An Interactive 3D Rubik's Cube Learning Application with Gesture-based Interaction and Usability Evaluation on Android

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ABSTRACT
The Rubik's Cube is a widely recognized three-dimensional puzzle that requires strong spatial reasoning and problem-solving skills; however, beginners often encounter difficulties due to the lack of interactive and accessible learning media. This study proposes the design and development of an interactive three-dimensional (3D) Rubik's Cube learning application on the Android platform using Unity, which simulates realistic cube behavior, including face rotations and full-cube manipulation, while providing a guided solving module to support step-by-step learning. The system models the cube as a 3×3×3 structure consisting of 27 individual units with dynamically updated states, implements a transformation-based rotation mechanism to replicate real-world movements, and incorporates a shuffle algorithm that generates randomized yet solvable configurations through valid move sequences. An intuitive touch-based interaction is also integrated to enhance user experience and engagement. To evaluate the proposed system, usability testing is conducted using the System Usability Scale (SUS), and the results indicate that the application achieves a satisfactory level of usability while effectively supporting users in learning and interacting with the Rubik's Cube in a virtual environment. These findings demonstrate that the integration of interactive 3D simulation and guided learning features can serve as an effective and accessible alternative to physical learning tools.

General Terms
Mobile Learning, Human-Computer Interaction, 3D Simulation, Educational Applications

Keywords
Rubik's Cube Simulator, Unity 3D, Android Application, Interactive Learning, Usability Evaluation, System Usability Scale (SUS)

1. INTRODUCTION
The Rubik's Cube is a well-known three-dimensional combinatorial puzzle that has been widely utilized not only as a recreational game but also as a tool for enhancing cognitive abilities such as spatial reasoning, problem-solving, and logical thinking [1]. Since its invention, the puzzle has attracted significant interest from both educational and computational perspectives, particularly due to its structured yet complex state space and algorithmic solvability [2]. Recent studies highlight the role of puzzle-based learning in improving analytical skills and cognitive engagement, especially when supported by interactive digital environments [3]. With the rapid growth of mobile technology, smartphones particularly those powered by the Android operating system have become a dominant platform for delivering interactive learning applications due to their accessibility, portability, and computational capabilities [4 –5]. Despite its educational potential, learning to solve the Rubik's Cube remains challenging for beginners due to the complexity of solving algorithms and the lack of intuitive learning tools [6]. Traditional learning methods, such as printed guides and video tutorials, often provide static instructions without interactive feedback, limiting user engagement and understanding [7]. Furthermore, the dependency on physical cubes restricts accessibility for users who do not possess the puzzle, thereby reducing opportunities for continuous practice and experimentation [8]. These limitations highlight the need for an interactive and accessible learning medium that can simulate real-world cube manipulation while providing guided assistance.

Several studies have explored the development of digital Rubik's Cube simulators and learning applications. Early works focused on desktop-based simulations with limited interactivity and visualization capabilities [9]. More recent research has leveraged game engines such as Unity to create three-dimensional (3D) environments that replicate the physical behavior of the cube, enabling real-time manipulation and visualization [10-11]. In addition, studies on interactive educational applications emphasize the importance of user-centered design and intuitive interfaces in improving learning outcomes [12]. Some approaches have also incorporated algorithmic solving methods and step-by-step guidance systems to assist users in understanding cube-solving strategies [13]. Parallel advancements in human–computer interaction (HCI) demonstrate that touch-based interaction and real-time visual feedback significantly enhance user engagement and usability in mobile learning applications [14-15].

However, despite these advancements, several research gaps remain. First, many existing Rubik's Cube applications primarily focus on simulation aspects without integrating structured guided learning mechanisms that effectively support beginners [16]. Second, some systems lack realistic rotation modeling that accurately reflects the physical behavior of the cube, reducing the authenticity of the learning experience [17]. Third, comprehensive usability evaluation is often overlooked, resulting in limited empirical evidence regarding the effectiveness of such applications as educational tools [18]. Additionally, the integration of intuitive interaction design with real-time cube state management and automated shuffling mechanisms has not been thoroughly explored in a unified framework [19-20].

