TangiBoard: A toolkit to reduce the implementation burden of Tangible User Interfaces in education

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***Abstract*—The use of Tangible User Interfaces (TUI) as an educational technology has gained sustained interest over the years with common agreement on its innate ability to engage and intrigue students in active-learning pedagogies. Whilst encouraging results have been obtained in research, the widespread adoption of TUI architectures is still hindered by a myriad of implementation burdens imposed by current toolkits. To this end, this paper presents an innovative TUI toolkit: TangiBoard, which enables the deployment of an interactive TUI system using low-cost, and presently available educational technology. Apart from curtailing setup costs and technical expertise required for adopting TUI systems, the toolkit provides an application framework to facilitate system calibration and development integration with GUI applications. This is enabled by a robust computer vision application that tracks a contributed passive marker set providing a range of tangible interactions to TUI frameworks. The effectiveness of this toolkit was evaluated by computer systems developers with respect to alternate toolkits for TUI design. Open-source versions of the TangiBoard toolkit together with marker sets are provided online through research license.**

Keywords—Tangible User Interface; TUI toolkit; Computer aided instruction; Higher Education.

I. INTRODUCTION

The interest in educational technology has recently experienced a drastic increase as emerging interaction techniques are yielding new possibilities for implementation [1]. Computer-based educational systems are nowadays exploiting novel and evermore intuitive interaction styles [2] and thus slowly revolutionizing the architectural frameworks employed from both hardware and software perspectives [3]. This interest is sustained by professionals in the domain, whereby educators seek to engage educational technologies evermore in designing active-learning pedagogies that promote constructive-based learning as opposed to traditional exposition-based teaching methodologies [4].

Tangible User Interfaces (TUI) quickly became an attractive technology to fulfil this scope. Prominent in this technology is the native capacity to interlace the physical and digital domains through enriched interactions for the manipulation and representation of data as defined within the MCRpd interaction model [5]. Moreover, by making use of more intuitive tangible objects instead of traditional digital-based wimp interfaces, TUI systems provide an extended platform which to aid in the teaching and learning of concepts [6].

The intrinsic interaction elements of TUI systems also provide numerous benefits to the educational pedagogy adopted, especially with their innate ability to motivate student engagement and enhance their learning experience [7]. TUI systems enable users to more effectively engage their motor cortex when manipulating tangible objects, easing the cognitive load needed to interact with the system and consequently enhancing their spatial imagination [8]. By employing a range of diverse audio-visual feedback elements, TUI systems exploit various sensory engagements and learning modalities, which aid students to comprehend the theoretical concepts being taught [9]. Furthermore, the physical aspect of TUI systems provides a more conducive opportunity for collaborative learning [10] and has also been attributed to yield deeper knowledge retention among students [11].

Albeit TUI implementations have yielded positively encouraging results in education, currently available toolkits and frameworks necessitate the creation of specific architectures for application [12]. These requests pose additional burdens over traditional lecturing methodologies hence hindering the adoption of this technology within the educational domain. Apart from scalable procurement expenses, current TUI setups occupy a significant footprint for operation, which in turn constrains the number of educational venues in which systems can be implemented. Furthermore, due to the complexities of current toolkits, operation of these architectures often involves the need for RFID systems, Hall effect sensors or specialized computer vision equipment. Thus, the physical setup and calibration processes required with current TUI systems demand the availability of on-site technical expertise to operate and maintain [13]. These burdens collectively hinder the proliferation of TUI systems within educational institutions, confining the technology mainly within specialized educational laboratories [14].

To this end, this paper proposes a novel TUI toolkit to mitigate the outlined impediments experienced within educational adoption. Making use of available classroom technology, this paper presents a TUI system which eliminates the need for dedicated TUI hardware setups and technical expertise, hence reducing the implementation burdens currently faced in TUI implementations. Further to an evaluation of current TUI architectural frameworks in Section II, Section III provides detail on proposed toolkit from both functionality as well as educational set-up aspects. The evaluation of the proposed system within a university context is explained in Section IV, where a discussion on the system's capabilities and ease of implementation is assessed. Finally, a conclusion on the proposed TUI toolkit is drawn in Section V.

