International Journal of Artificial Intelligence and Neural Networks – IJAINN

Volume 9 : Issue 1- [ISSN : 2250-3749] - Publication Date: 27 Dec, 2019

Review of Artificial Intelligence and Machine Learning Applications in Architectural Design

Dinooli S. Uduwarage
Faculty of Information Technology, University of Moratuwa, Sri Lanka.

K. A. Dilini T. Kulawansa
Department of Computational Mathematics University of Moratuwa, Sri Lanka.

P. Botejue
Department of Architecture, University of Moratuwa, Sri Lanka.

***Abstract*— The influence of Artificial Intelligence (AI) and Machine Learning (ML) fields for the betterment of architectural design field has been concentrated in this paper. Complexities in design problem scope and creative cognition involvement in designing of architectural elements have attempted to be empowered by techniques of AI and ML, when it comes to finding optimal solutions to design problems under given constraints. The status of the research in these fields is discussed here with their issues encountered and intended future directions.**

Keywords*— *Artificial Intelligence, Machine Learning, Architectural Design Process, Spatial Design Computing.

I. INTRODUCTION

Artificial Intelligence (AI) is one of the biggest scientific breaks through over past few decades, which was evolved on basis of the question "can machine think?" by Alan Turing [1]. This field of study evolved on the concept of machine that has self-improving capabilities to solve problems like human beings, on their own, which can mimic the complex functions of human brain. The essence of Artificial Intelligence has been a factor for revolutionary development in the field of architectural design, as many other subject areas constantly evolving with it.

Machine Learning (ML) is an advancing technology, where it promotes viable solutions by combining a large amount of data that is impossible to analyze with other technologies, which is a core sub route under AI, which utilizes statistical base to generate outputs. Machine learning in simple terminology is that an algorithm, from which the machine learns from its past experiences, input and output, where it gradually improves to work on its own to revamp the future output, without further human intermediation [2]. The core concepts in machine learning are practiced currently, where it substantially contributes in the improvement of the architecture industry.

Architecture is the scientific and philosophical study of the process of planning, designing and constructing buildings and structures, with artistic disciplines, blend of creativity and aesthetic influence [3]. An architect is a designer who practices some principles and theories incorporated with some portion of self-perception of artistic sense, who finds solution to building requirements under certain limitations, which is much challenging, complex and requires human intelligence and cognition to tackle the problems in composing a master piece. That complexity and challenging nature of it is addressed by the artificial intelligence and machine learning to aid in the architectural design process.

Yet, it is said that the architecture design process, which involves manipulation of functions, complex perception, intelligence on creativity and social impact is not likely to be taken over by the machines in fully.

II. OVERVIEW OF APPLICATIONS OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ON ARCHITECTURAL DESIGN

Artificial intelligence and Machine Learning are simply machines mimicking "cognitive functions" as humans, learning themselves and apply that knowledge and strategy on problem solving. Architectural design in practice always makes room for AI and ML empowerment to engage in a novel design, as it needs to go through past design experiences and building data to tackle the new problem upon modern expectations. The ability to process and learn from tons of previous data in a millisecond to aid in deriving optimal solutions and enhance the architecture design process by enabling most powerful cognitive design artifacts could work wonders.

Architectural design from an artistic and more imaginative point of view claims that structural and spatial design are the product of intuitive inspiration and creation [7]. Open-ended creative solutions are still reserved for humans, where computers are not so good at. But via automation, architects have been able to save time from doing repetitive tasks, where that time can be reinvested on intuitive design endeavours.

The architectural practice on daily basis relies on computer aided drawing and building information modeling [5], where the AI and ML comes into play. AI enables expert systems that is highly useful in designing spatial elements in architecture, which can suggest the formation and demarcation of spatial partitioning. Practical solutions to design challenges can be derived from training machines over huge data sets using machine learning. As these, artificial intelligence and touch of machine learning on the architecture has opened a gate of new era of evolution in the industry.

III. MAJOR RESEARCHES IN APPLICATIONS OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ON ARCHITECTURAL DESIGN

AI and ML driven systems has accelerated the architecture industry over the past few years by opening up new dimensions of potential privileges that could help the industry in its complexity and intuitive nature. Below is a briefing of selected major researches conducted on various possible avenues of applying AI and ML boost over architectural design process.

The research by K. Radziszewski and J. Cudzik is taken steps on presenting a set of algorithms that amplifies automation of design tools, which are used in sketching, forming complex structures etc., to overcome the limited capacity, and commands in contemporary design tools used by architects [5].