To address these limitations, this study proposes the design and evaluation of an interactive three-dimensional (3D) Rubik's

Cube learning application on the Android platform using Unity. The proposed system simulates realistic cube behavior through transformation-based rotation mechanisms and models the cube as a dynamic 3×3×3 structure with real-time state updates. A shuffle algorithm is implemented to generate randomized yet solvable cube configurations, while a guided learning module provides step-by-step assistance for users. Furthermore, an intuitive touch-based interaction system is developed to enhance usability and engagement. The application is evaluated using the System Usability Scale (SUS) to assess its effectiveness as a learning tool. This study makes three primary contributions: (1) the development of an interactive 3D Rubik's Cube simulator with realistic rotation and state management, (2) the integration of guided learning features to support beginner users, and (3) a systematic usability evaluation demonstrating the effectiveness of the proposed system as a mobile-based learning platform.

2. RESEARCH METHOD

The overall methodology of this study follows a system development and evaluation approach consisting of design, implementation, and usability assessment phases. As illustrated in Figure 1, the proposed system is structured as an integrated mobile-based learning platform that simulates the behavior of a physical Rubik's Cube within a three-dimensional (3D) virtual environment. The application enables users to interact with the cube using touch-based gestures, perform face and global rotations, and access guided solving instructions designed to support step-by-step learning. This integration of simulation, interaction, and instructional components provides a cohesive learning experience that enhances user engagement and understanding, aligning with recent findings that emphasize the effectiveness of interactive 3D environments in mobile learning applications [23-24].

As shown in Figure 1, the system architecture is organized into three primary layers: input, processing, and output. The input layer captures user interactions through touchscreen gestures such as swipe and drag, as well as command-based inputs including shuffle and guidance activation. These inputs are then transmitted to the processing layer, which functions as the core computational module of the system. This layer is responsible for managing the cube state dynamically, executing the rotation engine to simulate realistic cube movements, generating randomized yet solvable configurations through a shuffle algorithm, and handling interaction logic between user input and system response. The output layer subsequently renders the processed data into real-time 3D visualizations using the Unity engine, complemented by an intuitive user interface and an integrated learning guidance module. This layered architecture ensures modularity, responsiveness, and scalability, which are essential characteristics of modern mobile-based simulation systems [25-26]. Furthermore, the integration of real-time rendering and interaction handling has been shown to significantly improve usability and user experience in educational applications, particularly those involving spatial manipulation tasks [27].

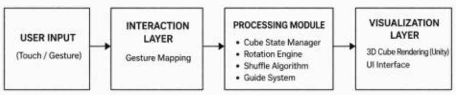

Fig 1: Interactive 3D Rubik's Cube Research Methodology

2.1 User Input

The User Input component represents the initial stage of interaction between the user and the system, where commands are captured through touch-based gestures on a mobile device. These interactions primarily include swipe and drag gestures, which reflect the user's intention to manipulate the Rubik's Cube [28]. From a computational perspective, each gesture can be modeled as a two-dimensional vector $\vec{g} = (x, y)$, where x and y denote the displacement of touch movement along the horizontal and vertical axes, respectively. The magnitude $|\vec{g}|$ and direction of this vector are critical parameters used to determine both the type and orientation of the cube rotation.

To ensure robustness and minimize unintended operations, a threshold function $T|\vec{g}|$ is applied [29] such that only gestures exceeding a predefined magnitude $|\vec{g}| > \delta$ are considered valid inputs, where δ represents a sensitivity threshold. This filtering mechanism reduces noise caused by minor or accidental touches and improves the accuracy of gesture recognition. Furthermore, the directional properties of the gesture vector are analyzed to distinguish between different rotation commands, enabling precise mapping to cube manipulation actions. Through this approach, continuous human input is effectively transformed into structured data representations that can be processed by subsequent system components.

2.2 Interaction Layer

The Interaction Layer serves as an intermediary module that translates raw user input into structured system commands, effectively bridging low-level gesture data and high-level cube operations [30]. This layer is responsible for interpreting touch-based gestures and mapping them into valid Rubik's Cube rotations, thereby enabling intuitive and responsive user interaction within the application. As illustrated in Fig 2, the interaction process consists of several sequential stages, including raw input acquisition, preprocessing, directional analysis, and mapping to cube operations[31]. Formally, the interaction process can be defined using a mapping function:

$$f: \vec{g} \rightarrow R \qquad (1)$$

Where $\vec{g} = (x, y)$ represents the input gesture vector derived from user touch movement, and R denotes the set of valid cube operations, defined as $R=\{U,D,L,R,F,B\}$. Each element in R corresponds to a specific face rotation of the Rubik's Cube (Up, Down, Left, Right, Front, and Back).

