A Design Approach for Tangible User Interfaces

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Abstract

Tangible interfaces allow physical control and representation of digital information. When designing such interfaces one needs to take into consideration the potential conflicts between the hardware of the artifact and the form of the user control. The design problem is a search for an appropriate fitness (or effortless co-existence) between these two aspects. This problem makes tangible interface design different from the traditional graphical interface design. In this paper we present an approach to aid the design of tangible interfaces based on the desired fitness. We investigate the potential conflicts of tangible interaction by addressing the fitness problem and propose a set of guidelines (in the form of eight questions) that help by defining the boundaries of the electro-mechanics (hardware) and ergonomic design space, identifying the nature of tangible interaction for various sub-tasks and finally fitting the various components of the electro-mechanics and physical-ergonomics of the artifact to provide a component level fitness. This component level fitness can form the basis for the final form of the tangible interfaces.

Keywords
Tangible computing, design approach, tangible user interface design, collaborative design.

INTRODUCTION

A research direction in Human-Computer Interaction that has re-surfaced in the last decade is the use of physical real-world artefacts to represent and control digital data. Tangible user interface is the popular term used to refer to such computing systems that use physical artefacts as representation and control of digital data. (Ullmer and Ishii, 2000; Dourish, 2001). Research in tangible user interface has broadly focused on developing systems for various application domains and proposing different frameworks to classify the different systems. Systems have been developed to exploit tangible user interfaces for desktop metaphor (e.g., Neurosurgical Props from Hinckley, 1994), virtual reality metaphor (e.g., Cubic Mouse from Frolich and Plate, 2001) or mixed reality metaphors. (e.g., DataTiles from Rekimoto, 2000). Frameworks have been proposed based on the type of interaction supported (continuous vs. discrete) (Ullmer, 2002) and level of mapping between the physical artefact and digital data (Wensveen et al, 2004).

However, to make tangible user interfaces a viable real-world interface we need an approach to facilitate the design of tangible interfaces. A first step in developing such an approach is specifying requirements for the design of a tangible user interface. While software engineers have mature *software thinking*, referring to the functionalities' structure and software interface in the desktop space, a *tangible thinking,* referring to the dynamics' structure in the real-world space, is still at its infancy.

In this paper, we investigate the potentially conflicting spaces of tangible interaction by addressing the fitness between the electro-mechanics and the physical-ergonomics of the tangible interface. In order to achieve the fitness, we propose a design approach. Used by a team of experts, this approach aims to provide a workflow and result to a *set of clear and coherent decisions*, i.e.: clear specifications that work coherently with the needed tasks. The approach is structured through eight questions (Table 1) in three phases: defining the boundaries (BO 1-2-3-4), orienting the components (OC 5-6) and fitting the components (FC 7-8) This approach will ease the location of problems that occurs during the development, facilitate their identification with the approach' terminology (Boundaries, orienting and/or fitting problem) and help to their formulation i.e. asking the right question to the right expert. Table one summarizes the eight questions and the next section explains the fitness concept.

Defining the Boundaries (BO)	**BO 1: What should user experience?**	
	BO 2: What are the human tasks?	
	BO 3: What would the artefact represent and control?	
	BO 4: What are the conventions?	• **Physical Ergonomics** • **Electro Mechanical**
Orienting the Components (OC)	**OC 5: a) What is the nature of the interaction for each sub-task?** **b) What are the electro-mechanical and physical ergonomic constraints for this task?**	• **Continuous** • **Discrete** • **Assembly**
	OC 6: Does the sub-task need to any relational interaction?	
Fitting the Components (FC)	**FC 7: What are the relations between the objects and the actions?**	
	FC 8: In what order tasks will occur when using the artefact?	

Table 1: The eight questions

THE FITNESS CONCEPT

Every design problem begins with an effort to achieve an appropriate fit between two entities: the form in question and its context (Alexander, 1964). A form is the desired solution to the problem and the context defines the problem (see Figure 1). One wants to put the context and the form into effortless contact or frictionless coexistence, i.e., one wants to find a good fit.

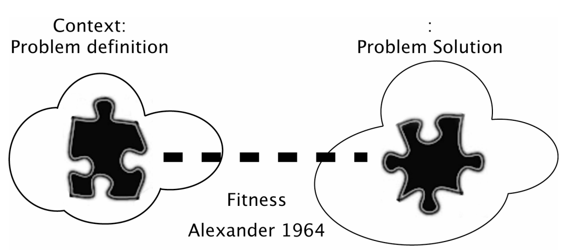

Figure 1: Alexander model of fitness

In TUIs, this fitness should occur between the physical artefact (form) that represents and controls information and the application (context) that defines the digital information (see Figure 2).