II. TANGIBLE USER INTERFACES

The ability to provide a physical interpretation to digital information has been exploited using various architectures for constructing TUIs [12]. This section provides a brief overview of the main genres of promising architectural frameworks employed within literature for educational aspects whilst outlining their unique strengths and shortcomings.

Pioneering TUI systems in educational applications were undertaken using constructive assembly architectures. Projects such as LEGO™ Mindstorms [15], Learning Cube [16] and System Blocks [17] were able to enhance problem solving skills in children within various domains, including; mathematics, robotics, and language translation. Whilst these frameworks allow for customization of digital content, their physical structure is quite specific and their I/O components usually small in size. This implies that albeit being relatively cheap to procure, only one student can tangibly interact with and visualized data, thus resulting in a scalability burden to utilize within classroom environments.

An alternative to this approach was devised by employing a tabletop-based workbench configuration. Systems like PIco [18] and Actuated Workbench [19] employ wireless RFID technology to locate objects around the tabletop. These systems make either use of a projector mounted on top of the table to project digital information on surfaces or employ electromagnets to actively track the position of tangibles [18]. Whilst capitalizing on the fact that multiple students can interact simultaneously with the system within a classroom set up [8], the electronic complexity and calibration requirements of these TUI architectures renders them expensive and challenging for widespread use outside of dedicated laboratories.

A more cost-effective table top architecture was proposed in the adoption of the reacTIVision [20] toolkit. As detailed in [21], such architectures visually track physical objects placed onto a semi-translucent interactive surface which is illuminated by an underneath digital projector. Examples of these TUI architectures have been successfully implemented in various educational systems such as 'BrainExplorer' [22] and 'Strip'TIC' [23] which obtained promising results in teaching neuroscience and interacting with airspace control respectively. Whilst the adoption of this visual-recognition toolkit facilitated the development of tabletop implementations, construction and setup of TUI architectures still require the costly procurement of specialized cameras and projectors to obtain a suitable educational setup [21]. Furthermore, the inherent nature of tabletop architectures poses a limit on the number of students that can collaboratively interact with the TUI system, thus constraining usability to only small cohorts of students [24].

This audience limitation was partially addressed using vertical peripherals in TUI setups. Systems such as "IP Network Design Workbench" [25] and "Disaster Simulation" [26] employ vertical monitors to display digital data to a wider audience. These arrangements, however, confute the intrinsic attributes of TUI systems by severing the physical/digital embodiment of information whilst also invalidate valuable aspects such as perceptual coupling in interaction [1]. An alternate approach to vertical TUI architectures is proposed by [27] through the use of active interpolating force-sensitive resistance (IFSR) sensors. Whilst providing an enriched interactive experience, this setup is complex to develop and operate, thus reducing its attractiveness to educational institutions. A more effective vertical TUI architecture was proposed by [28] who made use of a back-projection screen setup to display digital information and a frontal camera to track fiducial marker symbols. Whilst being able to more effectively address classroom-based requirements, the system is heavily restricted from a tangible aspect, since a frontal fiducial marker sticker must be attached to each object for camera recognition [28]. This, unfortunately, constrains the tangible embodiment and representation of information on familiar everyday objects, thus reducing the effective educational benefits aspired by TUI systems. Furthermore, the system is cumbersome and expensive to setup due to the physical dimensions required to back-project on the screen, the dedicated equipment for operation as well as the elaborate calibration needed upon every use.

III. Proposed TUI Toolkit

In light of the outlined challenges in adopting TUI systems, this paper proposes a novel TUI toolkit; TangiBoard, to mitigate the currently encountered burdens. In contrast to current literature, the proposed TangiBoard solution presents an alternative architecture to vertical TUI systems, which embodies all the attributes for tangible interaction as well as requisites for educational application. By making use of currently available classroom equipment instead of dedicated setups, TangiBoard provides a solution that minimizes additional hardware requirements and procurement expenses, thus facilitating the adoption of TUI systems. Furthermore, through algorithmic processing, the vertical architecture is designed to passively recognize and track a set of marker designs from a distance of 3.2 meters, facilitating both its design and deployment for small and larger user group interaction. Moreover, by curtailing technical setup and calibration needs, the proposed toolkit alleviates the implementation burden of designing an effective TUI system whilst allowing system developers and users to focus on its operational aspects.

