Designing a Table-Top Tangible User Interface System for Higher Education

Clifford De Raffaele, Geoffrey Buhagiar
School of Science and Technology
Middlesex University Malta
Pembroke, PBK1776, Malta
cderaffaele@ieee.org, geoffreybuhagiar@gmail.com

Serengul Smith, Orhan Gemikonakli
School of Science and Technology
Middlesex University
Hendon, NW4 4BT, UK
s.smith@mdx.ac.uk, o.gemikonakli@mdx.ac.uk

***Abstract*—Tangible User Interfaces (TUI) have garnered significant interest in the past years as a potential solution to embed smarter technologies for education. The intrinsic ability of this technology to engage and intrigue students in active learning pedagogies has recently been successfully proven across all ages using various techniques. Predominantly amongst the effective technologies, has been the development of tabletop approaches. However, these have mostly been bespoke implementations that lack proper formalisation. To this end, this paper construes the requirements to successfully implement TUI technology within higher educational contexts and proposes the design considerations for the smart adaptation of this technology. Following the implementation of the proposed smart system, the developed TUI design was evaluated within an undergraduate university programme for its effectiveness in teaching and learning object-oriented concepts. The obtained results illustrate a significant enhancement of student-experience during utilisation of such technology and quantitively outline the design's potentiation to convey complex concepts in higher education. Detailed blueprints of the proposed architecture are openly available on: http://itc.mdx.edu.mt.**

Keywords— educational technology; higher education; tabletop system; tangible user interface

I. INTRODUCTION

The interest in educational technologies has experienced rapid development in the past decade as technology became even more affordable and able to undertake complex and smart solutions. Consequently, higher educational institutions (HEI) recognize the fact that introducing technology in classrooms will maximise the opportunities for curriculum activity [1], and thus constantly seek to invest in new hardware and software systems to enhance the teaching and learning experience provided.

Smart ICT solutions have the flexibility to fit into a myriad of instructional approaches varying from traditional to innovative, hence allowing the HEIs to adapt their tuition according to the subjects being delivered and even in ways to provide students with the possibility of tailored feedback [2]. The authors in [3] describe that by facilitating the acquisition of basic skills, and by enhancing teacher training, the learner's engagement and motivation can be solicited by engaging with multimedia computer software, videos, sound and graphical representations. This observation was elaborated by [4], whereby appropriate use of ICT was correlated with inducing a paradigmatic shift in both HEI's content and pedagogy. Furthermore, the meta-analysis study undertaken by [5] reveals that students who used ICT-based instruction scored higher whilst learning in less time, compared to other students.

These results have been corroborated by [6] who highlighted that educational technology has the potential to accelerate, enrich and deepen a person's skills and as a result motivate and engage students further. These observations have led curricula to evolve in ways to integrate smart technologies as to achieve active learning pedagogies that invoke student's attractiveness towards the subject being thought [7]. Alas, as these technologies have brought about disruptive changes in education, their adaptability success has been driven by the ability to importantly enticing lecturers to embrace the new technology [8] as well as their ability to possibly entice students in learning as outlined by [9]; *"The key factor for the acceptance and adoption of new technologies is the ease of use and learning"*.

This has led various researchers to investigate the adoption of Tangible User Interface (TUI) as an alternative educational technology to traditional equipment like projectors, interactive whiteboards and PC-based software [10]. In TUI systems, WIMP (windows, icons, menus, pointers) interactions are replaced by tangible everyday objects, hence enabling users to interact to a smart technology using more relatable objects [11]. Albeit TUI technology is relatively new, researchers have obtained successful results when implementing the smart technology in specialist domains varying from primary education [12] to medical research [13]. Whilst a variety of hardware is adopted in these approaches, tabletop systems seem to be the most common versatile technique towards TUI implementation [14]. Nevertheless, the design and development of this smart technology is mostly ad hoc and thus far lacks formalisation on effective design considerations resulting in further difficulties to adopt TUI systems.

In light of the above constraints, this paper proposes the design of a smart TUI technology for the effective adoption within HEIs. Following a brief review in Section II on implementation of TUI systems, Section III proposes a formalised design for the successful development of TUI within HEI. Specific requirements are elicited for the use of TUI system in educational context and a number of innovative

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smart design considerations are provided which augment the student's experience. Section IV presents and discusses results obtained from evaluating the proposed TUI design and development within an undergraduate university programme. Finally, a conclusion on the applicability of TUI setups for HEI is drawn in Section V.

