Mapping Physical Objects to Digital Functions: a Tangible Interface for Querying and Navigating a Multimedia Database

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***Abstract*—In this work we propose a set of guidelines for tangible interfaces (TUI) for mapping physical objects and digital functions. These guidelines emphasize an aspect that has been only partly analyzed so far in TUI research: the role of the object shape as a means for suggesting how to manipulate the artifacts. The peculiarity of the proposal - general enough to be used for different application domains - is the mapping to discrete and continuous digital functions based on the type of surfaces that define the physical artifacts of the interface. The application of the guidelines to a widely diffused task, the query and navigation of a multimedia database, and its evaluation with a class of students gave us interesting insights about the appropriateness of the mapping and its learnability.**

***Keywords*-affordance; data query and navigation; discrete and continuous digital function; guideline; surface; TUI**

I. Introduction

Tangible user interfaces (TUI), that take advantage of physical artifacts for controlling and accessing the state of digital functions, are gaining popularity, mainly because of the increased pervasivity of the use of computers in terms of places, types of activity and time. In this work we propose a set of guidelines for TUI for guiding the mapping of the physical artifacts to the digital functions. A peculiarity of these guidelines is that they emphasize the role of the shape of the objects. While a relation between the morphology of the objects and the different types of digital functions has been suggested in literature [3] and some implementations have considered this issue [5], these guidelines are based on a deeper analysis of the qualities of the surfaces that make the solids. In particular these guidelines focus on the analysis of flat and curved surfaces, mapping them to discrete and continuous digital functions. The approach represents a novelty in relation to most of the TUI implementations realized so far, where often sets of the same geometric shape are used, even when such shapes are mapped to different types of variables. Besides, our proposal is characterized by a higher generality that permits its application to different interactive tasks. In this work the guidelines are applied to the design of a TUI for querying and navigating a database. This specific application was chosen because it is widely diffused and it includes activities, such as the selection and the navigation, that are representative of the interactive computing. The evaluation of the prototypical application with a class of students gave us interesting insights in terms of the appropriateness of the mapping and of its learnability, an initial result that encourages further experimentations for other applications domains.

II. Related Work

The term tangible user interface (TUI) was coined in 1997 [6] referring to systems that augment the real world by coupling digital information to tangible objects. As analyzed in a recent survey [7], different frameworks have been proposed for mapping the different TUI implementations into an unified vision or for suggesting guidelines and best practices for designing them. Unfortunately most of the approaches don't take into proper consideration the role of the shape, as suggested also in [2]. The latter work evidences how the attention towards the form is part of the product design tradition, but not yet part of the TUI design. We have tried to make a step further on this respect, on the top of the [3] and [9] frameworks, considering in detail the morphologic qualities of the surfaces. Ullmer et al. [9] propose an interesting classification of TUI, focused on the relation between *tokens*, graspable physical objects that represent digital information or a computational function, and *constraints*, complementary physical objects that limit the behavior of the tokens. The framework proposed by [3] is one of the few works that consider explicitly the issue of mapping physical objects to discrete and continuous information attributes, recommending a physical syntax for expressing them. In most TUI implementations the designers use the same type of shape for mapping both types of functions, underestimating its role as a cue for suggesting the connection with different types of variables. The Tagged Handles [5], where continuous controllers are associated to objects that express one or more discrete states, are one of the few implementations that consider explicitly the issue of a simultaneous mapping of discrete and continuous digital functions to physical objects. What we have tried to do is to define a general approach, for guiding the designer in different application contexts. A number of researchers [1] [9] have proposed TUI for navigating information systems related to different domains. In particular Camarata et al. [1]

designed and implemented a TUI based on a set of tangible labeled cubes for exploring historical information databases. In the Tangible Query Interfaces by Ullmer et al. [9], a set of wheels are used for representing both continuous and discrete database parameters. What distinguishes our approach from the cited query interfaces is the mapping of the geometric shapes to digital functions based on the type of surfaces that define the solids.

III. Guidelines for Mapping Physical Objects to Continuous and Discrete Digital Functions

The guidelines that we propose are focused on the objects morphology and exploit the cues given by the different types of surfaces that define the physical limits of the TUI objects. In particular, we recommend to:

1) map a single value/state of a discrete digital function to a flat surface;
2) map an interval of values of a continuous digital function to a convex surface;
3) map a state of indeterminacy of the value of a digital function to the edges of the associated surface.

