Analysis of Physicality Aspects in Physical User Interfaces of Embedded Systems

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Abstract

Embedded systems are becoming more significant in our daily lives with the advent of ubiquitous computing. The increasing demands of multifarious functionalities and other factors lead to an increased focus of development on internal software issues. Negligence towards the interaction aspects of physical interface is resulting in the generation of interaction complexities for the user. This work evaluates, compares, and highlights the significance of physicality aspects of embedded system interfaces using five subjects including; washing machine; camera; oven; sound system; and MP3 player. The quantitative evaluation approach helps in a simple investigation by applying the numeric values for each aspect. The result analysis highlights the significance of exposed state, tangible transition, and inverse action over other physicality aspects. This study is especially valuable for the embedded system developers who may not have exposure or expertise to Human-Computer Interaction or its sub-field, Physicality. Managing and incorporating physicality aspects in embedded systems is a key factor for producing natural interaction products.

Keywords: Human-computer interaction; physicality; embedded systems; interaction; complexity; physical user interface

1.0 INTRODUCTION

Embedded systems (ESs) are becoming major part of our daily requirements. As compared to a general purpose computer, an ES is application-specific, invisible, inseparable, and integrated part of real life objects having small size, intelligence, quick response and light weight.\textsuperscript{1-4} ESs encompass various areas including telecommunication, consumer appliances, medicine, transportation, built environment. A microprocessor chip is the fundamental part of an ES providing it the processing power.\textsuperscript{1} Approximately 98\% of 32-bit microprocessors currently in use worldwide are used in ESs and it is estimated that the common household or a modern car comprises of more than hundred processors each.\textsuperscript{5,6} The fast expansion of ESs increases the significance of their interface and interaction aspects with the users.\textsuperscript{7} The human
senses of vision, touch, and hearing are more frequently used for interaction. On the other hand, the ES’s visual, physical, and audible features of interface offer means of interaction. Complex physical user interfaces (PUIs) result in cognitive and hence physical burden on user. The products that offer usage difficulty are considered as complex or complicated by their users. Although, usability (a non-functional requirement in software engineering) is considered to be a candidate solution however, it does not address the physical aspects of interaction, if indeed applied properly at the first place.\(^8\) There are many other factors especially physicality aspects, besides usability, for improving the natural interaction with ESs. The working of ES is subject to physical interaction constraints including reaction to a physical environment, and execution on a physical platform\(^9,10\). Natural interaction results by managing the combination of human innate abilities and the physical visceral aspects of ESs\(^10\). Physicality, a sub-field of Human-Computer Interaction (HCI), deals with augmenting the natural interaction with embedded artefacts.\(^11\) Currently in practice, the methods or techniques aiming at increasing the naturalness of interfaces solely address the usability aspects while ignoring the detailed physicality aspects\(^12-34,37\). This work investigates and evaluates the existence of physicality aspects in ESs that include exposed state, compliant interaction, tangible transition, bounce back, inverse action, and compliant interaction. This investigation generates the numerical results by comparing the overall PUIs of ESs and it is not a comparison of the individual controls of each ES or the controls of different ESs.

The paper is organized as follows. The next section discusses the related work followed by an introduction to physicality principles. Subsequently, we assign the numeric values to these principles and then investigate the physical user interfaces of subject ESs. We discuss the results prior to conclusion.

## 2.0 RELATED WORK

The physical interface or interaction complexity has not considerably addressed by researchers\(^1,24,26,29,35,47-52\) as compared to the aspects of software complexity.\(^12,13\) The significance of user interface (UI) is increasing due to various factors including the demand for multi functionalities in a single product.\(^7\) The contemporary electronic devices are replacing the physical controls (like buttons, dials, and knobs) with digital screens or displays that are resulting in difficulty of use for common users and especially users with some vision problems. The physical controls recruit tangibility and softness that helps in easier manipulation.\(^25\) An empirical study\(^14\) highlights that the information complexity on ES’s UI affects the user performance. Likewise, a strong users’ trend of preferring the simpler UIs is observed. Another recent study\(^28\) discovers various complications of use with the thermostats at homes. The contemporary digital thermostats with sophisticated touch screens are consuming more energy than older manual counterparts with physical controls. The physical buttons, knobs, dials, slider bars and other controls help user in anticipating not only the underlying functionality attached to them but also the handling of these controls themselves.

