visuals, intangible values such as the history, lifestyle and folkloric music of the region are conveyed through audio elements (Nikolakopoulou et al., 2022).

A recent study in which a historical orphanage building is experienced with gamification and VR tools based on photogrammetric 3D modelling focuses on empathizing with the sociological context of the building through the use of intangible heritage elements such as children's and workers' memories and creating interactive environments that enhance a sense of place (Kalak et al., 2023). Combining practical documentation techniques such as photogrammetry and mobile scanning effectively with technologies that create interactive experiences for gamification is an area open to exploration. In a recent paper that maps out the publications in the field of gamified cultural heritage, it is figured out that gamification is generally used for engagement and creativity enhancement (Marques et al., 2023). In another study on the digitalization of architectural heritage, a fortress was modelled using a high-poly point cloud and a high-poly mesh by aerial photogrammetry. Then, the high-poly 3D model was transferred into a low-poly 3D model to optimize it for the game engines (Sancak et al., 2023). In gamified cultural heritage, mobile applications, AR and VR are found to be particularly prevalent. It is interpreted that future work on heritage will not only focus on transferring pre-existing knowledge but can align gamification with heritage as an ever-changing practice in aspects of identity, narrativity and belonging.

3. Material and Method

Especially in such studies for inheritance areas, it is even more important to accelerate the documentation process as much as possible for the in-situ conservation of artifacts like mosaics which are more sensitive in terms of material against external factors. In this direction, mobile scanning was preferred to be used in the first phase of the study.

3.1. DATA COLLECTION

The theoretical contribution of this study was to propose a method for comparing surface models based on the coordinate system. Firstly, the performance of the Apple iPad Pro LiDAR sensor is analysed in an outdoor scene with a building of significant size. The Frigidarium (Cold Room) chamber of the Great Roman Bath complex, including the large floor mosaic at the Syedra Ancient City, was scanned using a mobile LiDAR app and simultaneous 3D modelling with the aim of creating the most up-to-date model (Figure 1 left). The resulting model and texture data were exported in .fbx format and examined in the Blender 3D program. After conducting initial tests on various 3D scanning applications utilizing LiDAR sensors, four options were considered: 3D Scanner App, Polycam, Scaniverse, and SiteScape. These are some of the widely used apps that take place in similar studies (Łabędź et al., 2022). Following extensive evaluation, the Scaniverse app emerged as the preferred choice for further research due to its capability to generate highly accurate 3D models in the form of point clouds or meshes. Scaniverse allows users to visualize scanned models in both 3D and AR. The app facilitates exporting high-resolution models in a wide variety of formats. Notably, it offers flexibility in setting the scanning range, allowing users to skip unnecessary areas. The app can save the model in three resolutions: small object, medium object, and large object/area. There are three processing modes: speed, area, and detail. For the Frigidarium chamber, the "large object area" mode was used for scanning, and the "area" mode was used for processing. Despite user-friendly, time-

efficient, and high-quality 3D results, some deficiencies that need to be improved were also identified, such as the scanning range being limited to 5 meters and failures in the model due to insufficient lighting.

Numerous scanning attempts failed during execution, especially when dealing with fine details. There were instances where the scanning process had to be repeated multiple times for verification. Additionally, users can edit the scanned model within the application, enhancing its appearance or making necessary trims. The 3D model data obtained by LiDAR scanning coincides with the conventional measurements with minimal deviation (Figure 1 right). Another crucial feature includes the ability to measure the actual size of the scanned model. The scans were performed in September 2023 at the Syedra Ancient City. During this time of the year, there is a lot of sun causing high contrasts and brightness, creating non-demanding conditions for image acquisition and photogrammetric reconstruction.

Figure 1. (left) 3D laser scanning process with the LiDAR and (right) high-quality 3D model

For smaller models, the maximum scanning range of 5 m may be excessive, making it convenient to focus solely on specific objects. As an example, we examined a small sized statue, known for its intricate details and surface irregularities (Figure 2). For this figure, "medium object" mode was used for scanning and "detail" mode was used for processing in the Scaniverse app.

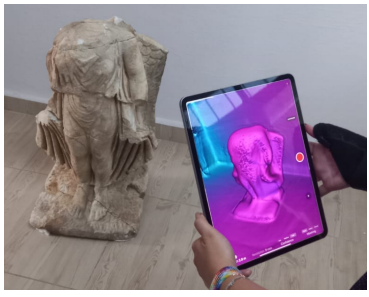

Figure 2. 3D scanning processes of a statue found in Syedra Ancient City

The iPad-derived point cloud displays noticeable regularity features and the resulting grid is marked by significant data simplification, resulting in a notable loss of

detail. Upon a detailed analysis of the distribution of the point cloud derived by, it became evident that the model's depressions yielded the least favourable results, while relatively satisfactory outcomes were achieved in convex areas. It is crucial to emphasize that the model showcased represents the optimal result obtained through the utilization of the Apple iPad Pro.

