Sánchez, J. (2017) Editor. Nuevas Ideas en Informática Educativa, Volumen 13, p. 188 - 194. Santiago de Chile.

Tangible User Interfaces; concepts and practice

Javier Mauricio Reyes Vera
Professor Universidad del Valle
Cali, Colombia
CAMALEÓN, Grupo de investigación
Tel: +57 2 3212375
javier.reyes@correounivalle.edu.co

Paola-J. Rodríguez-C
Professor Universidad del Valle
Cali, Colombia
CAMALEÓN, Grupo de Investigación
Tel: +57 2 3212100 ext. 2598
paola.rodriguez@correounivalle.edu.co

Ivette kafure Muñoz
Professora Universidade de Brasilia
Brasilia, Brasil
Grupo de pesquisa em Comunicação e Mediação da Informação
Tel: 61 3107 2632 e 2633
ivettek@unb.br

ABSTRACT
In this paper, we build a review of Tangible User Interfaces from two perspectives: 1) a conceptual view, through the systemic study of the state of the art in order to consolidate TUI's definition and classification, as well as characterize the elements that compose it (user-object and object-object relations). And, 2) the most used development methods. From a Technological viewpoint, to the development of a prototype that illustrates the way in which conceptual elements are combined. Finally, an analysis of the scope and applications of the TUI in the educational field is offered.

Categories and Subject Descriptors
[**Human-Centered Computing**]: Human Computer Interaction (HCI) – *Interaction Paradigms.*

General Terms
Design, Experimentation, Human Factors, Theory.

Keywords
Prototypes, Tangible User Interface, Taxonomies.

1. INTRODUCTION
Although the fist purposes of Tangible User Interfaces -TUI- have arisen in the academic literature since the end of the Nineties, it has recently gained in popularity in the academic-research field. A TUI, is referred to as a way to allow the manipulation of digital information through physical elements, that is to say, tangible objects that represent virtual information [1]. However, defining what are the TUI, characterizing their elements and their development methods leads to diverse answers depending on the creation purpose, as well as the identification techniques of recognition or association between the objects that compose it, such as barcodes, QR, fiducial markers, NC or RFDI labels, among others. Closing, the TUI allows a new way of interaction between the user and the digital information, where the user experience becomes a key element in taking advantage of the physical interaction, thus the contact user-interface is more direct [2].

Consequently, the main advantage of TUI is that the interaction is more natural compared to conventional user interfaces because the physical objects reflect the shape or movements of the real world, thus the user only need know what the interaction with the physical world is like to understand the meaning of interface and how to manipulate it. Additionally, this kind of interface permits the interaction of multiple users.

According to the above, this paper intends to consolidate a definition of TUI from a conceptual perspective, to characterize the elements that compound them from a technical and technological point of view, also to comprehend the way in which these elements are combined from the development of prototypes that allow us to glimpse its scopes and applications, mainly in the educational context.

2. TANGIBLES USER INTERFACES

2.1 Characterization
The beginning of TUI was influenced by works from diverse fields such as architecture, product design and educational technology. One of the first motivators was called *Slot Machine* [3] which consisted of a series of plastic plug-in boxes for helping to teach programming to children, it had the fundamental idea of allowing the manipulation of language constructs (actions, numbers, variables and/or conditions) in a pedagogical and direct way. Subsequently, the notion of [4], "*Graspable user Interfaces*" arose, this is a seminal work in the TUI area, it consists of the use of blocks to represent three key ideas: 1) physical artifacts that act as manipulated controls; 2)the advantage of experience of the physical world for people; and, 3)the multiplexed devices for space and time. Another relevant work was [5] cited on [6] whose objective was to achieve a better rapport with the users and more direct communication with the architects, it made use of 3D modeling and implemented strategies that allowed the

manipulation of a set of elements to establish an adequate space from a set of blocks.

Thus, the TUIs propose a new interaction paradigm with digital information where the user relates to the information by manipulating the data with their own hands [7].

Otherwise, the TUIs take advantage of the human haptic interaction abilities to give physical interactions from digital information. These representations turn into model-control of the information, despite facilitating the direct manipulation and a multisensory interaction. The TUI permits work in the real world with a model based on gestures and actions of context applications. They also facilitate cooperative interaction based on human skills to form better associations with tangible elements [8]. It allows a more meaningful user interaction and immersion [7].

