TangiGuru: A Tangible E-Learning Solution for Early Childhood Development

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***Abstract*—Exploration and manipulation of physical objects are essential for early childhood learning. Previous investigations found several TUI uses in other fields. Less research has been done on tangible learning for youngsters; thus, it's unclear if they are more collaborative, playful, or functional. TangiGuru consists of 12 tangible, manipulative objects known as TangiCubes, which are used as a tangible user interface between children and the e-Learning application. It can carry out cognitive learning activities related to colors, languages, shapes and basic math by dynamically varying assigned values by changing the external appearance of TangiCubes. This dynamic nature of the TangiCubes makes it possible to use the same tangibles with endless possibilities compared to traditional tangible learning solutions with static value for each tangible. After the prototyping phase, children were evaluated with the traditional tangible learning solutions compared to TangiGuru. They concluded that the more interactive tangible interfaces could make the children perform activities more engagingly.**

***Keywords*—TangiGuru, TangiCube, Tangible User Interface, Tangible Learning, e-Learning, Embedded Systems, Human-Computer Interaction (HCI)**

I. Introduction

Human-Computer Interaction (HCI) has recently shifted its attention to Graphical User Interface (GUI), which enables interaction with virtual objects via a computer screen, keyboard, or mouse. Now, a new research topic known as Tangible Interfaces has emerged to solve the GUIs' limitations, attracting the interest of HCI experts. The concept originated in the early 1990s when it was characterized as a representation of digital information and hand-held controls. [1]

The initial phase of research on tangibles was prototyping-focused. Researchers attempted to incorporate design and innovation into physical products such as cubes, playing cards, and puzzles. Researchers were able to develop tangible learning solutions for learning areas such as music, narrative, and programming. [1]

Collaboration and fun are crucial user experience characteristics for tangible learning solutions. [2] There is a deficiency of research evidence documenting the user experience or other variables in tangible learning for children. In this paper, the TangiCubes physical interface is proposed. TangiCube is a tangible user interface comprised of an OLED display, LEDs, and a vibration motor that may provide direct outputs to the user. Sensors are placed in the tangibles to detect their movement and evaluate the actions. The design will be dependent on two key elements.

- Children can learn better when playing and exploring the physical world. [3]
- Physical exercises contribute in the development of their cognitive abilities. [3]

TangiGuru aims to improve children's cognitive abilities while making learning more participatory. TangiGuru consists of nine TangiCubes with a dynamic humanoid face. Such interactive features in the TangiCubes increase interactivity and engagement among children. They will assist the students with the learning tasks. In addition, they are connected via a graphical user interface to offer the activities utilizing a single hub to manage data transfer.

This research will shed light on a previously unexplored issue, as earlier work compared GUIs with TUIs. [2] In this study, however, we blend TUIs with GUIs to analyze the consequences. Comparing TangiGuru to conventional tactile learning solutions and GUI-based e-Learning solutions, this study examines how TangiGuru facilitates cognitive learning tasks for youngsters.

This paper is structured as follows. First, our solution is introduced in detail. In section II,III,IV,V,VI,VII, and VIII the background for conducting this research, research methodology, technology that is implemented, technology constraints, user experience and the research results, and conclusion discussed respectively.

II. Background

The researchers attempt to improve the user experience by going beyond conventional GUIs. [4] Ishi and Ulmer coined the term "Tangible user interface" in 1970 to describe a new research field devoted to determining the relationship between digital information and physical information. [4] The TUI intends for computers to be ubiquitous. It is possible to integrate novel learning opportunities into kindergarten and school. As children are expected to play and advance in the real world, most activities are disconnected from the desktop or mobile device environment. Four to seven-year-olds will interact with the real world, manipulate various objects, and explore. [3] The tangible user interfaces allow direct manipulations between the children and the object. According to constructive learning with these tangibles, [4] children will learn while exploring and solving problems.