At the same time, scanning was done using the photogrammetric method in the Scaniverse application with an old version of iPad Pro that does not contain a LiDAR sensor. The application obtains point cloud data with photo captures on these old-version devices. The point cloud generated through photogrammetric methods exhibited a significantly lower sharpness than in the previous case. Specifically for the iPad data, the focus was on points situated on the statue's surface. Furthermore, the device that used the photogrammetric method during processing took much time compared to the iPad LiDAR. The photogrammetric method produces grids with high density and rough surfaces, while iPad LiDAR generates meshes with smoothness and a higher level of generalization. The LiDAR sensor integrates the points it measures with information captured by the RGB camera within the device. The utilization of the Apple LiDAR sensor is restricted to dedicated applications available for download exclusively from the App Store.

A detailed 2D orthophoto of the large floor mosaic was also obtained using the Agisoft Metashape application for photogrammetric processing of the high-resolution digital photographs taken by a drone on site (Figure 3). In order to properly compare the properties of the technologies under study, the scanning procedure with both the iPad device and photogrammetry was performed under the same lighting conditions, during similar times of the day. These conditions also varied depending on the object.

Figure 3. Orthophoto of the large floor mosaic obtained by photogrammetry (Ergürer, 2023)

For the production of the basic 2D and 3D visualizations, the data obtained both by 3D LiDAR scanning application and the digital photogrammetry application was used. The above-mentioned floor mosaic covering the floor of the Frigidarium chamber is a large unique mosaic including a mythological narrative depicting the "Twelve Labours of Heracles". The fact that each scene is placed in a continuous manner without interruption and that the hero is placed in different positions and in motion gives depth to the mosaic (Ergürer, 2023). Unfortunately, the mosaics depicting some scenes have been largely destroyed. It is planned that the digital completion of the mosaic will contribute to the perception of the work as a whole. If sufficient data is provided, digital completion of the completely destroyed roof and missing parts of the walls can be a future study that will strengthen the perception through AR.

3.2. A PRELIMINARY STUDY FOR GAMIFICATION: "MOSAIC PUZZLE"

In order to develop a preliminary study example for gamification, the high-resolution 2D orthophoto of the floor mosaic obtained by photogrammetry was converted into a puzzle game designed in UNITY. The interface of the puzzle game is seen in Figure 4. It is envisaged that the user will be able to establish a different relationship with the mosaic in a web-based platform. During this envisaged puzzle game, as each mythological scene is solved by the user, information and stories about that scene can be transferred to the user. In this case, when compared with photogrammetric processing, LiDAR is also an alternative technology that can be used to speed up the documentation process and create faster images for the gamification process.

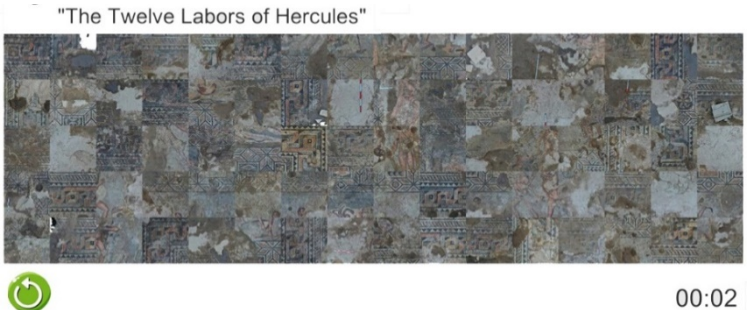

Figure 4. A preliminary study of the envisaged puzzle game "Mosaic Puzzle"

3.3. FUTURE WORK

The future work aims to enhance the perception of the above-mentioned archaeological heritage assets by adding storytelling and gamification elements through AR during the presentation of the artifacts to people away from the archaeological site. An audio narrative will be prepared about the artifacts in order to support intuitive interaction during the analogue and digital experiences. For this purpose, historical, archaeological and mythological data about the artifacts will be researched. If there is a lack of data, similar artifacts will be examined specifically for the digital completion phase (Figure 5). After creating a memorable text, the audio data will be created by vocalizing the story. An application supported by AI can be used for vocalization.

Figure 5. (left) The first scenes of the mosaic completed in 2D on the Procreate app after comparison with (right) a similar scene on a sarcophagus tomb presented in Konya Archaeological Museum (Dany, 2008)

For the analogue experience of the future work, a brochure is to be designed consisting of 2D visuals, including real rectified photographs of the mosaic derived by photogrammetry and also isometric photographs of the area derived by mobile laser scanning. For the digital experience, 2D and 3D digital completions will be produced by illustration and presented through AR to enhance the artifacts. Some areas of the floor mosaic reached during the 2019 excavations (Ergürer et al., 2023) have collapses and destructions due to the fall of the superstructure in the past, so the completion phase can help the visitors visualize the mosaic with ease. The first experimental phase includes the presentation of the designed brochure with 2D visuals to the control group (CG). To the first experimental group (EG1), the 2D brochure will be presented supported by an analogue puzzle game and to the second experimental group (EG2), the productions in which the visuals are digitally completed in 2D and 3D with AR will be presented. In the third experimental group (EG3), a digital gamification experience will be included in order to increase the interaction with the user. The steps explaining the planned experimental phase are also summarized in Table 1.