II. TANGIBLE USER INTERFACES

Ishii and Ullmer [15] describe the term of TUI as augmenting physical objects by pairing them to digital information whilst eliminating the distinction between input and output devices. This technology constitutes part of the wider concept of 'Ubiquitous Computing' whereby technological interaction with the digital realm blends seamlessly with natural physical movements [16]. The interaction of TUI systems is thus modelled over the "model-control-representation (physical and digital)" – MCRpd model, outlined in Fig. 1, which is a technological derivation of the well-known "model-view-control" – MVC used for software [17].

A. TUI as an educational technology

When using TUI, the familiarity of objects being manipulated can aid to overcome barriers in the case of user interaction. As a result, the use of TUI can ease the cognitive load and help the user to concentrate more on what is happening rather than being distracted with the control activities to manipulate the system's input [18]. This intrinsic benefit allows TUI systems to move away from the constraint of 'time-multiplexed' controls like mice and keyboards and instead adopt 'space-multiplexed' controls which are specifically design for particular interaction styles [19]. The choice of dedicated tangible objects employed by the TUI system allows developers to embody semantic information to the manipulative as well as exploit previous assimilation knowledge harboured by students [20]. This was evidenced in the application of cubical objects to teach children sequential programming concepts at earlier ages [21], capitalising on their familiarity with building blocks and similar toys.

The ability of TUI to interlace between the physical and digital world furthermore offers exciting possibilities as a learning platform. In the implementation undertaken by [22] to visualise abstract concepts, student's performance and their technological interactions were analysed when merging various media platforms to undertake simultaneous drawing in 2D/3D representations. This concurs with the observation undertaken by [23], which highlighted that; *three dimensional forms might be perceived and understood more easily through haptic and proprioceptive perception of tangible representations than through visual representation alone*".

Furthermore, the physical movement demanded by interaction with TUI setups invokes utilising a number spatial-skillsets which in turn augment student's thinking and learning capabilities [24]. In particular, authors in [25][26] highlight that this mode of TUI engagement positively effects the ability of children to recall, both in accordance to 'implicit' and 'explicit' cognitive theories, tasks of perspective thinking and spatial imagery.

Moreover, in contrast to traditional text-based environments, whereby opportunities for elaborative processing are hindered by the fact that the student's verbal channel is occupied in listening to the professor and working on written material [27], TUI systems intrinsically increase the potential for collaborative group work and thus facilitate the ability to exploit collaborative and experimental learning theories [28].

B. Interactive tabletop surface

Literature on TUI as an educational technology exposes the use of several disparate TUI implementations, each adopting distinctive technological configurations [29]. Withal, the tabletop architectural framework proposed by [30], has garnered substantial interest over the past years due to its potential to adopt to various implementations. Additionally, from a socio-educational perspective [31], the tabletop approach has also proven as an effective approach to entice older students in engaging with each other while at the same time develop their knowledge by collaboratively solving problems [14].

The interactive tabletop methodology, described in Fig. 1, is supported by a combination of open-source software licences (GPL, LGPL, BSD), most popular of which is 'reacTIVision' [30]. Common household objects are attached with a unique 2-dimensional monochrome code (known as 'fiducial marker') at the base which enables them to be identified and treated as tangible manipulatives. This rotation-variant 'marker' is read by the underneath camera as soon as objects are placed over the table top and as a result, the software determines the exact position of each fiducial in relation to the entire working surface [30].