Complex dimensions, concerns, parameters, properties of a given design space is characterized (aspectualized) using AI problem solving strategy, "Divide and Conquer", to reduce the complexity and focusing on most crucial aspects in designing

of functional spaces, in the research conducted by S. Bertel, C. Freksa and G. Vrachliotis [7].

Using a modification named pix2pixHD of Generative Adversarial Network (GAN), a model framework in machine learning, which can learn from input images pairs and generate new images based on inputs, W. Huang and H. Zheng have accomplished recognition of architectural drawings and generation of new floor plans by learning from recognized drawings, labeled colored floor maps [8].

M. Bhatt and C. Freksa have researched about a conception of assistance-driven analytical computing for spatial design, which supports representation of spatial design semantics and spatial reasoning in design computing [12].

Hon Wai Chun has presented about intelligent computer-aided architectural design system (ICAAD) that comprise of independent critic modules, with a design knowledge base, which evaluates architectural design over it and offers expertise advice. In this research two critic modules are developed: FPDX, which verifies residential apartment floor plans over government regulations and IDX, evaluates floor and furniture layout over interior designing guidelines [13].

A design assistant prototype aids in iterative design refinement using abstract, experiential terms, The Architect's Collaborator (TAC) which evaluates architectural design over set of pre-defined goals and presents explanation of suggestions for refinements with proposal for new creation has been a result of a research by Kimberle Koile [15].

A research by M. Bhatt et al. is focused on computational cognitive systems and assistive technology in adopting people-centred design system that identifies "visuo-spatial perception and cognition", human behavior and how human experience in spatial context as how people navigate, eye-catching elements and objects in space etc. and universally standardize the architects' designs of built environments suitable for all diverse user groups as disable people, different age groups etc.[16].

Design computing model and a framework that assist in design process for changing empty space into functional spatial designs as of Hospitals, Museums etc. in the context of visuo-locomotive perception and special cognition with an emphasis of human-centred notion has been researched by M. Bhatt et al. [19].

Machine learning supervised algorithm, "error backpropagation multilayer artificial neural network" to replace time consuming, error prone computer simulation to calculate the illuminance effect of direct sunlight and daylight inside buildings, applied in early stage of design process is a result of a research by K. Radziszewski, and M Waczyńska [20].

IV. Identifying Current Issues of Applications of Artificial Intelligence and MAchine LEARCNING on Architectural Design

Most crucial issue with the current systems, that they are lacking creative intuition. The machines can only engage in repetitive tasks with efficiency than humans, where it can only tackle the tamed problems, yet the modern design problems are more wicked with their scope and demands.

Relating designing and AI together, brings up some challenging problems to address generally as follows [23]:

- **Representation and interpretation of design**: how and what to represent and model the design knowledge and code & decode design semantics into AI based systems.
- **Inference in design**: how to combine implicit intentions, commonalities to make design decisions.
- **Indexing in design**: methods to store knowledge in memory to help choosing out the most applicable, richest design knowledge with effective searching techniques out of enormous data.
- **Dynamic modification- learning in design**: how to learn and modify the design knowledge and its application as time grows.
- **Generalization in design**: how to generalize design cases to draw conclusions effectively.
- **Situation Recognition in design**: recognizing design contexts and situations in strategic and semantic level.
- **Creativity in design**: how computers can be creative as human.
- **Evaluation in design**: how to evaluate a design in terms of technical performance, socio-ethical value and functionality.

Apart from these challenges, below are the limitations and problems faced by modern application efforts.

High computation resources demand for processing and analyzing the architectural data, which is more graphic based, be the bottleneck for limiting the frequent use of AI and ML powered solutions by architects [4]. The machine learning approach in calculating illuminance in buildings has limitations with its extreme memory consumption as well [20].

The design problem scope is vast, detailing objectives in terms of features and properties, identifying design variables are very complex, completely different from one another problem and too much comprehensive to define in proper format generally are challenging to address, when tackling an architectural problem with design computing [7]. Due to the ambiguity in design space, floor plan recognition can not be clearly distinguished when space demarcation in a floor plan is not bounding by walls, it cannot properly identify the floor area using pix2pixHD [8].

Results of research experiments of using ML algorithms is accurate as it uses hypothetical, plausible data sets, but in real world applications, results are not that accurate since data is prone to errors and ambiguity in data paves the algorithms to move to non-sustainable performances [9].

