

LuminAR

A Compact and Kinetic Projected Augmented Reality Interface

Natan Linder


B.A. in Computer Science, The Interdisciplinary Center, May 2003

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences
at the Massachusetts Institute of Technology

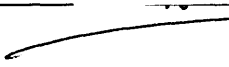
September 2011

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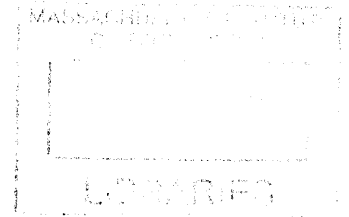
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Abstract

For quite some time, researchers and designers in the field of human computer interaction have strived to better integrate information interfaces into our physical environment. They envisioned a future where computing and interface components would be integrated into the physical environment, creating a seamless experience that uses all our senses. One possible approach to this problem employs projected augmented reality. Such systems project digital information and interfaces onto the physical world and are typically implemented using interactive projector-camera systems.

This thesis work is centered on design and implementation of a new form factor for computing, a system we call LuminAR. LuminAR is a compact and kinetic projected augmented reality interface embodied in familiar everyday objects, namely a light bulb and a task light. It allows users to dynamically augment physical surfaces and objects with superimposed digital information using gestural and multi-touch interfaces. This thesis documents LuminAR's design process, hardware and software implementation and interaction techniques. The work is motivated through a set of applications that explore scenarios for interactive and kinetic projected augmented reality interfaces. It also opens the door for further explorations of kinetic interaction and promotes the adoption of projected augmented reality as a commonplace user interface modality.

This thesis work was partially supported by a research grant from Intel Corporation.

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Totum factum.

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Acknowledgments

This thesis is a result of intensive collaboration with numerous colleagues, UROPs, faculty and staff, Media Lab sponsors and external collaborators.

First, I would like to thank my advisor, Pattie Maes, for her guidance and support throughout the research process. I would also like to thank my thesis readers Joe Paradiso and Cynthia Breazeal for their critique and thoughtful comments.

A special big thanks goes to Yoav Reches who came all the way from the London to join the project and to Iliya Tsekov who managed to work with me an entire year! Another big thanks are due to the relentless IF Robots duo, Matt Berlin and Jesse Gray – keep taking names. Thanks to Jason Robinson and Gian Pangaro & Co. of IDEO. It was an honor and a pleasure to undertake this crazy project with all of you guys.

Special thanks for the members of the Fluid Interfaces Group for their continued critique, advice and friendship, In particular I would like to thank Susanne Seitingner, Aaron Zinman, Sajid Sadi, Marcelo Coelho, Seth Hunter, Doug Fritz, Pol Pla, Roy Shilkrot, Amna Carreiro and Taya Leary.

Thanks to the amazing UROPs and interns that supported the project: Gaia Carini, David Jia, David Yamnitsky, Houston King, Miko Montemayor, Brain Wu, Alan Xu, Michelle Wang, Craig Broady, Toomas Sepp, Rebecca Kleinberger, Fei Ni and Michael Poon.

A special thanks to the great support I have got from the Media Lab staff and faculty, In particular: Andy Lippman, Hiroshi Ishii, Paula Aguilera, Jonathan Williams, Felice Gardner, Linda Peterson, Bob Swartz, Steve Otis and Alexandra Kahn.

I would like to acknowledge the generous support from our Media Lab sponsors. Specifically I would like to thank Mary Murphy-Hoye, Shailesh Chaudhry and Vanessa Foden from Intel and Neil McPhail and Matt Skally from Best Buy.

I would also like to acknowledge the support in kind I have received for Microvision and PMDTec, and thank Mark Freeman, Bernd Buxbaum and Thorsten Ringbeck.

Finally, I would like to thank Emmy and my family for all the support they have given me during my studies.

1 Introduction

The Current User Interface Challenge

We live in an era in which user interface design is central to the perception, creation and adoption of technology. It is in this same era that human society at large, has become almost completely technology-dependent. Battery powered electronic devices with digital interfaces now connect us to vast networks of information. In less than 30 years, we have miniaturized our personal computers to a hand held size. We can package enough computation in a matchbox to carry out massive processing that once required a room full of servers. We also expect wireless communication as we expect electricity.

The digital world has become an integral aspect of everything we do; whether it is work or play. We take it for granted that we can connect anywhere, anytime and gain access to any information. Only in the past few years has the web transformed into a cloud of services. At the same time, embedded computing, wireless communication and novel UI technologies matured quickly to a point where we think we have the Internet at the tip of our fingers at all times, but do we really? This thesis raises this question and asserts that there is in fact a discontinuity between our experiences in the physical world and our interactions with the digital world.

The problem is that the real world is complex, and we are still using it very much physically. Our current work environment, such as lab benches, architect tables and retail counters, provide a case in point for how we really work: multiple devices, notes, paper and various tools and objects. So in reality - the digital world and the physical world are not at all disconnected. A note we write finds its way to an email message, and a measurement we take will end up in a CAD model.

In reality, users have the responsibility of connecting the digital and the physical world. We humans did not evolve as quickly as our technology, and fundamentally, we have a very narrow pipe to process the vast amounts of information we can now reach. Our brains and sensory systems define a biological I/O bottleneck that we work hard to overcome, mainly because as users we have adapted ourselves to interfaces and not vice versa.

New Form Factors for Computing

It is very likely that the roots of this problem lie in the evolution of computing devices form factors. Essentially, we are still using display-centric devices, and as such they define the key modality of interaction, which hasn't changed substantially since the PC. I believe that humans are spatial creatures that were not 'designed' to spend most of their time in front of computers. And yet it seems that more and more of our work and play hours are spent in front of a screen. This defines an

'interface paradox' from a cognitive, ergonomics and design point of view - we are designing interfaces that change our essence. The direct impact of this phenomenon is at the core of thought and discourse of modern sociologists. Vast research is being carried out in an effort to define and measure how human perception, thinking and behavior is altered due to the massive proliferation of technology and interfaces to the digital world.

Another aspect of this meta-problem is the fact that we are constantly curating several consumer electronic devices that connect us to the digital world: laptops, smart-phones, e-book readers, digital cameras and the list goes on. We are responsible for updating software, running cables, charging, syncing and so on. Unfortunately, Wieser's Ubiquitous Computing vision [1] still seems far away, and poses a challenge to Human Computer Interaction research. Technology has yet to become transparent and embedded in our environment.

Projected Augmented Reality Interfaces

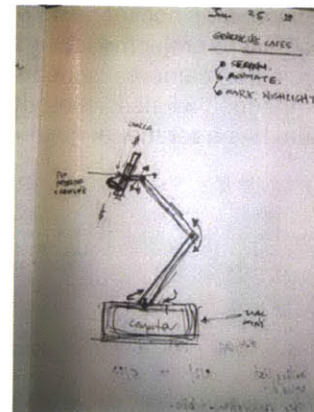
To address the challenges I introduced above, researchers and designers in the field of human computer interaction have pursued the research of augmented reality systems as a means to better integrate information interfaces into our physical environment. They envision a future where computing and interface components will be integrated in the physical environment, creating a seamless experience that uses all our senses.

One possible approach to this problem employs projected augmented reality [2]. Such systems project digital information and interfaces onto the physical world and are typically implemented using interactive projector-camera systems. However, classic projector camera systems are very limited as we discuss in detail in the next chapter.

Kinetic Projected Augmented Reality Interfaces

This thesis work is centered on the design and implementation of a new form factor for computing, a system we call LuminAR [3]. LuminAR is a compact and kinetic projected augmented reality interface embodied in familiar everyday objects, namely a light bulb and a task light. It allows users to dynamically augment physical surfaces and objects with superimposed digital information using gestural and multi-touch interfaces.

The goal of this thesis is to advance the state of the art of projected augmented reality interfaces. We intend to provide designers and engineers with a full-blown



LuminAR concept sketch

implementation of a compact and kinetic system that is feasible to build with current technology.

Another goal of this work was to provide a glimpse into the future potential applications of this technology in relevant real-world scenarios. We have focused on two areas: (1) future desktop environments and (2) augmented retail spaces.

The work on these applications enabled to distill a set of new interaction methods. These new techniques make use of the unique form factor components of the LuminAR system and their respective kinetic capabilities.

Finally, after several iterations of prototyping, we were able to refine our design and reach another goal of this work – embedding interface technology in everyday objects. In this work we emphasize the industrial and product design aspects, and part of the story this thesis tells is the one of the actual process in which we have refined our prototypes and achieved this goal.

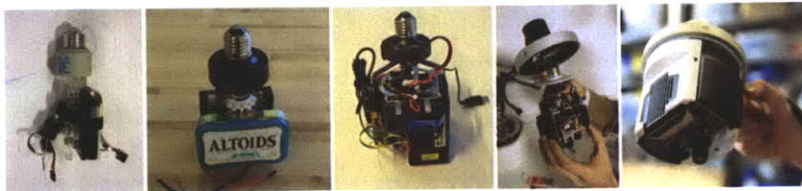
LuminAR Prototypes

We have developed three different systems that we used to explore the space of kinetic projected augmented reality interfaces: The LuminAR Bulb, LuminAR Lamp and the LuminAR Spotlight. The insights we derived from these prototypes can hopefully stir the discussion on a set of design principles for self contained, compact kinetic interfaces and associated interaction techniques.

We provide a brief description of the prototypes below.

LuminAR Bulb

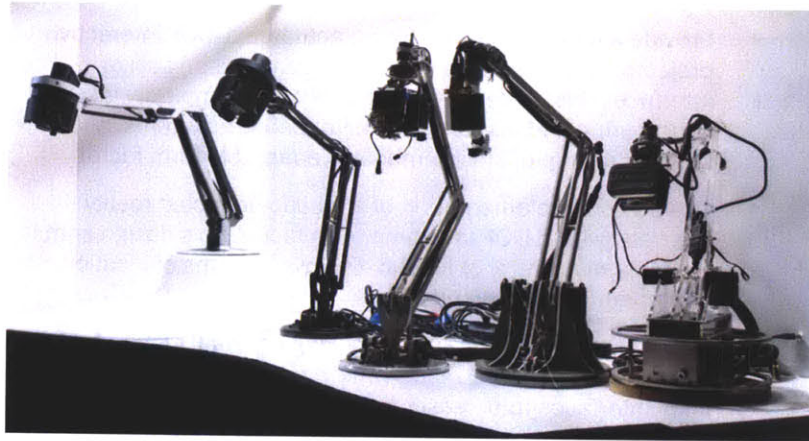
The LuminAR Bulb design is a fully realized two-way information device. The bulb was designed to require only AC power and wireless communication to operate. It was designed to fit in existing, standard Edison lamp sockets. The bulb is a compact and completely self-contained projector-sensors system that integrates a laser pico-projector, cameras, sensors, control electronics, power supply and an embedded wireless computer in the size of a large bulb. In addition, the bulb has a rotational degrees-of-freedom (DOFs).



The evolution of LuminAR Bulbs

LuminAR Lamp

The LuminAR Lamp is an articulated robotic arm, designed to interface and carry the LuminAR Bulb. The lamp's design follows the classic Anglepoise counter-balanced arm design allowing the bulb four DOFs. Each DOF has a motor, positional and torque sensors as well as motor control and power circuitry. The arm terminates in a lampshade with a standard Edison socket.



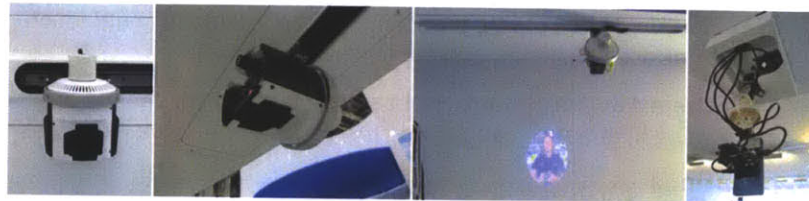
The evolution of LuminAR Lamps (photo: Doron Gild)

LuminAR Spotlight and Spotlight360

The LuminAR Spotlight system is an actuated track light. It is also designed to carry the LuminAR Bulb. The Spotlight can be mounted on a ceiling or wall, taking advantage of additional height and projection angles above and around a workspace.

The system consists of a linear track and a carriage with a tilting head, giving LuminAR Spotlight two degrees of freedom. The head interconnects with the LuminAR bulb through a standard Edison bulb screw socket. Spotlight's design is simple, allowing it to become almost invisible in its environments.

The Spotlight360 is another prototype for a wall or ceiling mounted LuminAR Bulb fixture, capable of rotating in 360 degrees. It is also mounted on a base servo that allows the bulb with an additional DOF.