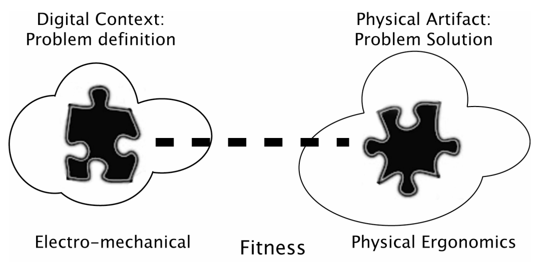

Figure 2: Alexander model of fitness

This is also evident from the MCR-pd interaction model proposed by Ishii and Ullmer (2000), which highlights a bridge between the physical world of atoms and the digital world of bits. This fitness problem is confounded by the potential conflict between the electro-mechanics (the sensors and actuators that go into the physical artefact) and ergonomics (how the user will use and control the artefact) of the design space. The problem is to find out what sensors to fit into the artefact and how to fit them so that the ergonomics of the artefact are not compromised. The user's ability to control the artefact is dictated by the ergonomics of the artefact whereas the ability of the artefact to represent and control the digital information is dictated by the electro-mechanics of the artefact. Thus, the fitness problem is also transformed into finding an effortless contact or frictionless co-existence of the physical-ergonomics of the artefact and its electro-mechanics.

RELATED WORKS

Brensen (2001), proposed the Modality Theory to allow developers to decide which input and output modalities to use for interaction. The Modality Theory provides a comprehensive analysis of all available modalities in the media of graphics, acoustics and haptics and can suggest a set of input and output modalities for a given application. However, the theory does not address the design of the final realization.

Bellotti et al., (2002), pose five questions that any developer of sensing system should address, for improved usability of their ubiquitous or tangible computing system. Their questions, which relate to initiating an interaction, specifying the actions and overcoming misunderstandings, are mostly focussed on the final outcome of the interaction and do not deal with specifying the requirements for designing the dynamics of the interaction.

Scenario-based design (Carroll et al, 1998) provides an advanced vision of an application. It creates a set of interaction requirements that can be used to design the application. However, it does not provide a means to factor in electro-mechanical constraints that might occur when designing tangible user interfaces for the application.

THE DESIGN APPROACH

Defining the Boundaries

One of the fundamental requirements is to be able to layout the parameters of the design space. These parameters specify the boundaries within which the TUI solutions are sought. To layout these parameters, we need to define the desired user experience, the resulting human tasks, and the digital information that will be represented and controlled.

User Experience

The desired user experience is usually the starting point for such a design process. On most occasions this comes from observations of everyday environments and tasks with a desire to augment the environment with sensors that will modify and enhance the user experience in interacting with them. For example, in mediaBlocks, one of the experiences sought was to use real-world gestures to manipulate digital media (multimedia presentation, video etc) without the need for an explicit computer.

Human Tasks

Based on user observation we can build a hierarchical task analysis tree, like the one in Figure 3, for the application. Usually, this tree is based on current practices in performing the task. One of the goals of the TUI designer is to incorporate the desired user experience by adapting this tree through subtle changes to certain tasks. While this is can be a challenge, it also lays out the boundaries of our design space. With reference to the first example, this means creating a task analysis tree of how users currently interact with digital media and identifying possible tasks that can be modified. Ishii and Ullmer chose to modify the current practice of capturing, transporting and reviewing pieces of digital media to achieve their desired user experience. The task analysis tree also suggests the possible ergonomic constraints the application might impose on the design.

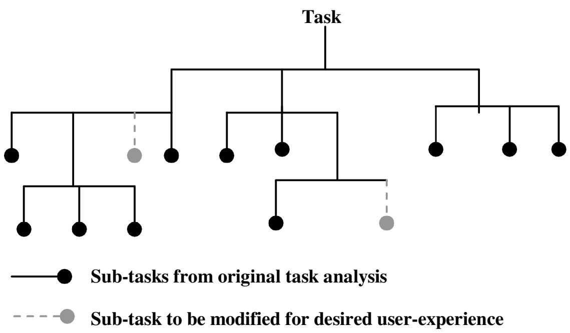

Figure 3: The task analysis tree

Artefact representation and control

By analysing the user experience the designer can also identify the different digital information that needs to be represented and controlled by the user. The task analysis tree also specifies details of the digital information that will be controlled by each sub-task. Based on this information, the designer can identify the specific sensors and actuators needed for physical control of the digital information. This will also suggest how impractical a physical control might be for certain digital information, thereby laying out the electro-mechanical constraints of the design space. At this stage, the sensors used are specified at a broad level (i.e., the designer knows s/he needs a force sensor and not a light sensor) without knowledge of the specific details of the sensor (what kind of force sensor, how many Newtons etc).

