

AR Educational Suite for Primary Students' Geometry and Literacy

R26-IM-005

Project Proposal Report

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March 2026

DECLARATION

I declare that this is my own work, and this proposal does not knowingly incorporate any material previously submitted for a degree or diploma at any other university or higher education institution, nor does it contain any material that has been previously published or written by another person apart from where proper acknowledgment is given in the text.

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ABSTRACT

Spatial visualization remains a critical bottleneck in primary geometry education, particularly within the Sri Lankan context where students struggle to bridge the conceptual gap between two-dimensional textbook nets and three - dimensional volumetric solids. This research addresses this limitation by proposing an AI-driven Augmented Reality framework designed to enhance spatial literacy through a generative "Sketch-to-AR" pipeline. Moving beyond traditional "asset-passive" AR tools that merely display pre-rendered models, the core contribution of this project is the development of a Real-time 2D-to-3D Geometry Validation and Metamorphosis Engine. This framework aims to transform geometry learning from passive observation into a kinetic, discovery-based experience, directly supporting Sustainable Development Goal (SDG) 4: Quality Education.

The system utilizes Deep Learning (Convolutional Neural Networks) for the autonomous extraction of geometric features from digital hand-drawn sketches created directly on the mobile interface, optimized via TensorFlow Lite for on-device processing. A specialized Topological Validation Logic, utilizing an adjacency matrix, is implemented to mathematically verify the structural integrity and "foldability" of a student's drawing before executing Procedural Mesh Generation. By leveraging ARCore for markerless spatial tracking and environment understanding, the system anchors these generated 3D models into the physical world with high precision. Ensuring low-latency performance on mid-range Android hardware, the system effectively democratizes high-tier educational technology, providing instantaneous, mathematically-grounded feedback to young learners.

Keywords: *Augmented Reality (AR), ARCore, Deep Learning (CNN), Geometry Validation, Procedural Mesh Generation.*

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to all those who have contributed to the conceptualization and successful completion of this research proposal.

First and foremost, I extend my deepest gratitude to my supervisor and co-supervisor for their invaluable guidance, technical insights, and continuous support. Their expertise in Augmented Reality and Artificial Intelligence was instrumental in refining the mathematical logic behind the Topological Validation Engine and the Procedural Mesh Generation components of this project. Their constructive feedback and academic direction greatly improved the technical robustness and pedagogical alignment of my individual research contribution.

I would also like to extend my gratitude to the academic staff of the Faculty of Computing at the Sri Lanka Institute of Information Technology (SLIIT) for providing the resources and the rigorous academic foundation that enabled me to undertake this study. The knowledge gained through my studies played a pivotal role in designing the CNN-based sketch recognition framework and ensuring its optimization for mid-range mobile hardware.

My sincere thanks are extended to my research group members for their seamless cooperation and for the valuable discussions that helped integrate my validation component into the overall system architecture. Their collaboration and shared commitment were vital in ensuring the functional coherence of the proposed AR-based geometry learning system.

Finally, I would like to express my heartfelt gratitude to my parents, family, and friends for their unwavering encouragement, patience, and motivation. Their support has been a constant source of strength throughout the intensive Research and Development phase of this proposal.

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LIST OF ABBREVIATIONS

Abbreviation	Expansion
AI	Artificial Intelligence
AR	Augmented Reality
CNN	Convolutional Neural Network
STEM	Science, Technology, Engineering, and Mathematics
API	Application Programming Interface
UI	User Interface
UX	User Experience
UAT	User Acceptance Testing
TRD	Technical Requirement Document

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1. INTRODUCTION

1.1 Background and Context

Spatial visualization is a fundamental cognitive skill essential for primary-level STEM education, particularly in mastering geometric principles. A pervasive challenge in the Sri Lankan primary education system is the "Representation Gap," where students struggle to mentally bridge the transition from two-dimensional textbook diagrams to three-dimensional physical structures [2], [14]. Mastery of concepts such as geometric nets, manifold folding, and volumetric properties requires a high degree of spatial reasoning a skill often underdeveloped due to the reliance on static pedagogical tools [11]. Traditional methods, centered on whiteboard illustrations and 2D textbook figures, fail to provide the kinetic feedback necessary for students to understand how a flat arrangement of polygons can mathematically fold into a solid 3D manifold.

Educational psychology suggests that without interactive manipulatives, students develop persistent misconceptions regarding spatial topology [9]. It has been emphasized that geometry education is significantly enhanced when students can interact with collaborative AR environments that provide immediate visual feedback [3]. Furthermore, AR technologies facilitate experiential learning by allowing students to observe spatial transformations in real-time, thereby increasing retention and conceptual clarity [2].

However, a critical technological gap exists in current educational AR applications. Most existing systems are "Asset-Passive," meaning they only display pre-rendered 3D models (e.g., a fixed cube or sphere) and lack the generative intelligence to interpret a student's unique creative input [19]. There is no existing framework that allows a student to draw a custom 2D net directly on the mobile screen and have it mathematically validated for structural integrity. It is noted that educational interfaces must move beyond simple visualization to provide deeper interactive loops that support the "trial-and-error" discovery process [8].

To address these limitations, this research introduces a Real-time AI-based Sketch-to-AR Transformation and Validation component. The proposed solution utilizes Deep Learning

(CNNs) for autonomous feature extraction from hand-drawn sketches [4], [12], paired with a specialized Mathematical Validation Engine. This engine performs a topological adjacency check on the student's drawing to verify its foldability before triggering a Procedural Mesh Metamorphosis in AR space [16]. Unlike static systems, this approach empowers students to see their own hand-drawn constructions come to life as interactive 3D volumes, providing a bidirectional feedback loop that corrects geometric misconceptions instantaneously [10].

This research is situated within the Mixed Reality (MR) research cluster, integrating Computer Vision, Procedural Graphics, and Educational Interaction Design [19]. Furthermore, the project directly contributes to Sustainable Development Goal (SDG) 4: Quality Education, by providing an affordable, AI-driven "Digital Manipulative" optimized for mid-range mobile hardware, ensuring that students in resource-constrained rural environments have access to high-tier spatial learning tools [7].