A. System Overview

Key to the architectural design proposed through the TangiBoard toolkit is the use of conventionally available educational technologies and classroom configurations to augment the teaching and learning experience provided. Employing a front-facing vertical TUI architecture as shown in Fig. 1, the system repurposes a conventional painted steel (a.k.a. magnetic) whiteboard as an interactive TUI surface. This is illuminated with digital content and feedback information using a standard-throw ceiling-mounted digital projector which is nowadays a commonplace educational technology in classrooms. Exploiting the fact that conventional installations include a considerable throwing distance for digital projection, the proposed architecture avails of an extended interactive surface area. This allows the TangiBoard setup to make use of larger tangible objects and digital representations, hence facilitating visualization and interaction to a larger student audience.

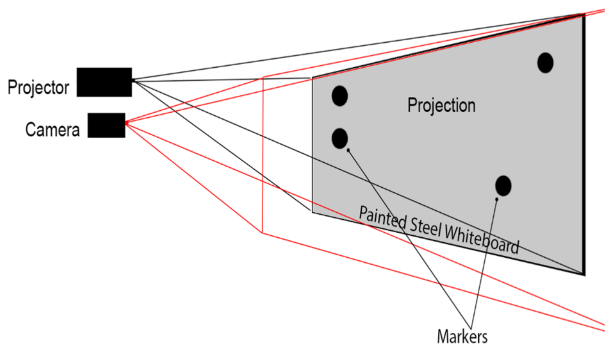

Fig. 1: TangiBoard architectural setup

The detection and recognition of tangible objects is performed using a front attached digital camera, which is affixed to the projection setup. To facilitate the system setup, the TangiBoard architecture is able to utilize any digital CCD camera and lens to provide TUI input feedback. The majority of better quality USB web-cameras (e.g. Logitech c920) are able to provide a suitable input to the system. In addition, to further reduce the financial and procurement burden, the proposed TangiBoard toolkit is also designed to integrate with all modern smartphone cameras on the market (tested with Samsung Note4). Thus, through open-source video applications, the TangiBoard toolkit interfaces natively with smartphones to either stream video via a Wi-Fi network or through a USB connection with the host laptop executing the TUI software. This is made possible since in difference to conventional TUI tabletop architectures, the hardware needed for TangiBoard operation does not demand specialized/specific technical requirements to capture the complete interactive area. Thus, TangiBoard is able to effectively recognize markers even at lower resolutions provided by cheaper camera or mobile phone devices.

From a usability perspective, this novel TUI architectural configuration allows for the provision of perceptual coupling to users on its large interactive surface, which cognitively heightens their sense of engagement with the system. Furthermore, from an educational aspect, the capability to provide physical placement and positioning of tangible objects with augmented digital data, allows students to further embody the represented information within the developed conceptual context.

B. *Tangible Objects*

The success and enhancements realized by TUIs are underpinned by the ability of such frameworks to adopt commonplace and familiar objects to manipulate and interact with the system [29]. The a priori assimilation users have of the embedded objects provides the ability to inherently associate these tangible components with a set of respective functionalities, further facilitating the system's intuitive interaction. To this end, TangiBoard is able to track and digitally augment any desired item, providing TUI designers the capability to incorporate everyday objects and artefacts, plastic and wooden geometric shapes as well as contextual 3D printed models.

As visualized in Fig. 2, these tangible objects are affixed on a circular cardboard upon which a marker design was printed and attached using either tape or magnetic coupling. The latter open source marker can be printed using an ordinary laser printer on office paper. As highlighted in Fig. 2, a

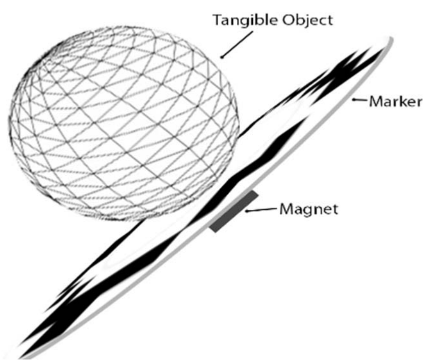

Fig. 2*:* Tangible objects attached to marker base sketch

neodymium magnet (20x5mm), providing up to 5kg of pulling force, is attached underneath the centre of the platforms which provides the ability to stick yet freely move the object around on painted steel whiteboards.