LuminAR Spotlight and Spotlight360

Contributions

This thesis work makes contributions in different areas, but mostly in the design and implementation of a compact and a kinetic form factor for a projected augmented reality interface. Specifically, the LuminAR project makes contributions in the following areas:

Hardware Engineering

- Provide a compact design for an actuated 1-DOF interactive projector-sensor system with a standard Edison socket interface. This design greatly reduces the complexity involved in designing and installing projector camera systems, and enables a simple, environmentally adaptable form factor
- Design and implementation of a kinetic projected reality interface with 5-DOF in a lamp form factor. This design enables the dynamic control of kinetic displays in terms of location, size and orientation of the display
- Design and implementation of ceiling and wall mounted kinetic projected augmented reality interfaces. This design allows for such interfaces to be easily installed in a physical space

Software Framework

- The design and implementation of an open and extensible software development environment that allows for easy application development for kinetic augmented reality applications

Interaction Techniques

- Design and implementation of a kinetic user interface methods with the ability to change point-of-view of projection and sensing using multiple DOF actuation, providing a more integrated and dynamic augmented reality experience
- Implementation of two-way input-output mechanisms supporting multiple modalities that combine natural user interfaces in real-time. For example providing object recognition and tracking in combination with traditional multi-touch or gesture recognition
- Defining and prototyping a set of new gestures we call *Dynamic Multi-touch*, that combine the traditional multi-touch interface with kinematic capabilities
- Context aware systems that can respond to user context and using kinematics can provide *just-in-time-and-place* interfaces

Applications

- Design and implementation of a set of novel augmented desktop applications, including the use of a spatial locative memory for menus and applications, as well as a gesture controlled kinetic application desktop prototype

- Design and Implementation for a full future scenario for an augmented retail environment, including interfaces that augment products on a display counter, embedding rich media in a new shopping experience, also allowing interaction with a remote expert

Product/Industrial Design

- Creating novel and fully implemented designs for a new form factor for computing, these interface objects push the boundary beyond a lab prototype result in terms of functionality and aesthetics

It is my hope that the result of this work can open the door for the adoption of augmented reality as a commonplace user interface modality. This thesis only touches upon the interaction techniques enabled, leaving additional assessment and formal evaluation to future work.

Thesis Outline

This thesis is divided to seven chapters. Below is a chapter-by-chapter breakdown:

Chapter 1: Introduction provides a high level review of the current interface challenges this thesis addresses and a brief overview of the LuminAR project

Chapter 2: Background and Related Work provides motivation for this thesis work. It covers the relevant human computer interaction theory and the previous work in augmented interactive spaces, multi-touch and gestural interfaces as well as personal robotics. It also positions the work with the context of projected augmented reality interfaces.

Chapter 3: LuminAR contains the design and implementation details of the various LuminAR prototypes. It also includes the description of the LuminAR's LuXor software stack.

Chapter 4: Interaction Techniques outlines proposed kinetic interaction methods supported by LuminAR

Chapter 5: Applications provides a comprehensive review of the applications created to test the LuminAR systems, focusing on the Augmented Desktop and the Augmented Product Counter

Chapter 6: User Experience presents user feedbacks and the collective findings from the various LuminAR live demos

Chapter 7: Conclusion and Future Work summarizes the lessons learned. It also provides an outlook for proposed future work as well as a long-term vision.

2 Background and Related Work

Motivation

This thesis is motivated by the desire to evolve new form factors for computers that explore further the yet unfulfilled promise of ubiquitous computing [1]. Computers have transformed human society. They carry the power of information, communication and creation to almost every aspect of our lives. However, it seems that we humans have adapted ourselves to our technology and not vice versa. Our interaction with digital information is dictated predominantly by screen based form factors and various input devices.

Interaction with digital information devices poses a challenge to us humans, as effectively we have become our very own human-computer I/O bottleneck. As we curate more devices and more connected devices, the complexity of using them increases. The goal of this work is to design new form factors that address this problem space directly from two key directions: (1) create fluid interfaces that seamlessly blend digital media with the real world, and (2) design form factors that embed computation in everyday objects.

Both approaches are still considered very much open challenges, though recent years have shown the potential and feasibility of combining the two. To stir the discussion of the related work, this section provides a quick overview of the key streams of HCI research that serve as foundations for the work presented here.

By the early eighties the personal computing revolution was well underway. PCs were powered by affordable microprocessor and had interfaces that at the time seemed reasonable for normal people to use, namely the keyboard, screen and the mouse. At the same time, another revolution was brewing, and a decade later Tim Berners Lee completed his work on the World Wide Web [4], and the Internet became a practical means to communicate and share digital media and information.

Both revolutions are in debt to pioneers like Vannevar Bush and Douglas Engelbart. Engelbart as early as 1968, demonstrated in the Mother of all Demos [5], what Bush has envisioned in his famous article to The Atlantic Monthly technology section: “As we may Think”[6]. Their work had possibly the most profound impact on the interfaces we actually use to interact with computers. Soon the adaptation of computer-based applications into daily life became a reality.

Spreadsheets, video games, word-processing were just a few early examples. Nowadays, it seems hard to find a niche where computers and networks did not invade. It was not long before HCI researchers and product designers realized that the benefits of computing,

networking and digital media also pose a great interface challenge. Researchers Mark Wieser and Hiroshi Ishii coined the terms Ubiquitous Computing and Tangible User Interfaces respectively [1], [7]. Both envisioned a future where computers become invisible, and interfaces to digital information become embedded in everyday objects.

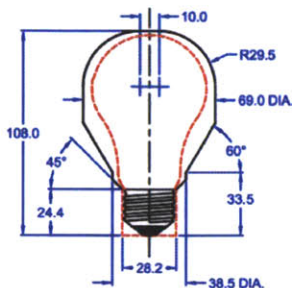


Philips MASTER LEDBulb
(source: Philips)

The evolution of computer interfaces. More than 40 years ago mainframe computers introduced a display centric user interface paradigm. This paradigm prevailed as interfaces miniaturized over the years. In the next era of user interfaces, our physical world will become our interface, where objects, surfaces, spaces become interactive, offering relevant information, based on context and interests of user.

The notion that the physical world is still relevant to how we actually interact with digital media spawned a mass of research. Several projects pursued post-desktop, post-WIMP (Window, Icon, menu, pointing device) interactions. Examples of such research domain include: virtual reality (VR), augmented reality (AR), pervasive computing, context-aware computing, multi-touch and gestural interfaces.

Human Computer interaction research has been strongly influenced by these ideas of “ubiquitous computing”, and vast efforts to implement some of these ideas have emerged over the years. AR is a good example of one such effort. There are several approaches in AR, some using goggles or glasses, others using handheld displays that blend digital information into the visual scene. In this thesis, I am particularly interested in Projected Augmented Reality systems (PAR) or AR interfaces that are implemented using Projector-Sensor systems.



NEMA A19 Bulb Specification
C78.20-210. (source: NEMA)

Another aspect of the interface challenge was well captured in the famous debate between Ben Shneiderman and Pattie Maes that juxtaposed Direct Manipulation vs. Interface Agents [8]. Maes suggested that computers interfaces are no longer self-contained and that computer screens became windows to vast networks of information, foreseeing the Cloud Computing era. She also discussed how computer interfaces were designed with 20 years old set of assumptions that are out of date.

Today, even though much progress was made, many of our interfaces are still designed with the same set of direct manipulation assumptions, which manifest in interface modalities of display centric devices (e.g. a tablet, a smart phone or a laptop computer).

LuminAR makes contributions to several technical and design domains. In this chapter I will review and position the contributions of this thesis

in the technical domain of projected augmented reality systems and interfaces. I will also situate the work in the relevant product and industrial design territories.

Design Space

LuminAR is an attempt to embed computation and interfaces in everyday objects. In this section we would like to provide the reader with a short background describing the history of the incandescent bulb, the Anglepoise lamp and the Track light fixture to provide context for our design considerations discussion further on in this document (See Chapter 3).

Lamps and Light bulbs

The discovery that a passage of electrical current through a filament creates light was completed in the early 1800s. It would take another eighty years or so for Thomas A. Edison to commercialize successfully the invention of the incandescent light bulb [9]. Since then, bulbs in various shapes, forms and technologies became an integral part of our habitats and urban spaces. The world adopted electric lights and never looked back.

Humans have tried to tame the medium of light for a very long time. It is possible that first lamps were natural objects that were filled with moss or other combustible material and were then lit. Pottery soon followed, the Greeks have become proficient in making terra-cotta lamps, and word lamp is derived from the Greek word lampas. This evolution continued and over the centuries with candle lamps, oil lamps and gaslights. It is likely that this history influenced the design and the adaptation of the modern light bulb.

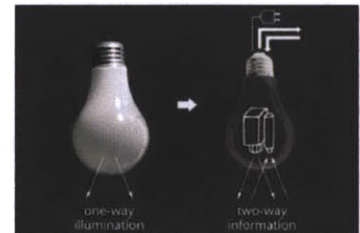
The General Electric Company led the way for this massive adaption in the US, pushing a set of standards for bulb power socket [10], [11]. These standards supported the needs of infrastructure development, as well as the business ecosystem of manufacturers, utilities companies and electricians.

Standards are important as they help reduce complexity and cost of integration when adapting new solutions to the masses. One of LuminAR's design goals was to adhere to existing power standards, while keeping the design open to emerging power standards such as Power over Ethernet (PoE) and DC power distribution grid [12].

Along with advancement in infrastructure, light bulbs are constantly evolving. The driving force for the recent innovation in bulb design comes from Solid State Lighting (SSL) technology. Specifically the integration of Light Emitting Diodes (LED) elements into new bulb design can substantially reduce energy consumption [13]. Another advantage lies in the fact that LED can be designed to be multichromatic, which has a greater impact when such bulb are deployed in dynamic lighting systems. Matt Aldrich from the Responsive Environment group at the MIT Media Lab provides an excellent review of the field in his thesis [14].



Edison Patent Model Lamp No. 10
(source: Edisonian Museum Antique Electric Exhibits 1830 - 1930)



I/O Bulb concept by John Underkoffler et al, 1999

Clearly we can't imagine our habitats today without electric lights, Marshal McLuhan described the light bulb as a medium without content saying that "... a light bulb creates an environment by its mere presence, ..." [15]. Later on John Underkoffler would build on this theory and suggest that the bulb should evolve into a two-way information device [16]. Later in this section we will position the LuminAR bulb in design and technical context to the I/O Bulb, while the design and engineering of our bulb is detailed in Chapter 3.



Lightolier Track Light, 1960
(source: Lightolier)

Track Lights

The LuminAR Spotlight system is an actuated track light. Track lighting is a method of attaching multiple light fixtures to a continuous conductive track. This method is fundamentally different than routing electric power to each individual lighting element. Track lights often operate DC current, employing a master transformer from the AC grid. Tracks can be mounted on walls and ceiling. Fixtures can be spotlights, floodlight or reflector (or others), once positioned on the track; the space lighting can be easily customized.

Lightolier invented Track Lighting in the early 1960's [17] , since then several many manufacturers produced several designs and products.

The Anglepoise Task Light

George Carwardine a British engineer and freelance design consultant, invented several of the mechanisms for car suspension. The key novelty of his invention involved the creation of counterbalancing devices, designed to support a payload in a given three-dimensional position. The core of his mechanical innovation is in a new type of spring which could be extended easily in every direction yet remain rigid when set in a position. When the springs are mounted in sequence, it is possible to devise an equilibrator device that is light and compact and has low inertia.



Anglepoise Lamp, 1932
(source: Wikipedia)

Since then, a multitude of configurations were designed and implemented in products [18]. French and Widden have provided an excellent mechanical engineering overview to Carwardine's spring-and-lever balancing mechanisms [19] which we recommend to readers who are interested in the physics, and mathematics that govern this fascinating system.

Carwardine thought of many different uses for his invention before applying it to lamps. He explored the mounting of power tools, microphones, mirrors and copyholders. Eventually, he designed and built the first counterbalanced task light. It was initially named Equipoise, and later on changed to Anglepoise. The key advantage of the new device was clear; light fixtures could now be repositioned to illuminate specific locations. Mounting a shade on the lamp created a focused beam that consumed less energy. Carwardine believed that it would be useful for office workers, providing a personal task light, but also considered use in factories, dentist clinics and operating theaters.

More than 70 years after its invention, the Anglepoise lamp, and its descendants (e.g. the classic Luxo lamps) became staple design

objects that celebrate form and function, due to the simplicity of the design and the obvious ergonomics benefits. For product designers, the Anglepoise lamp form has iconic status, much like the chair has within furniture design.

Deyan Sudjic recently discussed the key design aspects of the lamp he described it as an object that is part technology and part artifice [20]. He summarized the key design questions involving the Anglepoise:

"The Anglepoise is a brilliant synthesis of structure and mechanism, it's possible that it might have something to do with the sheer scope that an adjustable lamp offers, it's mix of technology and artifice. There is the whole question of the mechanism, the way that the structure is articulated to make finger tip pressure movement possible, then there is the structure itself and the means that the light source is powered and controlled. Finally, as critical as all the other elements, is the quality of the light source and the way it is diffused, directed and shaded."

— Deyan Sudjic, Director of the London Design Museum

It is the challenge of designers to answer the questions above when reinterpreting the classic form. It is a complex equation of functional requirements combined with technology, materials and aesthetics.

It is in this context that is relevant to briefly review lamp designs that served as a source of inspiration for LuminAR:

Anglepoise, Type 75

Designed by Kenneth Grange This version of the Type75 was launched in 2004 and was a redesign of the original 1970's Anglepoise.

Luxo L1

Designed by Jac Jacobsen in 1937. Originally designed as an 'architect lamp'. 25 million L-1 luminaires have been sold worldwide, and the lamp is considered a classic design that stood the test of time.