CONTROL GROUP-(CG) 30 people	FIRST EXPERIMENTAL GROUP-(EG1) 30 people	SECOND EXPERIMENTAL GROUP-(EG2) 30 people	THIRD EXPERIMENTAL GROUP-(EG3) 30 people
A brochure with 2D visuals (real photo of the mosaic, drawings and isometric photos of the area, etc.) + auditory narrative	Converting the brochure of 2D images into a 2D analogue game experience (ex: a puzzle to be completed by hand) + auditory narrative	On the brochure consisting of 2D images, completion of 2D mosaic (digital illustration / animation) and 3D model of the place through AR technology + auditory narrative	On the brochure consisting of 2D images, completion of 2D mosaic (digital illustration / animation) and 3D model of the place through AR technology + auditory narrative + a digital gamification experience (ex: interacting with 3D model appearing on the table)

Table 1. Experiences to be presented in an empty room to the control and experimental groups

Every experience will take place in an empty room, accompanied by the same auditory narrative that is about the history and mythological story of the artifacts. 2D and 3D digital illustrations will be developed by the Procreate application on Apple iPad Pro and animations will be produced by a compatible application such as Procreate Dreams or Adobe After Effects. For practical use, an experience with mobile tools such as smartphones or tablets is planned through an open-source AR application such as Artivive or Adobe Aero. Although the user will be able to experience the presentations with his/her own mobile device, it is planned to install the application on a tablet determined for this project in order to avoid disruptions during the experience.

4. Evaluation and Conclusion

This paper explores the potential of integrating gamification elements to make the archaeological site more engaging for visitors by documenting it using mobile 3D LiDAR technology and combining the precision of LiDAR with the portability of mobile devices. The preliminary results of this study show that the iPad Pro LiDAR

sensor shows better performance when used for medium-sized objects/areas and can be an important alternative to high-cost professional scanners due to its low cost, portability, speed and ease of use. In the future, depending on the innovations in sensor technology, the technical features of LiDAR sensors used in mobile devices are expected to improve and measure longer distances. The 3D models created by these recent technologies also become the basis for new heritage documentation, improving the traditional way of representing, studying and displaying the relics of the past.

Speaking of future work, the characters in the mosaic can be animated through AR depending on the story and the reality will be increased by the 2D and 3D completions that will appear on it without detaching the person from the original work. By adding gamification experience, its effect on the perception of the story will be investigated. Following the user experiences, surveys can help to find out the level of interaction of the users with the site. The advantages and disadvantages of the tools used to produce 2D and 3D presentations will be investigated, as well as AR and gamification elements supporting the storytelling. The people's interest and curiosity in the archaeological field will be compared by measuring what they have learned during the experiences. In light of the data obtained, the applicability of the developed technique to different areas can be discussed.

Following the surveys to be conducted after the user experiences, a comparative evaluation will be made by examining the effects of the different methods. One of the expected results is a better perception of the stories of archaeological artifacts by the presentation of digital completions produced on 2D visuals through AR and the integration of gamification elements. In addition, future innovative studies on mobile 3D LiDAR scanning and AR will enable their more widespread use in enhancing visitor interaction and making it more enjoyable. By demonstrating the positive impact of these technologies on archaeological sites, this paper aims to lay the foundation to facilitate the transition to gamification in future studies and provide inspiration for shaping ways to experience cultural heritage.

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REIMAGINING MUQARNAS:

Exploring Generative Design for Innovative Patterns in Iranian-Islamic Architecture

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Abstract. Muqarnas is one of the key identity-forming elements in Iranian-Islamic architecture, serving as both a structural component that fills the transitional zones between walls and domes as well as a decorative element derived from the same structural composition. This paper introduces a method for automatically generating muqarnas patterns parametrically and presents our findings indicating the relationship between subjective perceptions and objective characteristics of muqarnas. Our primary goals are optimizing muqarnas forms and attaining new, better-performing, and more efficient forms. Our analysis results revealed the relationships between design variables of muqarnas patterns, such as the number of facets, the displacement value that indicates structural strength, and the subjective evaluation of their design qualities, such as aesthetics, modernity, traditional quality, and tranquility, using quantifiable measures based on crowdsourcing. By identifying the relationships between the planned forms and their intrinsic attributes in a quantitative data format, this study lays the groundwork for generating new design patterns with specific characteristics.

Keywords. Muqarnas forms, generative design, traditional values.