Due to the spread of ubiquitous computing, physical controls like buttons, sliders, and knobs are experiencing a restoration phase and can be augmented by incorporating and exploiting the visceral emotional features in them.\(^25\) Another study\(^25\) reports the complexity of home appliances (e.g., remote controls) is becoming saddling and elevating the cognitive burden on users. Cavett et al.\(^27\) empirically discover the need to redesign the existing interface for the operator of unmanned aerial vehicles (UAVs) for reducing the operator’s cognitive workload.

A series of studies\(^15-18\) empirically report the usage complications present in mundane daily use electronic devices or ESs (e.g., table clock, camera etc.). These complications depend on prior experience and age of user, and appearance of ES. The appearance of ES’s interface and its components effect naturalness of interaction more than their location. Moreover, the older adults find more difficulty of use with ESs than younger ones.

Various studies highlight the need to develop tools and methods to improve the physical interaction aspects in ESs.\(^7,15,19\) For example, a study\(^7\) points out the cause of interaction complexities in ESs as the designing of UI after defining the requirements. The proposed solution suggests for eliciting and incorporating the user-experience envisioned during product planning phase into UI prior to other activities. The proposed process is evaluated by two experiments; one in a manufacturing equipment maker; and other in a home appliance maker company. Results show that time limitations in requirement defining phase, the UI design is often left unevaluated by the actual users and implemented as it is.

A series of studies\(^19-23\) empirically address some of the causes of naturalness in ES interaction. In addition to age and prior experience, these studies highlight the need for ES designers to match their perceptions (mental models\(^38-41\)) of ESs’ use with the perceptions of users. Designers need to be educated as well as equipped with certain tools and methods that can be employed earlier in the design process. Daily use ESs like microwave oven, simple and smart toaster, car controls, washing machine and laserplus show lack of natural interaction features\(^19-23\). Their proposed modeling approach named Goal-Action-Belief-Object (GABO) compares the similarities and differences between each user model and the designer model, checks the degree of compatibility, and takes appropriate design decisions. Although, this method is an example of developing tools and techniques for the ESs designers and developers however, it does not address the physicality aspects of interaction.

Perry et al.\(^29\) discover few causes of interaction complexities in PUIs of ESs including actions with no effect, false affordances; and perceived interaction motions. However, this work focuses on the interface of touch screen only. The study also points the need for a standardized interface design approach. Kang and Kim\(^35\) emphasize on the use of minimal, intuitive, and consistent controls. They conclude that intuitive use of ESs strongly depends on their PUI besides non-physical user interface (NPUI). The ESs offering both PUI and NPUI should use the more frequently used functions on PUI while the less frequently used functions should be included as part of NPUI. However, the study does not mention the specific physicality properties. Likewise, Han et al.\(^30\) generally mention the physical aspects of consumer products as significant part of its interface but do not discuss these in depth. Kim et al.\(^32\) include the PUI as part of their proposed framework for the development of ubiquitous computing device but do not address the reasons behind better or poor PUIs with respect to physicality aspects.

There are plenty of studies that evaluate the usability of ESs but ignore the physicality aspects\(^31-34\). It is important to note that traditionally usability deals with overall effectiveness, efficiency, and satisfaction of use\(^12,36\). For example, a study\(^33\) checks the usability and acceptance evaluation of cardiac rehabilitation system consisting of various medical hardware devices (in addition to a software interface). Although, in this environment, it is more significant to address physicality because both physicians and patients are the users of the system but the study only measures the “overall” likeness of the system while ignoring the aspects of physicality.
Therefore, it is necessary to develop tools and techniques addressing physicality aspects for the assistance of ES designers and developers for producing better interaction solutions.

### 3.0 PRINCIPLES OF PHYSICALITY

This section introduces some of the key principles of physicality related to UI of ESs. Norman states that physicality is the latest UI breakthrough by re-addressing the physical and mechanical controls that are now equipped with intelligent embedded processing and communicating facilities. Therefore, it is more significant now to produce intuitiveness in PUIs for the ease of users since they have to deal with those controls that offer more features in various ways than the conventional controls. Additionally, in order to produce intuitive PUI, the number of controls should be minimum leading to the need of multiple functionalities per control and compactness of the overall interface. Therefore, it is significant to investigate the principles of physicality to produce natural interaction aspects in the ESs.