Luxo Air LED 8132 – 8133

Designed by Jukka Setälä in 2009. Air LED is using LED technology, consuming only 9 Watts. It is also the standard issue task light at the new Media Lab building. Air LED will operate for 25 years in a regular office setting or more than 5 years in continuous use.

Artemide, Tizio

Original 1972 design by Richard Sapper. Featured in the London Design Museum and the Museum of Modern Art (MoMA), New York. The design is based on a cantilevered rod structure to carry power to the lamp without cables.



Anglepoise Type 75
(source: Anglepoise)



Luxo L1
(source: Luxo)



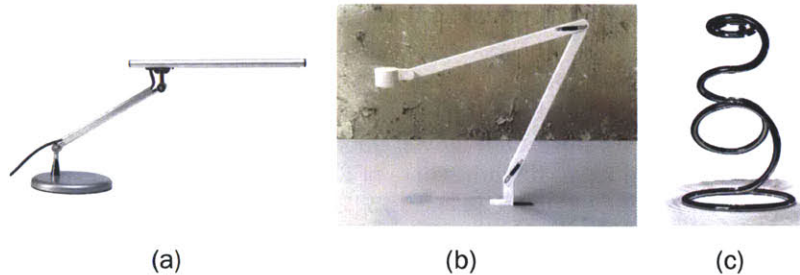
Luxo Air LED 8132 – 8133
(source: Luxo)

Details, Personal Underline

Design by Details a Steelcase company. The Personal Underline Light is streamlined, small, and very powerful LED task light, specifically designed for desk workspaces.

Polymer Light

Designed by Dirk Winkel in 2010. Polymer light is design exposes the use of gas springs, which facilitate a smooth movement. The lamp arms are made from solid plastics.



(a) Details, Personal Underline (b) Polymer Light by Dirk Winkel (c) iGuzzini / Ron Arad PizzaKobra (sources: Details, RCA, iGuzzini)

iGuzzini, PizzaKobra

Designed by Ron Arad in 2007. This work may have captured a future trend of task light design. Arad defined the task light as an object of desire. Below is how the designer described his provocative and unconventional task light:

"What does a task light do in the daytime? What can we do to make it look good, even when it's off? Who needs a crane on the desk when it has no job to do?"

How can we make it fully adjustable without it looking like a piece of technical equipment? I think it's a big job and needs a snake charmer, isn't amazing what can come out of a pizza box?" – Ron Arad

Luxo Jr., Pixar

Designed by John Lasseter for Pixar Animation Studios in 1986. Even though Luxo Jr. is not a physical lamp, Lasseter's character explored the realm of possibilities of an articulated lamp.



Animatronic Luxo Jr. in Disney's theme park

It gave life to an inanimate object and sparked the imagination of researchers and product designers [21], [22]. Disney has also created a life like robotic version for its theme park.

Conclusion

Finally, the evolution of task light into 'robotic task lights' will be covered in the section that will follow in this chapter. To summarize, this review sampled relevant and iconic task light designs. It seems that the task light has invaded our habitat since its invention and it seems it has become a companion to people providing light, design and pleasure of use. It is the design principles and values of the Anglepoise task light that enable us to unfold the design story of LuminAR.



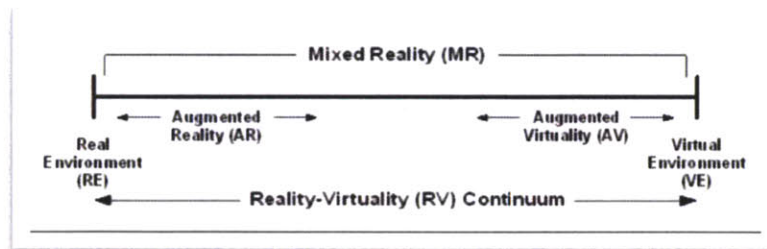
Pixar's Luxo and Luxo Jr.

Augmented Reality

Augmented Reality (AR) is a relatively young field, even though its origins can be mapped to early works of Sutherland in the 1960s [23] and Myron Kruger's Videodesk in 1985 [24]. It refers to a set of technologies, which allow computer generated virtual media to overlay physical objects in real time [25]. AR has been the goal of numerous research projects, which tried to create environments that seamlessly blend digital information with the real world.

This thesis work has been inspired and influenced by several excellent research projects that explored interactive systems that blend the physical world with the digital. We review below some of the most relevant prior work, highlighting similarities and differences.

Milgram positioned and classified AR as a subset within the Reality-Virtuality (RV) continuum [26]. He defined Mixed Reality as a taxonomy encompassing both Augmented Reality (AR) and Virtual Reality (AR), juxtaposing between fully virtual and fully real environments.



Reality-Virtuality Continuum (source: Milgram et al 1994; 1999)

Azuma provided a more formal definition of AR as a technology which (1) combines real and virtual, (2) is interactive in real time, and (3) registered in 3D [27].

Bimber and Raskar introduced the term Spatial Augmented Reality (SAR) to describe AR systems that make use of non-traditional display technologies such as digital projectors, holographic displays and

transparent screens [2]. SAR systems have a clear advantage as they enable an immersive blending of digital media and physical space. This approach also decouples the display from the user, as it does not require the user to wear a head mounted to display or use a hand-held device. However, most SAR systems to date usually lack mobility, due to fixed projector-camera setup. They can also suffer from problem like self-occlusion and ambient lighting conditions [25].

Current Challenges

Augmented Reality as a key user interface technology is still very far from adaption in real-world commercial scenarios. Although advances in computation power and display systems have made great leaps only in the past few years, current commercial experiences are very limited. Advanced AR systems are primarily found in academic and industrial research labs.

The use of Projection-based spatial displays in interactive systems also introduces several new problems [2]:

- A projected display is constrained by size, shape, projector resolution as well as the projection surface color
- Shadow casting of physical objects in the environment
- Sensitivity to ambient light conditions
- Self occlusions by the user can obstruct the projected image and complicate interaction
- Require adaptive and real time geometric projection model

Due to these constraints, most of the interactive AR experiences that were adapted for everyday use normally involve simple single channel I/O via fiducial marker scanning or image recognition. Immersive AR experiences involve custom setup of projector camera systems that require location-specific setup and calibration. Such systems normally require dedicated software to support the interaction. There is no out-of-the-box AR experience except those found in mobile AR products such Layar [28].

We identify three major interaction-limiting factors of existing AR systems: (1) AR is screen bounded (2) Context switch is required to complete the experience (3) The user's hands are not free to interact. We discuss these limitations below.

First, current AR interaction is screen-bounded. In order to interact with an AR system, users normally need to actively use a display as a mediator of the actual experience. Screens of various sizes and form factors (e.g. Head-Mounted Displays) are used as the view-port of the AR interface or information.

This leads directly to the second limiting factor: Context switching. Experiencing AR via a display view-port requires users to context switch back and forth between the physical space and the screen used to actually display the augmented scene. This introduces interaction

discontinuity, and poses challenges to create natural flow in AR applications, not to mention the violation of one of the key HCI principals of consistency.

Finally, the user's hands are not free. Mobile AR systems address some of the issues described above by allowing the user to carry the AR system in his hand; however, they are still suffering from similar interaction limitations. Users normally have to hold onto or wear (e.g. interaction gloves) marker objects in order to interact with the AR interface. Even more critical is the fact that in many cases the user holds the AR interface in one hand using the other hand to interact. Clearly, it is desirable in the case of situated AR to be able to use both hands. Mobile-Wearable systems like the SixthSense [29] device developed at the MIT Media Lab Fluid Interfaces Group, address this problem using a novel wearable form factor and a gestural interface that enables immersive mobile AR.

To some extent, wearable AR interfaces (HMD or HUD displays) address these problems directly, however they require the user to adapt by wearing additional computing components, which facilitate the interaction. This work is focused on solving these problems in the indoor domain assuming the user does not need to use any additional hardware.

In the sections that follow, we will focus the related work review in the key domains that provide technical foundations as well as interaction inspiration for LuminAR in light of the current challenges. We will focus the review on augmented interactive spaces, specifically with respect to projected AR techniques, tabletop computing, multi-touch and gestural interfaces. I will also address Kinetic Interfaces and review relevant work in the Personal Robotics domain.



DigitalDesk by Pierre Wellner

Interactive Spaces

In recent years enabling technologies for the design and implementation of augmented interactive spaces has been extensively researched. Some of the past work includes various computer vision based methods for interaction and augmented reality systems [2], [25].

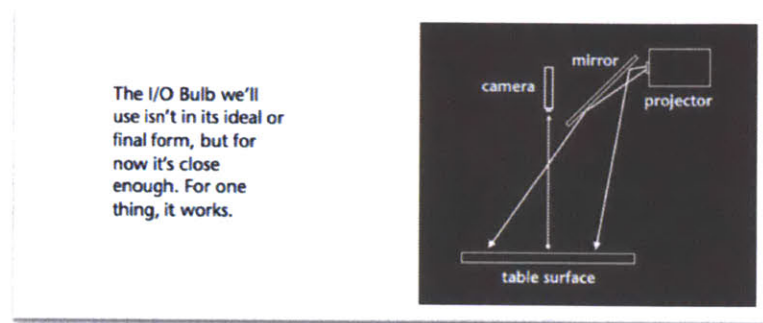
Augmented Interactive Spaces typically use a projector-camera system along with computer vision techniques to augment a physical space. Wellner's DigitalDesk system is considered one of the first pieces of work in this domain [30-32].

Rekimoto and Saitoh expanded on this approach by introducing wall, table and laptop cross-integration, allowing information to propagate between modalities and devices [33]. The EnhancedDesk [34] introduced real time finger tracking using IR light enabling the integration of paper and digital information.

The LuminAR system enables similar flat surface, desk and table based augmentation and interaction, yet it provides the advantage of portability and compact size, as the entire system is self-contained in

both the case of the LuminAR Bulb and the LuminAR Lamp form-factors.

Underkoffler et al. in his seminal work I/O Bulb and Luminous room [16], [35], [36] and Urp [37] have described a basic two-way optical information device and how it will be used to transform a room into an architectural information space. At the time, technology and cost issues prevented the full realization of this vision. The actual system implemented included spatially separated camera and projectors. Although a “real” I/O Bulb was described it has to date been unavailable in research labs and as a commercial product.



I/O Bulb and the Luminous room by John Underkoffler (source: [16])

The LuminAR Bulb introduces two major advances over this prior work. First, it realizes the I/O Bulb's vision, and efficiently integrates all the required components for the bulb (camera, computer, projector, sensors etc.) into a single system. It is thus a truly portable and scalable solution to implement customized augmented interaction spaces easily. Second, it adds actuated degrees of freedom, and robotic control elements that enable the LuminAR Bulb to dynamically change projection parameters.

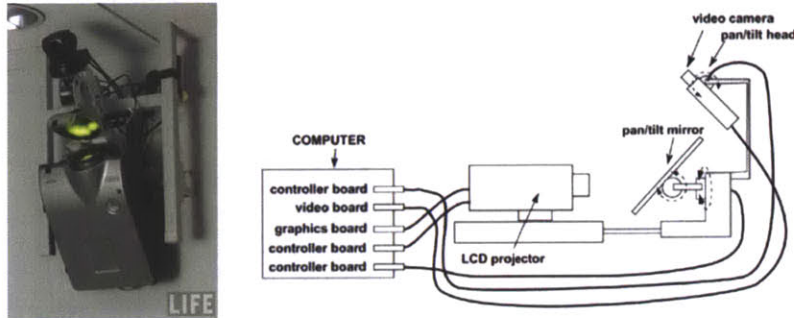
In later work, Pinhanez created the Everywhere Displays [38] that used a stationary projector using a rotating mirror to expand projection to multiple surfaces. He also proposed a portable solution the Everywhere Displays Lite [39]. This work introduced the concept of steerable interfaces that can appear on objects and surfaces anywhere in space, and can also dynamically adapt to form, function and location of the interface as well as user context.

However, even though the mirror element presented in Pinhanez's work offers more flexibility, it allows very limited animatronics compared to the articulated degrees of freedom of the LuminAR Lamp, and it also requires a complex setup. We will elaborate further on the concept of steerable interfaces in the discussion at the end of this chapter.

One of the challenges implementing a steerable and interactive projector camera system lies in the calibration of a generalized optical and mechanical system. Ashdown and Sato presented a method and algorithm for calibrating a steerable projector system, focusing on pan-

tilt mirror setups [40]. Their work represents an important step, though it is still limited as it is based on the projection of patterns.

Steerable projector systems that use a pan-tilt mirror setup indeed offer more flexibility, but are constrained in terms of calibration and ease of setup. LuminAR address these drawbacks by using a moving projector approach combined with simple one-time offline calibration.



EveryWhere Displays by Claudio Pinhanez et al, work done in IBM Research (source: IBM Research)

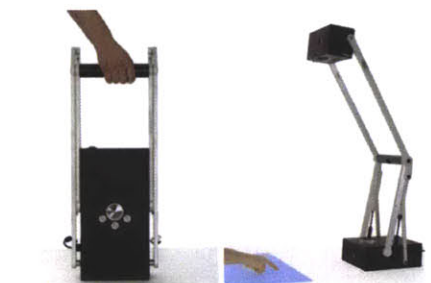
In recent years, important advances in portable and small-scale projector camera systems have been realized. Raskar et al. iLamps [41] presented an adaptive projection on non-planar surfaces enabling object augmentation with a hand-held projector, including interaction techniques.