The lack of information in TAC knowledge base and inability of the system to work with larger set of goals, implicit objectives are not designed to handle with current scope, architects carry the credit of handling unspecified goals and subconscious operational capacity of human have been a barrier for the TAC from generating optimal solutions over architects [15].

'AI for Design' notion has failed to create any practical industrial applications in terms of knowledge representation and reasoning, though concepts and theorems behind that have been revealed by research community [22]. The feelings of architects being replaced by AL and ML systems be a major reason of lack of use of the founded solutions and that demotivates the researchers, where the researches to be conducted in this area of study is yet so large.

V. Applications of Artificial Intelligence and Machine Learning on Architectural Design

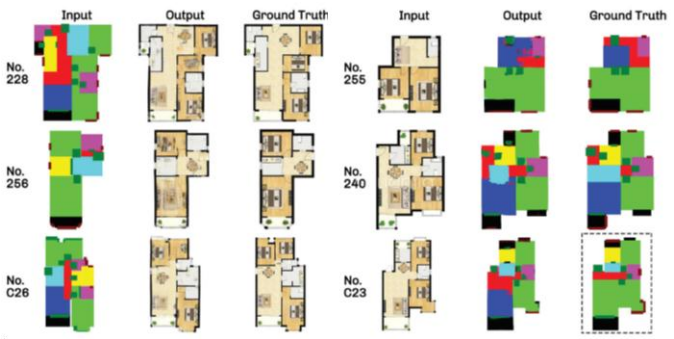
Whenever data are available, AI and ML can assist architects with plenty of analytical tasks, to get a better understanding of context, patterns in practice, spatial and material performances for both quantitative and qualitative characteristics of design and design tools are made powerful as well.

Knowledge representation and reasoning of AI have been the cornerstone of the AI approach in architectural design problem solving [22]. AI contributes in producing better theories on design processes, improves design process quality with intelligent tools and artifacts that aid when developing new design ideas, criticize designs and design it self keep architects away from mundane activities by expert systems, multi-agent systems, genetic algorithms, neural networks, case-based reasoning, qualitative reasoning, formal grammars, heuristic search and planning [17].

There are many significant applications of spatial inference techniques in the field of building design in following concerns: Design intent – assist in design process on qualitative aspects as user experience of spaces, lighting influences, arrangement of spatial elements and navigation between them; Conceptual consistency – detect and take necessary steps to contradictions between design requirements, constraints, rules and regulations; Design consistency – validate building information model for its compliance with user needs and prevailing rules based on the people-centred design concept [18].

Advancement of AI problem solving strategy "divide and conquer" named "Aspectualize And Conquer" is utilized in identifying the most crucial aspects of a given design problem and cognitive involvement in solving them. The design problem complexity is addressed with segmenting the problem into sub problems based on characteristics to apply the suitable design method [7].

"pix2pixHD", the ML model framework that analyses colored images and real photos in 2048*1024 resolution, encodes the images into matrices which has been used to learn from color labeled floor maps of functional areas and generate complex architectural floor plan drawings from it and vice versa [8].



Left: color labeled map input, output of functional floor plan and actual floor plan

Right: actual functional floor plan input, output of color labeled floor map and actual color map

Assistance-driven analytical computing for spatial design concept has been used to represent and model spatial informatics, spatial design semantics, artifacts, and assistive analytical aids related to creative spatial design with a CAAD tool and spatial reasoning is done based on human-centric perspective [12].

ICAAD is an expert system that validates and criticize floor plans with critic modules (FPDX & IDX), that comprise of independent knowledge base of validation criteria (governmental regulations, interior design guidelines initially). This intelligent system analyses the drawings using a front-end CAD system and object knowledge base and inference engine are used in spatial reasoning to process geometric information and critic modules triggered when violation of rule is experienced. Inference engine also suggest design improvements at rule violation events and suggestions are stored in a file [13].

AI techniques have been used to enrich the architectural design artifacts in case-based reasoning (past design experiences is stored enabling to derive essentials from them), artificial life(simulates interactions and influences of spatial outcomes) and on complexity and diversity in architecture and architectural style learning pattern recognition (patterns of spatial relationships between repeated spatial elements are identified to generate shape pattern descriptions), with CAAD [14]. Reasoning model based on context knowledge powered has been the focus for research to enhance the efficiency, quality and performance in existing design reasoning systems [21].