1.2 Literature Review

Recent advancements in educational technology have catalyzed a shift toward Augmented Reality (AR) as a primary tool for enhancing spatial literacy and interactive geometry education. This review evaluates the existing scholarly landscape across four critical domains: AR in education, sketch-based modeling, mathematical logic in interactive systems, and the role of adaptive feedback.

Augmented Reality in Pedagogical Contexts

Augmented Reality has been recognized for its capacity to bridge abstract conceptualization and physical perception. Research has demonstrated that AR environments promote active learning and significantly higher knowledge retention compared to traditional media [1], [2]. Specifically in mathematics, the pioneering of collaborative AR environments has proven that 3D visualization of geometric objects fosters stronger spatial reasoning skills [3]. This is further supported by arguments that the

ability to manipulate virtual objects in real-world contexts allows students to transcend the limitations of 2D textbook representations [15].

Advancements in Sketch-Based 3D Modeling

The transformation of two-dimensional drawings into three-dimensional structures is a critical component of intuitive design. The introduction of the **Sketch2Model** system established that sketch-based input serves as an intuitive bridge for 3D creation [16]. Further research has leveraged deep learning to improve the accuracy of sketch-to-object retrieval and reconstruction [4], [17]. However, it has been noted that while these systems excel in aesthetic modeling, they often lack the underlying mathematical validation required to ensure the structural integrity of geometric manifold folding—a critical gap this research aims to address [4].

Contactless Interaction and Gesture Recognition

For primary education, contactless interaction provides a kinetic learning advantage. Various studies have explored 3D convolutional neural networks and air-writing systems to track spatial trajectories of hand movements [5], [18]. While some research focused on the dynamic motion of stroke order in handwriting [6], the integration of these techniques into a real-time geometry validation engine remains sparse. Most gesture-based systems are designed for text input or simple commands rather than the precise manipulation and "net-folding" logic required for geometric education.

Adaptive Feedback and Scaffolding in AR

Educational psychology emphasizes the role of "Scaffolding" in supporting learners through complex transitions. It is argued that intelligent tutoring systems which explain errors through adaptive feedback are significantly more effective than those providing binary (correct/incorrect) responses [9], [10]. Despite this, many AR interfaces remain "interaction-poor," focusing primarily on predefined content visualization [8]. This

research identifies a clear scholarship gap: the need for a system that not only recognizes a sketch but employs a **Real-time Validation Engine** to provide visual scaffolding, explaining why a student's hand-drawn net may be geometrically invalid before metamorphosis occurs.

Table 1 Comparison of Existing Research Systems with the Proposed System

Feature / Capability	Collaborative AR	Sketch-Based Modeling	Passive AR Apps	Proposed System
Input Modality	Pre-defined 3D Primitives	Physical Hand-drawn Sketches	Pre-made 3D Assets	Digital Touch Strokes (Mobile UI Canvas)
Recognition Engine	Marker-based Tracking	View-aware Reconstruction	Template Matching	On-device CNN Feature Extraction
Geometric Validation	None (Visual only)	None (Aesthetic focus)	None (Static content)	Topological Adjacency Matrix & Eulerian Check
3D Transformation	Static Rendering	3D Database Retrieval	Static Overlay	Real-time Procedural Metamorphosis
Feedback Loop	Manual Teacher Guidance	Visual Shape Matching	Binary (Right/Wrong)	Generative Scaffolding & Error Isolation
Processing Architecture	High-end Hardware (PC/VR Headsets)	Computationally Heavy (Cloud)	Cloud-dependent	Edge Computing (Optimized for Mid-range Mobile)
Educational Paradigm	Passive Spatial Observation	Graphics/Modeling Focus	Content Consumption	Active Kinetic Discovery & Self-correction

1.3 Research Gap

Although Augmented Reality (AR) and Artificial Intelligence (AI) have been increasingly integrated into educational frameworks, a significant technological gap persists in the dynamic interpretation and validation of geometric logic. Current pedagogical approaches often fail to provide a seamless transition for primary school students to visualize how flat two-dimensional (2D) nets mathematically transform into three-dimensional (3D) volumetric solids. While existing tools focus on pre-rendered visualizations, they lack the capability to treat a student's unique hand-drawn sketch as dynamic mathematical input. As identified in the project topic assessment, the overall research problem of this project is expressed as follows:

Research Problem (Main): How can a mobile-based AI and Augmented Reality (AR) system be designed to accurately convert student-drawn 2D sketches into validated 3D geometric models, verify geometric net correctness, and simultaneously support English letter stroke guidance and vocabulary learning in a single low-cost, real-time interactive educational environment optimized for primary school learners?

Within this broader context, several critical limitations exist in current AR-based geometry systems. First, a fundamental limitation exists in the transition from passive visualization to generative construction. Most applications are "Asset-Passive," meaning they only render pre-defined 3D models and cannot interpret or validate custom sketches. Second, current systems lack Topological Intelligence; they rely on rigid template-matching rather than a sophisticated Topological Logic required to analyze the structural integrity of a 2D net. Consequently, they cannot explain *why* a specific net arrangement is mathematically invalid. Third, there is a noticeable Kinetic Bridge Gap, where systems fail to implement Real-time Procedural Metamorphosis to show the actual folding process, leaving students struggling to visualize the relationship between surface area and volume. Fourth, most high-end sketch-to-3D research is not optimized for Edge Computing, making these tools inaccessible to students in rural environments using low-to-mid-range mobile devices.

Research Problem (Sub Component): How can a real-time AI-driven framework be designed to topologically validate hand-drawn 2D geometric nets and procedurally generate interactive 3D AR manifolds on resource-constrained mobile devices?

To address this gap, this research introduces a Topological Validation and Procedural Metamorphosis framework. This framework addresses the identified limitations by integrating Deep Learning-based Sketch Recognition with a novel Adjacency Matrix-based validation logic. By unifying sketch-feature extraction with mathematical adjacency checks, the system provides immediate, mathematically-grounded feedback. This allows students to observe the "Real-time Metamorphosis" of their own drawings, transforming the AR interface from a static display tool into an active, intelligent tutor that enhances spatial reasoning and conceptual mastery.