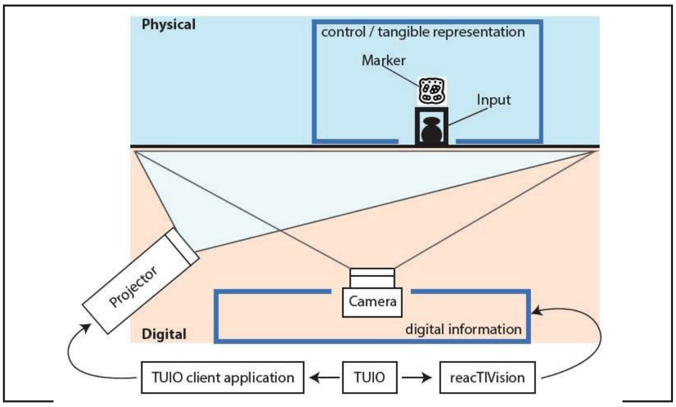

Fig. 1. Tabletop tangible interaction architectural model (adapted from [30])

This concept has been taken further by [32], which have included 3D projection to augment their software's ability to identify the position, shape and orientation of objects on the surface. Moreover, authors in [33] propose a series of algorithms within their 'BullsEye' to enhance optical field tracking by working on greyscale imagery, hence achieving a substantially higher positional accuracy at the expense of increased computational complexity.

III. Proposed TUI System

In light of the limitations outlined in literature and the lack of formalised design for a successful TUI deployment, this paper outlines various design considerations for a smart TUI tabletop implementation. The contribution of this paper considers the specific requirements imparted on a TUI system when used within an educational context and proposes innovate solutions to formalise an effective design and implementation of such a novel technology.

A. Requirements Elicitation

The deployment of a TUI system within HEI instils requirements which are peculiar to the context of teaching and learning. From a system specifications perspective, the maximisation of the interactive tabletop surface area is a critical provision for the development of complex algorithmic representations. This would also allow the utilization of several tangible objects concurrently, hence allowing the deployment of convoluted TUI interactions.

From an accessibility perspective, the TUI design needs to allow multiple users to interact with the surface simultaneously. This prerequisite affords the system to exploit an experimental and collaborative learning pedagogy whilst allowing the TUI system to be used by small cohorts of students together within seminar/laboratory sessions. Intrinsically, this requirement implies that the system needs to maximize the perimeter of usage for students, whilst also cater for students with different physical accessibility needs.

Within a HEI context, the design of a useable and convenient TUI system also needs to allow the system to be easily transferable between different laboratories and lecture halls. Thus, from portability perspective, the system necessitates a lightweight construction that can be easily transported within different buildings and compactable enough to fit inside conventional elevators. Moreover, this also implies that the system needs to be comfortably and quickly assembled/dismantled with no technical calibration procedures needed prior to usage.

Lastly, from an educational perspective, the TUI technology needs to ensure that students are able to focus on the conceptual subject being thought rather than the usability aspects of the system. This entails the need to simplify the interaction styles employed during operation whilst embedding assistive cues to aid with the teaching and learning of the specific HEI concepts.

B. Physical Design Considerations

The aforementioned requirements imparted a number of form-factor constrains on the system's physical design. Abiding with the architectural design guidelines by [34] comfortable reach and usability were ascertained by limiting the overall height of the system to a maximum of 90cm as illustrated in Fig. 2. This height was also identified in order to allow a group of students to gather around the TUI system and ensure that they can all easily visualise the entire tabletop area. From an education aspect, the design consideration would thus be able to allow all students, even ones not directly using the TUI system, to observe the information being projected as well as all the TUI component's being used. This would intrinsically aid the delivery of the chosen subject as well as heighten the engagement of the entire student cohort.

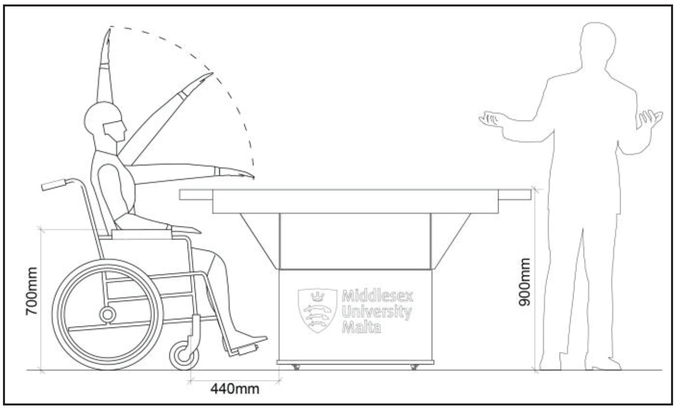

Fig. 2. TUI form-factor in consideration of accessability and useability constraints