1. Introduction

Muqarnas is a pivotal architectural embellishment that significantly contributes to the aesthetic enhancement of various Iranian structures, serving diverse purposes. Functioning as a computational design system, muqarnas found application in diverse architectural elements like vaults, domes, arches, and portals, facilitating seamless transitions within buildings. For instance, its prismatic arrangement in portals orchestrates a gradual transformation of architectural plans, creating expansive entrance spaces (Ödekan, 1975). The visual appeal of muqarnas lies in its sculptural

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quality, generating captivating light and shadow effects. Figure 1 shows the complex geometry and structure of muqarnas in several religious buildings.

Figure 1. Muqarnas geometry and complexity (Ahmed, 2022).

This study aims to contribute to ongoing research on muqarnas geometry/patterns by establishing groundwork for novel designs using algorithmic and parametric techniques. Emphasis will be placed on preserving Islamic architectural heritage while embracing innovative design methodologies. Exploring questions like enhancing muqarnas patterns through generative design and algorithms and preserving their intrinsic value within modern contexts, this research seeks to blend Iranian muqarnas' heritage with generative design frontiers.

2. Related Works

The reconstruction and restoration of muqarnas ornaments have been meticulously analyzed in various academic studies. Dold-Samplonius (1992) laid the foundational groundwork, serving as a cornerstone for Harmsen's algorithmic muqarnas reconstruction in 2006. Harmsen's approach treats the planar representation of muqarnas as a graph, storing three-dimensional data within its nodes. Furthermore, Takahashi (2020) contributed by presenting diverse muqarnas plane projections, including square and pole table styles.

In addition to these analytical studies, design-research investigations have aimed to push the boundaries and explore the creative possibilities of muqarnas geometry. For instance, Yaghan (2001, 2005) introduced new versions of classical muqarnas forms through innovative unit developments. Architect Imani (2017) proposed an alternative workflow for computer-aided muqarnas reconstruction, emphasizing motif-based and layer-based analyses of muqarnas patterns. Similarly, Alaçam, et al. (2017) delved into paper folding techniques to explore muqarnas tectonics conceptually, experimenting with form-finding approaches to understand its generative and structural aspects. Furthermore, Alaçam and Güzelci (2016) explored the potential of parametric modeling software in unlocking abstract muqarnas geometry to generate new designs.

The primary aim of our paper is to revitalize the traditional art of muqarnas by

conducting various algorithmic modeling methods. These methods aim to develop software tools for muqarnas modeling, ensuring the preservation of this cultural heritage for future generations. Additionally, modeling muqarnas represents a pivotal step toward a deeper understanding of these intricate geometrical forms.

3. Research Objective

The analysis of literature on 3-D Persian architectural elements, specifically muqarnas, underscores a predominant reliance on 2-D schematics for the examination and reconstruction of patterns despite the inherently three-dimensional nature of these elements. In the context of muqarnas plan projections, the diverse shapes of elements remain discernible; however, the attribution of elements to specific tiers remains elusive within these projections, necessitating a decoding process. Some authors endeavor to incorporate three-dimensional information within 2-D drawings (Gherardini & Leali, 2016).

The primary objective of this project is to employ a framework rooted in fundamental 2-D drawings alongside the utilization of the prevalent muqarnas patterns with various combinations of the parameters and procedural approaches derived from a sample of standard muqarnas patterns. This methodology aims to generate a multitude of muqarnas 3-D patterns based on Islamic 2-D patterns, thereby enabling the analysis and reconstruction of intricate 3-D patterns.

Our objective is to scrutinize various parametrically generated muqarnas patterns to identify combinations of parameters that resonate more closely with, for example, traditional, modern, or sacred designs, according to participant perceptions. Our analysis seeks not only to preserve traditional values but also to align with contemporary and modern architectural styles.

The outcomes of this study will manifest as a virtual, textured model showcasing precise shapes and positional attributes of architectural muqarnas. The proposed framework seeks to provide valuable support to researchers and scholars within the architectural domain by facilitating an in-depth analysis of muqarnas patterns and the underlying geometric principles applied through generative design methodologies.

4. Methods

This research explored the relationships between the subjective and objective values of muqarnas in the contemporary context while preserving traditional values through various methods and analyses aimed at defining, interpreting, and generalizing digital 3-D muqarnas patterns.

The following two methods were proposed in steps. In the first step, we developed a procedural method to generate 60 muqarnas design patterns parametrically. In the second step, we analyzed each of them based on analytically derived objective evaluations and subjective evaluations through crowdsourcing.

The proposed parametric models were implemented using the Rhinoceros software with a procedural approach created using the Grasshopper interface, which facilitates the fast and efficient development of algorithms accessible to non-programmers.

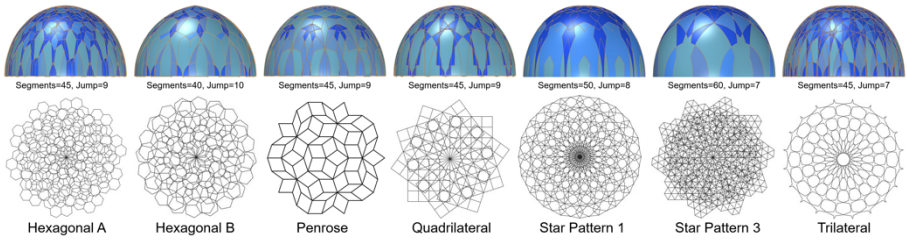


Figure 2. Seven types of Muqarnas patterns.