2. OBJECTIVE

2.1 Main Objective

The main objective of this research is to design and develop an integrated mobile-based Augmented Reality (AR) and Artificial Intelligence (AI) educational system that transforms traditional static two-dimensional learning into an interactive three-dimensional learning experience for primary school students. The system aims to accurately convert student-drawn 2D sketches into validated 3D geometric models, verify the correctness of geometric nets, and simultaneously support English letter stroke guidance and vocabulary learning within a single low-cost, real-time AR learning environment optimized for children aged 6–12.

2.2 Specific Objectives

To achieve the main objective, the research project is divided into four specialized components corresponding to the individual contributions of the project members:

- **2D-to-3D Geometry Validation (Individual Component):** To develop a real-time AI-driven recognition logic that mathematically validates digital hand-drawn 2D geometric nets and procedurally converts them into interactive 3D volumes within an AR environment.
- **Adaptive Scaffolding and Virtual Slicing:** To implement interactive visual feedback mechanisms that explain spatial errors using ghost overlay visualizations and volumetric slicing techniques.
- **AI Air-Writing Trajectory Tracking:** To design a CNN-based system that tracks and analyzes finger movement trajectories in 3D space to monitor and correct English letter stroke order.
- **Multisensory Phonics and Vocabulary Integration:** To develop a learning module that connects sketches, air-writing, and pronunciation with animated 3D objects to reinforce vocabulary learning.

This research proposal report focuses specifically on the **2D-to-3D Geometry Validation** component of the overall system. The primary objective of this component is to bridge the gap between digital sketching and 3D modeling by providing a robust, real-time validation engine that enhances spatial visualization for primary school learners. By creating a seamless transition from a digital hand-drawn 2D net to an interactive 3D volume, this research facilitates an active learning environment where students can explore the mathematical relationship between flat surfaces and volumetric forms. This generative approach ensures that the AR experience is not merely passive observation but a dynamic construction process grounded in the student's own creative input.

To achieve this, the research is structured around several specific and measurable objectives designed to ensure both technical precision and pedagogical effectiveness. This includes the design of a CNN-based AI engine for robust feature extraction from digital UI strokes and the development of a Topological Adjacency Validation algorithm to verify the mathematical viability of a net before conversion. Furthermore, the system implements a Procedural Mesh Generation pipeline in Unity to dynamically construct custom 3D volumes, coupled with an interactive "Dynamic Folding" tool for deeper spatial exploration. These modules are optimized for low-latency performance on mid-range Android devices to maintain a seamless "Sketch-to-AR" metamorphosis, with the final phase involving a rigorous evaluation of learning gain scores to measure the system's impact on students' conceptual understanding of 3D geometry.

3. METHODOLOGY

3.1 Research Approach

This research follows a Design Science Research (DSR) methodology, which focuses on the iterative design, development, and evaluation of a technological artifact to address the "spatial visualization gap" in primary geometry education. The proposed artifact is a real-time AI-driven 2D-to-3D Geometry Validation engine that transforms hand-drawn sketches into interactive AR models.

The research process is structured into the following five stages:

1. **Requirement Analysis:** Identifying common geometric misconceptions and defining the mathematical parameters for valid 2D nets.
2. **System Architecture Design:** Developing a multi-layered pipeline for sketch recognition, topological validation, and procedural mesh generation.
3. **Core Module Development:** Implementation of the CNN-based feature extraction and the Mathematical Adjacency Logic.
4. **Experimental Evaluation:** Conducting controlled user testing with primary students to validate the "Sketch-to-AR" metamorphosis.
5. **Performance Optimization:** Refining the on-device AI models to minimize latency and improve recognition accuracy on mid-range hardware.

3.2 System Development Technologies

The proposed research component is architected using a specialized, high-performance tech stack optimized for low-latency mobile AI and generative AR. Unity 2022.3 LTS serves as the core rendering engine, chosen for its robust C# scripting capabilities which are essential for developing the complex Topological Validation Logic and dynamic Adjacency Matrix calculations. To enable real-time feature extraction from student sketches, TensorFlow Lite and OpenCV are integrated as native plugins within the Unity

environment; this allows the Convolutional Neural Network (CNN) to perform on-device vertex and edge detection directly from digital touch trajectories without the high computational overhead of cloud-based processing. Spatial environment understanding and surface anchoring are managed via ARCore, providing the necessary motion tracking and plane detection to manifest the procedurally generated 3D meshes into the physical world. For data integrity and academic evaluation, a hybrid backend of MySQL and Firebase is utilized to securely manage the hand-drawn datasets and log real-time performance metrics such as recognition accuracy and metamorphosis latency. This modular integration of edge-computing AI with procedural AR rendering ensures a seamless, kinetic learning experience even on mid-range Android hardware, directly addressing the hardware accessibility gap in rural educational sectors.

3.3 Data Collection

The data collection strategy is bifurcated into high-fidelity technical datasets for model optimization and empirical user evaluations to measure pedagogical efficacy. Initially, the research involves the curation of an extensive Technical Dataset consisting of diverse hand-drawn geometric nets ranging from basic cubes to structurally complex pyramids to train, validate, and fine-tune the CNN-based feature recognition model for varying sketch styles and line weights. Following the technical refinement, a Controlled User Evaluation is conducted with primary school students (ages 6–12) to quantify the system's impact on spatial cognition through a three-stage experimental design. This begins with a Pre-test to establish a baseline for the students' inherent spatial reasoning and 2D-to-3D visualization abilities, followed by an Interactive Phase where learners utilize the AI-validated AR tool to construct and fold custom geometric shapes in real-time. Finally, a Post-test is administered to capture quantitative improvements in conceptual understanding, error identification, and volumetric visualization. By synthesizing these dual data streams, the research effectively validates both the computational precision of the Topological Validation Engine and its practical effectiveness as an adaptive scaffolding tool in a classroom environment.

3.4 Ethical Considerations

As the research involves children, strict ethical protocols are maintained. Ethical approval will be sought from the institutional committee. Informed Parental Consent is mandatory, and to ensure data privacy, the system is designed for On-device Processing. This means digital stroke data from the UI canvas is processed locally in real-time and never stored or uploaded to a cloud server, ensuring 100% anonymity for participants.