Whilst abiding to the accessibility constraint, the form-factor of the proposed TUI system needed to maximize the interactive surface area dimensions which impacts critically the scope and usability of the smart technology. To address this requirement, a 4:3 aspect ratio was selected for the interactive surface design as intrinsically this would yield a larger workable area for TUI system. To this end, a 3mm semi-transparent acrylic was used for the interactive tabletop covering an area of 1.3m^2 (1.3m x1.1m). The latter was attached to a solid frame made from aluminium laminated composite for structural rigidity. As shown in Fig. 3(b), illuminating this area within such a short distance necessitated the use of a short-throw projector which was installed beneath the tabletop so as to eliminate any projection shadows which user would experience whilst interacting with tangible objects.

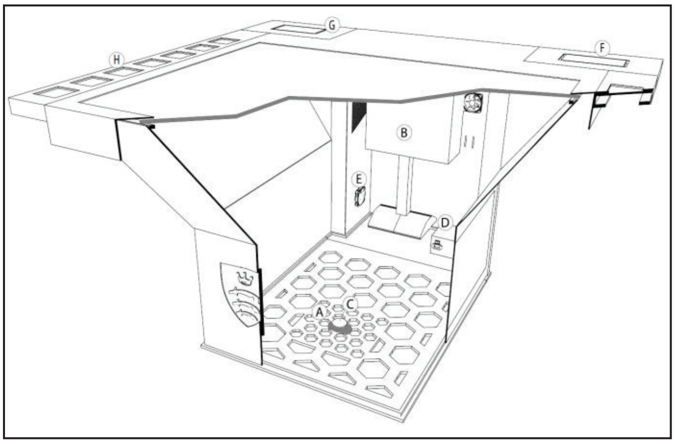

Fig. 3. Construction cross-section of the proposed smart TUI system design:
a) Wide-angle CCD camera with IR band-filter,
b) Short-throw projector,
c) Honeycomb PVC floor structure,
d) Processing computer,
e) Active cooling system,
f/g) Raising & Revolving TUI platforms,
h) Side trays with illuminated TUI placeholders

The smart technology proposed, provides feedback to the system from the recognition and identification of objects manipulated by the user as per the architectural framework depicted in Fig. 1. To avoid capturing occlusions from interacting users, a wide-angle CCD-sensor camera was installed underneath the surface as illustrated in Fig. 3(a). This placement option imparted a thickness constraint on the material selection of the interactive surface and thus a 3mm surface was purposely adopted to minimize the refraction of light through the semi-transparent acrylic pane. To further aid the capturing imaging quality, an infrared (IR) light 830nm band-filter was attached to the camera and an array of IR LEDs installed inside the table. Apart from flooding uniformly the captured area, this design approach aids in mitigating the light intensity variation arising from the projected images with different colour brightness and consequently aids in removing imaging constraints for TUI software development.

The portability constraint was abided by in the proposed design by undertaking numerous considerations in both material selection and construction. Aluminium laminated composite was chosen as the ideal material to build the main structure of the table. This material posits several advantages over traditional wood including; smooth finish, overall strength, absence of splintering, and less environment-dependent alterations or expansions which could lead to misalignment of the table components from the interactive surface. Furthermore, owing to the inherent rigidity of this material, 3mm thick sheets provided enough structural strength, whilst significantly curtailing the overall weight of the TUI system. To further contribute to the lightweight construction of the proposed system, PVC boards where installed at the base of the table, which as seen in Fig. 3(c), was perforated in a honey-comb structure to curb weight whilst aiding air-flow for cooling of active components inside. Transportation of the designed TUI system throughout the campus lecture halls and through elevators was rendered possible using castor wheels and appropriately designed hinged side panels as illustrated in Fig. 4. These panels were held in their different positions using neodymium magnets, hence rendering the proposed system easily assembled/compacted. Moreover, to mitigate the burden of technical calibration needed to align the camera setup and digital projection to the interactive surface, all active components are permanently affixed to the honeycomb base, thus retaining accurate positioning during transportation and reassembly.