According to the above, the elements of a TUI that differ from other kinds of interface are the set of physical objects of which they are composed (tokens & constraints) [9], *prop* [10], or *pyfo* [11]; and, they have the ability to respond to the interactions and interplays.
The *interactions* refer to the relationship user-object where the user directly handles the physical object and performs actions over it (such as shaking, pressing, turning, moving, etc.); or, related to another object.
The interplays referring to the object-to-object relationship (coupling, proximity, overlap, among others) are the result of a user interaction with the TUIs.
The conjunction of the elements, cited above, permits the establishment of different classifications for the TUIs, as presented in the next item.

2.2 Taxonomy of TUI

According to [12], the TUI have the following characteristics that must be considered in a taxonomical analysis.
Connection: The TUIs present a link between objects and the digital information that they represent. It can be dynamic or static.
Objects: TUIs imply objects that interact with the user and they have an interplay. Both are possible because of the spatiality, with relationships or with connections.
Embodiment: TUI are defined as the input-output method and are related in the physical space occupied.
Metaphor: The physical artefacts that compose a TUIs represent a particular thing to the user (mainly the analogies to the physical world).

Thus, we propose a taxonomy in which the TUI can be matched according to four criteria: *1) By the inference ability, 2) by the construction method, 3) By input and output; and, 4) By the metaphor used*. Directly below, each one is briefly explained [13], [14]:

1. *By the inference ability:*
   - ✓ ***TUI 'Reactives':*** This occurs when TUIs physical objects generate a response to the manipulation of another object that can be physical or digital. [15].
   - ✓ ***TUI 'Intelligents':*** Some objects from the TUI have the ability to identify other objects and respond to the captured variables from the other [16].

2. *By the construction method:*
   - ✓ ***Interactive Surfaces:*** These are capacitive displays that show digital information from the movement detection, identity and relationship through the objects [17], [18].
   - ✓ ***Auto-informative pieces:*** Here the physical objects have the ability to show information and change the properties from the interaction [19].
   - ✓ ***Tokens and Constraints (TAC):*** These establish a direct relationship according to the real engagement between the objects [2], [12], [20], [21], [22].

3. *By input and output* [23]*:*
   - ✓ ***Full:*** Input-Output device where each action is reflected.
   - ✓ ***Near:*** The output is near the object.
   - ✓ ***Environmental:*** The output is around the user or the environment.
   - ✓ ***Far:*** The output is in a different space, maybe another display or room.

4. *By the metaphor used:*
   - ✓ **Level 1. None:** an associated metaphor does not exist because the manipulation is not linked to the real world [24].
   - ✓ **Level 2.**
     - o **Noun:** it is analogous to the physical shape, appearance and sound of the system object. [25].
     - o **Verb:** associated to the action that is made [26].
   - ✓ **Level 3. Noun and Verb:** it is presented as a complete metaphor in which an action in a noun is one representation of an action in a noun of the real world [23].
   - ✓ **Level 4. Full:** a metaphor is not needed because the virtual system is the same as the physics [23].

The taxonomy established in this item shows a set of elements at starting point for the development to TUIs from a technological and conceptual point of view. It will be explained in section 3.

2.3 Design and Creation of a TUI

According to [20], the creation of a TUI is a complex process that implies multidisciplinary knowledge in computer science, Human Computer Interaction, Art (Digital Art, User interfaces Design) and Social Sciences. However, in practice they can be summarized as a synergy of three areas of knowledge where it can be not only the interaction (object-to-object) but the interplay (user-to-interface). These areas are: digital electronic, computer science and design (graphic and industrial) [13].

So, the contribution of each one will be explained.

- ✓ ***Digital electronic:*** It is necessary to known about top technology for the development of prototypes and end products, this is shown in the correct use of integrates, actuators, sensors, and analog-digital electrical connections.

- ✓ ***Computer Science:*** is conceived as a binding area because it makes sense of the electrical connections through the programming; thus, the main input is through interaction and interplay.
- ✓ ***Design (Industrial & Graphic):*** *´Graphic Design´* contributes through identity, the image, icons design and the composition; ´Industrial Design´ is an area that helps with object creation and the direct relationship to people. It is defined in Ergonomics (physical - cognitive), materials and process. And, development of the shape of the objects for an appropriate manipulation for the user´s individual needs.

Once the areas are clarified, it is important to take into account the elements that must be considered for the creation [20]:

- ✓ ***Modelling requirements:*** visualizing of constructs, being standard, being comprehensible, allowing for the general description of the problem, allowing for the representation of a wide range of TUI; and, it must be of a specific domain.
- ✓ ***Constructs:*** physical objects, hardware, software, sensors and actuators.
- ✓ ***Relations:*** between physical objects, between hardware components, between software components, between hardware components and software components, between physical objects and software components and between hardware components and hardware components.
- ✓ ***Modelling:*** realization of modelling UML for TUI
- ✓ ***Implementation:*** related to the constructs according to the modelling.