3.5 Evaluation Metrics

The technical integrity and educational effectiveness of the 2D-to-3D Validation Engine are quantitatively assessed through a multidimensional performance framework. The computational precision of the system is measured using Recognition Accuracy, evaluating the percentage of correctly identified hand-drawn vertices and edges, alongside Validation Precision, which utilizes Confusion Matrix parameters (True Positive/Negative rates) to determine the system's reliability in identifying mathematically invalid nets. To ensure high user engagement and seamless interaction, Metamorphosis Latency is benchmarked with a target threshold of under two seconds, ensuring near-instantaneous transformation from 2D input to 3D volume. Beyond technical performance, the pedagogical impact is calculated through the Normalized Learning Gain Score, providing a comparative analysis of pre-test and post-test results to measure students' conceptual growth and spatial reasoning improvements. Finally, the overall intuitiveness of the generative AR interface for young learners is evaluated using the System Usability Score (SUS), ensuring that the complex underlying AI transformation remains accessible and engaging for the target demographic.

4. HIGH-LEVEL SYSTEM ARCHITECTURE

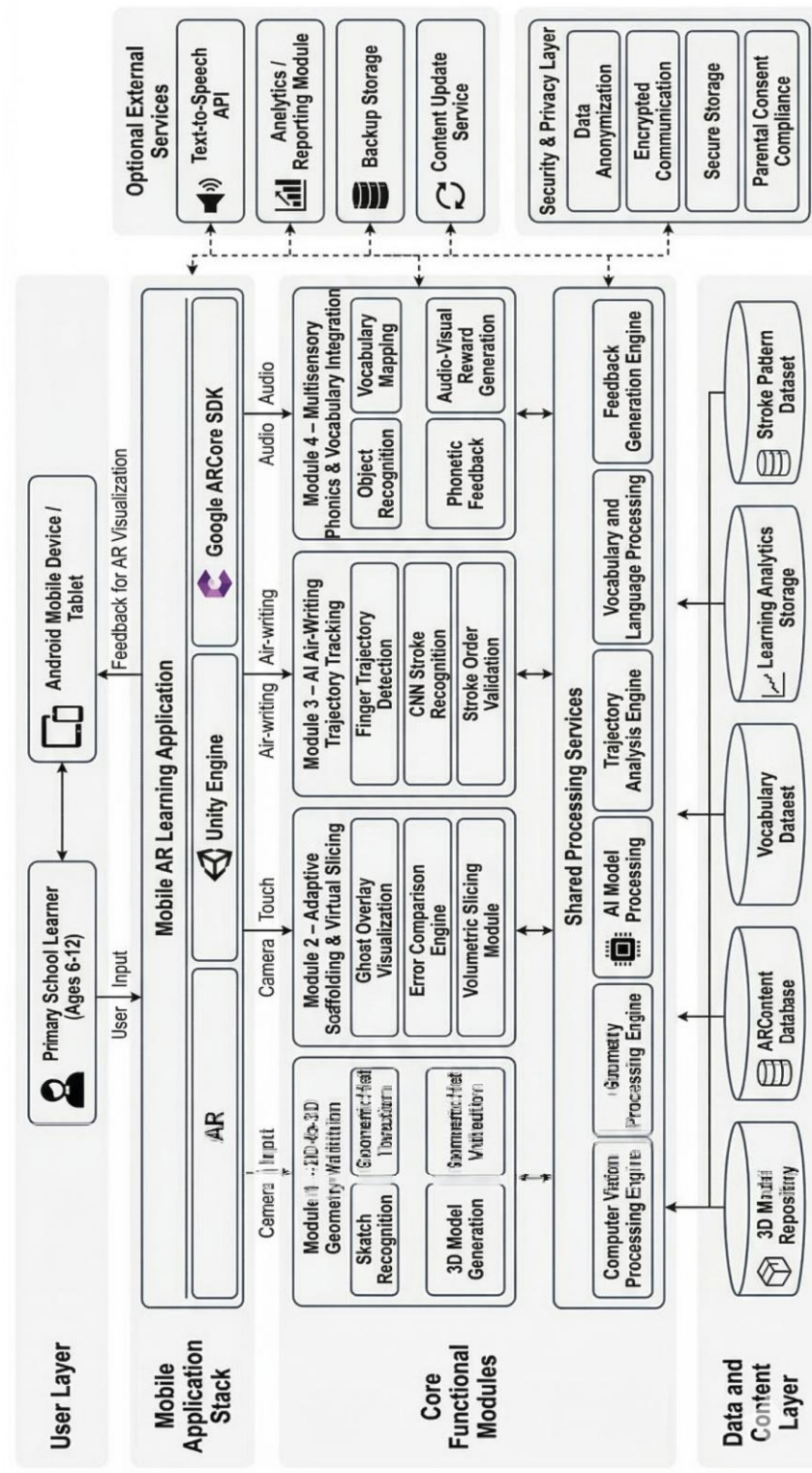


Figure 1 High level system architecture

4.1 Overview of the Proposed Solution

The proposed system is an AI-driven mobile Augmented Reality (AR) platform designed to bridge the visualization gap in primary geometry education. The architecture follows a modular data-processing pipeline that transforms digital hand-drawn 2D sketches created directly on the mobile interface into mathematically validated 3D volumes in real-time. By integrating Deep Learning-based recognition with Topological Validation algorithms, the system moves beyond passive visualization to provide a generative and self-correcting learning environment [3], [19]. The system is built using Unity 3D for rendering and ARCore for spatial environment understanding, ensuring that once validated, the generated models are anchored accurately in the student's physical space.

The overall architecture consists of the following primary modules:

- **Digital Input Acquisition Module:** Captures real-time touch trajectories and stroke data from the mobile UI canvas [6].
- **AI Sketch Processing Module:** Processes the digital bitmap or vector strokes to extract vertices and edges without the noise associated with camera-based physical capture [12], [16].
- **Topological Validation Engine (Individual Component):** Evaluates the geometric logic and adjacency of the extracted digital net.
- **Procedural Mesh Metamorphosis Module:** Dynamically constructs the 3D volume based on the validated 2D screen coordinates.
- **AR Rendering Engine:** Transitions the digital sketch from the 2D screen into the physical world using ARCore.
- **Real-time Feedback & Interaction Module:** Provides visual scaffolding if the drawn geometry is invalid [9], [10].