Conventions

A consequence of analysing the design space is a realization that we make many assumptions about the user expectations and interaction conventions. It is always useful to step out of the design process to reflect on the possible conventions that might be taken for granted. These conventions might impose newer constraints on the ergonomics or electro-mechanics of the design. For example, in the mediaBlocks, the user is assumed to carry the media block. This imposes weight and size restrictions on the block. While in this case the constraint is fairly easy to deduce, it might not be the case always.

Usually, defining the boundaries of our design space is an iterative process. The user experience desired will inevitably be refined after due consideration to the human tasks and the desired physical control. The following four questions can be used as a general guideline for laying out the boundaries of the design space.

1. What should the user experience?
2. What are the human tasks?
3. What would the artifact represent and control?
4. What are the conventions?

The next step in the design process is to take a closer look at the sub-tasks that need to be modified. These electro-mechanical and the ergonomic constraints have to be oriented based on the nature of the tangible interaction suited for these sub-tasks.

Orienting the components for the desired fitness

Ullmer (2002) has proposed a framework for Tangible Interfaces that identifies three classifications: Interactive Surfaces, Token+Constraint and Constructive Assemblies. This classification is partly based on the varying degree of support for continuous and discrete forms of interaction. More specifically, interactive surfaces support continuous interaction; token+constraint systems support a combination of (constrained) continuous and discrete interactions, while constructive assemblies almost never support continuous interaction but are instead aimed at discrete interactions.

Nature of Interaction

This part of the design process establishes the nature of physical interaction for each sub-task. The user control imposes newer constraints on the specifics of the sensors and actuators required for the electro-mechanics of the physical artefact. When designing physical artefacts for continuous interaction, the sensors will need to collect data at a higher frame-rate than when dealing with constructive assemblies. Similarly, depending on the kind of user action supported, the physical artefact might need to be wireless.

This part also provides newer insights into the ergonomics of the final design. When designing for continuous interaction on the table top, the weight of the physical artefact might not be a concern whereas the ability of the artefact to slide on the table-top might be an important physical-ergonomic constraint. Similarly, when designing physical artefacts with discrete control, the designer might have to provide mechanisms to restrict the user's movement of the physical artefact to discrete grids.

In case of the mediaBlocks a token+constraint approach is used to design the interactions. The following two questions may be used as a guideline for orienting the dynamics of the interaction:

5. What is the nature of the interaction for each sub-task? Will the sub-task require continuous or discrete interaction? What are the electro-mechanical requirements for this task and what are the ergonomic constraints for this task?
6. Does the sub-task need to any relational interaction? I.e. if two or more physical artefacts are combined to perform the sub-task, will the combination be interpreted in a relational manner (for example, will bringing two artefacts together result in adding the corresponding digital information)?

At this point one has identified the various electro-mechanical and physical-ergonomic components for the tangible interface. The next step is to create the fitness between these components. This is achieved by integrating the sub-tasks with the rest of the tasks in the task analysis tree (Question 2). This ensures that the user can easily initiate and exit from the sub-task to other tasks within the task analysis tree.

Fitting the components

A final step in creating a component level fitness is to integrate the modified sub-tasks with the remaining tasks in the task analysis tree and then identify the different sensor component for each sub-task.

Integrating the sub-tasks to the task analysis tree

A crucial part of the fitness is to integrate the modified sub-task with the rest of the tasks in the task analysis tree of Question 2. This integration can be achieved by looking at how the user will initiate and terminate interactions for this sub-task. In general it might be useful for the designer to carefully address the five questions raised by Bellotti et al, (2002). These questions not only integrate the sub-tasks but also provide detailed questions for a better fit between the electro-mechanics of the artifact and the ergonomics. The five questions are

- How does the user initiate (and terminate) interaction with the artefact?
- How does the artefact inform the user that is realizes that the user has initiated interactions with it?
- What are the user actions to which the artefact can react?
- How does the artefact inform the user that it has understood the user's actions and is responding to it?
- How can the user recover from a mistake or misunderstanding?