In HCI research, tangibles have been studied as user interfaces. Zhi Ying et al. investigate using a foldable 3D cube interface in conjunction with augmented reality technology for interactive storytelling. Camerata et al. use tangibles as physical bricks to explore the data space of a virtual museum, leveraging people's intuitive understanding of 3D spatial connections. [5] In a recent project, designers created a TV remote control by using a low-cost cube-shaped object, rotating it, and laying it back down to scroll through a list of six video streams representing favorite television shows. [3] Turning the cube would rapidly cycle through the programs, and placing it back on a flat surface would output the topmost video stream on the television. The cube had no displays on its surfaces and served only as an input device. They considered the physical cube an interface for various learning activities for children of varying ages when designing their learning devices. The obstacles included: [5]

- Identifying the same image.
- A word-image association.
- A vocabulary builder.
- Matching a variety of 2D perspectives.

These applications are based on the exploratory affordance of the cube and the establishment of a semantic connection between physical control and digital output. The proposed spatial geometry learning device offers a redundant learning interface by establishing a semantic connection between physical control, digital output, and abstract concept.

The Topaoko construction kit contains a microprocessor, sensors, an actuator, and hardboard parts. It allows users to construct their embedded-circuit kits and experiment with kit components. People learn fundamental robotics by building sensor, action, and operator blocks with roBlocks (now Cubelets) (now Cubelets). [5] It also encourages players to experiment with different blocks and build modular structures.

Cubement is a set of seven cubes for designing mechanical movement: a motor, bevel gear, gearbox, crank, jumper, breadboard, and support cube. Users can rapidly master the fundamentals of mechanics through the creation of diverse mechanical systems. Cube-in offers a more basic pre-built kit that allows users to play, observe, and learn about fundamental electronic concepts through simple interaction. Cube-in shares the ethos of earlier tactile learning kits, despite being more straightforward. [3]

Little Bits is a prior work that provides a tactile interface for children to comprehend the fundamentals of electronic circuitry. Little Bits offers a simple introduction to electronics via connections and modules. It is made up of magnetically interlocking modules. Modules can be as simple as LEDs or as complex as timeout modules, which permit users to specify timers within their circuits. Little Bits reduces the need to worry about frequent errors made by students, such as polarity. However, because circuit components are presented at a high level of abstraction and circuitry is hidden behind module components, it is ineffective for teaching elementary concepts. [3]

Since the early nineteenth century, education has been influenced by Friedrich Froebel's views on children's play and learning. Froebel created a series of objects known as "Gifts" that had the potential to connect real-world objects to children's everyday play.

Physical The Mindstorms work of Papert was related to programming objects. As a result of Papert's constructionist theories, numerous programming languages designed for children have been developed. Initially, the user interfaces of these programming languages were textual or graphical (GUIs). Text-based techniques require fundamentally rigid syntax and command names. In contrast, graphic designs were more adaptable, making participation possible for children to construct programming structures by dragging and connecting symbol representations on a computer screen using the keyboard and mouse. [6]

Time-Me is a tool that uses physical objects to represent time in relation to daily activities. The device helps children internalize and contextualize time based on routine activities. [7]. Algorithmic Bricks (A-Bricks) were developed to enhance the programming language experience by considering procedural language characteristics and utilizing them using algorithmic blocks to instruct programming fundamentals such as selection repetition. [8]In pairs, participants interacted with three distinct interface designs for a jigsaw puzzle: a physical (traditional), graphical, and tactile one. An exploratory study of children completing a spatial puzzle assignment and examining how tactile, visual, and physical interfaces may aid in developing cognitive skills. [9].

MagicBuns are engaging objects. This study aimed to determine how different combinations of concrete feedback supported various play behaviors and types associated with other child developmental stages. In addition, a comparison of the play behavior of children aged four to six and those aged ten to twelve was conducted. They established guidelines for building toys that can grow with children. [10]. A novel tangible user interface (TUI) design concept for a manipulative digital drawing pen has been proposed. The user interfaces for children ages 4 to 7 are based on focus group interviews, expert brainstorming sessions, and field survey results. Children could use the new tangible user interface to choose between the brush tools by touching and feeling the various patterns. By adjusting the tilt angle, the child can alter the thickness of the brush. [11]Early exposure to the physical environment can influence a child's mathematical development. Current research on tangible interaction focuses on the formal (symbolic) or numerical understanding of mathematics among preschoolers. On the other hand, recent development research highlights the importance of working principle number representation in math learning. [12]

Fig. 1. Prtotyped TangiCube

III. Methodology

TangiGuru is the central component of the modern tangible e-Learning solution for early childhood development, which combines traditional tangible learning solutions with modern technologies such as cloud computing and embedded systems. These technologies permit the dynamic assignment of TangiCubes to various teaching activities. Unlike conventional tangible learning solutions, which are prefabricated for one or a few specific learning activities, TangiCubes' dynamic nature enables users to utilize it for learning using a technically infinite number of different learning activities.