![Figure 1](image) (a)(b) Exposed state, (c)(d) Controlled state, (e)(f) Tangible transition

#### 3.1 Exposed State

When the physical state of the control reveals and exposes the underlying functionality then it is called an exposed state. The exposed state property helps the user in understanding the manipulation of control. A light switch (Figure 1a), for example, offers two physical states that is switch up and switch down. Each physical state has an attached logical state. Switch up is linked with light on functionality (Figure 1b). This one-to-one mapping of physical and logical states provides naturalness prior to and during interaction.

#### 3.2 Controlled State

After moving a physical control from its initial position to a new position, if the control stays there and the device restricts the user from taking it back to its original position, then this property of the control is called the controlled state. The handle of a mundane toaster (Figure 1c), for example, once pressed down to an on state cannot be pulled back up by the user, instead the device itself releases the handle (Figure 1d). Although, this seems to restrict the user’s control over the device but it helps in completing the job in various ways. Firstly, it informs the user that the device has accepted user’s input. Secondly, it also shows the user that the device is now busy in executing the job and the user may wait. Thirdly, during the operation, anytime the user may know the internal (logical) state of the device by looking at the physical state. Lastly, on job completion the device releases the control and allows it to reach its initial position while indicating the end of job to the user.

#### 3.3 Tangible Transition

The distinctive tangible feltness like subtle bump offered by any control at each logical state transition helps the user by informing about the state change without the need to look and focus at the control. This property is called tangible transition. For example, the dials of sound system (Figure 1e), MP3 players, car audio controls, etc. During the manipulation of a jog dial, a number of logical states can be traversed (Figure 1f). Tangible transitions provide eyes-free interaction with the control that is specifically useful for the mobile and compact devices.

#### 3.4 Bounce Back

Some controls offer physical bounce back reaction after contact. When the physical state of the control returns back to the original state as soon as the hand pressure is released then this property is called bounce back. When the physical state of the control returns back to the original state as soon as the hand pressure is released then this property is called bounce back. PC power button (Figure 2a), for example, and joysticks. The underlying logical state during the physical manipulation may be triggered on or off at any point like start, during or after pushing the control to its fullest or at any point on the returning path. Figure 2b shows an example where one physical state of a button is mapped to two states of PC (on and off) in a toggle fashion.
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### 3.5 Inverse Action

Inverse action is present in a control if the underlying logical functionality maps to the physical opposite states of the control. For example, when the temperature of a cooling system can be decreased by rotating the dial anticlockwise then the temperature must increase by rotating the dial clockwise. Likewise, the up/down or right/left movements of slider controls (Figure 2c and Figure 2d). The shape of the control also plays an important role. This is a powerful principle that helps the user during an interaction.

### 3.6 Compliant Interaction

Compliant interaction is the mutual symmetrical role of user and the control. A common example is the main washing dial of programmed washing machines (Figure 3). The solid arrows represent the user’s action while dashed arrows represent the system’s action. User sets the dial (by rotating it) at a particular setting; the washing starts; and the dial starts rotating back (to initial position), providing current state information to the user, lapsed and remaining time, and the speed of progress.

Some controls restrict the user to rotate backwards (against the direction of rotation) or forward (in the direction of rotation) depending on the requirement that may result in better understanding between the control and the user.

### 4.0 Assigning Values to Physicality Principles

The quantitative evaluation of PUIs can offer more advantages than qualitative approach for the developers of ESs. The resultant distinctive numeric values make it easier for the developers to better understand and apply the physicality aspects properly. There are various studies that have assigned numeric values to evaluate the usability of UIs and not physicality. Therefore, we have firstly assign values to physicality principles according to the level of their existence in a control as listed in Table 1.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Existence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full existence</td>
<td>Value of 2</td>
</tr>
<tr>
<td>Partial existence</td>
<td>Value of 1</td>
</tr>
<tr>
<td>Absence</td>
<td>Value of 0</td>
</tr>
</tbody>
</table>

The numeric values of two, one, and zero are assigned for the full existence (in all controls of an ES), partial existence (in half controls of an ES), and absence of a principle, respectively. There are cases when more than half and less than all controls support a principle and less than half of the controls support a principle. Therefore, values of 1.5 and 0.5 are also used for the former and latter cases, respectively, for precise rating.