The proposed design also allows the ability for the cardboard platform and magnets to be scaled according to the object size. To keep low tracking noise, current marker design allows a minimum diameter of 14cm, with at least 33.2cm^2 of central area allocated for the object attachment. This flexibility combined with the large interactive surface area used by the TangiBoard architecture eliminates the size constraint of artefacts that can be used within the TUI system, which has been a common limitation in literature through conventional TUI tabletop architectures. As pictured in Fig. 3 are seven tangibles attached to their appropriate marker which were used during a test run of a computer networks educational TUI, based on the TangiBoard architecture.

C. *Marker Design*

The requirements for the architectural simplicity and object diversification of the TangiBoard architecture imposed a number of constraints on the marker design evolution process. The proposed marker set, displayed partially in Fig. 4(a-g) is composed of circular matrices of black and white regions which encode a unique identification pattern. This high-contrast design provides the TangiBoard recognition engine with a large quantity of sharp edges which enable a robust detection and recognition from a capturing distance of over 3m away.

The highly compact geometry of the TangiBoard toolkit marker set is intended to provide an excessive set of features which provide the system with multiple unique patterns within each marker. Apart from increasing the hamming distance between each unique marker in the marker set, the designed patterns allow for rotational variance and hence angular orientation detection. The multiple unique patterns feature is further critical for the front-facing TangiBoard architecture since varying tangible object dimensions and camera perspective angles are likely to provide numerous occlusions to segments of the marker as pictured in Fig. 4(h), and thus this design provides a tested occlusion resistance of up to 35%.

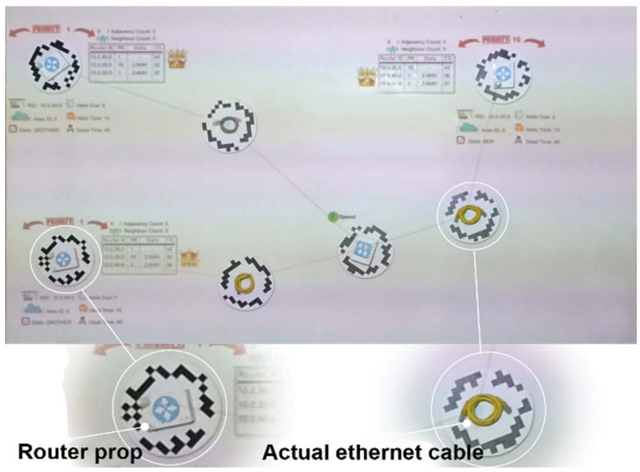

Fig. 3*:* Tangible objects attached to marker base

Furthermore, from a TUI usability perspective, the markers are intended to provide a visually similar pattern to users which is not natively decodeable. Within an educational context, the pattern design blends as a background to the object attached on top. Hence, this allows students to retain focus on the core object representation of the tangible marker thus reducing cognitive visual distractions currently provided by vertical TUI systems. In addition, the circular shape of the tangible platform provides users with a more intuitive interaction for rotational manipulations. The rotationally variant unique patterns are thus exploited TangiBoard toolkit, which provides TUI developers the ability to integrate this interaction through the angular tracking data of each independent marker.

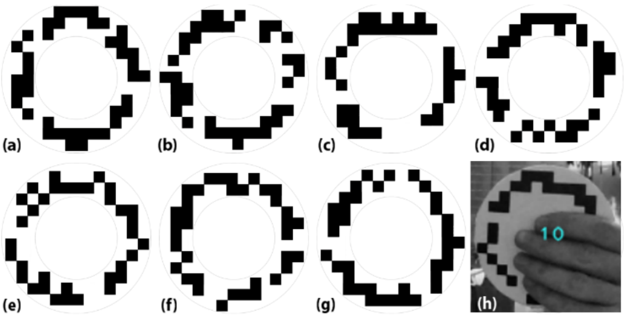

Fig. 4: a) Subset of designed marker-set h) TangiBoard marker recognition with occlusion

D. Recognition Engine

The TangiBoard toolkit processes the video stream acquired by the camera at a frame rate of 20fps to return quasi real-time data about all the identified markers within the interactive area via a call-back system to the requesting TUI applications. The TangiBoard recognition engine is composed of a modular chain of image processing algorithms which update and track information about each marker and allow listening API interfaces to receive data through an event based call-back mechanism for integration within TUI frameworks.