In the preprocessing stage, gesture filtering and normalization are applied to improve input quality. Filtering removes noise by enforcing a minimum magnitude threshold, while normalization converts the gesture vector into a unit vector to ensure consistency across different input speeds and lengths. Subsequently, the system performs directional analysis to determine the dominant axis of movement. A gesture is classified as horizontal if $|x| > |y|$ and vertical otherwise.

As depicted in Figure 2, horizontal gestures are mapped to rotations along the vertical axis of the cube, whereas vertical gestures correspond to rotations along the horizontal axis. Furthermore, the mapping process incorporates contextual information, such as the touched cube face and interaction region, allowing the system to distinguish between different rotation layers and directions. This contextual mapping mechanism ensures that user inputs are accurately translated into appropriate cube operations.

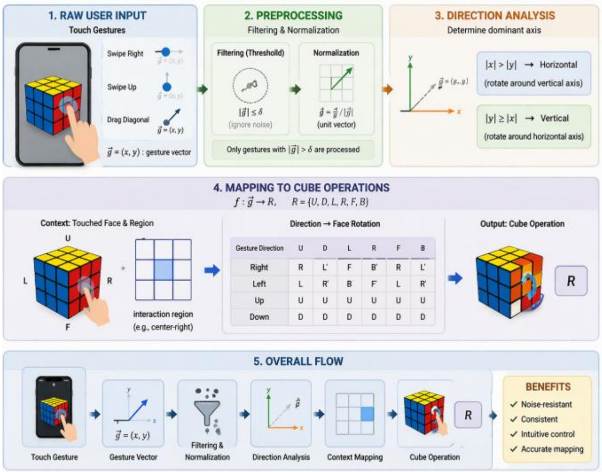

Fig 2: Interaction Layer

2.3 Processing Module

The Processing Module constitutes the core computational component of the proposed system, as illustrated in Figure 3. This module is responsible for managing the cube state, executing rotation operations, generating randomized yet solvable configurations, and supporting guided learning functionalities. It acts as the central processing unit that integrates user input with system logic to produce real-time interactive responses. The cube state is represented as a structured model of a 3×3×3 Rubik's Cube, where each face is defined as a matrix:

$$C_i \in \mathbb{R}^{3x3}, i \in \{1,2,3,4,5,6\} \qquad (2)$$

Where each element of C_i corresponds to a colored sticker on the cube. The Cube State Manager maintains and updates this representation dynamically in response to user interactions or automated processes, ensuring consistency across all cube transformations.

The Rotation Engine is responsible for simulating realistic cube movements through transformation operations. Each rotation is applied to a subset of cube elements and can be mathematically modeled using a rotation transformation:

$$C' = R(\theta).C, \theta \epsilon \{90°, 180°\} \qquad (3)$$

where $R(\theta)$ denotes the rotation matrix corresponding to a specific angle θ. These transformations are implemented to preserve the structural integrity of the cube while accurately reflecting real-world rotational behavior.

To introduce variability, the Shuffle Algorithm generates a sequence of valid moves defined as: $S=\{m_1,m_2,\ldots,m_n\}$, $m_i \epsilon R$ where each move mim_imi is selected from the set of allowable cube rotations. This approach guarantees that all generated configurations remain solvable, as they are derived from a sequence of legitimate transformations starting from the solved state.

In addition, the Guide System provides step-by-step solving instructions by mapping the current cube state to predefined solving procedures. This subsystem operates as a rule-based mechanism that assists users in transitioning from arbitrary configurations toward the solved state. By integrating instructional guidance with real-time interaction, the system enhances the learning experience and supports users in understanding fundamental cube-solving strategies.