Task order vs. artefact use order

At this point one should have the entire task analysis tree with the modified sub-tasks and the relevant electro-mechanical components identified for these sub tasks. The desired artefact ergonomics have also been identified for the sub tasks providing a component level fit between the electro-mechanical components and their artefact level ergonomics. In this stage it is important to make sure that the orders in which the various artefact components will be used reflect the order in which the tasks will be executed by the user.

The following two questions can be used to provide a component level fitness to the design problem:

7. How should the sub-tasks that use tangible interfaces be integrated with the other tasks in the tasks analysis tree?
8. Is the order in which the user is expected to use an artifact similar to the order in which the tasks occur? If the design has been carried out properly then this will be satisfied and so this question acts as a useful parity check.

CONCLUSIONS

TUI design as a Fitness problem

In this paper we adapted the original fitness problem proposed by Alexander (1964) to the design of tangible user interfaces. This approach allows the designer to work simultaneously with the potentially conflicting hardware and physical ergonomic requirements of the tangible interface design. Here we reduce the complexity of the hardware and physical ergonomic requirements and finally identify a component level fitness between the hardware and the physical-ergonomics. This component level fitness is a form of requirement specification that may be used by the design to identify the final form of the tangible interface for the given application.

Guidelines for TUI design

Our analysis of the conflicting requirements based on the fitness approach led to eight specific questions that might be used as guidelines for the design of tangible user interfaces. Figure 4 summarizes our eight questions. The first four questions define the space within which the desired tangible interface is sought. The next two questions orient the tangible interaction based on Ullmer's framework and finally we figure out the details of initiating and terminating the interaction using Bellotti's ideas. It might not always be easy to answer these questions, but its our belief that these questions can set the designer thinking about aspects of the design they might not have thought of otherwise. The Appendix shows how some of the existing systems would address these questions.

Towards a checklist for TUI design

The next step is to apply the guidelines methodically to the existing systems and see where the final design differs from the existing systems. This will give us a handle to evaluate the effectiveness of this approach to solving real-world tangible interface problems. This approach will eventually lead to a set of checklists the designer can use to monitor the progress of their design.

FUTURE WORK

In the future we intend to extend the checklist into a set of heuristics and then attempt to chart the cost-benefit tradeoffs at a component level. This chart can then lay the foundations for a predictive model for tangible interface design, in the lines of GOMS (Card et al., 1983) and Critical Path Analysis (Baber and Mellor, 2001). Such models permit early evaluation of designs (prior to building and testing of prototypes) by employing predictive models of user performance to evaluate competing designs.

REFERENCES

Alexander C. 1964 *Notes on the synthesis of form*, Havard University Press, Cambridge, Massachusetts.

Baber, C.; Mellor, B., (2001), "Using critical path analysis to model multimodal human-computer interaction**",** in International Journal of Human Computer Studies, 2001 54(1), 613-636.

Bellotti, V., Back, M., Edwards, W. K., Grinter, R. E., Henderson, A. and Lopes, C. (2002), "Making Sense of Sensing Systems: Five Questions for Designers and Researchers", in Proceedings of CHI'02 Conference on Human Factors in Computing Systems, 415–422. ACM Press.

Bernsen, N. O. (2001), "Multimodality in language and speech systems - from theory to design support tool", Chapter in Granström, B. (Ed.): *Multimodality in Language and Speech Systems.* Dordrecht: Kluwer Academic Publishers.

Card, S; Thomas M and Allen N (1983), "*The Psychology of Human-Computer Interaction*", Hillsdale, New Jersey: Lawrence Erlbaum

Carroll JM, Rosson MB, Chin Jr George, Koenemann Jürgen (1998) "Requirements development in scenario-based design", in IEEE Transactions on Software Engineering, 1156-1170.

Dourish P. (2001) *Where the Action is: The Foundation for Embodied Interaction* ,Cambridge: MIT Press.

Fitzmaurice, G. W., Ishii, H., & Buxton, W. A. S. (1995) “Bricks: laying the foundations for graspable user interfaces”, in Proceedings of the CHI’95 conference on Human factors in computing systems, 442–449. ACM Press.

Frohlich, B. and Plate, J. (2000), “The Cubic Mouse: A New Device for Three-Dimensional Input”, in proceedings of CHI'00 Conference on Human Factors in Computing Systems, 526 – 531. ACM Press.