The rationale behind these guidelines is to take advantage of the morphologic qualities of the different surfaces that compose the artifacts, that can be easily identified by the user, as a cue that suggests the relation with specific types of digital functions. The lack of variation of a flat surface (see Fig. 1 on the left) is associated to a specific value of a discrete function, while the smoothness and progressive variation of a convex surface (see the center of Fig. 1) is associated to the progressive variation of the values of a continuous digital fuction. Finally, the sudden variation that may characterize the edge of a surface is associated to the indeterminacy of the value of a digital function. For improving this cue, we suggest to use edges with no tangential continuity (G1), as the one visualized in Fig. 1 on the right. While the selection mechanism of specific values of the discrete and continuous variables may be different, in this work we anchor it to the relation of the physical artifacts with one or more flat constraints. Constraints have a special role in guiding the manipulation of physical artifacts, as underlined in [9]. In this work we exploit the specific visual and haptic feedback that derives from the contact of the different types of surfaces of the artifacts with them. For designing the selection mechanism we have focused in particular on flat constraints (e.g., a table, a pavement, etc.), because they populate most of the inhabited spaces that may host a TUI. For this reason we have limited our interest to artifacts made of flat and convex surfaces, because all their points can be put in contact with this type of constraint. Concerning the first situation of use (flat surface and flat constraint), we consider a specific value/state as selected when all the points of the surface are in contact with the constraint (see Fig. 1 on the left). The selection of a specific value can be easily haptically identified by

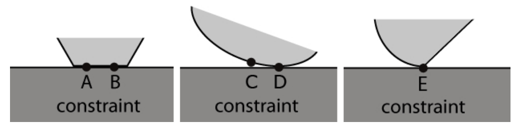


Figure 1. Relations between surfaces, edges and constraints

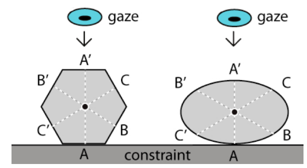


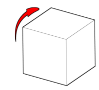
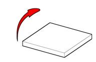
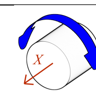
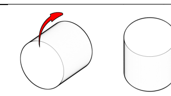
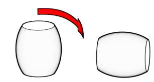
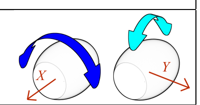
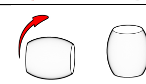
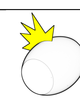
Figure 2. Relations between the user gaze, the artifacts and the constraints

the user that manipulates the object. In many situations, for example in the case of regular geometric objects, this spatial configuration can be kept even when the user doesn't touch the object anymore, because it represents a condition of stable equilibrium. Concerning the second situation of use (convex surface and flat constraint), we consider a value of the continuous digital function as selected when one or more points of the convex surface are in touch with the constraint (e.g., one point for a spherical surface, a set of points for a cylindrical surface). Any incremental motion of the convex object that redefines the set of points in touch with the constraint (e.g., the point D instead of the point C, see the center of Fig. 1) determines the association with a new value of the continuous variable. The transition between different values of the same digital function corresponds to a sense of smooth rolling on the constraint that can be clearly haptically identified by the user. For both types of surfaces a manipulation that leads towards one of the edges is transformed into a rotation along the edge points and can be clearly haptically perceived by the user (see the point E in Fig. 1, on the right). The adoption of symmetric objects - such as prisms, cylinders or spheres - and the application of textures to the surfaces permits to give to the user an additional visual feedback about the currently selected digital value. As shown by Fig. 2, the adoption of this recommendation allows to present to the user gaze the state of a digital variable selected on the opposite side of a geometric object made of flat or convex surfaces. The solution represents a generalization of what happens for simple dices or, in TUI research, for what has been conceived for proposals such as the Navigational Blocks [1].

