Designing Physical Interaction with Sensor Drawbacks in Mind

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ABSTRACT
Physical interaction often relies on information stemming from sensors perceiving the real world. Sensors however, have imperfections resulting in drawbacks such as uncertainty and latency. Consequently, the improvement of sensors and perception methods is important. In this paper we argue however that imperfections of sensing will remain and that the key to better physical interaction lies in taking into account those sensor drawbacks explicitly during the design of the interaction. In order to take a first step in this direction we analyze sensor drawbacks and their effects on physical interaction. Based on this discussion we propose example solutions to the arising problems.

1. INTRODUCTION
As computer systems gradually find their place in everyday life, interaction with real world user interfaces becomes more and more important. The term *physical interaction* embodies the paradigm, where real world artifacts become part of the user interface. Researchers from the fields of ubiquitous computing, interaction design, augmented reality and human-computer-interaction all are working on new interaction metaphors based on physical interaction [10].

Acquiring the users input from the real world is one of the challenges that most of the projects in physical interaction have to face. Most often sensors are used to capture real world actions. For this, research can draw on work from the fields of sensor technology and pattern recognition. Appropriate sensor selection can often simplify the recognition of real world actions. Pattern recognition techniques offer methods for acquiring more complex actions.

Although it is often taken for granted many modern household and office appliances already have physical interfaces beyond switches and dials. “Intelligent” air-condition systems switch off as soon as someone opens the window in the room. Refrigerators sound an alarm tone when the door is left open too long. The simplicity with witch these two examples acquire information about the users actions, is why they work so well. Another type of applications are automatic doors, which open when someone is nearby or water dispensers, which start as soon as someone’s hand is under the faucet. Often though, problems occur. Automatic doors don’t open before you get really close to them, or they open when you are only standing close by. Water dispensers don’t react until you have found the exact position. Frustration or even changes in people’s behavior can be the result. A count on a Swiss train showed, that approx. 70% of the passengers wave their hand in front of the infrared sensor to make the door open.

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These applications rely on sensed information to react. This information is often uncertain or ambiguous. As physical interaction is mostly based on sensor systems to recognize actions in the world, the problem of uncertainty will have to be addressed in many of these systems. In this paper we propose how incorporating sensor drawbacks can lead to better physical interaction.

Sensors drawbacks are only one part of the problem that HCI researchers face. Many other technical problems related to bandwidth, connectivity, latency, and power will have to be dealt with. Here we focus on the drawbacks of sensing systems

In particular we analyze the effects that sensing systems have on human-computer interaction. We give an overview over sensing tasks of interest for HCI, and discuss main sensor drawbacks. We then propose a set of design ideas to make physical interaction clearer and more useable.

2. SENSOR CHARACTERISTICS
By analyzing the effects sensor systems have on physical interaction we hope to bridge the gap between sensor research and physical interaction design. In this section we analyze sensing systems with respect to important sensing tasks for physical interfaces.

In Table 1 a few representative perception tasks for physical interaction interfaces are listed. The perception tasks are sorted by increasing task complexity. The sensing system is decomposed in the actual sensors and the recognition system. The column “recognition system” describes the actual sensor data processing algorithm used. This can either be a complex statistical pattern recognition system or a simple thresholding algorithm amongst others. The examples are either applications or projects that make use of the perception tasks for their interfaces.

Table 1: Perception tasks ordered by increasing complexity

Perception Task	Sensors	Recognition System	Main Drawbacks	Examples
Wireless switches/sliders	Switches/sliders		Latency	iStuff [7], Phydgets **Error! Reference source not found.**
Detecting persons presence	IR-sensor	Threshold	Latency, ambiguity	Automatic door, water faucet, auto. urinal
	Floor weight switch	Threshold	Latency	
Object location	IR-based location	Triangulation, time of flight	Precision	MediaCup [5]
	Ultrasonic location		Precision	
Object identification	Rf-id tags	Database	Too many items	Smart shopping cart
	Weight sensors	Weight matching	Ambiguity	Weight surfaces [6], Tangible bricks [2]
Object movements	Inertial (accel. & gyros)	Dead reckoning	Sensor precision, ambiguities	MediaCup [5]
People's location	GPS	Map lookup	Robustness, doesn't work indoors	Tourist guide [11]
	Ultrasonic, …	Triangulation	Precision	Active bat, …
Gestures (depends on number of commands)	Inertial	Various HMM, in general pattern recognition	Recognition rate, latency, ambiguity	Sign language recognition, interactive narrative systems …
	Vision			
	Combined			
Handwriting recognition	Scanner, touch sensitive screen	Optical character recognition (OCR)	Learning time, latency, recognition rate	PDA input systems, recognizing handwritten notes
Speech recognition (commands)	Audio	Signal matching HMM, …	Robustness	Voice dialing
Speech recognition in general	Audio	HMM's, other pattern recg.	Recognition rate, latency	Taking down a text
Situation detection	Audio & video	Statistical pattern recognition	Recognition rate	Context sensitive notification
Activity recognition	Video, inertial	Statistical pattern recognition	Recognition rate	Context sensitive notification, surveillance