A. Tangible Layer

Different TangiGuru layers will collaborate to support the children's educational pursuits, as illustrated in Fig. 2,

The Tangible layer comprises a developed set of TangiCubes supported by the e-learning platform. TangiCube is a digitally augmented physical cube. It is constructed from acrylic sheets to give the children the impression of a real cuboid. A second reason for choosing the cuboid shape is that it enables children to connect and engage in more activities. The cube's primary interaction interface is an OLED display. It can display the humanoid interface and text-based outputs to carry out the tasks that the software-based TangiGuru application will generate. The RGB addressable LEDs can provide the cube with various color combinations. The haptic feedback module can give the children feedback. The accelerometer and gyroscope can detect the cubes' motion. The magnetic sensors will determine the cubes' connections. Fig. 3 depicts an open cube containing integrated hardware. The assembled cube can be seen on the right side, which children can use to perform the application software's activities.

TangiCube is an excellent platform for cognitive learning activities. These cubes can be connected or shaken to perform the learning activities. According to Fig. 1, various activities will be delivered through the cloud-hosted e-Learning application. When a TangiCube is powered, the OLED display will display a humanoid interface to keep children engaged. After that, the central hub will connect it to the cloud-based

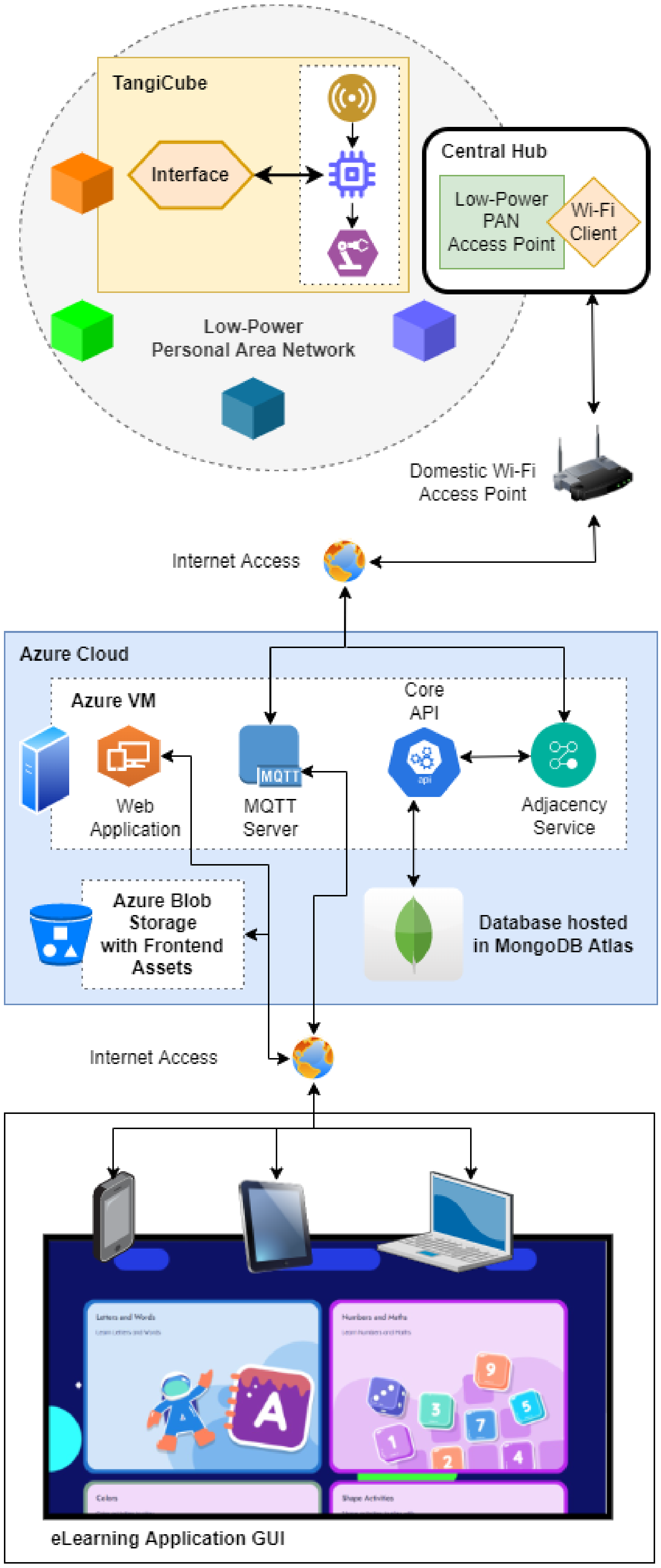

Fig. 2. System Overview

backend. The primary platform provides numerous types of learning activities, including multiple-choice questionnaires. The TangiGuru will provide two fundamental manipulations for TangiCubes to correctly complete the learning activities. In each activity, category answers are provided by either shaking the cube or connecting adjacent cubes (placing them next to each other, forming a row). If the activity category is color-based, the RGB LED strip will provide the color required to display the activity. If it is a letter, number, or shape activity, the OLED display will show the corresponding letter, number, or shape.

B. Interconnection (Communication Layer)

This function is responsible for interconnecting the virtual and tangible counterparts of TangiGuru, which are manipulative TangiCubes and the e-Learning platform which hosts the cognitive learning activities. Interconnection of these components is done in three different levels as follows.

1) Application-level connection
2) Network-level connection
3) Tangible-level connection

All the software components belonging to TangiGuru are hosted in cloud environments to improve the affordability of TangiGuru as a commercial product. As a result, the e-learning application backend (Core API) is hosted on an Azure VM, and the frontend is hosted in Azure Blob Storage. Delivering the frontend to user equipment and connecting it with the backend services such as Core API and Adjacency Service is achieved at the application level.

