THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

The Ultimate Display

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Abstract

In 1965 Ivan E. Sutherland envisioned the Ultimate Display, a room in which a computer can directly control the existence of matter. This type of display would merge the digital and the physical world, dramatically changing how people interact with computers. This thesis explores flat displays, deformable displays, flexible materials, static, and mobile projection displays in dynamic environments. Two aspects of the dynamic environment are considered. One is mobile human nature – a person moving through or inside an environment. The other is the change or movement of the environment itself.

The initial study consisted of a mixed reality application, based on recent motor learning research. It tested if a performer's attentional focus on markers external to the body improves the accuracy and duration of acquiring a motor skill, as compared with the performer focusing on their own body accompanied by verbal instructions. This experiment showed the need for displays that resemble physical reality.

Deformable displays and Organic User Interfaces (OUIs) leverage shape, material, and the inherent properties of matter in order to create natural, intuitive forms of interaction. We suggested designing OUIs employing depth sensors as 3D input, deformable displays as 3D output, and identifying attributes that couple matter to human perception and motor skills. Flexible materials were explored by developing a soft gripper able to hold everyday objects of various shapes and sizes. It did not use complex hardware or control algorithms, but rather combined sheets of flexible plastic materials and a single servo motor. The gripper showed how a simple design with a minimal control mechanism can solve a complex problem in a dynamic environment. It serves as an example application for merging the digital and the physical through flexible materials, embodied computation, and actuation.

The next two experiments merge digital information with the physical dynamic environment by using mobile and static projectors. The mobile projector experiment consisted of GPS navigation using a bike-mounted projector, displaying a map on the pavement in front of the bike. We found out that if compared with a bike-mounted smartphone, the mobile projector yields a lower cognitive load for the map navigation task. A dynamic space emerges from the navigation task requirements, and the projected display becomes a part of the physical environment.

In the final experiment, a person interacts with a changing, growing environment, on which digital information is projected from above using a static projector. The interactive space consists of cardboard building blocks, the arrangement of which are limited by the area of projection. The user adds cardboard blocks to the cluster based upon feedback projected from above. Concepts from artificial intelligence and architecture were applied for understanding the interaction between the environment, the user, the morphology, and the material of the physical building system.

Keywords: Interactive Space, Dynamic Environment, Mobile Projector, Static Projector, Deformable Displays, Flexible Materials, Perception, Physical World

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Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Alexandru Dancu, Motor Learning in a Mixed Reality Environment, Work-in-progress, Poster, Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design, NordiCHI'12, Oct 14-17 2012, Copenhagen, Denmark.
Paper B	Alexandru Dancu, Kristina Knaving, Workshop paper at the Organic Experiences: (Re-)Shaping Interactions with Deformable Displays Workshop, Conference on Human Factors in Computing Systems, CHI'13, April 27 – May 2, 2013, Paris, France.
Paper C	Stig Anton Nielsen, Alexandru Dancu, Embodied Computation in Soft Gripper, Work-in-progress, Poster, Proceedings of the ACM/IEEE International Conference on Human-robot Interaction, HRI'14, March 3–6, 2014, Bielefeld, Germany.
Paper D	Alexandru Dancu, Zlatko Franjcic, Morten Fjeld, Smart Flashlight: Map Navigation Using a Bike-mounted Projector, Note, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI'14, April 26–May 1, 2014, Toronto, Canada.
Paper E	Alexandru Dancu, Zlatko Franjcic, Morten Fjeld, Finding a Suitable Projection Surface using an Environment-Aware Mobile Projector, in submission
Paper F	Stig Anton Nielsen, Alexandru Dancu, Layered Subsumption in Intelligent Material Building Systems, Work-in-progress, Demo, Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction, TEI'14, Feb 16 – Feb 19, 2014, Munich, Germany.

Contents

Part I
Extended Summary

One goal of Human-Computer Interaction is to design a display that supports perception of information and minimizes the gap between what the user wants to achieve and how the computing device supports that task. “The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in” [Sut65]. Current computing devices with displays tend to separate us from our physical environment. People check their phones’ display on average 150 times[1] a day. This changes their behavior and creates a gap between the physical world and the digital domain. We can instead make our environment become a responsive part of the information domain, by merging the digital and the physical world. This thesis explores flat displays, deformable displays, flexible materials, static, and mobile projection displays in dynamic environments. Two aspects of the dynamic environment are considered. One is mobile human nature – a person moving through or inside an environment. The other is the change or movement of the environment itself.

The assumption of this thesis is that the experience of the world is closely coupled to how you act in it; perception, action, and environment are interdependent. Interactive systems cannot be separated from the continuously changing environment in which they are embedded [Dou04; Hur02; Noë04]. According to philosopher and cognitive scientist Alva Noë, “the brain and nervous system, insofar as they enable perceptual awareness of the environment, are not in the business of generating feeling; rather, they are in the business of enabling us to interact dynamically with the environment. Our experience and capacities depend on the full character of that skillful interaction. [..] We are partly constituted by a flow of activities with the world around us. We are partly constituted by the world around us. Which is just to say that, in an important sense, we are not separate from the world, we are of it, part of it” [Noë09]. These ideas originate partly from researching sensorimotor skills, action and perception. This was also the starting point in our research. Alva Noë’s remarks: “unless you are very much a novice – an absolute beginner learning a musical instrument, for example – you will disrupt your performance if you focus not on the task at hand, or the goal, but on the bodily mechanics of execution”. This agrees with a motor learning theory validated during the last ten years – The Constrained Action Hypothesis – which claims that external focus of attention (effects of the performer on the environment) is more beneficial in motor learning than internal focus of attention (concentration on performer’s own body movements) [Wul07].