Most problems with the use of sensors for physical interaction arise because of the uncertainty which is inherent in sensor systems. Where uncertainty comes from can be analyzed by regarding the different aspects of sensor uncertainty. Here we differentiate between four aspects, namely robustness, recognition rate, precision, and ambiguity.

Robustness of a system describes how well a system performs over all external conditions that make sense for a specific task. This includes changes of lighting conditions, changes in the noise level, and changes of the number of people in the environment. The *recognition rate* quantifies the performance of a classification system for a recognition task under fixed external conditions. Often the rate is gained during experiments with a set of example test data. In contrast the *precision* of a sensing system describes how well the output of the sensor system represents the real world phenomenon. Finally, *ambiguity* describes how well different physical phenomena can be held apart using a certain sensor configuration. When two real world actions have similar effects on the sensor system they become hard to distinguish, i.e. ambiguous.

Table 2 gives an overview of the different aspects of uncertainty. It relates the different aspects to the level from which they emerge in the sensing system.

If a system is *not robust* towards environmental changes this can be very annoying and surprising to the user. For example mobile phone voice dialing systems are expected to work wherever you are. However close to a noisy street, it would be surprising if such a system would work. Similarly the Global Positioning System (GPS) will not always have satellite contact in a city with tall skyscrapers.

Similarly, a sensor system with a *low recognition rate* can become interruptive. When using a gesture based interface the user doesn't want to have to repeat every third gesture just because the system didn't understand. In the example of a retina scanner for access control purposes a low recognition rate would definitely be cumbersome.

The *precision* of a sensor influences the previously mentioned recognition rate, but also has its own influences on physical interaction systems. Sensors with inherently low precision will only be used for tasks with minor importance, if at all. Variations in precision during use of the sensor will result in effects of annoyance and surprise to the user. Most indoor positioning systems still are not very precise. This may be one reason for them not being successful in many commercial applications.

Sensing *ambiguities* in systems can also have disturbing effects on physical interaction. The automatic opening of a train door

Table 2: Aspects of uncertainty in sensor systems

Sensing system level	Uncertainty aspect
Task	*Robustness*
Classification System	*Recognition Rate*
Sensor	*Precision*
Physical Signal	*Ambiguity*

when a passenger is turning a page of his newspaper is at least surprising, sometimes even bothering. Ambiguities during speech input can have serious implications. If you are talking to your office neighbor about "deleting files", you definitely don't want your system to take such a drastic action.

All sensor drawbacks mentioned until now were directly related to the uncertainty of sensing systems. Beyond uncertainty, the *latency* of a sensor system is important for physical interaction. Latency directly influences the interactivity of a system. Slow systems become cumbersome to use, as the flow of action is always interrupted by pauses. In the worst case systems may even loose causality. This happens when delays become so long that the user is unable to make the connection between his input and the systems reaction.

Although sensor system researchers are making vast amounts of progress, it is clear that uncertainties will always remain. We believe that these remaining uncertainties and sensor latency needs to be incorporated into interaction design. By integrating these sensor drawbacks systems will become less interruptive and less cumbersome.

The effects that sensor uncertainty and latency have on the interaction experience range from being surprising over disturbing to totally interrupting. These effects are well known from the general field of HCI and have been discussed widely under the names of *principle of least surprise* [14] and *principal of fluid interaction* [15]. Systems designed with these principals in mind are easier to use and find greater acceptance. Designing physical interaction systems with these principles in mind is only the next step. In the next section we propose simple design guidelines to comply with these principles.

3. DESIGNING INTERACTION WITH SENSOR DRAWBACKS IN MIND

To enable more usable physical interaction, sensor and interaction researchers need to work together. On the sensor side researchers need to become aware of the effects of their systems on interaction. For example, robustness of systems could be increased if the exact task profile for the usage of the system is clearly defined. Defining sensor system characteristics should always be done with respect to a given task.

A paramount goal of interaction design is to keep the user's mental model [14] of the system as simple as possible. The system should appear causal to the user. This is why the *principle of least surprise* has such great importance. Keeping sensor drawbacks in mind during the design of physical interaction results in a more precise anticipation of the mental model the user will have.