Potentials of Genetic Algorithms, Analytic Hierarchy Process and Fuzzy approaches are highly utilized to address the increasing demand and challenges faced at designing optimal, economical and ecofriendly green architectural solutions [24].

VI. Discussion

Design decisions can become much smarter, which might lead to new hybrid vocabularies, and novel dynamic, adaptive, and synthesized compositions we never thought of.

As AI and ML advances, the spirit of these technologies has spreaded over the field of architecture, to consolidate the comprehensive process of designing to accomplish real world building design expectations. When AI take care of mundane work, designers must cope with machines speed and accuracy, intensify their decision making in the sensible environment, and be ready to do innovative and creative tasks with computer and technological literacy [25]. Yet the innovative applications and outcomes of researches in the fields of AI and ML are insufficient to cater the whole industry and as the current inventions are not very much establish to practice by the architects, still the tri-fields of studies have a very long journey to move on [10]. The role of the architect is still decisive, who can evaluate and synthesize unique insightful solutions and credit of creativity is with human architect, when it comes to designing of master pieces upon numerous demanding environments, which would remain unchallenged by computational technologies, for over many decades.

Following table presents comparison of some selected researches, that is mentioned in this paper.

TABLE 1: SUMMARY OF SOME RELEVANT RESEARCHES

Title of the Research Paper	Aim and Problems Addressed	Limitations/ Challenges	Future Directions

Artificial Intelligence Aided Architectural Design	Artificial intelligent based architecture design tools in behavior-based design, optimization process and supervised machine learning. Architectural practices applied with AI algorithms: neural networks, swarm intelligence, evolutionary algorithms Vision and robotics based analogue data input & output methods.	Still the role of architects' involvement is decisive, to decide the best solution between computed results. The AI systems are not yet fully autonomous or controllable as needed by the designer. Use of ML in the field of architectural design tools, is still limited. Most design process computational models elaborated here are based on the same user defined set of rules of principles.	Fully autonomous AI systems which is based on structured architectural data by the process of Building Information Modelling. Digital artificial intelligence aided designer's assistant, which helps to solve design problems, suggesting many solutions on their own, prior learning designer's behavior and thinking patterns.
Computer Aided Design and Artificial Intelligence in Urban and Architectural Design	The support of an expert system which is capable of proposing design model and structural solutions for an urban architectural design, considering the aspects of urban environment, morphology, topology and urban growth is discussed here.	In weak AI systems, the choices made by the system and why they are proposed over others cannot be explained with reasoning, as they are of a synthesis process, which cannot be re-generated analytically, yet the weak AI system is considered here for the interpretation purposes.	Input plan supplied to the system has to be in vectoral file format for immediate recognition by the calculation algorithms.
Aspectualize and Conquer in Architectural Design	Complexity in the spatial design process is characterized based on cognitive principles, using AI problem solving strategy, "Divide and Conquer". Aspectualizing and conquering of the variables and features in design problems space to derive design decisions.	The lack of well-defined design problem space is challenging in design process analysis. It is much complex to identify variables, which are then sub-divided again based on many aspects, in the field of design space to sort out the design problem. Detailing the design objectives is complex in the number of features and properties of them same.	Methods to find well defined problems space for analyzing the design process.
Architectural Drawings Recognition and Generation through Machine Learning	Use of pix2pixHD, an advancement of Generative Adversarial Network (GAN), which is a model framework in machine learning that can compare image data and generate new output, in recognizing and generating of architectural drawings and understanding the concept and procedure behind it.	In recognition of floor areas, it can't clearly distinguish between floor areas as living room, walkway and dining room, if they are not clearly bounded by walls, where they were marked as one. Therefore, many architects interpreted them differently, as it was hard to distinguish. In some images of floor areas in the data set, positions of TV, sofa was not clearly identified in the results.	The experiments can be further developed into prototypes of a powerful tools for drawing review, digitalization, and drawing assistance. Develop advance networks with faster recognition and architectural drawings generation more reliably, which could keep off architects from engaging repetitive works and escalate provoking of design solutions with the sense of