Connecting the TangiKit with TangiGuru backend services is achieved at the network level. This connection connects the TangiKit to the internet and provides it a passage to communicate with the TangiGuru Core API via an MQTT broker. As the MQTT broker, a Mosquitto MQTT broker is hosted on the Azure VM. The use of MQTT as the communication protocol for this level makes it possible to maintain delay-sensitive real-time communication between the tangible and virtual ends of TangiGuru.The microcontroller firmware of the Central Hub, a component of TangiKit, consists of a Wi-Fi client to connect the TangiKit to the internet. A mobile application is available to allow the users to set Wi-Fi network credentials on the Central Hub.

TangiKit consists of 9 TangiCubes programmed to communicate with its designated TangiKit. This communication takes place at the tangible level. For tangible-level communication, a low-power Personal Area Network (PAN) is created by a specially developed component of TangiKit called Central Hub. The PAN is made using a microcontroller programmed to work as a Wi-Fi access point. A Network Address Translation router is implemented by firmware between the Wi-Fi access point and the Wi-Fi client to bridge the two networks.

C. Child-Friendly e-Learning Application (Virtual Layer)

A child-friendly, interactive user interface was developed for the e-Learning platform, complete with images and audio that children can easily comprehend. The e-Learning platform's learning activities are also designed to accommodate this child-friendly user experience. When designing the user interface for children, designers considered colors, font size, and font styles. The color scheme is the primary visual guide for most of their activities, attracting attention and evoking emotions. Through this child-friendly user interface, children can engage in various learning activities about elementary mathematics concepts, color recognition, similarity recognition, word construction, and shape recognition. Through these activities, these outcomes foster the child's social, emotional, and physical development. Following the learning activity, the performed activity will be automatically evaluated.

IV. Technology that is implemented

A. Hardware Architecture

The TangiCube is based on a simple architecture with a low-power microcontroller, wireless capability, and a set of sensors and actuators. The accelerometer can identify movement, and the orientation can be determined using the accelerometer and the gyroscope. The OLED display is connected to the controller using the I2C connection mode. The LED strip is also connected to the controller to a data line. Also, a vibration motor is bound to give children haptic feedback, which will be one of the main output methods to the users, according to Fig. 3 An accelerometer and a gyroscope are available to implement the input methods in each TangiCube. Also, magnetic sensors are implemented across tangibles to identify each tangible block by each other. A lithium polymer battery will power the whole system. Each cube will work as an individual system within the TangiGuru eco-system when performing the activities.