Wilson outlined a more advanced variation on portable projection systems in his project PlayAnywhere [42]. This project explores paper, hand and object recognition using a projection system. The system supports various wall and tabletop use cases.

More recent work has combined pico-projectors and cameras in a lamp form factor. A prominent example is the DockLamp by Kaplan, et al [43]. In addition, Microsoft research has created the Mobile Surface [44] as part of their effort to push forward the domain of Surface Computing. Both pieces of work address both the issue of a smaller form factor and the different hand gestures that will enable users to interact with augmented reality interface.

Even though these examples demonstrate substantial, yet incremental improvements in portable AR interfaces, unfortunately all of the systems described above are completely static once they are installed in a space. This fact limits the scope of interaction and augmentation experience these systems can provide. The LuminAR Bulb and Lamp's robotic capabilities address this limitation directly.

Projects like DeskJockey [45] and Bonfire [46] have introduced PC-centric workspace extension using projection. DeskJockey used a fixed projector to superimpose widgets in the space around a PC. Interactions were possible via proxy window on the PC desktop only. The Bonfire project suggested another approach, presenting a nomadic projection system attached to a laptop using two pico-projectors. In



DockLamp by Frederic Kaplan et al



Bonfire by Shaun Kane et al developed in collaboration with Intel Lab (source: Intel Labs)

contrast, the LuminAR approach does not require or assume a PC to augment a space and it is not dedicated to PC based interaction. The LuminAR system has a dedicated computer that allows it to remain portable and to easily interface to different displays in its vicinity.

Prior research in augmented interactive surfaces has extended surface based interactions to more elaborate object-based physical/digital interactions. Systems like metaDesk [47], WeSpace [48], UbiTable [49] and MemTable [50] introduced object based interactions to retrieve documents or interact with the projection surface. These systems typically use fiducial markers, RFID or other wireless mediums (e.g. Bluetooth, Sigsbee etc.) to register object in the system. LuminAR is designed to support both marker and marker-less object registration and recognition. This approach yields an enhanced user experience, as shown in recent work like the OASIS project from Intel Research Lab [51]. OASIS introduces a framework for general-purpose object recognition for interactive systems. The framework is integrated with a projected display to create interactive “islands” in everyday environments.

Multi-touch and Gestural Interfaces

Multi-touch and gestural interfaces provide the foundations of interaction techniques this work presents. One of the earliest visions of gesture base interfaces was introduced in the StarFire video prototype [52]. Early gestural interfaces systems employ simple computer-vision based freehand-gesture recognition techniques [53-55].

In the past decade, the domain of gestural and multi-touch interfaces has been extensively researched. The key element of such systems is the implementation of robust touch detection mechanisms that allow direct manipulation of data using natural gestures [56-58]. Buxton provided an excellent summary of such systems in [59]. Multi-touch systems use a large variety of sensing technologies. The most common of them include: (1) Periphery, front or back mounted camera using custom surface as a display and interaction surface [60-62] (2) IR Cameras [53], [63] and multiple (stereo-vision) cameras [54], [64] (3) Embedded capacitive or resistive sensors [56], [58] and (4) Acoustic sensors [65].

The fundamental drawback of such multi-touch systems is that they are only able to detect physical touch events, and therefore incapable of supporting touch independent freehand gestures or to detect arbitrary objects. They also involve a non-trivial setup of several independent components (i.e. computers, projectors, mirrors etc.) that complicates deployment, and in most cases they require users to perform manual calibration steps. Current gesture recognition systems discussed below, unfortunately still suffers from similar limitations. Our approach uses computer vision techniques to create a system that supports both touch interactions as well as gesture recognition in a portable form factor, addressing many of the drawbacks described above.

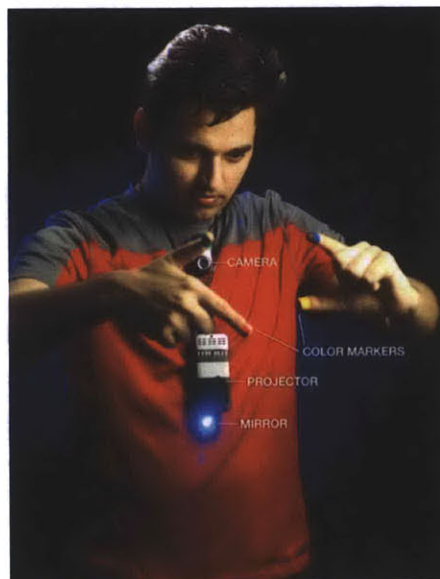
In recent years, various advanced gesture interaction paradigms have been explored including hand gestures [66-68]. Additional examples include the HoloWall [60] project and Oblong's g-speak system [69]



Oblong G-Speak System (source: Oblong Industries)

Continuing advances in miniaturization of projection technology, embedded computing and computer vision algorithms enabled several portable, mobile and wearable gestural interfaces systems in the past few years. Examples of such systems include the SixthSense device [29], [70], the iLamps project [41], and additional examples are [71-74].

These systems generally involve a user who either wears or holds a projector, using it to augment a surface or an object. Our work is distinct from the handheld gestural interfaces as it leaves the user's hands free to interact. It is also distinct from wearable systems, as it does not require the user to wear anything in order to interact with the system. Since LuminAR is a situated AR system, our work emphasizes portability over mobility. By "portability", we refer to the ability to simply unplug the system and move it to a different location, without the need for a complex setup or further calibration.



SixthSense device by Pranav Mistry and Pattie Maes (source: MIT Media Lab)

Finally, in 2010, Light Blue Optics a UK based projection systems start up, introduced Light Touch [75] a portable, interactive laser pico-projector platform that is capable of projecting a virtual touch screen.



Light Touch by Light Blue Optics

Kinetic and Robotic Interfaces

The field of personal robotics has advanced at a fast pace since the introduction of microcontrollers. Domestic robots have become a commercial reality in areas such as companion toy robots such as Sony's AIBO and Innovo Labs' Pleo [76], [77], service robots such as the Roomba and Scooba from iRobot [78], personal surveillance and security [79]. Social robots that serve as robotic coaches have also recently emerged from the labs [80].

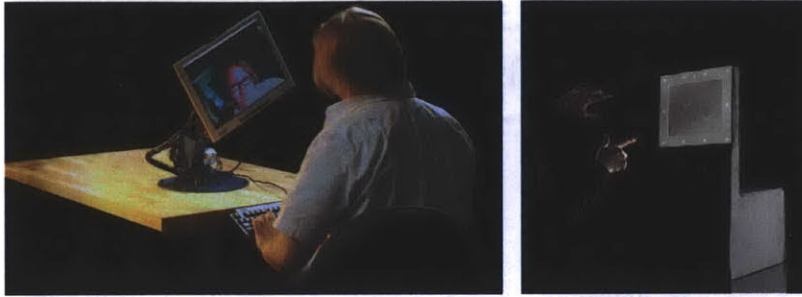


Personal Robotics: (a) Innovo Labs Pleo (b) Sony Aibo (c) WooWee Rovio (d) Intuitive Automata Autom (e) iRobot Roomba (image sources from respective companies)

However personal robots designed as 'information interactive robots' are still in a very embryonic stage. It is clear that the future will make more use of AR techniques to facilitate a more expressive interface for robots themselves. Green et al. detailed the case for AR enabled robots in a comprehensive review [81], [82]. We are interested in using robotic capabilities to enhance interactive information driven application. This work explores the design of such robots and their use in real-world scenarios.

Recent projects explore different aspects of human-robot interaction (HRI). Specifically, they explore robotic form factors for personal

computing. Examples of such projects include RoCo [83] which is considered the first robotic computer. RoCo was designed with the ability to move its monitor in subtly expressive ways that respond to and encourage its user's own postural movement. RoCo was mainly used as an HRI research platform and did not address the requirements of supporting an augmented reality interface.



(a)

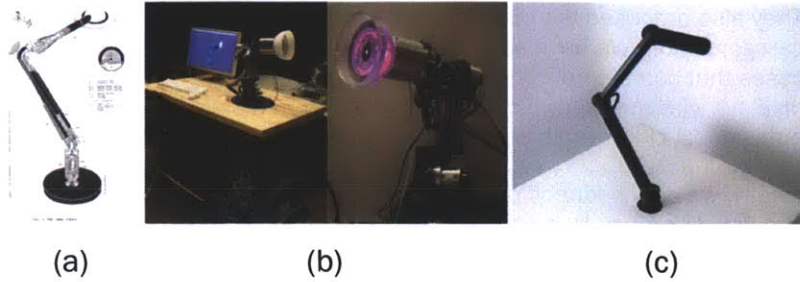
(b)

Kinetic/robotic interfaces: (a) RoCo by Breazeal et al (b) OZWE QB1 Robot – a computer with social skills (source: MIT Media Lab, OZWE)

Another example is the QB1 Robot [84], which is a social robot that learns about its user and offers an expressive, animatronics interface to different media applications. QB1 also utilizes a gestural interface. However, QB1, like RoCo, uses computer-screens as its display medium. This limits substantially their ability to augment their environment. Our approach integrates an actuated robotic arm and a projected display into a single system. We believe this approach will offer better support for interactive scenarios.

Besselink et al. created the first robotic lamp the author is aware of in 1991 [85]. Their lamp robot was developed for future scenarios for home use. They also suggested applications for handicapped users. They also proposed a unique memory-metal actuation technique, and integrated speech recognition for user interaction.

Hoffman created - a robotic desk lamp, which acts as a collaborative lighting assistant [21]. AUR was used to explore the concept of fluency in human-robot collaboration. Finally, Stubbe and Lerner, created Outerspace Robot [86], a reactive robotic creature designed to explore the surrounding space and interact with people through touch and behaviors. These projects are good examples of robotic arms that are specifically designed for human interaction, but they are very limited in digital media interaction capabilities, as they have no display and very little spatial sensing.

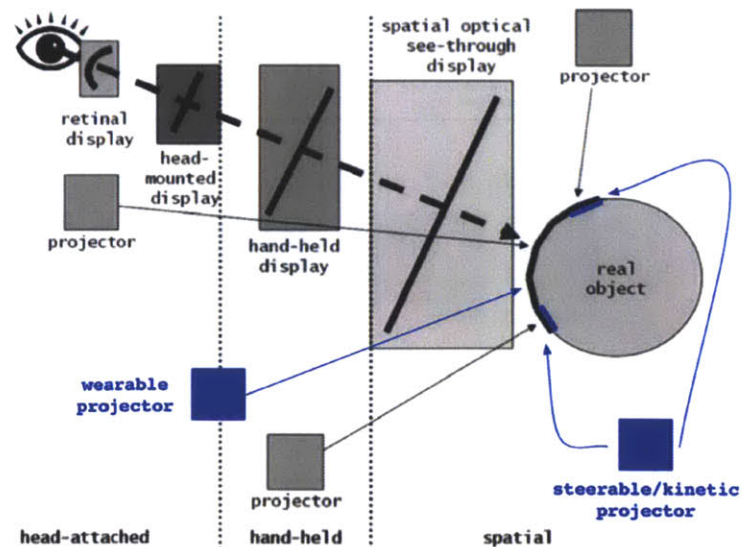


(a) Besselink et. al. Robotic Lamp (b) Hoffman's AUR (c) Stubbe and Lerner Outerspace Robot (source: J. Phys. IV France, MIT Media Lab, A. Stubbe)

Projected Augmented Reality Interfaces Classification

For the purpose of this thesis, and in light of the abundant work in the domain of augmented reality, it is important to position the LuminAR work within the context of the previous work. Several surveys also classify and analyze different technical aspects of the actual display and sensing sub-systems, and we refer the readers to the latest survey by D.W.F. van Krevelen and R. Poelman [87] for further reading.

Bimber and Raskar [2] classified the approaches to augmented reality displays technologies into head-attached, hand-held, and spatial displays.