4.1. MUQARNAS DESIGN PATTERN GENERATION

As we discussed in the previous section, 3-D patterns of muqarnas predominantly rely on 2-D schematics of Islamic patterns, so we carefully selected appropriate 2-D shapes for the muqarnas, serving as a fundamental element for subsequent work. The parametric modeling of these base patterns allowed for the creation of variations while maintaining geometric continuity, thereby unveiling the potential of parametric design. The following four steps were performed to generate 60 muqarnas patterns.

Step 1: Seven types of 2-D patterns were carefully selected and developed for this study – Hexagonal A, Hexagonal B, Penrose, Quadrilateral, StarPattern 1, StarPattern 3, and Trilateral (Figure 2). For the initial 2-D pattern generation, we used the Parakeet3D plugin (2023), a powerful tool in Grasshopper for creating intricate designs, and we further modified them to satisfy a wide range of variations ranging from those that resemble traditional muqarnas patterns to those that suggest speculative design patterns, which serve as suitable 2-D bases for parametrically generating various muqarnas patterns.

Step 2: The generation of 3-D muqarnas patterns relied on two primary parameters: segment number and jump number, which were originally defined within the Parakeet plugin. Segment number defines the number of vertices radially around the base area of muqarnas. The jump number defines the region offset ratio from the originally defined 2-D pattern module in Parakeet when tiling them. Two of the authors, who are professionally trained Iranian architects, further finetuned and modified the patterns based on Islamic 2-D shapes. Based on the combinations of two parameters, 60 new muqarnas patterns were generated.

Step 3: Arranging parameters was instrumental in constructing 3-D patterns, leveraging the proportional features of the patterns to generate them while ensuring the creation of 2-D projections that fill the intended area without gaps or overlaps. The numbering sequence that alters the 3-D patterns deviates from the classical tiering system, reflecting the divergence from traditional muqarnas patterns.

Step 4: Morphing a collection of 3-D shapes to a reference dome-like geometry marked the finalization of the muqarnas pattern modeling. This step underscored the potential of the parametric design workflow. These 3-D shapes originated from basic muqarnas 2-D patterns, which are prevalent in Iranian muqarnas. As a result, the patterns derived in this step are similar to muqarnas elements and their fundamental patterns.

4.2. DATASET CREATION AND EVALUATIONS

After generating 60 patterns of muqarnas in 3-D, we conducted a series of evaluations to understand the relationships between parameters that define geometries and their performances, using both analytical results that are objectively defined and perceptive impressions quantified by subjective evaluations through crowdsourcing on each pattern.

4.2.1. Objective Evaluations

Our objective evaluations include calculating the number of facets used and the structural behavior in terms of a maximum displacement in each pattern.

Facets represent individual panel modules or surfaces that compose the muqarnas, often comprising intricate geometries. These facets contribute to the overall aesthetics, structural stability, or load-bearing capabilities of the muqarnas. The number of facets can be interpreted as the number of elements necessary to construct each muqarnas pattern, indirectly indicating labor for assembly and production, which is approximately proportional to the number of facets (the higher the facet count, the higher the construction cost). Also, higher facet counts lead to more visually denser patterns with more panels.

For conducting structural analyses of different muqarnas patterns, we employed Karamba3D (Preisinger, 2013), an interactive, parametric structural engineering tool in Grasshopper based on Finite Element Analysis (FEA). Using parameters such as a gravity load, a muqarnas pattern, boundary element conditions, and interior forces, Karamba3D provides accurate analyses of muqarnas shells. The analysis outputs from Karamba3D include a maximum displacement in millimeters within one pattern, which indicates the stability of muqarnas structures with varying patterns under a consistent loading condition.

4.2.2. Subjective Scores

Crowdsourcing the generated 3-D models involved soliciting participant feedback through six questions to gauge subjective values associated with the muqarnas. For the assessment, 60 muqarnas images were randomly selected, and the following six question statements were formulated for each image:

Q1: It is a traditional muqarnas design.

Q2: Its impression is modern and contemporary.

Q3: It is an aesthetically pleasing beautiful design.

Q4: It is a peaceful, calming, restful design, perfect for meditation.

Q5: It is a sacred design appropriate for a religious purpose.

Q6: Overall, it is personally a preferable design for me.

In total, 25 reviewers participated in this evaluation, all of whom are architects in Iran. This time, we aim to study subjective evaluations by participants who are culturally accustomed to Iranian traditional architectural heritage and patterns, including muqarnas. Each floor plan was evaluated by participants based on a five-grade score on a scale of 1 (strongly disagree) to 5 (strongly agree). Only the muqarnas images were shown to participants for evaluation. A task completion control was

implemented, and the participants had to answer all the assigned questions to complete the task; otherwise, their responses were not included in the study. Each participant was asked to evaluate 20 muqarnas images. As a result, each pattern was evaluated by 8 to 11 individuals.