			creativity is the next move of the research.
Towards the Application of Machine Learning on Architectural Projects	Introduction to machine learning, Machine learning potential to aid in architectural urban design. Examples of application of ML in architecture: identifying main streets in an urban environment, door scheduling with the use of machine learning algorithms. Classification of scheduling processes in architecture is done using ML.	Geographical Information Systems (GIS) generates large quantity of data without a sense of intelligent and lack of any inference capacities. Selecting features to be used in the training data set is challenging when constructing urban typology into ML context. It assumes, only types of rooms as a factor in the experiment for determining door schedule, while in real world many factors are to be considered. The data sets are prone to human errors and will not be consistent and clean in real world scenario, therefore learning algorithm results would be less accurate.	Conducting the experiment on large amount of real-world data set normalized over a collection of real projects, which needs to be pre-processed and analyzed to determine the better classification attributes.
Computational Intelligence in architectural and interior design: a state-of-the-art and outlook on the field	Overview of computational intelligence and machine learning advancement on architectural and interior design, with an analysis on data models. Several learning models applied on challenges in interior designing: furniture arrangement, furniture type selection, ornamental decoration, style compatibility. Description about an ongoing research of a commercial solution, which aims to apply learning outcomes on interior design challenges, personalizing furniture organization for a given floor plan.	The system, Bayesian model for learning the occurrence of furniture in different types of rooms and a Gaussian Mixture Models for capturing arrangement patterns is trained on small amount of user-provided data set which limited the capturing of abstract and robust patterns. The amalgamation of real-world-ready scenarios left as an open problem, in data-driven approaches, whereas pure data-oriented model is still not capable of capturing stylish and rigorous furnishing subtleties.	Since the project is to be in commercial use, real-world expectations are imposed, which are challenging to address, such as robustness, high scalability, flexibility and customization incorporating many preferences as desired functionality, acknowledgements of usability and choices of furnishing, when developing the ongoing project.
Analytical Computing for Spatial Design: An Artificial Intelligence Perspective	Use of artificial intelligence and cognitive science in the scientific design process of spatial representation, spatial artefacts. Reviews about an AI based assistance-driven analytical computing system for (spatial) design	It is impossible to model the spatial artefacts, range space in sensory devices, that is not exactly a spatial entity. There is no potential for a knowledge-based system to create inferences about the conceptual design and its geometric interpretation within a	Specialized spatial reasoning systems unlocks new potentials and programming standards for design problem solving which are not computationally controllable, integration of generalized logic-based reasoning and

	representation and reasoning.	CAAD model, even with contemporary design tools. Reasoning about what it is and what can be the functional and conceptual consistency for design analytics in hypothetical reasoning is challenging. Within a qualitative context, hypothetical reasoning under auxiliary limitations of physical realizability and architecture domain-specific heuristics, causes challenges.	techniques of specialized spatial reasoning.
Intelligent Critic System for Architectural Design	AN intelligent computer-aided architectural design system (ICAAD), which is an expert system of architecture, capable of criticizing and suggest changes, ideas evaluating floor plans against government regulations and interior design, furniture layout against best practices, interior design	The breadth and depth of knowledge required to fully perceive the principles of design and all types of governmental regulations are greater in quantity. Design principles and regulations considered here are only related to two-dimensional reasoning and furniture and layout of single floor of a one apartment. Very simple floor plans were used with limited number of	Extension of the scope of ICADS to capture vast knowledge and increment of number of critic modules. Amplify the critic modules knowledge with case-based knowledge of predefined better floor plans, which can be utilized to produce a sketch of suggested floor plans.
	guidelines.	furniture and appliances on the floor whereas real world applications are more complex.	
Utilization of Artificial Intelligence Concepts and Techniques for enriching the Quality of Architectural Design Artifacts	Use of artificial intelligence concepts and techniques to aid in the architectural design process and supplement the quality of architectural design artifacts. Elaborates three examples of applications: pattern recognition of architectural style learning, case-based architectural design, and complexity and diversity in architecture with artificial life.	For limiting the scope, only three AI techniques discussed here, though there are plenty, that can be implied for supple the quality of architectural design artifacts. Though there are tools developed with the sense of AI to be used in architectural design process, it has been practically applied less by architects, in the fear of losing their creative sense, taken over by computers. Shape pattern representation system is only focusing on isometric transformation relationships out of many shape relationships, to describe shape patterns.	The research on AI applications for supplementing the quality of architectural design process must be done in great quantities to establish a fashion of utilizing then as a practice.
An Intelligent Assistant for Conceptual Design	Analyzing architectural design and suggest creative design ideas based on the abstract	Lack of information in the knowledge base of TAC sometimes limits the performances of it, when it	Knowledge base of TAC could be advanced with knowledge of materials, light effects