Following calibration pre-processing of the captured stream, detailed in a subsequent section, the Scale Invariant Feature Transform (SIFT) [30] algorithm is adopted on frame data for identifying marker features and deriving their unique descriptors. The recognition of markers is then undertaken through a Random Sample Consensus (RANSAC) [31] algorithm which accounts for the scale, rotation and perspective variance of captured markers. Finally, a dictionary matching search is adopted to retrieve the unique marker ID from the resultant feature set.

The position of a TangiBoard marker is calculated as the centroid of all features found on the marker symbol, allowing a near perfect estimation even at over 3m capturing distance. The rotational angle of the marker symbols is calculated as the arctangent between the vectors from the marker centroid towards the symbol virtual corners as illustrated in Fig. 5a. This enables the precise determination of the marker orientation even if the latter is partially occluded by attached objects. Moreover, these attributes enhance the toolkit's movement sensitivity and system responsiveness, which at maximal capturing distance of over 3m away was calculated to be not greater than 4mm on the interactive surface.

The calculated attributes on every marker, as visualized in Fig. 5b, are encoded and transmitted to all listening applications in a data structure as outlined in the inter-process communication section hereunder. The positional and orientation data from previous frames is further employed in the TangiBoard toolkit to filter false-positive appearances in isolated frames thus providing a more robust TUI data stream than current toolkits outlined in literature.

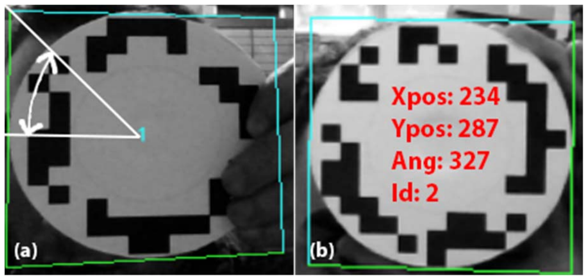

Fig. 5: Determination of captured marker's positional and rotational information

E. Human Detection

Intrinsic to the front-facing TangiBoard architecture is the frequent occurrence of human occlusion whilst interacting with the interactive surface. This problem is further compounded by the collaborative nature of the proposed TUI architecture, especially when employed in an educational context. During these instances, the tangible objects would be partially occluded from the camera's field of view for numerous frames which result in a loss of input data towards the TUI application.

To mitigate this common issue in current TUI toolkits, TangiBoard makes use of a human detection algorithm to identify these instances and rectifies the input data accordingly. The latter is based on a Haar feature-based Cascade classifier [32], which was trained with a data set of human head and shoulders silhouettes. As evidenced in Fig. 6, the TangiBoard system identifies these instances and preserves the last-known values of the occluded markers whilst updating the positional information of markers still in view thus providing a robust marker continuity to TUI frameworks and projected information.

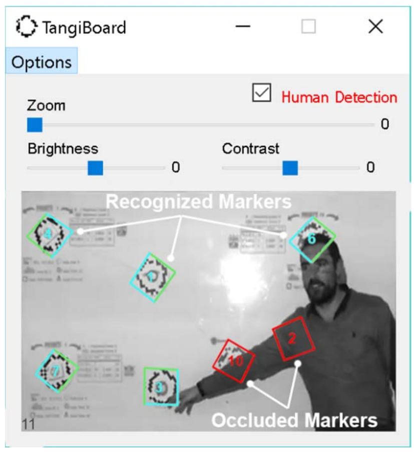

Fig. 6: Human detection algorithm and marker detection

IV. TangiBoard Usage

A. *TangiBoard Application Handling*

To aid overcome technical burdens in setting up and using the TangiBoard Toolkit, a clean user interface was developed for the application which shows users actual camera footage superimposed in real-time with visual responds on the recognition and identification of each individual marker. As pictured in Fig. 7, the toolkit can be furthered configured through a GUI menu from which the user can select the following options;

- Identify the input video stream (between USB cameras or IP camera connection)
- Edit the camera parameter options
- Calibrate the system
- Show human location
- Restore to default values