Paper A tests this hypothesis in a mixed reality environment, by showing that when acquiring a motor skill , focusing on virtual markers is faster and more accurate than focusing on your own body. The proposed mixed reality environment shows a virtual avatar that closely follows the movements of the user and of a virtual trainer performing the correct movement. The experiment was between-groups, with one group performing instruction-based and the other performing marker-based motor learning. The mixed reality environment was limited by the space of interaction in front of a large

[1] `http://www.kpcb.com/insights/2013-internet-trends`

flat display, and by the visual information suggesting hand path movements in a virtual world displayed on a flat screen. To improve visual feedback, one could develop better visualization methods on a flat screen, or explore other display types that resemble better the physical world.

Paper B discusses current flexible and transparent display technologies and applications, as well as materials which can change their shape and color. Deformable displays [Ale+13] and Organic User Interfaces [Oui] are new classes of "visual output devices [that] extend beyond the rigid, flat surfaces with which we are familiar, to those that the user or the machine can deform. These will allow users to physically push, pull, bend, fold or flex the display and facilitate a range of self-deformation to better represent on-screen content or support new modes of interaction" [Ale+13]. Physical objects have properties that are built on their three dimensional geometry, enabling certain actions. These properties, or action hooks, couple matter to human perception and motor skills. Identifying and applying them in the design process can lead to improved usability and new techniques in interaction design [Dja+04; Red08; VR07a]. Appropriate action hooks couple matter to human perception and motor skills. The role of the interaction designer is to enhance the communication between human and material by identifying intuitive action hooks and using them to satisfy human needs. Identifying action hooks in terms of displays, materials, and the motor skills they afford could help in designing deformable displays and Organic User Interfaces.

Flexible materials were explored in **paper C**, which proposes an underactuated soft gripper, able to hold everyday objects of various shapes and sizes. It does not use complex hardware or control algorithms, but rather combines sheets of flexible plastic materials and a single servo motor. Starting with a prototype, where simple actuation performs complex and varied gripping operations solely through the material system and its inherent physical computation, the paper discusses how embodied computation might exist in a material aggregate that tunes and balances its morphology and material properties. Mobile phones with flexible and transparent displays can already be built, but harnessing the potential of flexible displays doesn't lie in combining the new materials with the old interaction techniques. The power of flexible materials lies in their inherent properties which can enable completely new ways of interacting. The soft gripper showed how a simple design with a minimal control mechanism could solve a complex problem in a dynamic environment. Moreover, it is an example of merging the digital and the physical through embodied computation and actuation.

Using a mobile projected display to merge the physical and the digital was the purpose of **paper D**. A mobile projector was mounted on a bike, displaying a map on the pavement ahead of the user, enabling GPS navigation while cycling. The projected display became part of the environment, demonstrating an application for interaction in motion. Interaction in motion involves several challenges, such as cognitive load, physical constraints of the human body, and properties of the terrain and environment [MT13]. Two applications were studied: the map was either displayed on a smartphone, or projected on the road. A prototype was implemented, comparing the two applications for use in a navigation system for nighttime cycling. The experiment showed that the projector-based system required less mental load while cycling on the different routes indicated on the map. The proposed system makes use of an already known setting – riding a bike equipped with a flashlight – and augmented it with map and route information. The paper also suggested and discussed visuo-spatial factors influencing navigation.

Paper E explored finding suitable projection surfaces with mobile projectors. While using a projector in motion, users frequently encounter uneven surfaces with lower visibility. A handheld system and method was proposed that recognizes apparent uneven and discontinuous projection surfaces in real-time. When a gap or disturbance is identified on an approximately planar projection surface, the system changes the projected image in that region, encouraging the user to find another suitable area. The paper discussed interaction principles and identified a series of important considerations for designing mobile projection systems.

While paper D and E focused on the movement of the user through the environment, **paper F** focused on modifying the environment within a static, limited area of projection. The dynamic environment consisted of cardboard building blocks. The user adds cardboard blocks to a cluster, based on feedback projected from above, with the purpose of making a balanced structure. Rodney A. Brooks proposes a digital control system for artificial intelligence, called layered subsumption, that proves to be robust in interaction with the real world [Bro91]. We investigate how this robust layered subsumption acts both digitally and through functionality embedded in the material of the building system itself. We describe a building system with computational control over the building process, arguing how layered subsumption exists seamlessly, shared between the digital and the physical material of the system. If a system using layered subsumption is able to modify its entire environment, we argue, that subsumption must be found embedded within the morphology and material of the environment.