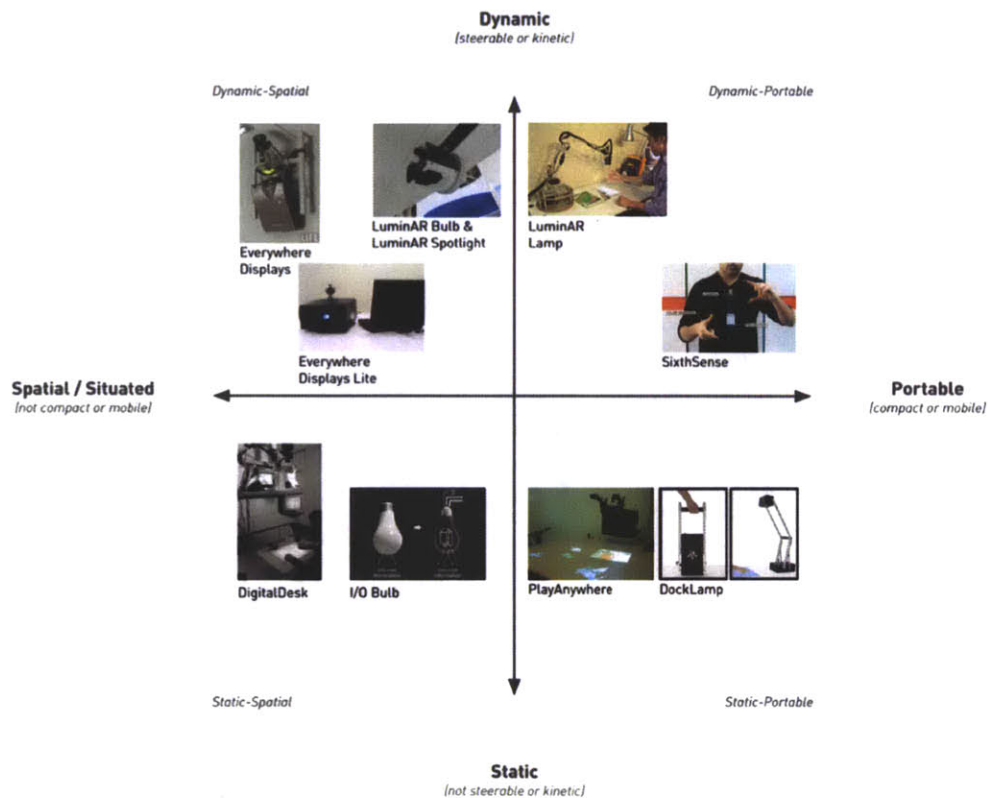


Positioning wearable projectors and steerable/kinetic projector system in the context of Spatial Augmented Reality, we have updated the original diagram by Bimber and Raskar to include the cases of wearable projector and steerable/spatial projector in blue. (source: Oliver Bimber and Ramesh Raskar)

They also proposed the diagram below to summarize this categorization. We have added to their classification two additional cases that complement the definition of spatial augmented reality displays with new approaches that were reported since their work was published: (1) wearable projector, and (2) steerable/kinetic projector.

Finally, we define kinetic projectors as a subset of steerable projectors. The key difference being the fact that kinetic projectors have their own actuated degrees of freedom of the actual projection source. According to these definitions, LuminAR devices can be classified as kinetic projection-based spatial displays.

To visualize the unique positioning of LuminAR as a new class of augmented reality interface, we created a Projected Augmented Reality Interfaces Classification quadrant diagram. We use a semiotic square relationship that juxtaposes two sets of properties that define our system: (1) steerable/kinetic vs. static and (2) portable vs. not spatial/situated.



Projected Augmented Reality Interfaces Classification

Using this diagram we can roughly define four distinct categories of projected augmented reality interfaces:

- **Static-spatial:** non-steerable or kinetic systems that are permanently installed in a space. Interaction is commonly constrained to a predefined and fixed space. Examples of such systems are: [16], [32]
- **Static-portable:** compact non-steerable or kinetic systems that can be relatively easily relocated from one space to another, commonly support automatic calibration. Examples of such systems are: [42], [43]
- **Dynamic-spatial:** steerable or kinetic systems that are statically installed in a space. Examples of such systems are the Everywhere Display [38], [39] as well as the LuminAR Spotlight
- **Dynamic-portable:** compact steerable or kinetic systems that can be easily relocated. LuminAR lamp is the only example of such system we are aware of. We can also consider the SixthSense device [29] to be a dynamic-portable system, as it is a wearable system that adapts to the user viewpoint

Characteristics of Steerable and Kinetic Systems

Pingali et al's groundbreaking work on steerable interfaces [88] presented an alternate approach for pervasive computing interfaces. In their vision, interfaces to computing should appear where and when the user needs it, and when ever he needs it. They outlined the salient characteristics of such steerable interfaces:

- **Support moveable input and out output:** interactive interface that can move around the physical environment and appear on ordinary objects or surfaces.
- **Adaptation to user context:** interface should respond to some sensing of user needs based on location, physical function or other data. Freeing the user from a single point access to a computer with a traditional mouse and keyboard interaction
- **Adaptation to environmental context:** interfaces that adapt to the characteristics of the environment and change accordingly in terms, of location, size, shape color etc. This normally means that the system should be aware of the geometric and ambient parameters of the physical space.
- **Device Free and Natural Interaction:** steerable interface is able to sense and support forms of interaction such as speech, hand gestures, motion of body, touch etc. which are based on the human body and do not require special devices.

Through this thesis work, and the design of the LuminAR form factors we can propose new characteristics to complement the set above and

possibly drive forward the adaptation and investigation of steerable and kinetic projected augmented reality interfaces:

- **System portability:** Users should be able to reconfigure and change their environment. Projected augmented reality systems should be designed to be compact and simple, such that a user may decide and easily relocate the system in a physical space. To achieve such portability it is important to design compact systems, which support automatic calibration of the projected display. It is also required that such systems are able to sense and map the environment to support interaction
- **Embedding computation in everyday objects:** Closely related to the need for high portability is the need to design pervasive interfaces that disappear into the physical environment. To achieve that it is required to design computation functionality into everyday objects that already exist. Examples are desks, lamps and light bulbs
- **Integrating User Interface Modalities:** projected kinematic interfaces should be designed to support multiple user interface modalities that utilize traditional multi-touch combined with hand gestures and object manipulation. Users should be able to seamlessly and naturally mix all modalities
- **Using Physical Motion:** physical motion can greatly enhance interfaces, as humans are responsive to kinesthetic sensations. It is possible to create a richer user interface that uses motion cues as part of the interface feedback loop. Further more, actuation and animatronics sequences can be used to direct a user or even embody information

3 LuminAR

The LuminAR prototypes were developed through several design and implementation iterations, aiming to push the technical boundaries of existing augmented reality interfaces, but also to break new ground in terms of the industrial design of new form factors.

In this chapter we describe the technical implementation details for the family of LuminAR devices we have designed and developed in course of this thesis work. We begin with discussing the design principles LuminAR devices share, and continue to describe each of the prototype systems we have built. We begin with the heart of the system - the LuminAR Bulb. We then discuss the prototypes of the LuminAR Lamps, which are comprised of specifically designed robotic arms that carry the LuminAR Bulb. Finally, we discuss the LuminAR Spotlight device prototypes.

For each of the different systems, we provide technical details of the hardware we developed, and discuss relevant industrial design considerations. We conclude this chapter with an overview of the LuminAR LuXor software framework that is shared across the devices.

While this chapter focuses on the technical details and physical design aspects of the LuminAR devices, it sets the ground for the next chapter, which deals with the interaction techniques LuminAR enables. The two chapters are closely related, and together they form a complete description of the design goals and the implementation. Finally, we also refer the readers to the appendix where we included a fairly complete mechanical specification for the various LuminAR devices described in this chapter.

Design Principles

In chapter 2, we presented and discussed the properties of steerable and kinetic interfaces. This background research was the driving force for the LuminAR design, resulting in a novel compact and kinetic projected augmented reality interface. In this section we describe the common design principles that guided our work.

Simple everyday objects that hide technology

Hide computation and interfaces in familiar devices, which have common, everyday form-factor. The forms LuminAR devices take on today are those of a light bulb, an Anglepoise task light and a track light fixture. From a user's perspective these objects should obfuscate the underlying technology they use. At the same time, when used, they provide known affordances and almost natural, contextual interaction techniques, using hand gestures, multi-touch and kinesthetic (we delve into the details of LuminAR's interaction design principles in chapter 4).

Portable, compact and self-calibrating

Design compact and portable devices, which are capable of dynamically forming an interaction space. A non-technical user can easily relocate a LuminAR device from one place to another. The system should function without the need for any prior knowledge of the space it is deployed in. This dictates the use of simple power and data interfaces, but also the need to support automatic calibration of the AR subsystem.

Embedded, connected and modular

Directly derived from the need for portability, is the need for the LuminAR devices to be self contained computing systems. This dictates the design of the LuminAR bulb, the heart of the each LuminAR device as a wireless embedded computer with all required peripheral interfaces for display, actuation and sensing.

The LuminAR bulb can connect to a network connection. The network can provide content, interfaces and facilitate data exchange with other LuminAR devices. It also allows LuminAR devices with modularity, in two key aspects: (1) off-loading computation to remote devices or other network services, and (2) supporting interaction scenarios where two or more LuminAR devices are used in parallel.

Kinetics

The ability to move makes interfaces dynamic (i.e. not statically situated in space). This principle is juxtaposed with existing display centric devices that by definition are static once positioned within a workspace. LuminAR devices can dynamically reposition a projected interactive display. They can also use motion to enhance user interaction.

Design for product

Product design balances the need for functionality and aesthetics. As one of the goals of this thesis work was to push the boundaries of current computer form factors, product design methodologies played a key role. We considered issues that go beyond a pure interaction research agenda, and considered core product design issues such as ergonomics, safety, standards, heat dissipation and work envelopes.

Product design also assumes that prototypes mature and down the road manufactured. This is the reason we tried, as much as possible, to use existing, off-the-shelf available technologies. We selected components that can be mass-produced, making LuminAR devices low cost and commercially viable.

LuminAR Bulb

The LuminAR Bulb is compact, kinetic and interactive projector-sensor system. The system is designed to follow the physical metaphor and



The bulb's LEGO bricks mockup model



Testing of early version of the bulb in a Luxo Lamp



Overnight weight testing the bulb in a snap on spotlight lampshade

design language of a classic light bulb, evolving it to an interactive computing device.

In chapter 2, we provided an overview the design space of light bulbs. While trying to adhere to the dogma of bulbs that fit into a standard power distribution grid, we were also inspired by the conceptual underpinning Underkoffler provided in his work on I/O Bulb [16]. Recent advances in technology provided additional motivation, and ten years after the I/O bulb publication, this thesis attempts to fully realize the vision of the I/O bulb within the design parameters of an actual light bulb.

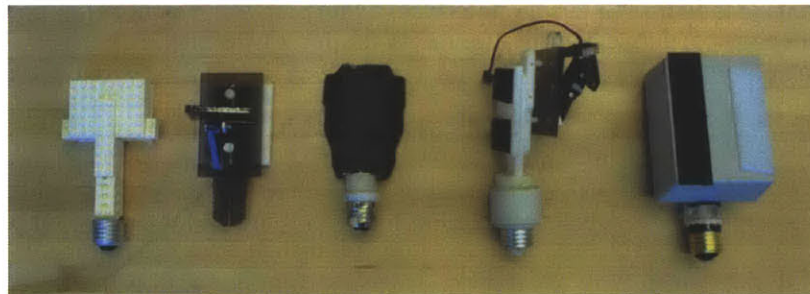
Design Goals

With this general goal in mind, we also had concrete design goals that guided the design work of the LuminAR Bulb:

- Create a fully realized two-way information device, which requires only AC power and wireless communication to operate.
- Design the bulb to fit in standard Edison bulb sockets.
- The bulb should be compact and completely self-contained projector-sensor system. It should integrate a laser pico-projector, cameras, sensors, control electronics, power supply and an embedded wireless computer.
- The bulb should have its own DOFs for pivot rotation, and camera tilt.

Design Process

The design and development involved several iterations. Initial exploration of form and fit to light fixtures were constructed from LEGO bricks, but we quickly moved on to advanced materials in the prototype that followed. The shape and weight of the bulb were critical factors to observe, as we tried to integrate together several components. Fitting the bulb in standard fixtures and lampshades dictated our general circumference and a weight constrains. To explore physical constraints we created a set of conceptual prototypes.



Early mock up models and conceptual prototypes of the LuminAR Bulb

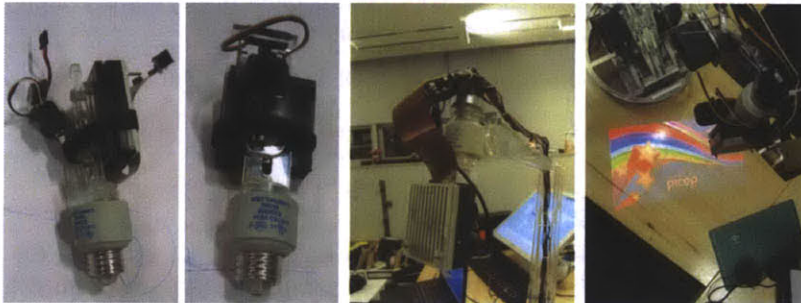
As our work progressed we were able to refine the design and consider different packaging strategies. We go into the details in the sections that follow. We focus our discussion on the latest and most relevant iterations of the LuminAR Bulb.

Early Versions – Make it work!

Our first version of the LuminAR Bulb was very much a learning prototype and had limited functionality. Based on our initial mock-ups, we designed a frame to carry a pico-projector and a webcam. The frame was also fitted with a standard male Edison screw using a hacked bulb screw adapter. At the base of the frame we constructed a stationary double disc part. The stationary part was glued to the screw cavity, providing support and pivot-axis rotation. The rotation axis was not actuated, but we could manually set the radial position of the bulb.

This bulb's frame was constructed from laser-cut acrylic parts that were press fitted and glued. The frame was designed to support the adjustment of the projector plane and camera plane individually. This was done to allow us to experiment with different hardware calibration parameters for the computer vision software.

However, This version of the bulb did not include any power circuitry, and we used external power cables to supply the bulb.