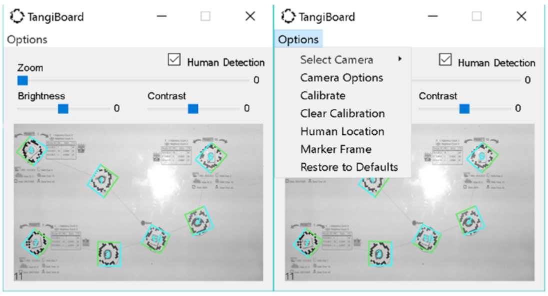

Fig. 7: Graphical User Interface for TangiBoard usage

Due to long-throw architectural nature of the setup, this interface further provides a zoom slider within main GUI, which allows the capability to align and focus the captured stream on the interactive area. This hastens the calibration process whilst enhancing the real-time marker recognition rate. Furthermore, two additional sliders for brightness and contrast were integrated within the GUI elements which enable the user to alter in real-time the camera parameters whilst monitoring the marker detection performance of the TangiBoard recognition engine. The application also provides users with a human detection/location option, which enables the potential need for discrimination in instances when digital graphics resembling a human are projected on the whiteboard and thus avoid the generation of false positive human detection results.

B. *Calibration Procedure and Parameters Settings*

To drastically reduce the setup and calibration burdens currently experienced in adopting TUI setups with current recognition toolkits, an automated calibration process was further developed within the TangiBoard toolkit. A calibration algorithm was designed to dynamically adjust for the various physical setups supported by the system, whilst accounting for differences in lighting, camera/projection parameters and illumination/capturing perspective angles. These imaging parameters are subsequently utilized by the toolkit for pre-processing of the captured image stream throughout execution.

Employing a simple set of calibration markers, pictured in Fig. 8a, which are purposely designed to be cut in a ¾ circle with a ¼ corner angle in line with the marker edges, the setup alignment is facilitated for users as illustrated in Fig. 8b. Following the selection of the interactive area through the alignment of the four markers visible within the camera, the automated calibration procedure can be started by clicking the calibrate button. Through the recognition of these calibrating markers, the TangiBoard toolkit automatically aligns the camera and projection perspective, digitally select the camera image section based on the interactive surface area and corrects for the perspective transformation matrix as shown in Fig. 8c.

Following this calibration routine, the toolkit reasserts visibility and detection of all sections of the TUI surface through these calibrating markers and informs the user about the calibration success accordingly. Whilst the automated routine is intended to expedite the system setup without requiring any technical expertise, the parameters can still be accessed and manually altered through the GUI interface for more specific setup instances. Further information about this process is beyond the scope of this paper and can be referenced in the toolkit's repository website and documentation.

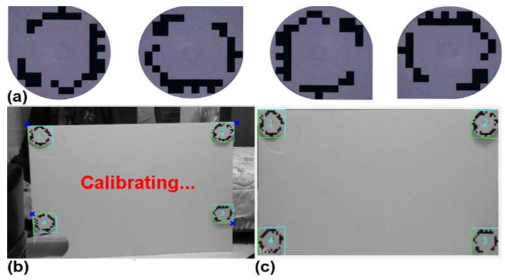

Fig. 8: Automated calibration procedure for easier setup

C. *TUI Application Programming*

The TangiBoard toolkit is designed to integrate natively with software applications and provide TUI functionality without requiring the software developers to hold knowledge on the architectural and image processing aspects of the toolkit. To this end, a number of API commands and communication services are employed which allow TangiBoard to be integrated with current TUI software and provide a more feasible TUI alternative in educational contexts than conventional TUI table top architectures.

The current inter-process communication between TangiBoard and other object-oriented software languages such as C#, C++, Java and Processing is done by an event-based call-back mechanism. Structured marker information including; visibility, positional coordinates, orientation angle, and human detection flags are updated on every frame processed. This is undertaken using the JavaScript Object Notation which the TangiBoard toolkit adopts to transmit the marker state data to the conventional software development applications used to design and develop the graphical and computational interfaces.

Integration of the TangiBoard toolkit within development applications is implemented through the inclusion of a library. Thus, whilst the recognition engine continuously updates events from the media stream information through background processes, the toolkit can be interfaced through the object-oriented software integration. Thus, the toolkit further provides a set of marker status functions within the retrieved object data such as *getDegrees(), getLocationX(), getLocationY()* and *isHumanDetected()*, These convenient callback methods enable the faster development of TUI software as well as easier integration with already developed educational software packages.