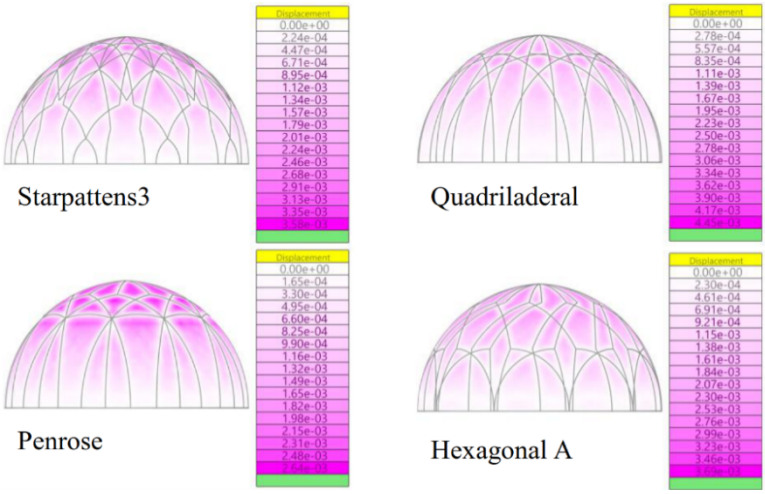
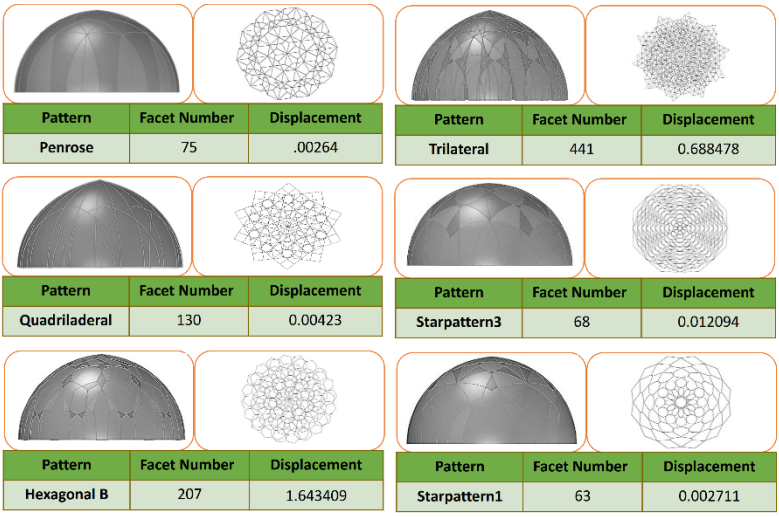


Figure 3. Displacement number of Muqarnas 3-D patterns by Karamba3D.



Pattern	Facet Number	Displacement
Penrose	75	.00264

Pattern	Facet Number	Displacement
Trilateral	441	0.688478

Pattern	Facet Number	Displacement
Quadriladeral	130	0.00423

Pattern	Facet Number	Displacement
Starpattern3	68	0.012094

Pattern	Facet Number	Displacement
Hexagonal B	207	1.643409

Pattern	Facet Number	Displacement
Starpattern1	63	0.002711

Figure 4. Facet number and Displacement in different patterns.

5. Results

The outcomes from questionnaires and objective evaluations, including structural analyses and facet counts, were analyzed to establish a credible basis for discussion and conclusions.

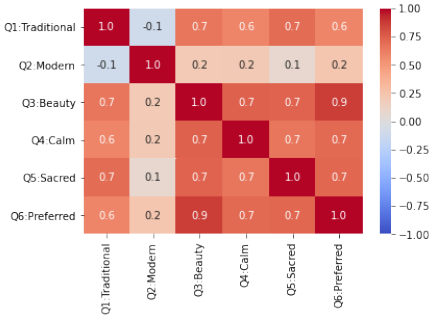


Table 1: Pearson correlation matrix (n=60)

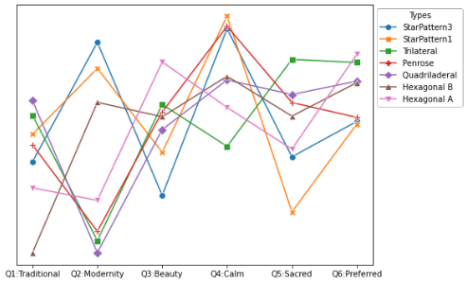


Figure 5: Mean scores of all variations from each of the seven patterns for six criteria