B. Communication

Combined multiple technology stacks have been used for the three communication levels in TangiGuru implementation. Each of these levels works independently but only interacts

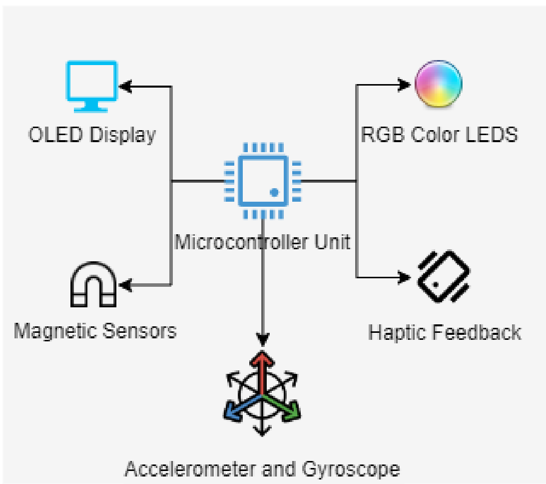

Fig. 3. Hardware Assembly

when data is transferred from one level to another.

1) Application-level communication: In application-level communication, the communication is done between the front and backend of the e-learning application. It also includes the delivery of the frontend to the user equipment, done by the Nginx web server. The web server serves all the static web application files that will render at the client's end. An Azure Blob Storage container is used to host the media assets related to the learning activities, which will be pulled by the e-learning application frontend when necessary.

2) Network-level communication: Interconnection of TangiKit with the e-Learning application backend is done in network-level communication. A Mosquitto MQTT broker is installed on an Azure VM to provide the real-time delay-sensitive communication link between the TangiCubes and the e-Learning application. Both TangiCubes and the e-Learning application publish and subscribe to the relevant MQTT topics on the MQTT broker to send and receive data between the respective components. Besides MQTT, Wi-Fi is also used for network-level communication to connect the TangiKit to TangiGuru backend services. Central Hub, a component of TangiKit, connects to any user-defined Wi-Fi network with WPA2 security to provide internet access to the TangiKit. A mobile application is developed using React Native to configure the Wi-Fi client in the Central Hub. This mobile app allows changing the Wi-Fi credentials of the TangiKit whenever the TangiKit is required to connect to a different Wi-Fi network.

3) Tangible Level Communication: The same Wi-Fi technology is used at tangible-level communication by creating a low-power wireless Personal Area Network (PAN) with a Wi-Fi access point on the Central Hub microcontroller. An ESP-WROOM-32 microcontroller is used for Central Hub as it is built-in with a Wi-Fi radio. This same Wi-Fi radio is simultaneously used for the Wi-Fi access point of PAN and the Wi-Fi client by creating the Wi-Fi PAN on the same Wi-Fi channel as the Wi-Fi client's network. All the TangiCubes are pre-programmed to connect to this PAN. The PAN is bridged to the public internet via a NAT router in the Central Hub.

C. Software

The e-Learning platform is a web application with a graphical user interface that interacts with the child and enables the selection of required activities. The software will give the cubes instructions based on the selected activity. The cube will evaluate and display the results in real-time when a child performs the learning activity.

V. TECHNOLOGY CONSTRAINTS AND OPPORTUNITIES

One side of the TangiCubes features an OLED display. Consequently, there was an issue with the orientation of the tangible. Therefore, the TangiCubes needed to be placed upright by the users. Hight of the TangiCubes is less than their length and width to maintain their cuboid shape. The child will only have two options when the height decreases: keep the display side on top or the display side on the bottom. Due to the humanoid interface of the display, it will always be on top. The design will therefore eliminate the user's confusion regarding six equal sides.