IV. Applying the Guidelines to the Query and the Navigation of a Multimedia Database

We applied the guidelines, conceived for supporting the design of TUI for different application domains, to a widely diffused task, the query and navigation of a multimedia database. The implementation and the following evaluation gave us interesting insights about the appropriateness of our approach. The specific case study was focused on the query and navigation of a database of about 200 images, characterized by discrete, continuous and Boolean parameters: six different *categories* (nature, architecture, people, objects, culture, space), a continuous interval of levels of *brightness* and the declaration of a *copyright*. The implemented application allows the user to express the values of the parameters of the query and to navigate the results through the manipulation of a set of physical objects. The user receives both an haptic feedback given by the manipulation of the physical objects themselves and a visual feedback given by the physical objects and by a front screen where the multimedia objects extracted by the database are visualized. The mappings between the surfaces and the digital functions, compliant with the guidelines described in the previous section, is resumed in Table I. For the query phase, we had to map the selection of the query parameters values. The discrete and the Boolean variables of the query were mapped to a cube and a plate. Please note that the Boolean variable is a special case of discrete variable, characterized by only two values. The continuous interval of values of the continuous query variable was mapped to the convex surface of a cylinder. The planar surfaces of the cylinder were mapped to a state corresponding to the simultaneous selection of all the values of the interval. Most surfaces were textured for representing the parameters values and enhancing therefore the visual feedback. For the navigation phase we had to map three different functionalities: the navigation through the results, the zooming of a specific result and the change of state between the query and the navigation phases. Because of the scheme chosen for the visual presentation of the results (i.e., a grid of zoomable miniatures, see Fig. 3 on the right), the navigation functionality required to move along two orthogonal directions of the screen for selecting a specific image. We chose the shape of the barrel because the double convexity of its lateral surface suggested the association with the continuous variables corresponding to the translations along the x and y axes of the grid of images. The flat bases permitted the identification of the query state, alternative to the navigation. The increased complexity of the digital functions associated to a single object led us to consider the iconic shape of the barrel also for having an additional cue suggesting the meaningfulness of the act of pouring (see Fig. 3 on the left), related to the execution of the query. Finally, the image zooming was mapped to the act of tapping the barrel. Two constraints were introduced for guiding the manipulations of the geometric objects: a table and a cylinder support (see Fig. 3). The table invites the users to place the flat surfaces of the query and navigation objects in a number of positions of stable equilibrium, permitting to select values of a discrete variable or to identify the state of a discrete digital function. Besides, the table, put in relation with the convex surfaces of the cylinder and the barrel, suggests to roll the objects. The support for the cylinder

Table I
DIGITAL FUNCTIONS AND GEOMETRICAL SHAPES

digital function	geometric shape and manipulation
Selection of a value of the discrete variable *category*; each face of the cube is mapped to a discrete value: *nature/architecture/people/objects/culture/space*	
Selection of a value of the Boolean variable *copyright*; each face of the plate is mapped to a value: *true/false*	
Selection of a single value of the continuous variable *brightness*; the convex surface of the cylinder is mapped to a continuous interval of *brightness* values	
Selection of all the values of the continuous variable *brightness*; the bases of the cylinder are mapped to the selection of all the values of the interval	
Triggering of the query execution and shifting to the navigation of the results; the convex surface of the barrel is mapped to the navigation state of the system	
Navigation of the results; the rotations along the x and y axes of the barrel are mapped to the translations along the x and y axes of the visual grid of the interface	
Return to the query composition; the base of the barrel is mapped to the query state of the system	
Image zooming in and out; the tapping of the barrel is mapped to the zooming in and out function	