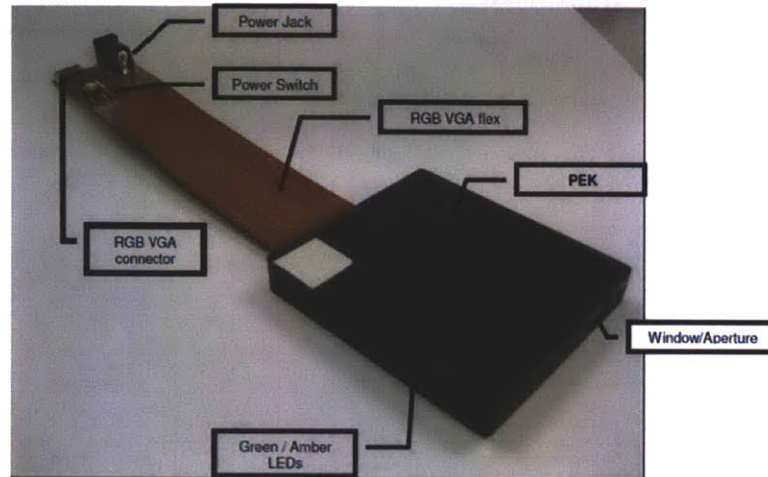


LuminAR Bulb early versions. Bulbs are fitted with Microvision PEK-1 laser pico-projector with a custom heat sink

We selected the Microvision's PicoP™ Evaluation Kit v1 (PEK-1) as our projection engine. The PEK-1 served as excellent prototyping platform. It has standard VGA display interface, a thin profile and small mechanical dimensions (H 10mm x W 61 mm x L 68mm). It also uses 5V power supply.

The main advantage the PEK-1 has is that it is a full color laser projection device. It provides a resolution of 848x480 (WVGA) with 16bit color depth and 16:9 aspect ratio. It has a focal range between 200mm-2000mm; in this range the image is always in focus, ideal for a dynamic kinetic platform like LuminAR. In addition our version of the PEK-1 was upgraded to Class 3R Laser device, outputting 15 lumens, which was bright enough for many of applications even in bright daylight conditions.

The PEK-1 has to be fitted with a heat sink element for ongoing operation. To conserve the bulb's small footprint, we replaced the PEK-1 original heat sink that extended the PEK's mechanical dimensions with our own compact design. Our heat sink was designed to fit the PEK-1 enclosure. It was fabricated from three 0.125" aluminum sheets with 11 ribs of approximately 0.1" inch wide.



Microvision's Pico™ Evaluation Kit v1 (PEK-1)
(source: Microvision)



Microvision SHOW-WX Pico Projector
(source: Microvision)

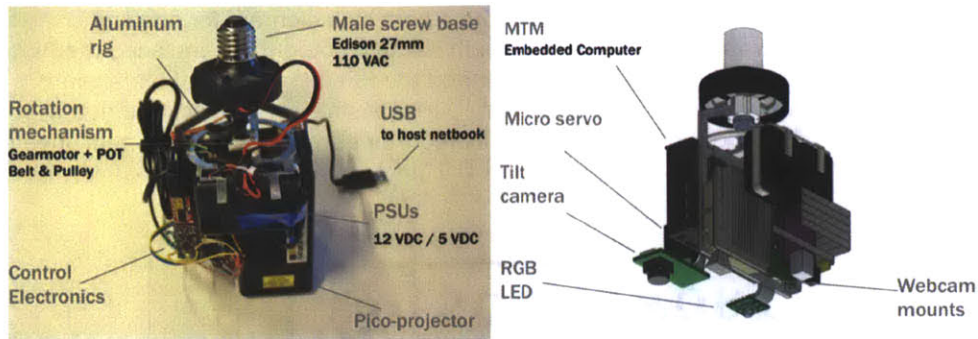
Since we only had one PEK-1 unit, in some iterations, and for prototyping purposes we also used Microvision's SHOW-WX Laser Pico Projector, which has similar specifications, except for a low power laser – Class 2, which makes it a bit less bright.

We used a micro R/C servo fitted with a custom made horn to provide support for the webcam. We selected the Microsoft LifeCam NX 2000 webcam, mainly as it has a very small footprint for both the optics and the electronics, but also as it was relatively inexpensive to the quality of the images it provided (2 megapixel).

LuminAR Bulb version 1 was mainly used in fixed light fixtures to facilitate software development, but was also the main bulb we used for the LuminAR Lamps Optimus and Aluminum models we describe later in this chapter.

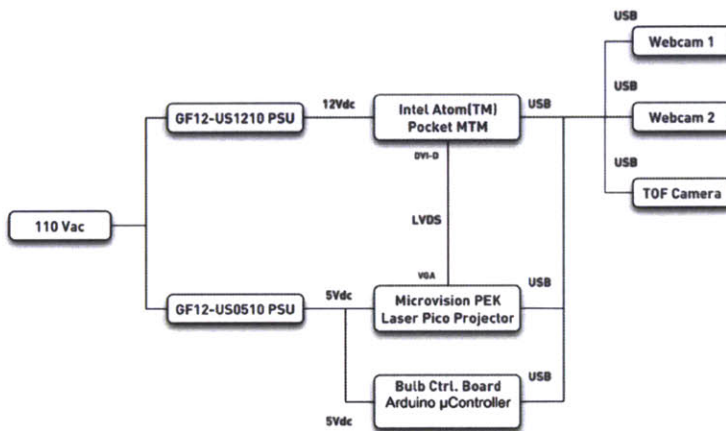
Integrating subsystems

The following two LuminAR Bulb iterations, focused on subsystem integration. With the goal to develop a fully functional prototype, design details were intentionally left for later revisions.



LuminAR Bulb integration version: on the right we show a view of the CAD design and on the left we show the physical prototype.

The block diagram below shows a general overview of the bulb's components and their respective connections.



LuminAR Bulb power and connections schematics

Power Circuitry

The bulb was designed for use with standard Edison sockets. To accomplish this, we had to incorporate AC/DC switching power supply units internally. The pico-projector and control electronics were supplied using a 5V/2A line. To support the embedded computer we need a 12V/1A line. USB peripherals were fed 5V directly from the USB lines.

To maintain the bulb's limited space constraints we selected two small 5V and 12V PSU package from Go Forward GF 12 series (GF12-US0510 and GF12-US1210 respectively). The GF12 series were ideal, with mechanical dimensions of: LxWxH:45.4x33.3x24.7 (mm).

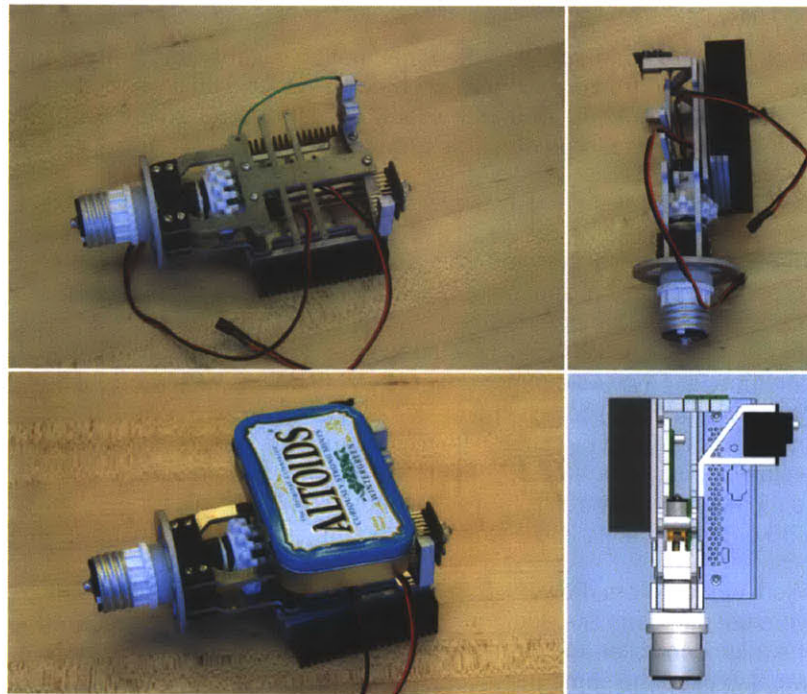


Go Forward GF 12 series PSU
(source: Go Forward)

Integration into the bulb included hacking the units, eliminating the original wall plug and jack connectors, leaving only the plastic case, a power and ground wires. Keeping the PSUs plastic case also helped deal with the heat dissipation.

Lightweight aluminum rig

First, to support a complex integration of electronics, motors, cables and components (i.e. webcam, embedded computer etc.), we had to design a light yet strong rig that would be able to mount all the components in place, and provide us with a platform to test different configurations. The rig was constructed from 0.125 aluminum sheets. The use of aluminum also allowed the frame to serve as an additional heat sink. On one side of the rig we attached the PEK-1, and the other side was reserved for an embedded computer.

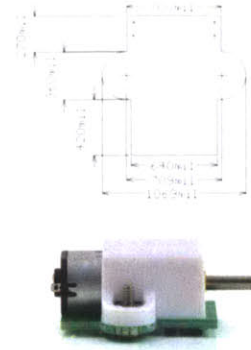


LuminAR Bulb integration version lightweight aluminum rig. This sequence shows one of the earlier designs, the Altoids box serves as a placeholder for the MTM Atom embedded computer. This rotation mechanism in this version used a central shaft solution.

Rotation Mechanism

The top section of the rig was used to house a rotation mechanism, which was coupled to the male Edison #27 bulb screw interface. The shaft is rigidly fixed to the screw through a flange. Managing the bulb mass and cabling made supporting pivot-axis rotation a difficult task. We tested two alternatives for the rotation mechanism.

Our initial approach used a central shaft coupled to a micro gearmotor mounted on the rigs' top section. We used Pololu Micro Metal gearmotor, which is extremely small and efficient, thus ideal for use in embedded systems. The motor ran at 5V with a gear ratio of 250:1, capable of an approximate torque of 4kg-cm. The motor was also coupled with a wheel optical encoder. The plastic ribbed wheel was designed to generate reading for the phototransistors on the encoder board. The encoder board was attached to the motor using a custom plastic bracket. The encoder was running at 5V providing 48 counts per revolution, a linear resolution of approximately 3 mm.



Pololu micro gearmotor and encoder board

This initial approach did not prove mechanically robust enough over continuous runs. Moreover, sensing the bulb's position proved challenging using the wheel encoder. However, the biggest hurdle was the size of the wheel encoder. This led us to replace both the rotation and the sensing mechanisms.

In our second approach, the rotational motion is generated by the same gearmotor and transmitted through a belt drive. The bulb's structure rotates below the belt around the central shaft. We selected a shaftless potentiometer mounted directly on the main shaft.

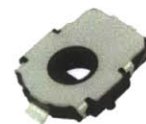
Control, Electronics and Firmware

The bulb's electrical systems were designed to digitally control the rotation mechanism, sensing, LEDs and additional servomotors. To accomplish this, we programmed a small microcontroller system (Arduino Pro Mini 328 - 5V/16MHz) to interface with a small and commercially available motor driver board (Pololu Qik 2s9v1 Dual Serial Motor Controller). The board provided us with means to control the motor's speed and direction. The rotation motion was monitored using a closed loop, continuously reading the potentiometer position. The feedback loop provided relative accurate positioning in a range close to 350 degrees (taking into account the potentiometer dead zone).



Belt and Pulley mechanism prototype

Micro servomotors (Power HD Sub-Micro Digital Servo DS65HB) that were used to carry the additional webcam, were interfaced directly to the microcontroller and were controlled using standard PWM signals. We also used the same microcontroller to interface to an RGB LED (ShiftBrite RGB LED).



Panasonic shaftless potentiometer (source: Panasonic)

The bulb's firmware provided simple interfaces to control the bulb orientation and query its encoder position. This interface was used by LuminAR application to define user interface projection orientation.

The bulb's host computer, using RS-232 serial communication over an FTDI USB connection, controlled the bulb's board. The diagram below shows the bulb's electrical schematics. This design was also used for future version but actual layout was changed to fit the physical dimensions of the new design.

an external MicroSD card that can support upto 32 GB of storage. These specs enabled us to run the LuminAR software stack and perform computationally intensive tasks such as real-time control, computer vision as well as communication and graphics rendering.

Unfortunately even though our design takes into account key embedded system engineering issues such as heat dissipation, connectors, and mechanical mounting, we stumbled on a major roadblock in the final integration step. The MTM display adapter and the Microvision PEK display input were incompatible. The PEK expected an analog VGA input, while the MTM output was digital signal DVI-S. At the time this thesis work had to complete, we decided not to invest in developing our own convertor, and off-the-shelf convertors were simply too big for our design. However, we are aware that future display adapter formats (e.g. DisplayPort) can solve this issue in the future.

Our intermediate solution for development and demo purposes was to use Atom based netbooks. We selected Asus Eee PC 1015PN and Eee PC 1215N both Atom based and with very similar specifications to the MTM. The constraint of having the actual computer external to the bulb mandate additional complexity when managing VGA and USB cables, which was particularly challenging in our final revisions.

Webcams

The bottom part of the rig was designed to carry a stationary webcam, and tilt web cam. The stationary webcam was aligned to the pico-projector aperture. Since the positions of the projector and the webcam were statically fixed with respect to each other, we could support easy semi-automatic calibration when installing the bulb in different locations.