VI. USER AND USER EXPERIENCE

TangiGuru's design process has been continuously improved with feedback from industry experts and intended users regarding what works and what does not. During the phase prototyping, we designed five learning activities for each category based on colors, shapes, numbers, and shapes. Children were given the application and three TangiCubes to play with the appliance. Children were not concerned with the orientation of the TangiCube and viewed it as usual. They understood what they needed to do with the TangiCubes because the applications directed the child to perform an activity. Due to the ongoing nature of the project, an informal user study was conducted. The finalized prototype was used for this study, and a small group of children participated. The study's primary objective is to determine how children will interact with the TangiCube when using the application. We are curious about:

- What are the exciting interfaces of the cubes?
- How will the cognitive abilities of children be enhanced?
- What makes the operations easy or difficult?
- What is the connection between the e-Learning platform TangiCube and the user experience?

VII. RESULTS AND ANLYSIS

With parental consent, the TangiCubes were initially tested with 27 children, and the time it took them to part with TangiGuru was measured compared to a traditional tangible learning solution. There were five children aged 4, seven children aged 5, seven children aged 6, and eight children aged 7. Each child was given unrestricted access to a traditional tangible learning kit for an entire day during the first week of the study. Each child was given unlimited time to play with TangiGuru one week later. Each child's time at each activity was calculated and analyzed.

Table I displays each age group's average time interacting with a conventional tangible learning solution and TangiGuru. The mean time for each age group reveals how children respond to each solution. According to the values in the table, all children have demonstrated a more significant interest in

TABLE I
AVERAGE CONSECUTIVE TIME ON A TRADITIONAL TANGIBLE LEARNING SOLUTION VS. TANGIGURU

Age	Traditional Solution	TangiGuru
4 years	10.7 minutes	23.1 minutes
5 years	10.9 minutes	27.4 minutes
6 years	13 minutes	34.6 minutes
7 years	15.3 minutes	35.2 minutes

Fig. 4. 6 years old test subject performing the activities

TABLE II
AVERAGE TIME ON THE CONTROLLED INTERFACES

Age	Humanoid Interface and Haptic Feedback disabled	Humanoid Interface disabled	Haptic Feedback disabled
4 years	8.2 minutes	12.3 minutes	14.7 minutes
5 years	8.3 minutes	11.9 minutes	14.9 minutes
6 years	8.8 minutes	12.6 minutes	15.3 minutes
7 years	10.1 minutes	13 minutes	16.2 minutes

TangiGuru by interacting with it for more extended periods than with the conventional tangible learning kit. Notably, TangiGuru's interaction time was nearly double that of the traditional tangible learning kit.

The interaction time was then measured by controlling and re-testing the interactive parameters. The TangiCubes' haptic feedback and humanoid interface were the controlled parameters. Table II determined that the interaction time was reduced to an average of 9 minutes when both parameters were disabled. With the addition of haptic feedback, the average play time increased to 12 minutes. After disabling haptic feedback and enabling the humanoid interface, the average playtime increased by 15 minutes.

VIII. CONCLUSION

This study introduces a novel e-Learning device called TangiGuru, a tangible learning solution comprised of 12 TangiCubes, which are manipulable tangibles. Using the shape of a typical cuboid, we were able to implement a platform that would allow children to engage independently in cognitive learning. Children can use this method to enhance their cognitive abilities by manipulating TangiCubes by connecting or shaking them. TangiGuru consists of various tasks to complete with its collection of modernized tangibles, TangiCubes. The initial evaluation demonstrates that having a different physical form and a different group of tangibles will increase participation in the activities. Children will identify the learning platform as an interactive toy rather than a conventional learning kit or e-Learning application. Therefore, TangiGuru can be utilized to instruct children who are easily distracted and lose interest in learning activities. They will be encouraged to participate more actively in the activities. Therefore, this study can challenge the conventional methods of computer instruction. The research demonstrated that tangible objects could reduce interaction time compared to GUI applications. Additionally, the interface type will significantly affect the physical objects. Regarding this paper's limitations, TangiGuru cannot provide customized learning experiences for its users based on their individual learning patterns. Therefore, all users have the same experience, regardless of how well or poorly they learn. TangiGuru can only identify adjacent tangibles when placed linearly, even if it can identify adjacent tangibles when put together. The above feature enables TangiGuru to assess the ability to construct words and sentences and solve mathematical equations. However, TangiGuru cannot evaluate complex assessments such as picture puzzles and scrabble-like games.

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