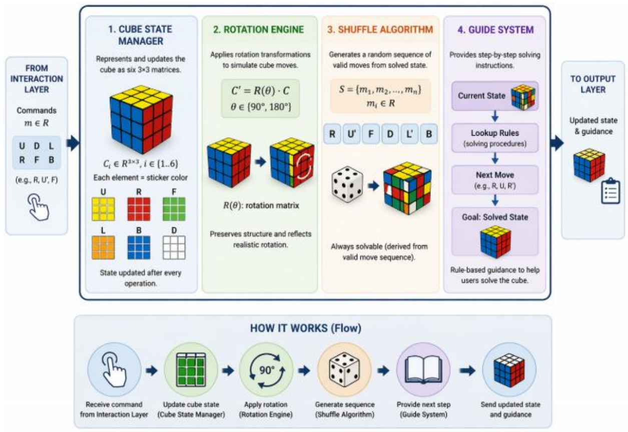

Fig 3: Processing Module

2.4 Visualization Layer

The Visualization Layer represents the final stage of the system pipeline, where processed data from the Processing Module is transformed into a real-time graphical representation. As shown in Figure 1, this layer utilizes the Unity engine to render the Rubik's Cube in a three-dimensional environment. Each cube piece is modeled as an individual mesh object, whose transformation properties, such as position and rotation—are continuously updated based on the output of the Processing Module. This ensures tight synchronization between the logical cube state and its visual representation, maintaining consistency and realism during user interaction.

Furthermore, the rendering process is directly driven by the rotation and state update operations defined in the Processing Module (Fig 3), allowing users to visually perceive the effects of their gestures in real time. Smooth animation transitions are implemented to replicate physical cube movements, thereby enhancing realism and user immersion.

In addition to 3D rendering, this layer incorporates a user interface (UI) that provides interactive controls such as shuffle, guided solving, and navigation menus. The system employs an optimized rendering pipeline to maintain frame stability and responsiveness, which are essential for delivering a seamless interactive experience on mobile devices. By combining real-time visualization with responsive interaction, the Visualization Layer not only enhances user engagement but also reinforces learning through immediate visual feedback.

3. RESULT AND DISCUSSION

This section presents the results obtained from the implementation and evaluation of the proposed interactive 3D Rubik's Cube learning application. The system is assessed in terms of its functional performance, interaction accuracy, and user experience during real-time usage. The analysis focuses on how effectively the application translates user gestures into cube operations, maintains consistent cube state transformations, and delivers responsive visual feedback. In addition, the usability aspect is examined to determine the extent to which the application supports intuitive learning and user engagement. The findings provide insights into the strengths of the system as well as areas that may require further improvement.

3.1 System Implementation

The proposed system was successfully implemented as an Android-based application using the Unity game engine. The application integrates all components described in the methodology, including the Interaction Layer, Processing Module, and Visualization Layer, into a unified and functional system. The overall implementation, including the user interface, interaction mechanism, and system workflow, is illustrated in Fig 4.

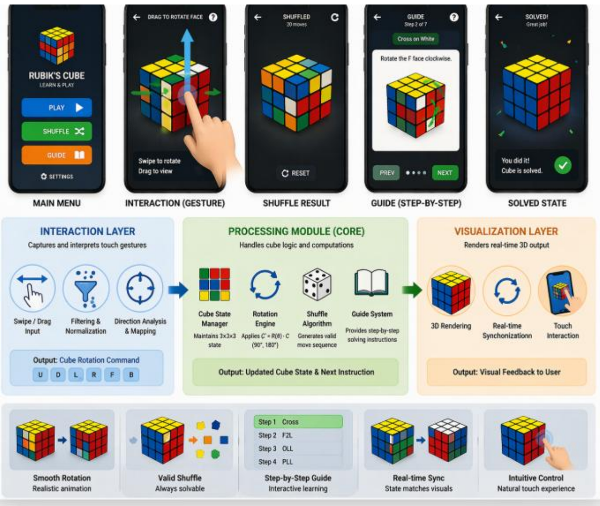

Fig 4: Implementation of The Proposed System

As shown in Figure 4, the Interaction Layer effectively captures and interprets user gestures such as swipe and drag inputs. These gestures are processed through filtering, normalization, and directional analysis, allowing accurate mapping into cube rotation commands. Based on experimental observation, the gesture recognition mechanism demonstrates consistent responsiveness and minimizes unintended rotations due to noise filtering.