The partial existence (value one) can be of various types in between full existence and absence of a principle. For an exposed state, for example, refer to Figure 1b, if the user can perform one of the two actions then it implicates that exposed state property half exists. In other words, if the control offers toggle function having two state transitions but the user can perceive only one of these transitions then this control exhibits partial exposed state. The physical state transition is there but unperceivable to user until the user’s finger actually engages the control. Likewise, for controlled state, referring to Figure 1d, if the pressed lever at its fullest (down) can be lifted back up towards initial position at some intermediate point then the control offers partial controlled state.

When the distinctive tangible feltness offered by a control (like dial) do not equally map to the underlying logical state changes then the dial supports partial principle of tangible transition. If a control offers bounce back but returns back to initial position after some delay, with slow motion, or with play (violating a straight path), then this control is classified as having partial bounce back effect. For inverse action, if the two sides of a control (left/right, up/down) have vague or unequal physical-digital mappings compared to each other means the control offers partial inverse action.
Table 1  Physicality analysis ratings

<table>
<thead>
<tr>
<th>#</th>
<th>Principles</th>
<th>Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exposed State</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Partially supported i.e., only half number of exposed states</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Fully supported i.e., all exposed states</td>
</tr>
<tr>
<td>2</td>
<td>Controlled State</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Partially supported i.e., intermediate state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Fully supported i.e., no intermediate state</td>
</tr>
<tr>
<td>3</td>
<td>Tangible Transitions</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Partially supported i.e., missing mappings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Fully supported i.e., no missing mappings</td>
</tr>
<tr>
<td>4</td>
<td>Bounce Back</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Weakly supported i.e., delay and play on the return path</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Strongly supported i.e., no delay at return</td>
</tr>
<tr>
<td>5</td>
<td>Inverse Action</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Vague and/or unequal number of mappings at each side</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Clear and/or equal number of mappings at each side</td>
</tr>
<tr>
<td>6</td>
<td>Compliant Interaction</td>
<td>0</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Weak compliance i.e., no means available for user to go back during symmetric motion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Strong compliance i.e., user has some means available to go back</td>
</tr>
<tr>
<td></td>
<td>For all principles</td>
<td>0.5</td>
<td>For conditions between values zero and one</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>For conditions between values one and two</td>
</tr>
</tbody>
</table>

If a user, in case of compliant interaction, can be able to move the control to any previous or forward state, directly or indirectly, then it is strong compliance while if a control does not allow user by any means to return to any previous or forward state, then it is weak compliance. An example of the indirect return to a previous state, mentioned in former case, is the availability of forward movement of a washing machine dial by the user all the way around returning to previous position.

5.0 INVESTIGATING THE PUIs

Five ES PUIs are used for this study including washing machine; camera; oven; sound system; and MP3 player shown in Figure 4.

Washing machine PUI has four controls; all dials. Camera has six controls; all push buttons. Oven has three controls; a toggle button and two dials. Sound system has four controls; a push button and three dials. Lastly, MP3 player has a slider and five buttons of various types. Table 2 introduces the subject ESs by listing the number and types of controls present in them.

Table 2 Controls of subject ESs

<table>
<thead>
<tr>
<th>Controls</th>
<th>Washing Machine</th>
<th>Camera</th>
<th>Oven</th>
<th>Sound System</th>
<th>MP3 Player</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push Button</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Surface Button</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Toggle Button</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dial</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Slider</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total Controls</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
As mentioned in the Introduction section that this investigation generates the numerical results by comparing the overall PUIs of ESs and it is not a comparison of the individual controls of each ES or the controls of different ESs. Using expert analysis method the values are applied on subject ES and the results are listed in Table 3.

Table 3 Physicality analysis results

<table>
<thead>
<tr>
<th>#</th>
<th>Principles</th>
<th>Washing Machine</th>
<th>Camera</th>
<th>Oven</th>
<th>Sound System</th>
<th>MP3 Player</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exposed State</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Controlled State</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Tangible Transitions</td>
<td>2</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Bounce Back</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>Inverse Action</td>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>Compliant Interaction</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>6.5</td>
<td>3</td>
<td>5.5</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The controls of washing machine and oven offer strong exposed states. The controls of sound system offer exposed state but due to the strong similarity of shape and orientation between push button and dials, it takes time to distinguish them from each other. All camera controls offer weaker exposed state compared to washing machine and oven. The surface buttons at the front panel of MP3 player afford partial exposed state. Additionally, it is difficult to operate them without looking at them or in low light context. The slider and push buttons offer better exposed state. However, taking an average of all six controls, the exposed state of overall interface (of controls) is rated with value one.