The tilt camera was mounted on a small micro-servo and was positioned to serve both for interaction purposes, but also to capture the users face or objects in the workspace. With a range of motion of approximately 90 degrees, the camera could be positioned down vertically to view the tabletop, of horizontally to view the space in front of the bulb.

Physical configurations

We explored several different options for the bulb's component integration configurations. We tried to come up with different designs that would make the bulb feasible to use in different light fixtures. The domain of light bulb design is highly standardized, and we refer the reader to [90] for more information. We include some of our design configuration evolution in the figure below.



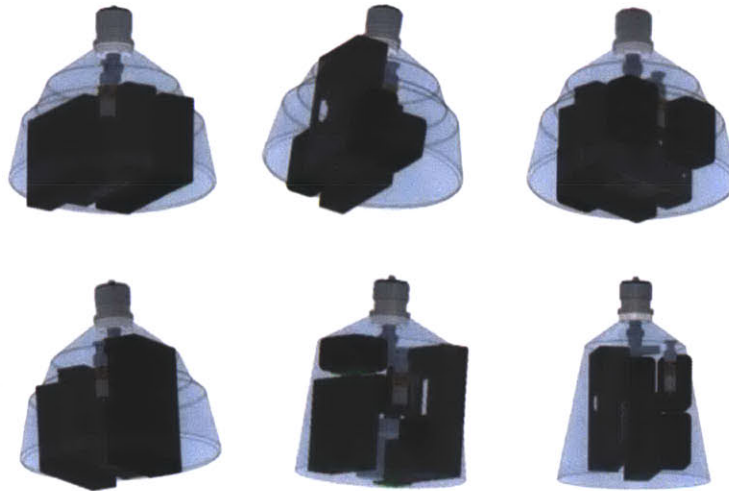
Intel Atom MTM
(source: Intel)



Microsoft LifeCam NX-6000 was hacked to serve as the bulb's tilt webcam
(source: Microsoft)



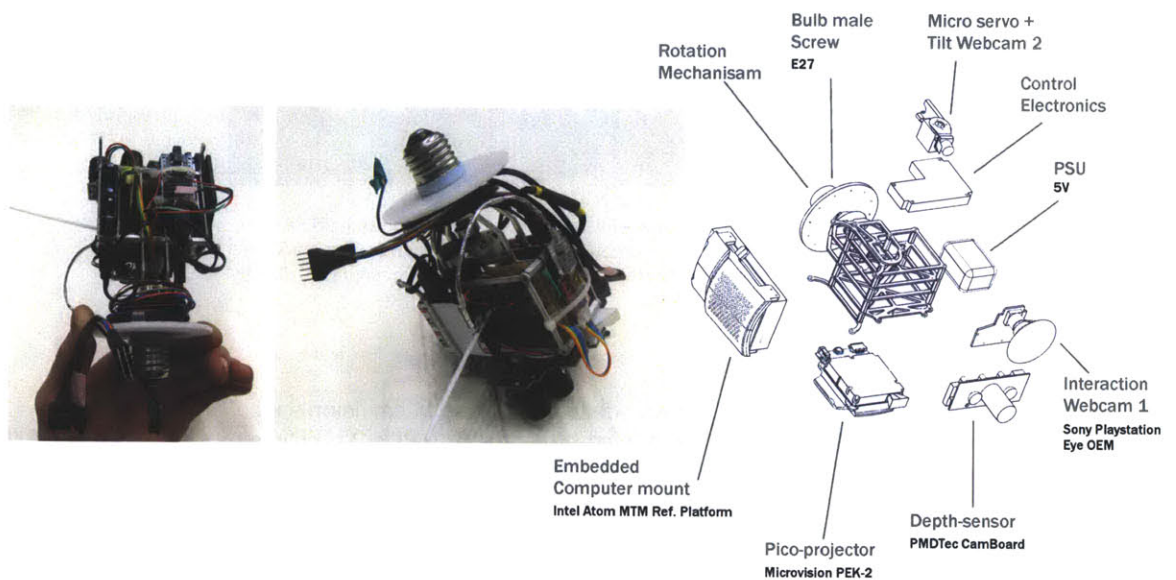
Sony Playstation 3 Eye Camera was hacked to serve as the bulb's stationary webcam
(source: Sony)



Exploring physical configurations for the bulb

Final version - compact design and packaging

The final bulb iteration focused on compacting and streamlining the design and packaging the bulb in product-like covers. Based on our previous integration iteration, we were able to reduce the bulb size by approximately 30% without its covers.



Luminar Bulb – final version

Improved rig, electronics and cable management

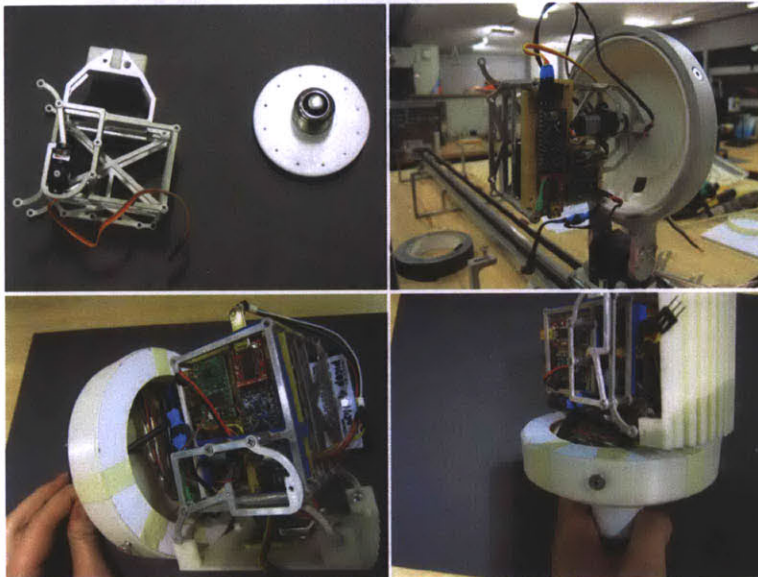
The rig of the final version was made of 1/16" Aluminum sheets. The design follows a layered approach. Spacers separate each layer of the frame. The electronics board design was improved to fit internally in one of the bulb's frame layer.

The rotation mechanism was also redesigned for additional robustness. The shaft was reinforced with a collar. The pulley was also reinforced with additional trust bearing to handle radial load.

Cable management posed an additional challenge, as we aimed support close to 360 degrees of rotation of the bulb. To accomplish this, we designed a cavity in the top section of the bulb, under the E27 screw that allowed the cables to rotate freely around bulb's main shaft.



Microvision PEK2 laser
pico-projector



The LuminAR Bulb final lightweight aluminum rig design. The rig allowed efficient component mounting. It also took into account the need for efficient cable management. Cables were coiled in a special cavity created above the rotation mechanism, directly below the Edison bulb socket interface.

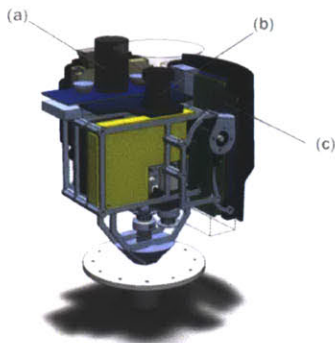
Even smaller projector

The final version of the bulb was designed to use Microvision's PicoPTM Evaluation Kit v2 (PEK-2) Laser pico-projector. The PEK-2 replaces the PEK-1 kit we in the earlier versions. It's main advantage is its extremely small mechanical dimensions, of W x L x H 55mm x 68 mm x 21 mm. It also has a simpler display adapter interface with no additional Flex cable.

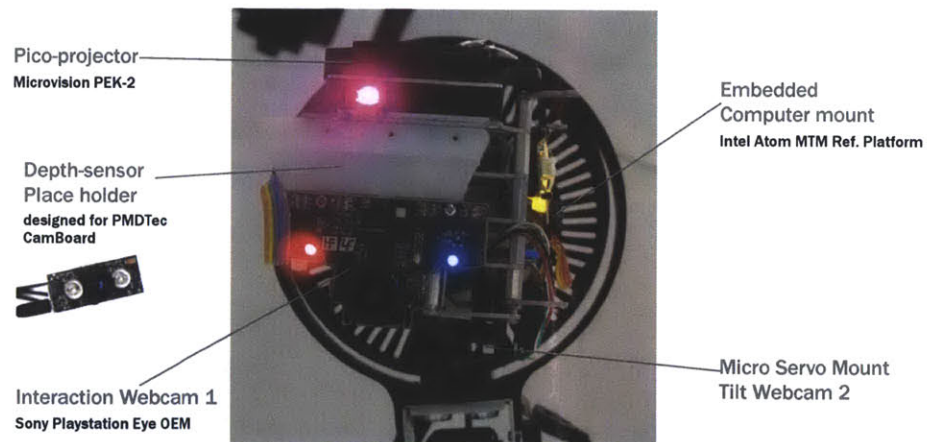
Adding webcams and sensors and putting it all together

On the bottom section of the rig we mounted webcams and sensors.

Sensor	Manufacturer/Model	Description/Purpose
Interaction Webcam 1	Sony Playstation Eye (PS3) OEM	A stationary webcam, aligned to the pico-projector aperture. Used to capture interaction gestures, capture imagery and detect fiducials.
Tilt Webcam 2	Microsoft LifeCam NX-6000	A rotating webcam, mounted on a servo. Designed to swivel 90 degrees between a position looking down, and a front facing position. This camera can be used for teleconferencing or track a user's face.
Depth sensor	PMDTec CamBoard	A USB based TOF sensor. Producing a depth map of 200x200 pixels. Capable of effective detection in a short range of 40cm. Used for hand gesture and multi-touch detection.



LuminAR Bulb sensors: (a) PMDTec CamBoard (b) Sony PS3 Eye Webcam (c) Microsoft Lifecam NX-6000



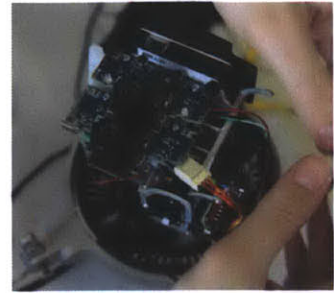
LuminAR Bulb webcams and sensors

The final design iteration of the bulb was specifically developed to match the LuminAR Blackjack and LuminAR Retail Arms (we describe these systems later in this chapter). While dealing with demo deadlines and hardware integration pains, our efforts to fully integrate the PMDTec sensor with the bulb failed. The cause is most likely due to electrical ground noise in our design that damaged the PMDTec sensors. To work around this issue and meet our demo deadlines we

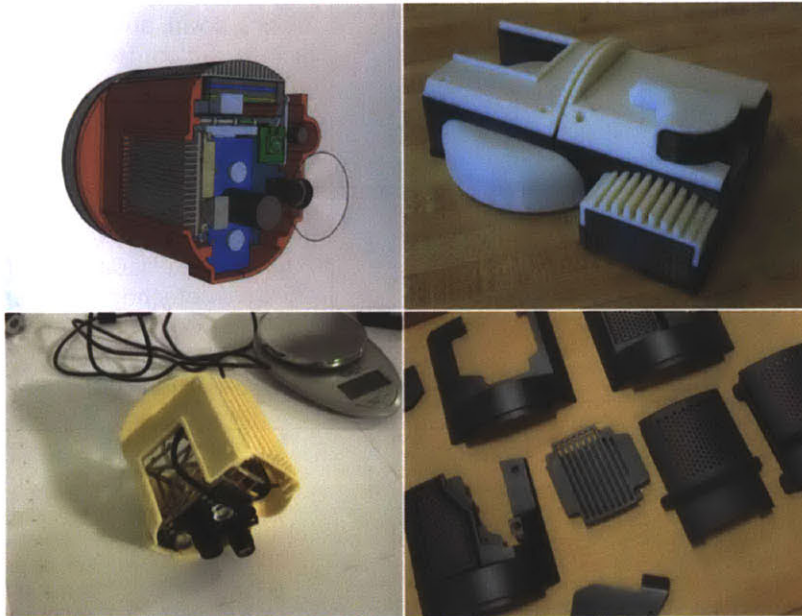
created another version of the bulb using an additional Sony PS3 webcam instead of the CamBoard.

Designing the shells

Finally, the bulb is enclosed in four shells: one fixed, attached to the main shaft flange, and the rest connected to the aluminum frame. The pico-projector and the onboard computer both have custom heat sinks used as part of the bulb shell. The shells were designed in two iterations, we 3D printed the initial design and performed basic fit testing to the frame. Later on, the design was refined and was fabricated from ABS plastic.



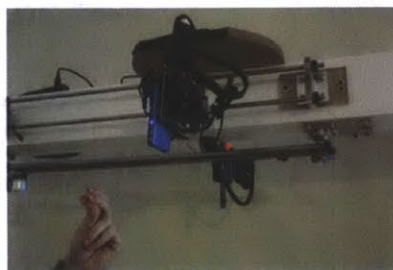
Mounting two Sony PS3 webcams, on the bulb



Steps in the design of the bulb covers included iterations of rapid prototyping using 3D printed covers. Final covers were fabricated from ABS plastic.