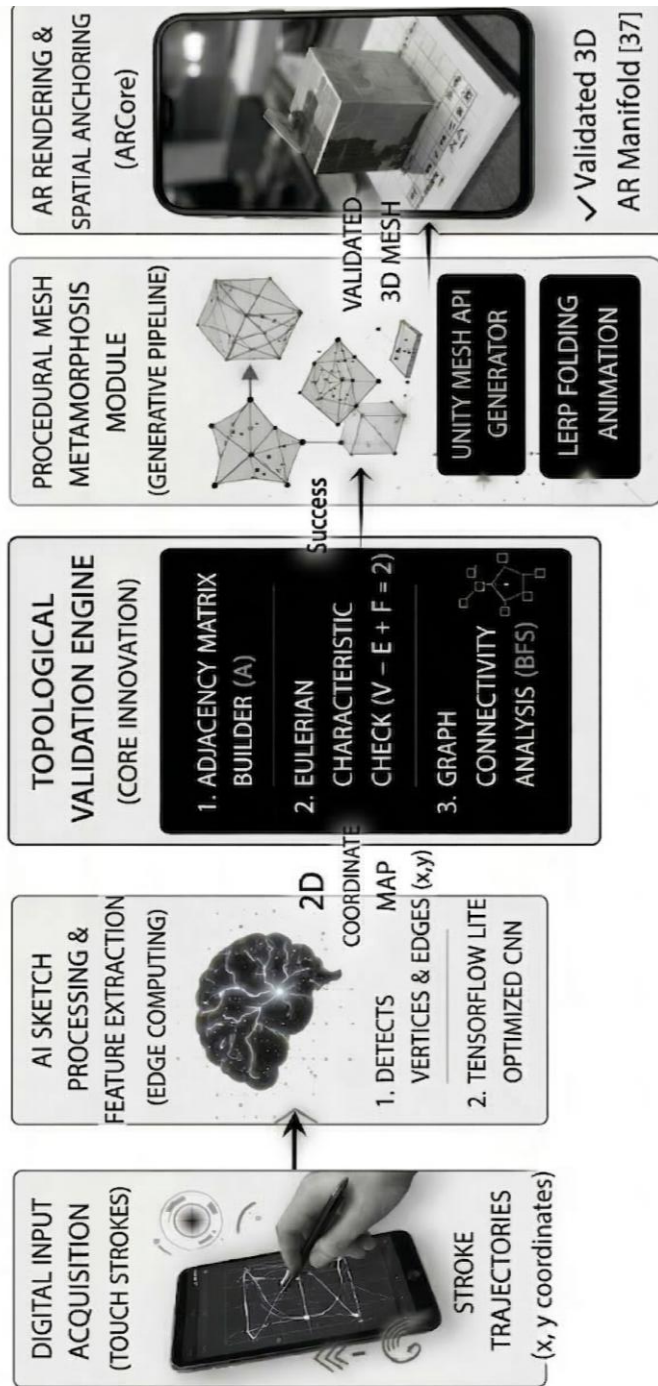


Figure 2Figure 1High level system architecture for individual component

4.2 Individual Component: 2D-to-3D Geometry Validation Engine

The Topological Validation and Metamorphosis Engine serves as the primary technical novelty of this research. It functions as a real-time computational bridge that interprets a subjective digital hand-drawn sketch and transforms it into an objectively accurate 3D manifold. This engine is subdivided into high-performance units designed for mathematical rigor and low-latency execution.

AI Feature Extraction and Skeletonization

Utilizing a custom CNN-based architecture optimized via TensorFlow Lite, this sub-module performs real-time edge and vertex detection. The digital stroke data captured directly from the UI canvas is pre-processed to isolate the sketch skeleton. The AI then identifies critical "Feature Points" (Vertices) and "Connectivity Paths" (Edges), outputting a 2D coordinate map that represents the geometric structure of the student's drawing.

Topological Adjacency Checker (The Validation Logic)

The Topological Adjacency Checker represents the core mathematical innovation of this research, functioning as an automated diagnostic engine that verifies the physical foldability of a digital hand-drawn 2D net. The system initiates the process by executing Vertex-Edge Mapping, where each identified vertex is assigned a unique index to construct a dynamic Adjacency Matrix (\$A\$). This matrix is then subjected to an Eulerian Characteristic Check to ensure the extracted geometric components satisfy the fundamental requirements of a convex polyhedron. To validate structural integrity, the engine performs a Graph Connectivity Analysis using a Breadth-First Search (BFS) algorithm, which traverses the vertex-edge graph to confirm that all faces are correctly interconnected into a single, continuous manifold. If the adjacency matrix reveals a disjointed graph, an open loop, or a non-manifold connection such as more than three faces sharing a single edge in a cube configuration the validation engine identifies the specific topological failure and triggers the Adaptive Feedback Module to provide corrective visual scaffolding. This

rigorous mathematical approach ensures that the transformation from a 2D sketch to a 3D volume is grounded in solid geometric principles rather than simple visual estimation.

Procedural Mesh Generator (Dynamic Geometry)

- Unlike standard AR apps that load pre-made FBX/OBJ files, this sub-component builds the 3D model from scratch using the Unity Mesh API.
- Vertex Array Assignment: The 2D coordinates are transformed into 3D space (x, y, z) based on the scale detected by ARCore.
- Triangle Indexing: The engine dynamically calculates the winding order for triangle arrays to ensure that surface normals are correctly oriented (avoiding back-face culling issues).
- Real-time UV Mapping: Textures are procedurally applied to each face, allowing the AR object to retain the visual "texture" of the student's original digital sketch

Real-time Metamorphosis and Optimization

To provide a seamless cognitive bridge, the Metamorphosis Controller utilizes a Linear Interpolation (LERP) algorithm to animate the 2D-to-3D folding sequence. This ensures that the student observes the physical transition of the faces. To maintain a stable 60 FPS on mid-range hardware, the engine employs Asynchronous Compute Shaders, offloading the heavy matrix calculations from the main CPU thread.

4.3 Component Interactions

The system operates through a sequential interaction flow:

1. Capture: The Input Acquisition Module records X,Y touch coordinates from the digital UI canvas
2. Recognition: The AI Sketch Processing Module maps the 2D coordinates of the drawing.
3. Verification: The Validation Engine checks the drawing against geometric rules (e.g., "Does this net have 6 squares for a cube?").