Gorbet, Matthew G, Orth M, Ishii H. (1998), “Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography”, in the Proceedings of CHI '98 conference on Human factors in computing systems, 1-8. ACM Press.

Greenberg, S. and Fitchett, C. (2001), “Phidgets: Easy Development of Physical Interfaces through Physical Widgets**”,** Proceedings of the UIST 2001 14th Annual ACM Symposium on User Interface Software and Technology, 209-218, ACM Press.

Hinckley, K; Pausch, R; Goble, J. and Kassell, N. (1994), “Passive Real-World Interface Props for Neurosurgical Visualization”**,** in Proceedings of CHI'94 Conference on Human Factors in Computing Systems, 452-458. ACM Press.

Kaptelimin V., Nardi B, Macaulay C. (1999), “Methods & Tools: The activity checklist: A tool for representing the “space” of context”, Interaction, july+august 1999, 27-39. Quote from the book: Leont’ev, A. N. *Problems of the Development of Mind*. Progress, Moscow, 1981.

Rauterberg, M., Fjeld, M., Krueger, H., Bichsel, M., Leonhard, U. and Meier, M. (1997), “BUILD-IT: A Computer Vision-based Interaction Technique for a Planning Tool”, in Proceedings of HCI '97, 303-314. Springer

Rekimoto, J., Ullmer, B., & Oba, H. (2001), “ Datatiles: a modular platform for mixed physical and graphical interactions”, in Proceedings of the CHI’01 conference on Human factors in computing systems, 269–276. ACM Press.

Ullmer, B., Ishii, H., and Glas, D (1998). “ MediaBlocks: Physical Containers, Transports, and Controls for Online Media”, in Proceedings of SIGGRAPH'98 conference on Computer Graphics, July 19-24, 1998, 379-386. ACM Press.

Ullmer, B., & Ishii, H. (1997), “The Metadesk: models and prototypes for tangible user interfaces”, in Proceedings of the 10th annual ACM symposium on user interface software and technology, 223–232. ACM Press.

Ullmer, B. and Ishii, H. (2000), “Emerging Frameworks for Tangible User Interfaces”, IBM Systems Journal, 393(3) 915-931.

Ullmer, B. (2002), “Tangible Interfaces for Manipulating Aggregates of Digital Information”, Unpublished doctoral dissertation, Massachusetts Institute of Technology.

Wensveen S.A.G., Djajadiningrat J.P., Overbeeke C.J. (2004), “Interaction Frogger: a Design Framework to Couple Action and Function through Feedback and Feedforward”, in proceedings of DIS 2004, in press. ACM Press.

APPENDIX

This section tabulates how some of the existing systems address the fitness problem. We've tried to define the fitness desired and orient the nature of the fitness. The last two questions relating to the component level fitness are not discussed here since they relate to the designers idea of the solution and different designers might provide different component level fitness.

	What should the user experience?	**What are the human tasks?**	**What would the artefact represent and control?**	**What are the conventions?**	**What is the nature of the interaction for each sub-task?**	**Does the sub-task need to any relational interaction?**
MediaBlocks (Ullmer et al, 1998)	-Record and carry data without using computer interface. -Display data	-Putting info into a container. -Carry the information. -Sequence the information.	**Represent:** Container **Control:** Media' sequence	**Ergonomic:** -Easy to carry **Electro-Mechanical:** -Connect to several devices.	Media Sequences Device **(Discrete Interaction)**	Sub-tasks performed in combination with: Video Camera Video Display Printer Digital white board.
Triangles Module (Gorbet et al. 1998)	Manipulate, connect and combine information chunk.	-Grasp and manipulate digital information. Build 2 and 3D shapes	**Represent:** Chunk of information to be connected and assembled. **Control:** The arrangement of the information by triggering events in the digital space based on a user manipulation of a physical element.	**Ergonomic:** Must allow the construction of 2 and 3D shapes. **Electro-Mechanical:** Easy to connect and disconnect. Must produce the manipulated information in real time	The information are connected to each other both physically and digitally **(Constructive interaction)**	The information physical arrangement must be connected to a display.
Built-it System (Rauterberg et al. 1997)	Planning a plan layout and simultaneously the result in real time.	Navigating Positioning	**Represent:** The object within the space. **Control:** Positioning and rotating the object.	**Ergonomic:** Simultaneous 2D and 3D view. **Electro-Mechanical:** Displaying Positioning 3DOF	The information is displayed in real time. **(Continuous interaction)**	Printing

Table 1

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