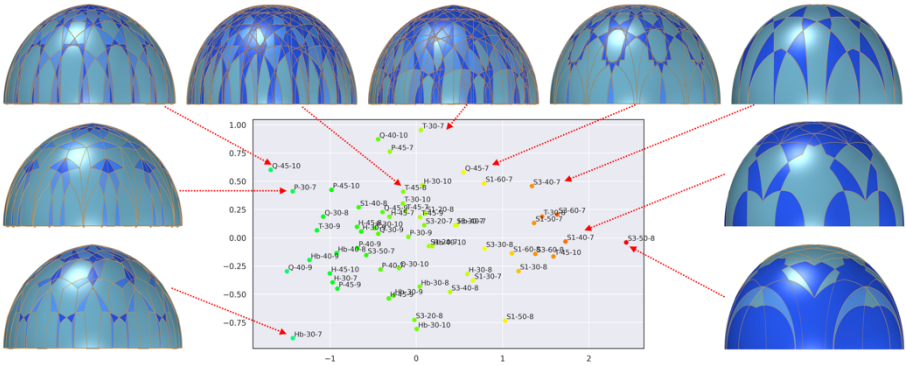


Figure 6: PCA visualizations of 60 Muqarnas patterns based on their performance scores in six criteria as their features. The color of a marker is based on the average score of all criteria from each pattern (green being higher and red being lower).

5.1. ANALYSES BASED ON OBJECTIVE EVALUATIONS

Figure 3 shows the displacement values assigned to each of the muqarnas patterns, indicating their deflections when subjected to gravity and internal loads, which are contingent upon the 3-D pattern types, muqarnas supports, and their material composition. A lower displacement value indicates greater stability for the muqarnas, while a higher value denotes less stability. Although influenced by several factors, the analysis unmistakably demonstrates a direct correlation between displacement and the number of facets—more facets in a pattern lead to increased displacement, implying higher stress on the muqarnas structures.

The facet number significantly impacts structural analyses in various ways. Factors such as the facet counts, their shapes, configurations within the pattern, and individual sizes collectively influence the structural analyses of muqarnas. Determining each factor's precise role in increasing or decreasing stress within the muqarnas structure is a complex process. However, as a general observation, 3-D patterns with higher facet counts and smaller facet sizes tend to exhibit increased displacements in muqarnas

structures, while the opposite holds true for patterns with fewer facets and larger facet sizes (Figure 4).

5.2. ANALYSES BASED ON SUBJECTIVE EVALUATIONS

After analyzing the responses of all participants to the six questions concerning each pattern, we have arrived at the following results:

As shown in Table 1, besides Q2 (Modernity), our five criteria show strong positive correlations among them. Especially we find the highest correlation between the ratings of Q3 (beauty) and Q6 (preferred) ($r = 0.9$, $p < 0.0001$, as shown in Table 1), suggesting that participants primarily looked at aesthetic value when judging their overall preference for muqarnas patterns. On the other hand, we did not find any correlation between Q2 (Modernity) and other criteria, even including Q1 (traditional). Our study shows that the ratings for modernity and traditional values do not have a simple inverse relationship but rather a more complex one. For example, Hexagonal A demonstrated relatively neutral results with lower scores simultaneously in both Q1 and Q2, yet it was the most overall preferred pattern in Q6 and Q3 (Beauty). Contrary to our general understanding, we found that Q1 (Traditional) and Q2 (Modernity) are not always in an opposite relationship. Furthermore, whether participants' impressions of design patterns are new or old does not influence their overall preference for their design as much as other criteria.

As shown in Figure 5, the Hexagonal A and Trilateral patterns are preferred overall among participants, whereas the Star Patterns 1 and 3 with curved lines exhibit the least popularity (Q6). The preference for the most popular patterns correlates with their abundance of straight lines, traditional facets/shapes within the patterns, and a higher degree of segmentation akin to traditional muqarnas designs. Conversely, the less popular patterns tend to feature curved lines and exhibit fewer segmented forms, deviating from the traditional muqarnas structure, which potentially influences their lower appeal among participants. It is notable that Star Patterns 1 and 3, with the worst overall preferred ratings in Q6, scored the highest in Q2 (Modernity) and Q4 (Calm, Tranquility), defining their unique characteristics.

Figure 6 shows the distribution of 60 muqarnas patterns based on their ratings in six criteria as their features using Principal Component Analysis (PCA). PCA is a dimensionality reduction technique that arranges layouts in a 2-D plot with similar features (performance characteristics) closer together. Similar patterns are plotted closer together, implying that similar geometric patterns perform similarly, as seen from the ID tags of markers such as "Q" (i.e., Quadratic) in Figure 6. Each pattern has strengths and weaknesses. Star-shape-based patterns (S1 & S3) distributed closer to the right side of the plot in Figure 5 have lower overall scores.

5.3. SUMMARY OF THE ANALYSES

In summary, the traditional aspect of muqarnas exhibits positive correlations with various attributes, such as beauty and tranquility, except for modernity. This observation suggests that muqarnas patterns aligned with traditional forms from the past tend to be favored among the participants. Furthermore, it indicates that despite employing virtual generative design techniques, our generated muqarnas patterns

retain their traditional values and remain deeply rooted in culturally accepted muqarnas aesthetics.