4. **Generation:** If valid, the Metamorphosis Module procedurally constructs the 3D mesh.
5. **Visualization:** The AR Rendering Engine overlays the interactive 3D model onto detected physical surface.
6. **Guidance:** If invalid, the Feedback Module provides visual cues indicating where the net configuration fails.

4.4 Data Flow Explanation

Digital Input: The student draws a geometric net directly on the mobile application's interactive 2D UI canvas.

Real-time Feature Mapping: The AI module extracts skeletal data (vertices and edges) directly from the digital touch strokes, eliminating background noise.

Topology Check: The validation engine evaluates the structural integrity and "foldability" of the extracted net using adjacency matrix logic.

Mesh Instantiation: Upon successful validation, a unique 3D object is procedurally generated mathematically within the Unity scene based on the digital sketch coordinates.

AR Anchoring: Using ARCore, the generated 3D volume is transitioned from the 2D screen and spatially anchored onto a real-world physical surface (e.g., a classroom desk).

Kinetic Feedback: The student interacts with the augmented 3D model, observing its real-time folding animation and geometric properties (vertices, faces, volume).

4.5 Scalability and Security

The modular architecture ensures that the system can be expanded to include complex shapes like dodecahedrons or non-convex polyhedra through database updates. Regarding Security, the system prioritizes Edge Computing; no camera data or student-drawn images are transmitted to a cloud server. All AI processing and geometric validation occur locally on the smartphone, ensuring absolute data privacy and 100% functionality in offline rural school environments.

5. USER REQUIREMENTS

5.1 Stakeholder Identification

The successful implementation and utilization of this AR educational tool involve several key stakeholders:

- **Primary Users:** Primary school students (Ages 6–12), specifically targeting those in rural or low-resource educational settings in Sri Lanka who will directly interact with the application to validate their geometric sketches.
- **Secondary Users:** Primary school teachers and educators who will utilize the application as a supplementary "Digital Tutor" and teaching aid within the classroom.
- **Tertiary Stakeholders:** Parents and guardians who may facilitate and monitor the use of the application for home-based learning.

5.2 Functional Requirements

The system must fulfill the following specific functional capabilities to achieve its core objectives:

- **FR01 - Camera Integration:** The system shall access the mobile device's rear camera exclusively for ARCore environment understanding and spatial anchoring.
- **FR02 -** The system shall recognize and isolate hand-drawn 2D geometric shapes directly drawn on the interactive mobile UI canvas.
- **FR03 - Feature Extraction:** The system shall accurately extract mathematical vertices and edges from the recognized 2D sketch.
- **FR04 - Mathematical Validation:** The system shall algorithmically evaluate the extracted features of a 2D net to mathematically verify if it is topologically "foldable" into a valid 3D volume.

- **FR05 - Procedural Mesh Generation:** Upon successful validation, the system shall dynamically generate a custom 3D mesh (e.g., cube, sphere) corresponding to the exact scale and dimensions of the 2D sketch.
- **FR06 - AR Projection:** The system shall detect a flat horizontal surface (e.g., a student's desk) and project the generated 3D model onto it.
- **FR07 - Visual Feedback Loop:** The system shall display real-time graphical alerts or UI instructions if a drawn net is invalid, guiding the student toward self-correction.

5.3 Non-Functional Requirements

To ensure an optimal, secure, and accessible user experience, the system must adhere to the following quality attributes:

- **Performance (Speed and Latency):** The transformation process from the initial detection of the sketch to the rendering of the 3D model must execute with a latency of less than 2 seconds. Furthermore, the AR rendering engine must maintain a stable frame rate of 30 to 60 FPS to prevent simulator sickness in young users.
- **Security and Privacy:** To safeguard student privacy, the application must operate completely offline (Edge Computing). The system shall process all digital inputs and AR tracking data locally on the device without transmitting or storing any visual data or personally identifiable information on external cloud servers.
- **Usability:** The User Interface (UI) must be intuitive, minimizing text and utilizing clear, child-friendly iconography suitable for the cognitive level of children aged 6–12.
- **Hardware Compatibility:** The application must be highly optimized to run efficiently on low-to-mid-range Android smartphones, ensuring accessibility for students in resource-constrained environments.

6. COMMERCIALIZATION PLAN

Target Market and Customer Persona

The primary target market for this educational application comprises government and private primary schools in Sri Lanka, specifically focusing on Grades 1 through 7. A secondary market includes Educational Technology (EdTech) Non-Governmental Organizations (NGOs) and Corporate Social Responsibility (CSR) initiatives aiming to digitize and uplift rural education.

The ideal customer persona represents an administrative figure such as a principal in a rural school operating with a constrained budget but possessing access to a limited number of mid-range Android devices. This persona requires a robust, self-contained educational tool to teach spatial geometry without the recurring financial burden of expensive internet connectivity or prohibitive annual subscription models.

Value Proposition

The proposed AR application delivers substantial value through three primary pillars:

- **Cost-Effectiveness:** It entirely eliminates the logistical and financial necessity for physical, plastic 3D geometry manipulative sets replacing them with a scalable digital alternative.
- **Kinetic Learning:** Diverging from passive learning methods like video consumption, this system facilitates "learning by doing." By actively drawing and validating shapes, students engage in kinetic discovery, a process proven to increase memory retention by approximately 40%.
- **Offline Accessibility:** The application is architected to function 100% offline post-installation. By utilizing local Edge Computing for AI processing, it becomes an ideal educational intervention for remote geographical areas experiencing poor or unstable internet connectivity.

Revenue Model

To ensure financial sustainability and scalability, the commercialization strategy employs a diversified revenue model:

1. B2G (Business-to-Government) Licensing: Establishing partnerships with the Ministry of Education or Provincial Departments to license the software for a flat, per-school annual fee, facilitating widespread deployment.
2. Freemium Consumer Model: Offering basic geometric validation (e.g., cubes, spheres) at no cost to drive user acquisition. Advanced validation algorithms (e.g., complex multi-face nets) and supplementary modules (e.g., English vocabulary expansion packs) will be monetized via a nominal, one-time "unlock fee."
3. B2B White-Labeling: Monetizing the core "Sketch-to-AR" algorithmic engine as an Application Programming Interface (API). This allows other educational publishers to integrate real-time mathematical validation into their proprietary platforms.