Consequently, the modelling of a TUI differs from conventional modelling of software (web or mobile); for this reason, in academic literature, different methods have been found for the development at [9], where they propose a set of diagrams that abstract the relationship between objects but do not describe the digital dimension; otherwise, authors like [10], [21], [27] make a visualization of TUI schemes. This is a very important issue in conceiving the complexity in its implementation; but, the elements for modelling are not clear yet, such as physical modelling with its components and the User Experience.

Thus, to develop a TUI one needs to adopt methods and tools from diverse areas. In [28] they used the method proposed by Pugh [29] cited on [28], which consists of a set of interactions with activities that permit gradual procedure in the product life cycle. In figure 1 the purpose is shown. Next, the general aspect will be explained.

1. Idea generation: uses brainstorming techniques to generate ideas, storyboards to define details and general sketches.

2. Concept definition: low fidelity prototypes, stages, conceptual maps.

3. System prototype: The concept is divided into mechanical and technical sub-problems for making functional prototypes with integrated cards (Arduino, Raspberry, etc.). This is important for interactions.

4. Integrated prototype: All the sub-solutions are integrated into a final prototype; a flow chart is used for communicating the different components and visualizing the interaction with the scheme. A 3D press or laser cut is made for developing the final prototypes. The plates are printed to refine the dimensions of the prototypes.

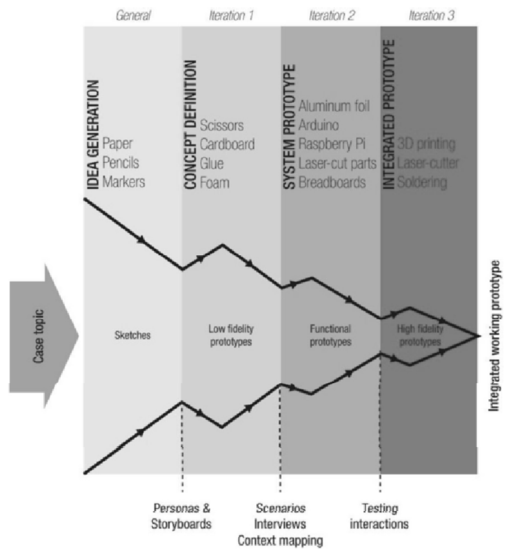

Figure 1. ***Method proposed by Pugh*** [29]

Likewise, in (Carandang & Campbell, 2013; Coutrix et al., 2013; Guan, Qin, Hou, & Linhong, 2014; Hornecker, 2005) explain this process as a kind of black box where the design and its development evolve with poor documentation. This is evidence of integrative methods for the design of a TUI.

Otherwise, the evaluation phase of TUI is made of functional empirical tests with final users [2], [35], [36]. In general, the test looks to measure the user facility, the metaphor and the rate of satisfaction, where video is used as a main tool.

In this way, the evaluations found are comparative studies, frequently, laboratory quantitative studies, heuristic evaluation and direct observation [11]. The comparative studies try to quantify the cost and the tangible interaction benefits compared to other interaction styles GUI (*Graphical User Interfaces*).

2.4 TUI educational applications

Certainly, the context which has had the most developing TUI prototypes has been education, as stated in [37] research and learning theory pursue the role of personification, physical movement and multi-modal interaction. Also, gesture can stimulate learning and thinking [38] cited in [11]. In this way, the characteristics of the TUI are potentiated in the educational area. Nevertheless, in the literature revision, only were found generic and conceptual frameworks; thus, the development of educational specific tools is an open research field. Below some proposal applied education, but the developing process, do not include artifacts that reflect the educational design.

As an example of the above, some interesting works are *´Tinkersheets´* which support logic learning by paper-based tangible simulations [39], *´Illuminating Clay´* a learning environment of holography and optics. Other TUI prototypes combine learning and entertainment such as learning toys and museum facilities [40] [41], *´Digital Manipulatives´* are a kind of teaching toy regarded as building kits, building blocks and Montessori materials that allow children to explore basic programming concepts[24][42].