	terminology used between architects and clients mapped to measurable features of design. Proposes and discusses the functioning of a prototype design assistant, The Architect's Collaborator (TAC), with an architectural knowledge base, which explores possible design solution ideas, satisfying the set of abstract goals set by architects and clients, which is to re-design spaces prevailing with certain problems to be repaired.	comes to compare with an architect's solution to unspecified goals. The architect's design solution in some cases are optimized as they can work with larger set of goals than the TAC. Some goals were not input to TAC as its behavior is not defined accordingly, while in some cases the goals were out of the scope of current operators of TAC. Though architects suggest solutions, to tackle implicit goals, based on assumptions, TAC does not know to work as that.	and sociological influences on physical forms, which empirical qualities of a space. TAC could be integrated with a sketching tool, so it can draft the redesign solutions and an interface which enables users to vary the design characteristi cs' values and spot the changes resulting in physical form. Enabling TAC's control structure to be extended to support specification and refinement of goals as to facilitate re-specifying goals while the working process is going on and continue with newly defined goals.
Machine learning algorithm-based tool and digital framework for substituting daylight simulations in early-stage architectural design evaluation	Introduce supervised learning algorithm to reduce time consumption and improve quality and accuracy of results of lighting effects inside a building.	High memory consumption. Sensitivity towards count of neurons and hidden layers is prone to prediction errors.	Training can be done by cloud-based software simulations results instead preset data. Conditions as shading, optical material properties, external geometries, European Daylight Standards must be embedded.

VII. Future Directions of Applications of Artificial Intelligence and Machine Learning on Architectural Design

The research works on AI application over architectural design process must be conducted in great numbers to make it a trendy fashion of utilizing AI touch in extravagant design master pieces [14], where the engagements is still not adequate to use the results in general applications of design problems, where practical industrial applications are found very hardly [22].

Due to the complexities of characteristics and properties of architectural design elements, most of the researches have been done on user-defined simple data sets and based on pre-defined rules, lesser number of principles, practices in use, for the clarity of expected results. But for commercial use, the systems should develop to be coped with real world challenging design expectations, which must operate with more complex functionalities, high customizability, scalability, robustness and solutions should be modeled based on much comprehensive constraints such as best practices, rules and regulations, user preferences, principles and theories in architecture [11]. The research experiments are aimed to be done with more comprehensive real-world data-sets, to get more accurate and relevant outputs [9].

Development of AI systems to provoke design solutions with the sense of creativity, other than repetitive tasks achieved by the current systems, is the highly anticipated next move [8].

Moving on to some of major research projects' future dimensions, it is said in ICAD, the intelligent critic system is to be comprise more critic modules, whereas the knowledge-base of existing modules must be evolved with all the rules and regulations by the government and authorities when constructing a building and interior designing principles and concerns in practice to validate against, when evaluating real floor plans and providing improving solutions[13].

The future of Computer-Aided Architecture Design (CAAD) is focused at how the conception of representation of design semantics, constraints and people centric design perceptions bring up to integrate with ontology and design computing [12]. The ICAAD system is looking forward to suggesting design improvements in hierarchical manner as per the priority and severeness of the violated rules [13]. Other than advancing the knowledge-base with more architectural information and integrating sketching tool to facilitate the system with generating sketches of what it suggests, the TAC is expected to advance with the capability of refinements of goals, while half way gone in design process and resumes generating its output with redefined goals as well [15].

The data used in architecture should be properly structured and be in a standard format to be generally used in AI systems, as Building Information Models [5], maybe universal standards must be introduced when using them in larger scales. It will be more advanced if it is to use cloud

services to process the architectural data, when it comes to machine learning services applied on architectural applications, to overcome high demand of computational resources [4].

The design computing model and framework developed for designing empty space into functional space has planned to improve to be applied on conceptual stage of design by diagrammatic representation of early plans, along with extending the scope into much comprehensive functional building places [19].

Yet it has a far more in the journey of AI and ML, when it comes to replacing the human architects, in the means of creativity and intuition and this paper is planned to be enriched with more research findings further.

ACKNOWLEDGMENT

I am pleased to offer my sincere thanks giving to my parents and my brother for everything they have done for helping me on this paper and bringing me up to this state. I am truly grateful for the authors and researches, who have dedicated their efforts to research, review and publish the findings about this study field and to their generosity towards allowing the articles to be accessed to the followers.

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I am Dinooli Susith Uduwarage, third year undergraduate at faculty of Information Technology, university of Moratuwa, Sri Lanka, following the bachelors' degree in Information Technology.