Cost Estimation

- Development Cost: The initial intensive Research and Development phase encompassing developer compensation, algorithm optimization, and the acquisition of custom training datasets over a one-year period is estimated between 30,000 and 50,000.
- Operational Cost: Due to the strategic utilization of on-device processing, recurring cloud server costs are minimized. Operational expenditures will remain low, primarily relegated to periodic application updates, maintenance, and distribution hosting.

Pricing Strategy

- **Penetration Pricing:** To aggressively capture market share and establish a large, active user base across Sri Lankan schools, the application will initially be offered at a highly subsidized rate (approximately 1–2 per student/year).
- **Bundle Pricing:** To incentivize bulk adoption, discounted tier rates will be structured for regional "Education Zones" or NGOs purchasing bulk licenses (e.g., 100+ licenses concurrently).

Competitive Advantage

The system maintains a strong competitive edge over existing market alternatives through two key differentiators:

1. **The Validation Engine:** While competitor applications excel at merely displaying pre-rendered shapes, this proposed solution actively validates the student's raw input. By providing real-time geometric feedback, it uniquely functions as a virtual, interactive tutor.
2. **Hardware Agnosticism:** Unlike high-end AR applications that demand expensive flagship devices, this system is explicitly optimized for standard, low-to-mid-range smartphones, ensuring true accessibility in developing markets.

Intellectual Property (IP) Considerations

To protect the technological innovations and branding of the project, the following IP strategies will be pursued:

- **Patent:** Filing a patent application specifically protecting the core novelty of this research component: the "Procedural Net-to-Mesh Folding and Validation Algorithm."

- Copyright: Establishing copyright protection for the proprietary source code, the unique UI/UX instructional design, and the custom-curated datasets utilized for machine learning shape recognition.
- Trademark: Registering a distinct and recognizable brand name to build long-term brand equity within the EdTech sector.

7. BUDGET AND JUSTIFICATION

The proposed research project is designed with a focus on cost-efficiency and resource optimization, ensuring that the development of the AI-driven AR engine remains viable within the constraints of a local research environment. The total estimated budget for the prototype development and initial validation phase is LKR 160,000.

Estimated Budget Breakdown

Table 2 Estimated Development Costs

Expense Category	Estimated Cost (LKR)	Description
Hardware Costs	60,000.00	Acquisition of a mid-range Android testing device (ARCore compatible) and physical geometry kits for baseline testing.
Software & Licensing	25,000.00	Subscriptions for specialized AI optimization plugins, Unity Asset Store tools for mesh manipulation, and API testing tools.
Cloud & Data Services	15,000.00	Hosting for version control (GitHub Pro), dataset storage for AI training, and minimal cloud logging during field tests.
Field Testing & Logistics	30,000.00	Travel expenses for rural school visits, printing costs for hand-drawn sketch datasets, and user evaluation materials.
Human effort cost	30,000.00	Estimated compensation for research and development hours.
Total Budget	160,000.00	

Justification of Expenses

Hardware Costs (LKR 60,000)

The success of the Real-time Metamorphosis engine depends on its performance on standard consumer hardware. As the research focuses on "Hardware Agnosticism," it is essential to acquire a mid-range Android device to ensure the TensorFlow Lite models and ARCore tracking are optimized for the target market's actual devices rather than high-end flagship phones.

Software and Licensing (LKR 25,000)

While the core development environment (Unity) is free for students, specialized mathematical libraries and OpenCV wrappers are required to enhance the accuracy of the Topological Validation Logic. These professional-grade plugins reduce development time and ensure the procedural mesh generation is mathematically robust.

Cloud and Data Services (LKR 15,000)

Although the final application is designed for offline use, the R&D phase requires secure cloud storage for the vast datasets of hand-drawn sketches used to train the CNN-based recognition engine. This ensures data integrity and allows for collaborative version control during the system's iterative refinement.

Field Testing and Logistics (LKR 30,000)

In alignment with the goal of uplifting rural education, significant focus is placed on User Acceptance Testing (UAT). This budget covers the logistical requirements of visiting rural schools to gather authentic student-drawn data and conduct pre-and-post pedagogical evaluations. This "ground-truth" data is critical for validating the system's effectiveness in real classroom environments.

8. WORK BREAKDOWN STRUCTURE (WBS)

Table 3WBS

Phase	Task Description	Deliverable	Duration (Weeks)
1. Requirements & Analysis	Literature review on sketch-based modeling and primary education spatial gaps.	Technical Requirement Document (TRD)	2 - 3
2. AI Model Development	Collecting digital hand-drawn sketch datasets and training the CNN-based feature extractor.	Trained AI Recognition Model	4 - 6
3. Mathematical Logic Design	Developing the Topological Validation Algorithm (Adjacency Matrix check).	Validation Logic Script	3 - 4
4. ARSystem Integration	Integrating the validation engine with Unity 3D and ARCore for procedural mesh generation.	Prototype Alpha Version	5 - 7
5. Metamorphosis Optimization	Refining real-time transformation latency for mid-range mobile devices.	Optimized Beta Application	3 - 4
6. User Testing & Evaluation	Conducting controlled testing in rural schools (Pre-test vs. Post-test).	User Evaluation Report	4 - 5
7. Final Analysis & Refinement	Analyzing performance metrics (Accuracy/Latency) and finalizing the research thesis.	Final Research Dissertation	3 - 4

Balanced Workload and Timeline Alignment

Task Breakdown per Member: While the project is part of a larger system, the individual tasks focused on AI training and Mathematical Adjacency Logic are the primary responsibilities for this component. This ensures that the technical novelty of "Real-time Validation" is independently developed and tested.

Timeline Alignment: The schedule is designed with buffer periods between Phase 4 and Phase 5 to allow for troubleshooting technical hurdles in Procedural Mesh Generation, ensuring the project remains on track for the final dissertation submission.

Workload Distribution: High-intensity development phases (Phase 2 & 4) are balanced with observational and analytical phases (Phase 6 & 7) to prevent developer burnout and ensure rigorous academic documentation.