The Processing Module operates as the computational core, where cube state management, rotation execution, shuffle generation, and guided solving are performed. As depicted in Fig 4, the Cube State Manager maintains a consistent representation of the cube, while the Rotation Engine successfully simulates real-world cube movements with smooth transitions. The Shuffle Algorithm generates randomized configurations that remain solvable, ensuring logical correctness of the system. Additionally, the Guide System provides structured step-by-step instructions, enabling users to follow solving procedures interactively. Furthermore, Fig 4 demonstrates the Visualization Layer, where the cube is rendered in a real-time 3D environment along with the application interface. Each cube element is dynamically updated according to the system state, ensuring synchronization between computation and visual output. The integration of animation and touch interaction enhances realism and user immersion, allowing users to intuitively interact with the virtual Rubik's Cube.

3.2 Functional Testing

Functional testing was conducted to evaluate whether each system component performs according to its intended design. The testing process covers key functionalities, including gesture input handling, rotation accuracy, cube state consistency, shuffle validity, and guide system performance. Each component was tested using specific scenarios to verify that the system produces the expected outputs under normal operation. The evaluation focuses on the correctness, consistency, and reliability of the system in processing user interactions and executing cube transformations.

The results of the functional testing indicate that gesture inputs are accurately translated into corresponding cube rotation commands. The Rotation Engine performs transformations correctly while maintaining the structural integrity of the cube. The Cube State Manager ensures that all state transitions remain consistent, even after multiple sequential operations. Furthermore, the Shuffle Algorithm consistently generates randomized configurations that remain solvable, confirming the validity of the implemented move sequences. The Guide System also performs as expected by providing appropriate step-by-step instructions based on the current cube state. The detailed results of the functional testing are summarized in Table 1, indicating that all core components function correctly and meet the system requirements.

Table 1. Funtional Testing Result

Component	Description	Result
Gesture Input	Gesture mapped to rotation command	Pass
Rotation Engine	Cube rotation execution	Pass
Cube State Manager	State consistency after operations	Pass
Shuffle Algorithm	Generates solvable configurations	Pass
Guide System	Provides correct solving steps	Pass

3.3 Usability Evaluation (SUS)

To evaluate the usability of the proposed application from the user perspective, a usability study was conducted using the System Usability Scale (SUS). This evaluation aims to measure the ease of use, learnability, and overall user satisfaction when interacting with the system. The summary of the SUS evaluation results is presented in Table 2.

Table 2. Summary of SUS Evaluation

Item	Score
Number of Respondents	30
Mean SUS Score	78.5
Standard Deviation	6.8
Usability Grade	B
Acceptability Range	Acceptable

A total of 30 participants were involved in the evaluation, consisting of users with varying levels of familiarity with the Rubik's Cube. Each participant was asked to interact with the application, perform basic cube manipulations, and follow the guided solving feature before completing the SUS questionnaire. The SUS score was calculated using the standard scoring method. The results show that the application achieved a mean SUS score of 78.5, with a standard deviation of 6.8, indicating a relatively consistent user experience among participants. Based on the SUS interpretation scale, this score falls into the "Good" usability category, corresponding to a grade B and classified within the acceptable range.

The evaluation results indicate that the application provides a good level of usability and is generally well accepted by users. Most participants found the system easy to use, particularly in terms of gesture-based interaction and real-time visual feedback. The integration of interactive 3D visualization with guided solving features was perceived as helpful in supporting the learning process, especially for beginner users. However, some participants reported minor difficulties in controlling rotation precision during rapid gestures, suggesting that further refinement of gesture sensitivity could improve interaction accuracy. Despite this limitation, the overall findings confirm that the system delivers an intuitive, engaging, and effective user experience.

4. CONCLUSION

This study presents the design and evaluation of an interactive 3D Rubik's Cube learning application on the Android platform using Unity. The results demonstrate that the proposed system successfully integrates gesture-based interaction, real-time cube state processing, and 3D visualization into a unified and functional application. Functional testing confirms that all system components operate reliably and in accordance with the intended design, while usability evaluation using the System Usability Scale (SUS) indicates that the application achieves a good level of usability and is well accepted by users. The inclusion of guided solving features further enhances the learning experience, particularly for beginner users. Overall, the proposed application proves to be an effective and accessible tool for supporting interactive learning of the Rubik's Cube. Future work may focus on improving gesture sensitivity and incorporating adaptive solving strategies to further enhance user experience and system performance.

5. ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Universitas Gunadarma for the institutional support and academic environment that facilitated the completion of this research.

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