Likewise, *´Lego Mindstorms´* are a kit for building robots and enable children to design simple robots without any knowledge of electronics or computing [42], *´Pico Crickets´* allow users to create their own scientific devices using sensors, triggers and robotic parts without needing any advanced knowledge[1], *´Computationally enhanced construction kits´* that are blocks that allow building models and learning by means of the interaction; and, the *Smart Blocks* are a kind of augmented math in which students are able to explore volume and area concepts using a 3D surface made by themselves [43] cited in [6].

Other interesting examples are [44] a TUI for solving programming problems, inclusive education [45], tools for simulation, information visualization in music and social communication.

Furthermore, some works show the TUI support collaborative work such as [46], [47], [48], [49], [50] cited in [51] and significantly improve user experience [52], [53], [48], [54] cited in [51] because they help to stimulate different senses (sight, hearing, smell), and even promote greater inclusion of people with disabilities [7].

While there has been extensive development of TUI prototypes in the area of education, it has not been possible to find out how the educational component is regarded and modeled in the process of creating the TUI prototypes.

3. EARLY PROTOTYPES

In the context of the research project "Guidelines for content and information design for TUI", funded by the *Universidad del Valle* a set of prototypes were developed that evolved in complexity and allowed the exploring of different technologies. Each prototype has its evaluation process with a small end user group. A *Touch Board* was used for its development, which is an electronic device compatible with Arduino®, and an electric ink called Electric Paint.

The first prototype was *Carta-Menú,* a menu TUI that speaks the name of a set of restaurant dishes according to the user selection. This prototype allows us to understand *Touch Board* and Electric Pink fundamentals. The second one was *Touch-TUI* prototype that simulates a musical instrument (a piano) by means of a cardboard surface. With this prototype, users can play tunes using first octave notes. The third prototype was an improvement on Touch TUI. It is called *MIDITouchTUI* and its main contribution is understanding how to connect the TUI with a computer program. For the prototype, that little change meant that MIDITouchTUI could be used as a component instrument that has the ability to reproduce sounds of other types of instruments. Finally, *AnimalesTUI* was developed (see Figure 2), a TUI consisting of a cardboard surface and 12 tokens representing a set of animals. Once the user places each card in its corresponding position on the surface, an audio feedback and the projection of a video associated with the selected animal is generated [13].

Figure 2. ***AnimalesTUI*** **prototype**

The development process of this last prototype will be shown as follows, illustrating the conceptual elements set out in the previous section:

- ✓ **Level 1. Basic Description**: *AnimalesTUI* is a tangible application that associates tokens with shapes of different animals on a surface. When the token is placed in the correct position on the surface, a sound and a video are played enabling the children to know more about that animal.

- ✓ **Level 2. Identification and association of structural elements:** *AnimalesTUI* is classified as a Token and Constraint TUI where the surface limits the tokens behavior because tokens must be placed in a specific way on the surface in order to get system feedback. Additionally, this prototype allows us to implement an interaction (user-token relation) and interplay (Surface-token relation).

- ✓ **Level 3. Metaphor description:** the figures associated with the tokens used in the TUI are closely related to the shape of animals in the physical world and cartoons will be used rather than real photographs.

- ✓ **Level 4. Functional Aspects**: AnimalesTUI will be supported by a Java application that will use a *javax.sound.midi* for reading MIDI devices. Code is made up of three classes: *LeerMIDI* (responsible for reading the MIDI drivers), *Main* (contains interface visual elements) and EntradaMIDI (manages the touch board card pins and generates the feedback, taking into account the pin selected by the user). Furthermore, the touch board card was previously programmed to behave as a MIDI controller.

- ✓ **Level 5. User case diagram:** Figure 3, shows the essential functionality of the prototype that is generated when the user takes and places the token on the surface.

[11] https://picocricket.com/

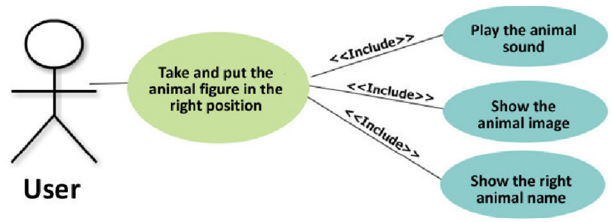

Figure 3. Essential User Case for *AnimalsTUI*.

- ✓ **Level 6. Paper Prototype:** that is synthesized in figure 4, and shows the initial sketch for AnimalesTUI.