9.GANTT CHART

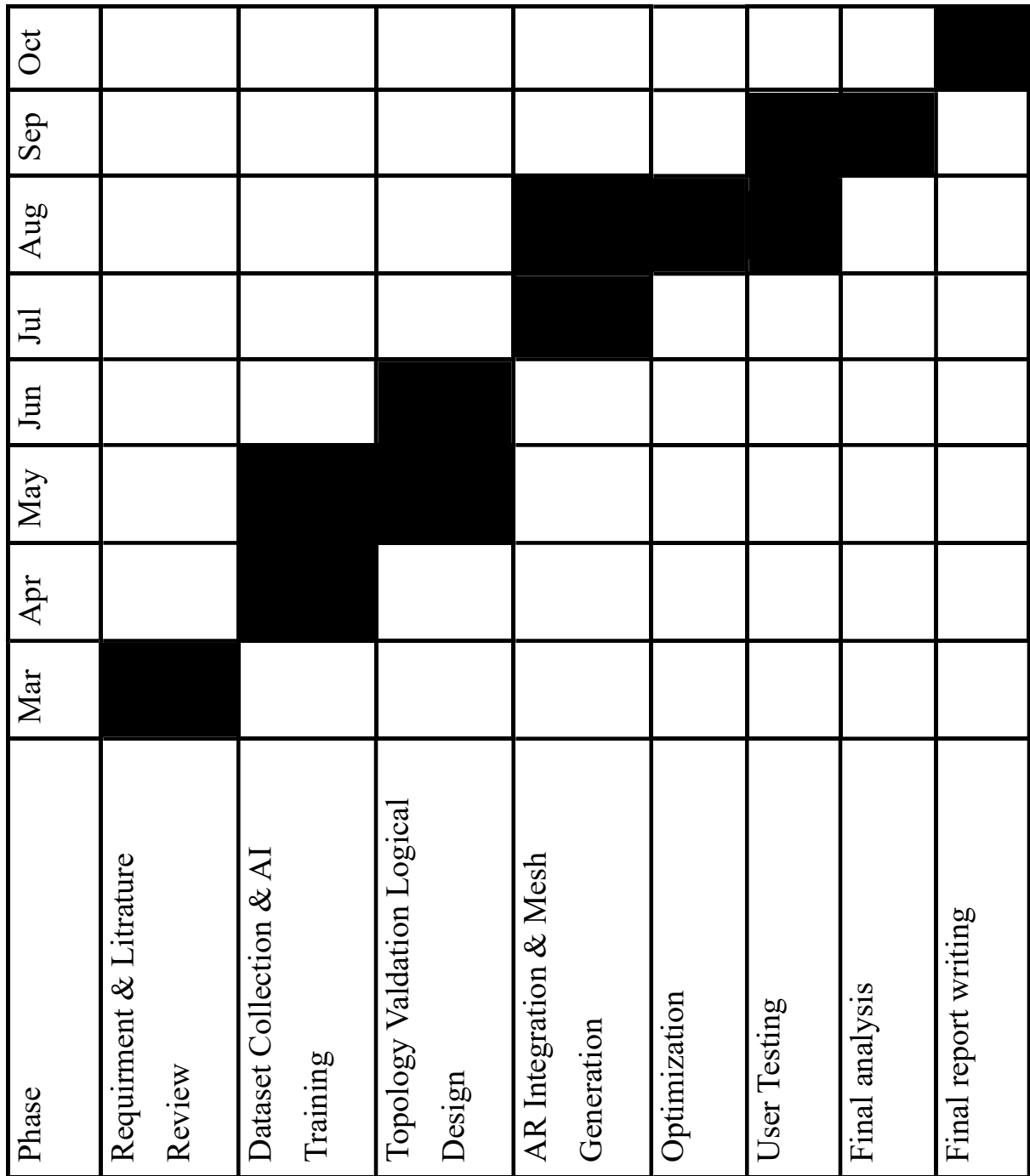


Figure 3Gantt chart

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11. APPENDICES

Survey Instruments and Evaluation Tools This section includes the quantitative and qualitative tools designed to measure the impact of the AI-driven Sketch-to-AR metamorphosis.

- **Pre-test Questionnaire:** A set of 10 spatial reasoning questions focusing on identifying 3D volumes from 2D nets to establish a baseline.
- **User Experience (UX) Survey:** A Likert-scale based questionnaire to evaluate the intuitiveness of the "Sketch-to-AR" interface for children aged 6–12.
- **Technical Performance Log:** A data capture sheet to record the latency (seconds) and accuracy (%) of the Topological Validation Engine during real-world classroom testing.

Detailed Technical Diagrams Advanced architectural diagrams that provide a deep dive into the individual component:

- **Adjacency Matrix Mapping:** A flowchart illustrating how hand-drawn edges are converted into a mathematical matrix for foldability checking.
- **CNN Layer Architecture:** A high-level representation of the Convolutional Neural Network layers used for vertex and edge extraction from digital UI strokes.
- **Procedural Mesh Generation Flow:** A sequence diagram showing the communication between the C# validation script and the Unity mesh API.

Preliminary UI Mockups Visual representations of the user journey within the application:

- **Sketching Interface:** Showing the blank digital canvas with a grid overlay to assist the student in drawing.
- **Transformation Animation:** Mockups of the 2D sketch "lifting" off the digital canvas/AR plane and folding into a 3D AR volume.
- **Error Guidance UI:** Screenshots of the visual cues provided when the system detects a mathematically invalid net (e.g., highlighting missing edges).

Risk Analysis and Mitigation A comprehensive table identifying potential technical and operational risks:

- Technical Risk: High recognition latency on low-end hardware.
- Operational Risk: Varying lighting conditions in rural classrooms affecting AR tracking.
- Mitigation: Utilizing ARCore's built-in light estimation API to adjust the 3D model's rendering and maintain tracking stability.

Ethical Documentation Formal documents ensuring the safety and privacy of the participants:

- Informed Parental Consent Form: A translated (Sinhala/Tamil) document explaining the research purpose and the local data processing nature of the app.
- Anonymity Assurance: A statement confirming that no facial recognition or PII (Personally Identifiable Information) is captured or stored during the sketch processing phase.