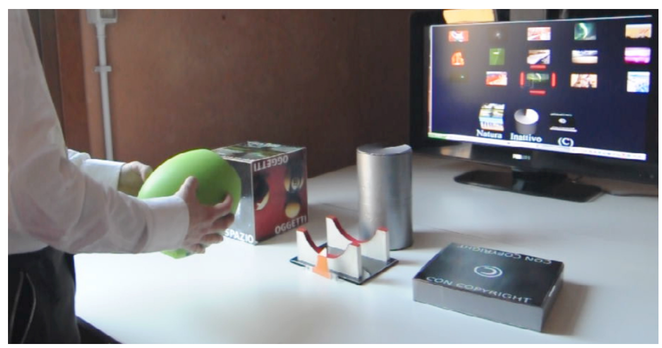


Figure 3. The prototypical TUI

was used as a modifier of the relation between the convex surface of the object and the underlying table, introducing the possibility to freeze the cylinder in a specific position. Resuming, the TUI enables the users to compose the query manipulating a set of three objects and to trigger the query rotating a fourth object, the barrel, initially positioned on one of its bases. The results are presented as a navigable grid of zoomable images (see Fig. 3 on the right). The red frame surrounding one of the miniatures identifies the currently selected image. The user may decide to navigate to other images, rolling and pitching the barrel, or to have details about the current image, tapping the physical artifact. The user may also return to the query phase placing again the barrel on one of its bases. All the software components are based on web technologies, including the visual interface based on X3D, the ISO standard for visualizing 3D objects on the net. All the objects were built with paper and wood, with the only exception of the barrel, that was made of high-density polyurethane foam for giving a comfortable experience during the tapping. Their size was designed to allow an easy manipulation and to embed a set of Wii Remote controls monitoring the manipulation of the artifacts.

V. Interface Evaluation

For testing the mappings and the learnability of the TUI we performed a test with a group of students (9 males and 8 females, average age 23.5) of the Fine Arts Academy of Venice. The activities were organized as follows:

1) collective initial briefing;
2) individual free manipulation of the TUI (3 minutes);
3) individual execution of the query task (2 minutes; 4 iterations of the task), such as: *find all the pictures belonging to the category nature, with a brightness level equal to 5.5 and without copyright*;
4) individual execution of the navigation task (2 minutes; 4 iterations of the task), such as: *select from the results the image representing a tree and zoom it*;
5) individual post-test questionnaire.

The measurements performed during the test included:

- for the free manipulation: subjective evaluation of the comprehension of the functionality associated to each physical artifact of the TUI, based on the comments by the users and on their observation by two experts;
- for the query and navigation phases: measurement of the users' successes and failures related to the use of each artifact in relation to a specific query and navigation activity; registration of the time needed to complete each session of the different phases.

The post-test questionnaire included:

- an evaluation, measured along a 5-points scale, of the appropriateness of the mapping of the physical artifacts to the digital functions, for each object of the TUI;
- the possibility to propose alternative shapes and manipulation modalities for the artifacts;
- an extended version of the NASA Task Load Index test [4], focused on the dimensions of the effort needed for managing a user interface (i.e., *mental*, *physical* and *temporal demand*, *performance*, *learning effort* and *frustration*), measured along a 5-points scale; additional parameters (i.e., *ease of use*, *naturalness* and *aesthetic quality* of the interface) were added.

A. Results

1) Free manipulation phase: The results show that most users understood the mappings to digital functions for the cube (90%), the plate (90%) and the cylinder when rolled along its x axis (80%). The possibility of placing the cylinder on one of its flat bases was not considered by many users (20%), probably because of the strong cue given by the initial horizontal position of the cylinder and by the introduction of a support for maintaining such position. The manipulation of the barrel gave mixed results. A significant number of users (60%) fully understood the relation between the act of pouring and the query activation. Only a few users (20%) fully understood the relation between the rolling and the pitching of the barrel along its curved surface and the navigation along the grid of results. None considered the possibility of tapping the barrel for zooming the results.

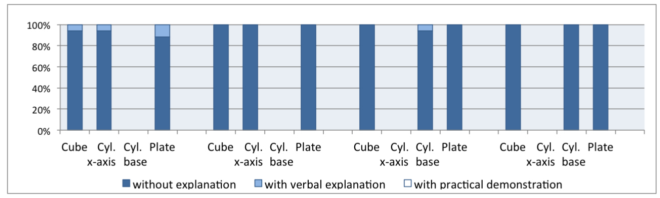


Figure 4. Query phase: analysis of the task execution without explanation, with explanation and with a practical demonstration; four iterations

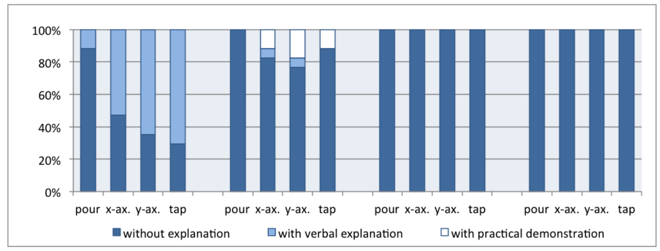


Figure 5. Nav. phase: analysis of the task execution without explanation, with explanation and with a practical demonstration; four iterations