According to participant responses, the overall preferred muqarnas patterns exhibit moderately high correlations with both the facet number and their geometry types. Patterns with greater facet numbers, which are closer to the facet division sizes of existing conventional shapes and configurations of the 3-D muqarnas patterns, tend to obtain moderately higher scores in Q3 (Beauty), Q5 (Sacred), and Q6 (Preferred) from the participants (i.e., the denser patterns obtained better overall average scores). However, there are no correlations between facet counts and Q1 (Traditional), Q2 (Modernity), or Q3 (Calm, Tranquility). This implies that patterns closely related to traditional muqarnas are more preferred among participants, although some characteristics, such as modernity, are irrespective of facet sizes and counts.

5.4. LIMITATIONS

One limitation of our study is the absence of significant connections found between certain factors governing the geometries, specifically segment numbers and offset parameters used to establish the pattern region for tiling, known as the jump number, and crowdsourced ratings. Further investigation into better parameter selections for geometrical outputs is warranted. Structural performance was estimated based on approximated three-dimensional shapes on the dorm surface, which could be more extensively modeled in future research. Additionally, a more homogeneous projection approach for 2-D to 3-D geometries is required to reduce panel division elongation at the lower half of the dorm shape.

Our analysis yields new insights into how different Muqarnas patterns influence various subjective impressions of designs. While our current focus is on understanding evaluations by participants already familiar with Iranian traditional architecture, expanding these investigations with a larger number of samples and participants would enhance the credibility of our study and allow us to utilize the dataset as training data for various machine learning applications. For example, existing research utilizes such datasets to develop deep neural network models for predicting subjective functionality and comfort from architectural floor plans (Narahara & Yamasaki, 2022; Kitabayashi et al., 2022). Furthermore, there are proposed generative models for architectural designs using data-driven approaches, though these avenues remain as future endeavors.

6. Conclusion

As discussed above, the research aimed to formulate a parametric generative process for new muqarnas patterns. The methodology proposed in this paper could be utilized to generate numerous new designs of muqarnas forms, drawing upon Islamic architectural concepts pertaining to muqarnas patterns and their intrinsic relationship with the aesthetically pleasing nature of muqarnas geometry. The generative design process showcased in this research demonstrates its capability to produce diverse muqarnas patterns while retaining traditional values and aesthetics, ultimately achieving identity-oriented design. The study's conclusion emphasizes that Iranian architects are inclined not only toward novel methodologies for generating muqarnas

and employing parametric solutions for creative patterns but also a strong preference for upholding traditional values and proportions in muqarnas pattern design.

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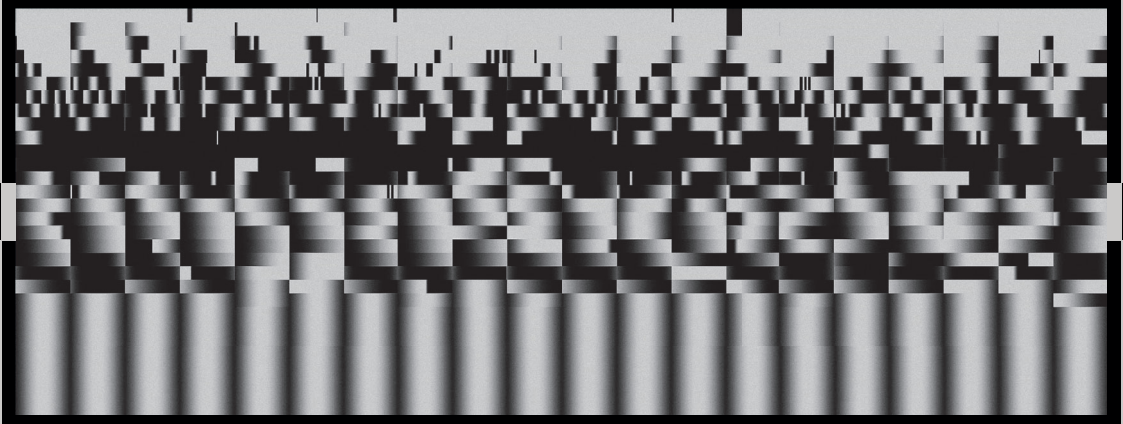

Can and should design be accelerated? To what extent and to what end? Or perhaps, design must decelerate instead? Accelerated Design is an urgent call for a critical reflection of and creative action by architecture during this challenging time of accelerating climate crisis, unrestricted data surveillances, generative AI copyright infringements, global geopolitical conflicts, hyperconcentration of digital power, post-pandemic mental health deterioration, and widespread disinformation attacks.

CAADRIA2024 seeks contributions in addressing the conference theme by discussing and debating the role of design and designers in the midst of accelerated changes brought about by and on technology, economy, environment, and governance, to construct new ways of thinking, teaching, researching and practising architecture in the age of artificial intelligence and climate change.

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