None of the controls of all devices offer controlled state, therefore, all PUIs are rated as zero. All the dials of washing machine offer tangible transitions, so rated with a value two. So, the score of this principle for washing machine is two, whilst others are ranked zero. Meanwhile, camera controls do offer tangible feedback at transitions, yet with a very subtle feedback, so it is rated with a value 0.5. Two out of three controls of oven offer tangible transitions i.e., toggle button and a dial. However, the number of tangible transitions offered by the said dial is so large in number that their purpose approximately vanishes as user cannot recognize the two adjacent setting values displayed with the dial. Therefore, overall a value of one is assigned. Two out of four controls of sound system i.e., power push button and volume dial, offer tangible transitions while other two dials for bass and treble does not offer tangible transitions. Therefore, a value of one is assigned. Among all controls of MP3 player, only slider control (for power) offers sufficient tangible transition while other controls offer meager and insufficient tangible transitions.

For the bounce back, the dials of washing machine do not offer bounce back hence rated zero. The controls of camera and some controls of MP3 player offer weak bounce back hence assigned value one and 0.5, respectively. Oven controls does not offer bounce back, so rated zero while one of four controls of sound system offers bounce back, so overall rated 0.5. The controls of washing machine, oven, and sound system offer strong inverse action. The camera’s quad-button is a multi-purpose button hence offering weak inverse action, so overall camera’s inverse action is rated with value 0.5. Similarly, the forward and backward buttons of MP3 player, two out of six controls, offer weak inverse action while the slider offers strong inverse action, so an average value of one is assigned to overall PUI. One control of washing machine offers compliant interaction; the main wash dial; therefore an average value of 0.5 is assigned. Similarly, a control of oven offers compliant interaction; the baking dial; therefore an average value of 0.5. Other PUIs do not offer compliant interaction hence rated zero.

According to these results, washing machine PUI offers highest and MP3 player PUI offers lowest value of physicality principles. Exposed state, tangible transitions, and inverse action play significant role in the ratings of washing machine. On the other hand, MP3 player lacks in strong exposed state, bounce back, and inverse action. Oven and sound system PUIs offer strong exposed state and inverse action principles. Camera PUI is slightly better than MP3 player due to comparatively better bounce back effect. Overall, washing machine PUI offers highest physicality value than other subject PUIs.

6.0 DISCUSSION

The analysis of five PUIs highlights the significance of exposed state, tangible transitions, and inverse action. The results of this study verified that these principles are more significant in augmenting the natural interaction. Additionally, even a single control offering good compliant interaction, depending upon device’s underlying functionality, also helps in enhancing the overall performance of device. Although dials are powerful controls but do not offer bounce back that is more significant with other controls especially buttons. The PUIs with buttons should offer bounce back effect properly as it is missing in some of the subject ESs. Controlled state is not a frequently used principle and none of the subject interfaces offered it. These principles recruit users’ innate subconscious abilities. Users’ prior experience with other like devices also helps in building the abilities of use. The physicality principles help in building a kind of mutual understanding between the user and the control. This results in alleviating the cognitive requirements and visual concentration especially by tangible transitions, bounce back, and inverse action. The quantitative ratings help ES developers in easily managing these principles in their developed products. The introduction of physicality principles in PUIs of ESs helps in reducing the complexity of interaction and augmenting the naturalness of interaction. Previously, these principles were not applied to the ESs.

7.0 CONCLUSION

There is a need to incorporate physicality aspects in PUIs of ESs. This study has investigated the physicality principles in the PUIs of various ESs including washing machine; camera; oven; sound system; and MP3 player. The results revealed that the washing machine interface offers most physicality principles while MP3 player offers the least. The principles of exposed state, tangible
transitions, and inverse action are found to be more significant than other principles in producing visceral interaction. The quantitative analysis approach has helped us to easily highlight the key issues related to physicality of devices. This approach is especially helpful for the ES developers having less exposure to the techniques and methods of Human-Computer Interaction or its sub-field Physicality. The developers can use this approach to incorporate, manage, evaluate, and hence enhance the physicality aspects. This practice will result in the development of naturally interactive ESs since these aspects were not addressed before. The evaluation of this approach by the ES developers is in progress.

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