There are several ways of dealing with sensor drawbacks in interactive systems. MacColl et al. [1] describe the basic idea of explicitly presenting uncertainty. They describe four ways to present uncertain information: pessimistic, optimistic, cautious, and opportunistic. Horvitz [13] proposes systems that vary their self-initiative depending on uncertainty and the expected utility of an action. Mankoff et al. [17] present the technique of mediation, where the user can chooses from several possible recognition results.

While studying the effects of uncertainty as a whole is important, we believe that the different aspects of uncertainty identified in the previous section need to be considered individually and in more detail. In the remainder of this section we do this by presenting examples.

When insufficient *robustness* is the cause of error, the user should be informed why the system is not working. It may simply be that the system doesn't work in a loud environment, as in the example of using voice dialing close to a noisy street. Telling the user the reason for the lack of robustness, gives him the possibility to change the setting. Many GPS Systems for example, let the user know how well the system is working by showing the number of satellites available.

When systems have low *recognition rates* they become interrupting whenever they make wrong decisions. Presenting the results non-destructively is one way around constantly interrupting the user. For example, handwriting recognition in the Interactive Workspaces Project [9] presents the recognized text beside the handwritten text. In this way the user is not interrupted by wrong recognitions but can still be aware of the systems recognition.

Applying sensor systems with low *precision* needs to be done with grate care with respect to the effects wrong results may have. Automatic system actions have to be designed with the precision of the sensor in mind. Drastic actions should only be taken when precision is high.

For both systems with low recognition rates and low precision it may be useful to display a confidence level of the system. For a recognition system this may be the recognition probability or an external evaluation. For a sensing system with imprecision on the sensor level the momentary precision depending on the external conditions could be shown to the user.

In systems with inherent *ambiguity* interaction should be designed to minimize surprising the user by unexpected actions. This can be done by informing the user about what is sensed. For example, a train passenger will be less surprised about an automatically opening door when he turns a page in his newspaper, if he knows how far the sensor reaches. A method for actually reducing ambiguity has already been used in speech recognition systems. Here *quasimodes* [12] let the user activate the system by pressing a key on the keyboard. Using this no more mistakes happen when the system was listening and you thought it wasn't.

Beyond uncertainty, dealing with *latency* of sensing systems is a highly important task. Offering the user immediate feedback is often invaluable. Giving the user a notion of how long an action will take can also be encoded in feedback. In [16] a tactile display is presented which gives feedback of how far a task on a mobile device has advanced. The stronger the device shakes the further the task has progressed.

Informing the user on how far his request to the system has advanced, could be accomplished using a *feedback chain.* The idea of a feedback chain is to inform the user about how far his command to the system has been processed. This could be done on each relevant level. For example, pressing a wireless button would give an immediate local feedback by lighting an LED on the device. When the system recognizes the event, further feedback could be given on an ambient display. When finally the command is processed it could be reported back to the user by letting the wireless button shake or flash an LED. Such a feedback chain would help the user build a mental model of the system. Beyond that it could be a useful tool for anticipating system errors.

4. DISCUSSION

Although sensor drawbacks will always exist it is still necessary to further investigate innovative sensing approaches using various sensors and algorithms. Most importantly sensor systems need to be evaluated on real interaction tasks. For this, sensor researchers need to work together with interaction designers.

In the HCI community, the task conditions in which interaction will take place need to be clearly stated. Beyond this, the drawbacks inherent to sensor systems need to be taken into account. Thus an informed design can take place. Overall, the loop between interaction designers and sensor researchers needs to be lived.

In the examples presented in this paper we didn't distinguish between explicit and implicit interaction [8]. Sensor drawbacks equally effect both explicit and implicit interaction. In many cases implicit interaction is effected more than explicit interaction as it often heavily relies on sensor information. Presenting feedback explicitly as proposed in this paper could be a solution to make implicit interaction more useable. In applications where sensor drawbacks cause too many problems implicit interaction will have to be extended by disambiguating explicit mechanisms.

5. CONCLUSIONS

In this paper we take first steps towards dealing with sensor drawbacks in physical interaction. We analyzed sensor drawbacks to discover the effects they have on HCI. By decomposing the notion of uncertainty into its aspects it was possible to clarify where the different effects on interaction come from. To deal with the problems we present design techniques that mostly have already been used in different applications.

Most importantly, we believe that the quite separate research communities for sensing and HCI need to work together more closely. On one side the sensing community needs to take the tasks settings into account while evaluating their work. On the other side the HCI community needs to be aware of potential sensor drawbacks and take them into account appropriately during their design. We believe that this contribution is a first step in answering the five questions in designing physical interaction posed by Bellotti et al. [4].

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