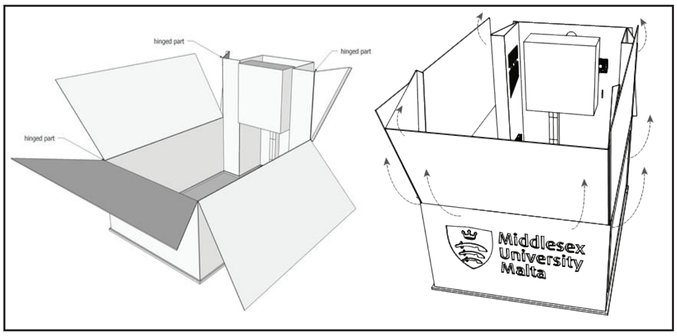

Fig. 4. TUI form-factor in consideration of portability constraints

C. Smart Perhiperals

In contrast to setups proposed in literature [35-37]. the proposed TUI system design embodies a number of innovative peripheral technologies to aid in the effectiveness of teaching and learning. Designed in a modular approach, the proposed system makes use of the TUI-enhancing technologies, illustrated in Fig. 5, to help engaging students whilst enhancing the usability aspects of TUI systems. These smart modules, which are attached to sides of the TUI interactive surface are controlled through an Arduino microprocessor and directed via serial communication from the TUI software executed through the computer.

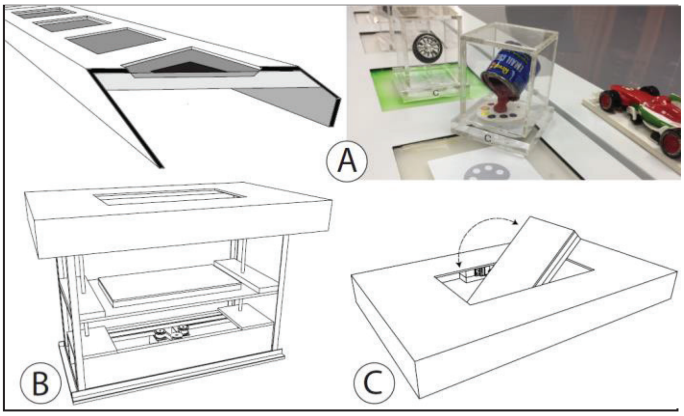

Fig. 5. Innovative TUI smart technologies embedded in proposed system:
a) Side trays with illuminated TUI placeholders,
b) Raising TUI platform,
c) Revolving TUI platform.

The placeholding trays, shown in Fig. 5(a), were designed as attachments on either side of the system's tabletop which serve to hold tangible objects that would not be currently in use. Apart from reducing object clutter on the interactive surface, the placeholders were designed with individually-controlled RGB LEDs. This functionality was designed to provide interactive feedback to the user whilst using the TUI system using a combination of flashing and/or colour-coded lighting. These algorithmically controlled cues were in fact able to direct student's activities by either prompting the selection of a particular object or even evidencing the options of object choice for the student as a result of a previously performed action on the interactive TUI surface.

The smart raising and revolving modular platforms, illustrated respectively in Fig. 5(b) and Fig. 5(c), are contrastingly used to provide students with a different interactive experience. Marking use of individually-controlled servo motors and integrated RGB LEDs, these modular devices are able to reveal tangible objects that would not have been available beforehand. By capitalizing on the curiosity aspect of an appearing tangible object throughout the execution, the proposed smart system is able to positively condition the student's interaction to investigate the effect of the appearing object. Furthermore, the revealing effect of these technologies intrinsically heightens interest within students and thus serves to enhance their engagement with the TUI system.

IV. SYSTEM EVALUATON AND DISCUSSION

A. Experimental Methodology

To evaluate the applicability of the proposed smart system, a typical TUI case-scenario was implemented at Middlesex University Malta within an undergraduate degree in Computer Science. First year students reading a module on 'Introduction to Java programming' were chosen for evaluation. The delivery of object-oriented concepts formed the threshold concepts within the syllabus, and the evaluation session was timed to concur with the scheduled delivery of a particular lecture introducing the concept of instantiation of objects from classes.

Student selection was based on a convenience sampling approach and the selected class was composed of forty-one students (41) ranging between the ages of seventeen (17) to thirty-nine (39). The students were not forewarned about the upcoming research study and following their normal attendance to class, a split was undertaken to divide the class in two groups. Twenty (20) students were randomly chosen for inclusion within the experimental group, whilst the remaining twenty-one (21) students were grouped to form part of the control group.