V. Experimental Results and Discussion

A. Evaluation Methodology

The evaluation of the TangiBoard toolkit was undertaken to assess the implementation capabilities and feasibility provided towards the development of TUI systems. To this end, a team of twelve (12) system developers with prior experience in developing tangible user interfaces were selected for evaluation. Demographically, participants were aged between 24-35 years of age, consisted of eleven (11) males and one (1) female and had at least 2 years of software development experience. In line with current research in the field of TUI architectures, all participants outlined prior experience with the design and development of table top TUI architectures through software integration using the reacTIVision toolkit [20]. Thus, exploiting this experience, the evaluation methodology was adapted to provide a direct comparative analysis of the proposed TangiBoard toolkit with respect to the current state-of-the-art TUI toolkit adopted in research.

After consenting and compiling a participant profile sheet eliciting the demographic and technical experience in design and development of TUI systems, participants were provided a short introduction to the TangiBoard toolkit. This session was delivered concurrently to all participants at the start of their evaluation, following which participants were asked to individually deploy their previously developed TUI software applications on both the control reacTIVision and the proposed TangiBoard architectures. At the end of their development, participants were provided with a questionnaire aimed at assessing their comparative experience in developing and implementing both setups using the respective toolkits. The criteria outlined in Fig. 9 were thus assessed through a set of 7 questions answered on a 5-point Likert scale ranging from 'bad' (1) to 'excellent' (5) respectively.

B. Session Results and Discussion

Equitable analysis was undertaken on the assessments marked by each participant on both the control and experimental toolkit using a statistical software package. The obtained data from each participant was analysed through a paired-sample t-test, whereby a mean comparative difference of 48% was registered at a statistically significance of ($p<0.05$). These results outline the meaningful discrepancy from participants with respect to the perceived ease-of-use as well as behaviour intention of the TUI developers to adopt the proposed technology as evidenced from the comparatively visualized radar chart ratings in Fig. 9.

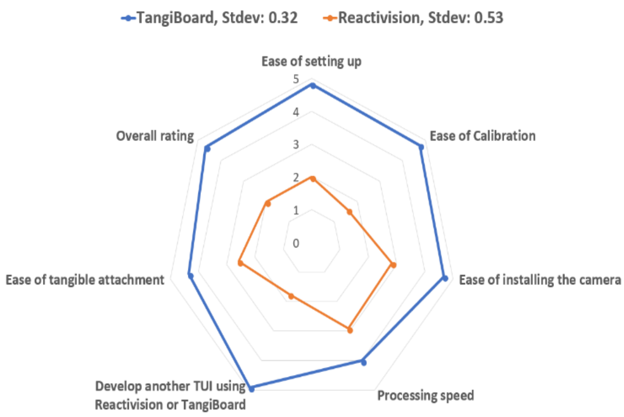

Fig. 9: Comparative results of the determinants evaluated by system designers on both TUI platforms respectively.

The compelling difference was also observed and noted through the obtained student feedback and comments on the evaluation deployments. The latter further attest to the suitability and effectiveness of the TangiBoard toolkit for designing and developing TUI systems, whereby participants routinely outlined the disparity in ease of adoption and implementation of their software within the proposed architecture as well as the significant enhancement in collaborative interactivity afforded by the TangiBoard architecture.

VI. Conclusion

This paper presents and describes the development and implementation a novel TUI toolkit that aims to directly mitigate the adoption barriers currently experienced with tangible technology in educational and commercial contexts. Aimed directly at minimizing the current requirements needed to procure, set-up, calibrate, develop and operate a TUI system, this contribution presents TangiBoard through an open source marker set together with a software application toolkit for user interface designers and developers. The paper outlines TangiBoard's ability to utilize conventional educational equipment to provide an interactive TUI setup without requiring on-site technical expertise for deploying and calibrating tangible systems. Through analysis of implemented evaluation methodology, the effectiveness of the proposed system was objectively quantified with respect to perceived ease-of-use and behavior intention of software developers who significantly favored the TangiBoard architecture in direct comparison to TUI table-top setups currently being adopted in literature.

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