2) Query phase: Fig. 4 shows that only a few users needed support during the first iteration of the query composition and that none needed it for the second and the fourth iteration of the task. The need for a partial support during the third iteration can be explained by the fact that in this case users were asked to retrieve images considering all the levels of brightness, and this request implied the awareness of the act of putting the cylinder on one of its flat bases. The lesson learned was then applied by all the users in the fourth iteration, that included the same request. The result of the third iteration - compared to the initial free manipulation phase - is anyway interesting because it suggests that giving a specific task stimulates the users to find solutions, exploring further the manipulation possibilities of the objects.

3) Navigation phase: Fig. 5 displays the results of the navigation phase, confirming that the manipulation of the barrel was more difficult. During the first iteration of the task, good levels of performance were obtained only for the act of pouring, which triggered the query (see Fig. 5, labels *pour*). Concerning the navigation, nearly fifty per cent of the users associated the rolling of the barrel (Fig. 5, labels *x-ax.*) to the horizontal navigation of the grid. About a third of the users associated the pitching of the barrel to the vertical navigation (Fig. 5, labels *y-ax.*). Again, it can be noticed that the definition of a specific task stimulated the users to try different manipulation styles and increased the level of understanding. During the second iteration, some users that didn't understand the previous verbal explanations were given again a verbal briefing, and, if the difficulties persisted, were given a practical demonstration. The following iterations show the high degree of learnability of the interface, because no additional support was necessary.

4) Post-test questionnaire: Concerning the appropriateness of the mapping, we obtained a confirmation of the design choices for all the shapes associated to the query composition. For the cube, the cylinder and the plate we obtained average values of appropriateness of, respectively, 4.5, 4.3 and 4.2 points, measured along a 5-points scale. For the barrel we obtained lower results (3.3 points for the navigation functionality and 2.7 points for the zooming functionality). None of the users suggested alternative shapes based on curved surfaces for representing the discrete and the Boolean variables. One of the users suggested to use a set of plates for representing the discrete variable. Besides, none suggested to use solids based only on flat surfaces as an alternative for the cylinder. Instead, some users suggested the use of an alternative curved shape, the sphere. For the navigation phase, the users proposed a number of curve-based alternatives to the barrel: a sphere, a cylinder and a wheel. Concerning the extended NASA Task Load Index test, we decided after the first day of the test to request distinct answers for the query and the navigation phase. We decided this modification after having noticed a different attitude of the users in relation to the query and navigation objects. During the second day (9 users), for the query phase we obtained satisfactory values for the *mental demand* (2 points), *physical demand* (1.2 points), *learning effort* (2.1 points) and *frustration* (1.2 points), maintaining good results for the other variables. For the navigation phase we obtained higher values for the *mental demand* (3.2 points), *physical demand* (1.7 points), *learning effort* (2.6 points) and *frustration* (2.4 points). The need for a superior effort was reflected also in the differences of the values for the extended parameters that we introduced for this test: 3.8 vs. 3.1 points for the *pleasantness* and 3.2 vs. 2.6 points for the *naturalness*.

VI. Conclusion

The test results confirmed the appropriateness of the mapping of the physical objects to digital functions suggested by the proposed guidelines. All the alternative suggestions belonged to the same classes of surfaces that were chosen for the interface in the design phase. The prototypical TUI permitted the users to exploit autonomously most of the query compositions. Users needed some support during the navigation phase, probably because of the higher number of functionalities associated to a single object. In spite of these difficulties, we notice that the iconic shape of the barrel, belonging to the everyday experience, had positive effects, because many users tried the act of pouring and then associated it to the related digital function. The act of tapping was not discovered autonomously by most users. This result may be related to the fact that, while the rest of the user interaction with the TUI is characterized by *smooth* manipulations, the act of tapping can be described as a *destructive* action that usually is not applied to a physical artifact, aside from situations related to frustration. Overall, the interface demonstrated a high degree of learnability for both the query and the navigation, that suggests its suitability for casual users. The findings of this work have been confirmed by the results that we obtained with a slightly modified version of the interface for preschoolers [8] and encourage us to experiment the proposed guidelines for other tasks and application domains.

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