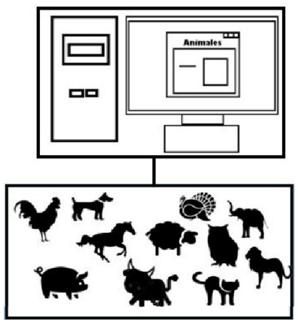

Figure 4. Paper Prototype for *AnimalesTUI*

- ✓ **Level 7. Dialog Diagram**: this diagram was omitted because it did not provide greater informative value for the development process. This is because only one interaction was implemented.
- ✓ **Level 8. Task Diagram:** this is one of the most important diagrams found in the literature which allows us to illustrate the interactions at the physical level of the TUI. However, as mentioned in the previous section, the computational events that must occur when physical interactions occur is not modeled by this diagram. In this way, we propose the use of pseudocode to complement this diagram. Figure 5 summarizes the events generated from the physical world and the behavioral modeling of the digital world for *AnimalesTUI*.

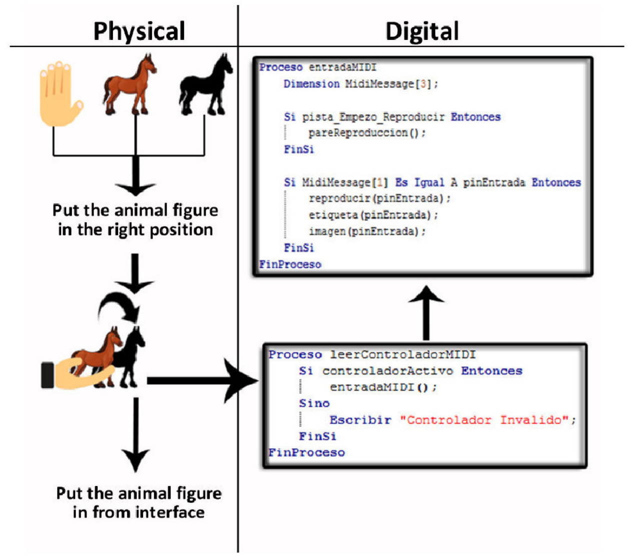

Figure 5. Improved task diagram with pseudo-codes as mechanism for modeling the digital world

As we can see, the modelling diagram allows the representation of the TUI elements in an abstract way and their relationships. Nonetheless, the task diagram is an integrator medium because it allows us to link other views of modeling (as the pseudocode proposal that represents the digital world); how would it fit in the educational context; and, the identification of the elements that compound the pedagogical aspect using TUI.

In summary, for prototype evaluation the task script was established (what to do? - description of task without asking ´How?´ in order to discover communicative break points), an evaluation plan (where the main objective is planned, population, the evaluation process, consent release form); characteristics and comments (to write some conclusions according to user behavior in the tests); absences (the missing prototype elements are high-lighted); a heuristic evaluation (where the usability principles were evaluated); and, conclusions.

With the above in mind, a set of observations was obtained by improving the design (modifying or selecting an analogy from the real world to make it easier for the TUI user to understand). In most of the cases, the final users quickly got used to interacting directly with the interface. This helps to prove that the modelling proposed allows us to improve the prototypes´ implementation.

4. CONCLUSIONS AND FUTURE WORK

The main conclusions of this work are that:

- ✓ The definitions of TUIs are obscure because it is a relatively new technological proposal; however, clearly there must exist minimal elements where the physical relation to the user is the target which gives the TUIs a new interaction paradigm status; and, it is more akin to the reality of the user.
- ✓ The existing modelling methods can be framed in a conceptual category because this allows the TUI to be presented in an abstract way. The task diagrams can be used as integrator artefacts which help to link other views of the

modelling process. For example, in the prototypes, we used pseudocode to represent the operations with the digital world according to the physical actions generated.

- ✓ Specific methods or techniques for evaluation of TUI are not found in the academic review. However, an empirical test was certainly used with a few sets of final users, taking into account the measure of the ease of use, validating the metaphors and satisfaction. The favorite forms of registration are videos that, generally, work with observation methods and some heuristic cases.
- ✓ During the prototype implementation process, it was necessary to listen to user-expert opinions to ensure its functionality, which shows the need to form an interdisciplinary group with at least one expert in electronics, in industrial/graphic design, and in programming.
- ✓ Education has so far been a favorite area for the TUI prototype construction. Nonetheless, Education is an accessible working area for the generating of guidelines and artefacts that allow us to shape teaching decisions associated with the physical interaction of TUI.

In future projects, we anticipate testing touch surfaces, image recognition, different kinds of sensors combined with Augmented Reality to provide the best quality interactions. Additionally, we intend to suggest guidelines and artefacts for the educational component in order to undertake a complete study of the education-TUI relationship.

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