Subsequent to the split, each group underwent a lecturing delivery of the same topic in a different room. The control group were introduced to the concept of programming class abstraction and instantiation via a traditional lecturing session. This made use of conventional educational technologies such as an overhead data-projector, smartboard and a PC laboratory. Conversely, the experimental group were subjected to a lecture of the same technical object-oriented concepts using the proposed TUI system via an appropriately designed software as illustrated in Fig. 6. In both instances, the tuition session was conducted for a fixed-time period by the same designated lecturer and the same car-based analogy was used to explain different object instances. These variables were monitored so as to ensure minimal bias between the control and experiment group.

Fig. 6. Evaluation session of the proposed TUI system for teaching and learning object-oriented concepts using a car-based analogy.

Upon completion of each respective session, students were provided with a short survey to quantify their experience. Five (5) statements were posed to each student, for which a seven-point Likert scale was adopted to rank preference, ranging from strongly disagree (score: 1) to strongly agree (score: 7). The questions were structured to assess different aspects of the student's educational experience as follows:

1) *Perceived Usefulness (PUST):*
   Through the technology I have learnt the subject effectively.
2) *Perceived Enjoyment (PENJ):*
   I had fun using the educational technology.
3) *Ease of Use (EOU):*
   The used technology was rather difficult to operate.
4) *Interactivity (INT):*
   The feedback was intuitive.
5) *Lecture Attention Span (LESP):*
   I felt very attentive during this lecture.

B. Results and Discussion

The survey technique was designed to provide a quantitative evaluation of the student's perception on the use of the proposed smart TUI design within the context of HEI lecture delivery. The obtained results from participants were tabulated in Fig. 7 whereby the responses for each question by the different student groups are averaged.

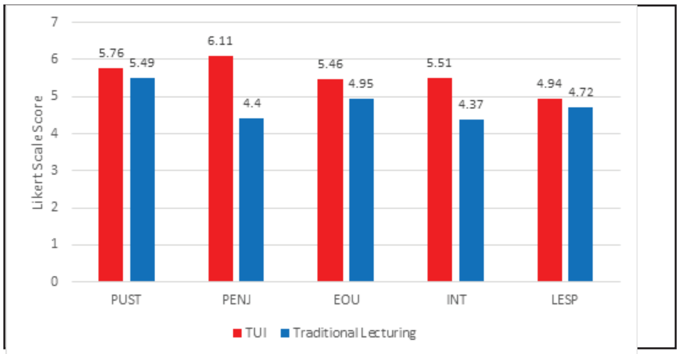

Fig. 7. Student evaluation of proposed TUI system with respect to traditional educational technologies using a likert-scale ranging from strongly disagree (score: 1) to strongly agree (score: 7).

Fig. 7 clearly highlight that the overall experience of students using the proposed smart TUI system was enhanced. Major improvements were in fact measured in the perceived sense of enjoyment whereby students undertaking the lecture registered a more pleasurable learning experience with an average score of 6.1 (SD: 0.82) with respect to the traditional lecture control group 4.4 (SD: 0.73).

A qualitative interview with the lecturer following both sessions also corroborated the observation that student engagement was significantly higher during the TUI session with respect to the control group. This intrinsically prompted students making use of the TUI system to discuss and collaborate together during the lecturing session. These observations were substantiated by objective measurements, undertaken on students, which outlined that the TUI provided a more immersive experience and required less time to grasp the concept successfully. On the other hand, it was noted that handling large groups becomes increasingly challenging with the TUI system, and students far away from the perimeter tend to be less intrigued with the system.

V. CONCLUSION

The paper introduced the formalized design of a tabletop tangible user interface for adoption within higher educational institutions. With difference to current limitations in literature on TUI usage, the proposed design takes into consideration the design criteria needed to maximize the operational success of a smart TUI system within the educational context. The proposed novel aspects were further implemented within a University's undergraduate degree programme and an evaluation process conducted during the introduction of object-oriented programming concepts. Following the equitable analysis of the obtained results, it has been objectively quantified that the smart TUI system proposed was able to enhance the teaching and learning experience of students, hence outlining the ability of this technology to be effectively adapted within HEI contexts.

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