Conclusion

The bulbs we fabricated during the integration iterations met an important functionality goal. We developed a functional bulb prototype and were able to test it both on LuminAR Arms and as standalone installations in standard sockets. The final design of the LuminAR bulb completed a series of explorations that pushes forward the design and engineering of compact projector-camera systems. It is also to the best knowledge of the author, the first example of a kinetic and computer embedded

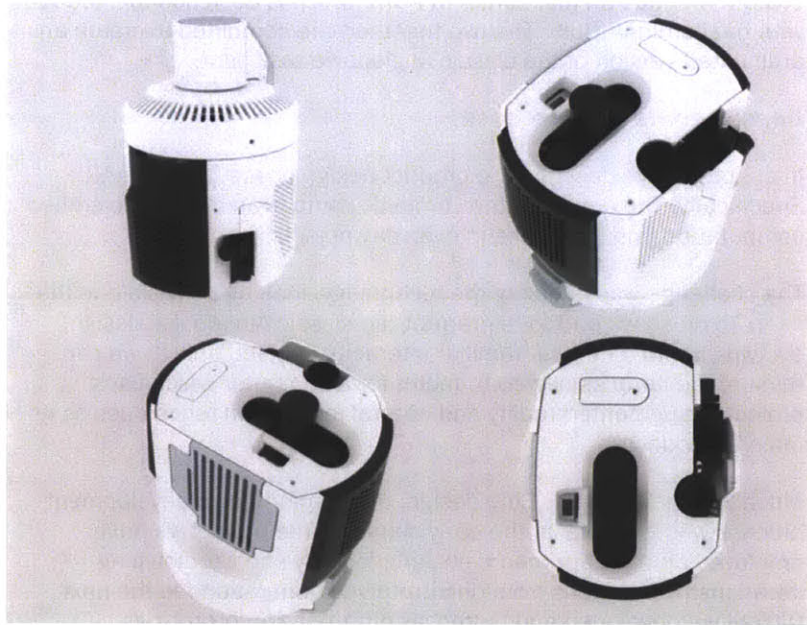


Testing the LuminAR Bulb in a standard light fixture

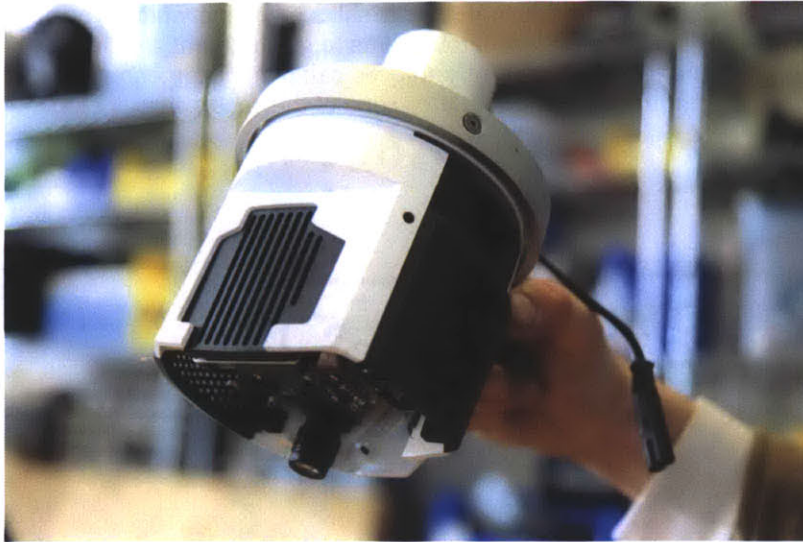
system. Naturally the LuminAR bulb is still a preliminary prototype and has to go through several improvements (e.g. integrating ambient sensors, better depth sensing, improved cable management etc.), but those are at this point, beyond the scope of this thesis work.



Steps in constructing the final prototype of the LuminAR Bulb



Renders of the final design for the LuminAR Bulb (rendering: Jason Robinson)



The final LuminAR Bulb

LuminAR Lamp

For the sake of formal definition, the LuminAR Lamp is comprised of custom robotic arm (i.e. LuminAR Arm), which is designed to interface with the LuminAR Bulb. The two together, are combined to create an articulated version of the classic Anglepoise task light.

Design goals and process

In chapter 2, we describe the product design space for LuminAR. Specifically, The design of the LuminAR Lamp is an attempt to embed computation and interfaces in everyday objects.

The challenge was in hiding the technology, making it invisible to the user. To do so we had to reinterpret the classic Anglepoise design, evolving it into a new yet familiar interactive object. In fact, we can think of the lamp as new form factor for a computer which uses projected augmented reality and natural interaction techniques as its main UI modality.

Much like the LuminAR Bulb design, the LuminAR arm development process was iterative. In the early stages of the project we have employed an agile approach, pushing for very short prototyping iterations. The lessons from one prototype generation fed the next. Overall we developed and tested six different arm prototypes.

The Anglepoise Type 75 Reference

In chapter 2 we provided a brief review of inspirational task lights that served as inputs for our design process. However to translate our design into actual mechanically operational system we decided to use the Anglepoise Type 75 as our main study model. Early on the LuminAR arms follow the proportions and to some extent some of its aesthetics.



Testing of the first LuminAR arm proportions compared to an Anglepoise Type 75 Lamp

Mechanical System

Before we dive into the description of the various LuminAR Lamp prototypes, it is important to review the basic mechanical operation principles they all share.

As we described in chapter 2, LuminAR follows the classic Anglepoise counter balanced arm design, where the force of gravity of the bulb and lampshade is counteracted by extension springs. This allows static positioning of the arm within its affective reach envelope.

The arm uses a four-bar linkage system, more specifically a parallelogram, to translate the movement of the upper arm of the system to a small linkage closer to the base. This enables the counterbalancing spring and any actuator for the upper arm to apply actuation on the small bar and, as a result, be positioned lower, closer to the base.

For a complete review of the physical, mathematical model and mechanical working principle that govern counterbalance systems we refer the reader to the excellent review by French et al. [19].

Topology

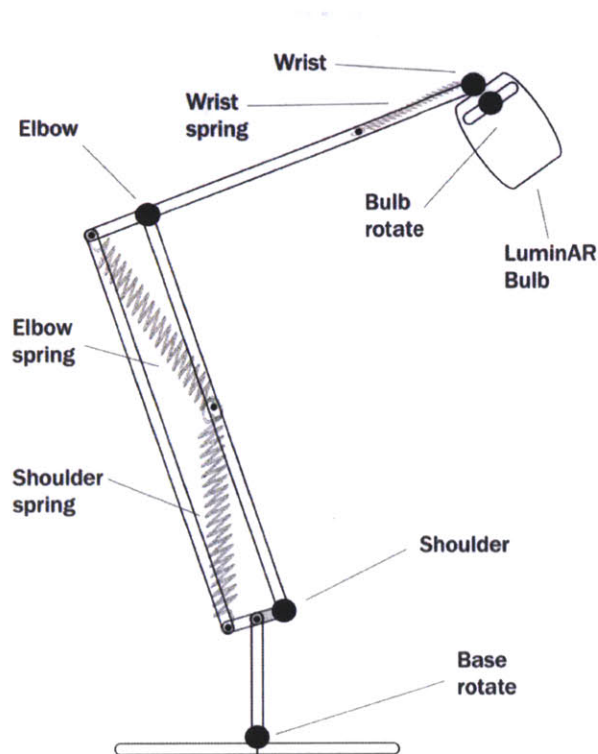
The arm itself has four rotational degrees-of-freedom (DOFs). The first DOF is located in the base of the lamp, allowing the Base-DOF to rotate in the horizontal plane, in a range slightly less than a full 360 degrees.

Next, The DOFs are named accordingly with respect to human arm metaphor: the Shoulder-DOF, Elbow-DOF, and the Wrist-DOF are located on a single plane, orthogonal to the Base-DOF. The Shoulder-DOF and the Elbow-DOF are positioned directly above the base on a mechanical fork structure.

The fork is a support structure for the servomotors and shafts that actuate the elbow and shoulder links of the arm. Finally, the Wrist-DOF is located at the end of the Elbow-link, though the actuator can be mounted elsewhere in the structure of the lamp.

The Shoulder, Elbow and Wrist DOFs are spring loaded, each with it's own separate extension coil spring. The springs counter the mass of the links and the arm's payload, and the LuminAR bulb. Actuating the balanced arm required to output enough torque to overcome the friction load. The Wrist-link has an interface for the Edison 27mm

female bulb socket. Overall, the lamp has 5 rotational DOFs, including the additional rotation inside the Bulb.



LuminAR Lamp mechanical system topology, the diagram shows the lamp's DOFs and extension springs.

In the sections that follow we describe the different LuminAR lamps we have developed over the course of this thesis work.

Prototypes

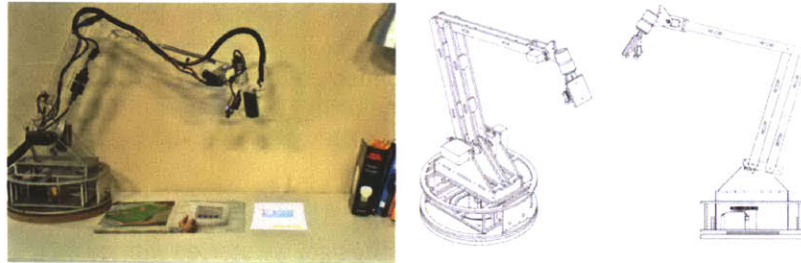
LuminAR Optimus

Optimus was our first fully functional prototype. Its main purpose was to serve as a learning platform for the mechanical subsystems and begin exploring concepts of kinetic user interfaces.

Optimus had a heavy round base that was constructed from a heavy 0.5" MDO board, fitted with an aluminum construction (0.25" Aluminum sheets). The base rotation mechanism used a central stationary shaft fitted with a gear. A servomotor with a 1:2 gear ratio was engaged to central shaft gear giving it 180 degrees of rotation.

On top of base structure we designed an acrylic structure that supported the elbow and shoulder servomotors. The elbow and shoulder springs extended from the four-bar arm linkage to a screw-bolt

holder in the bottom of the base. The arm was also constructed from acrylic laser cut parts that were press-fitted and glued.



LuminAR Optimus

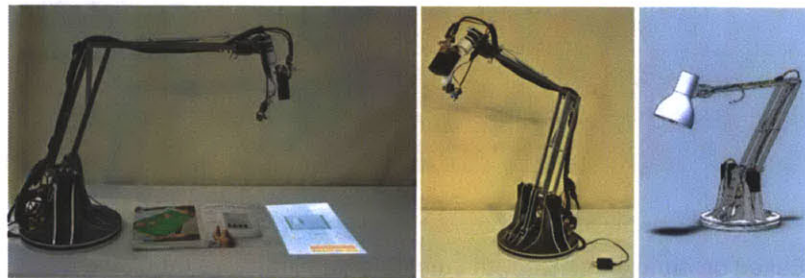
Optimus had a bulb socket construction, but it did not provide power. One of the early LuminAR Bulb rough prototypes was installed on Optimus. Wiring was done through the gap between the arm bars, making sure the cable has enough bend profile. This problem persisted and always required attention in all of the prototypes we created.

Optimus was used extensively in our concept mock-up scenarios, and some of the demos we created are available on the MIT Media Lab – LabCast website [91].

LuminAR Aluminum

Our second prototype was named Aluminum, as it was the main material used for this prototype. The transition to metal was trivial, as wood and acrylic did not provide the robustness and accuracy desired for the kinetic interaction we envisioned.

Aluminum also had a refined low profile base. The base was implemented using a simple turntable and a central gear. The servomotors mounting structure and the actual arms were also streamlined, pushing towards a design that resembles a real Anglepoise task light.



LuminAR Aluminum

Actuation

Both Aluminum and Optimus were actuated using simple R/C servomotors. To control them we used the commercially available servo control board Maestro Micro from Polulu. The Maestro Micro major

advantages are its tiny size, and the simple USB-based programming interface.

Control

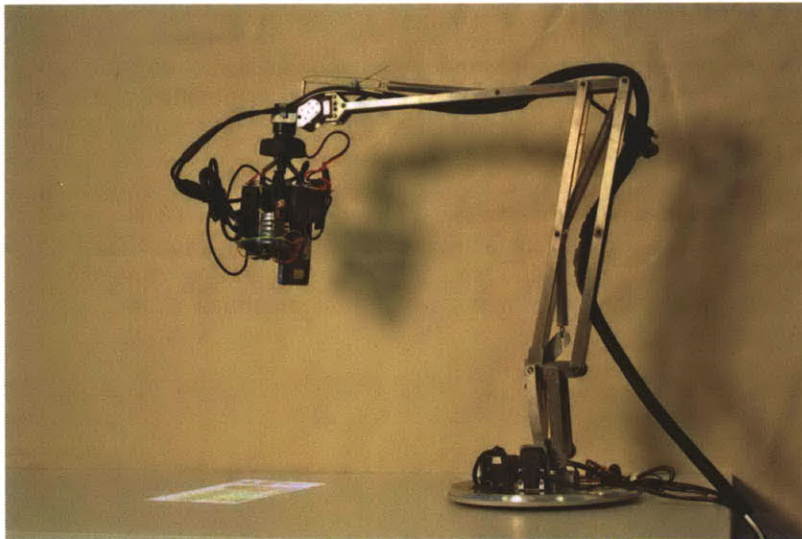
Optimus and Aluminum were both connected to a netbook running Linux (Ubuntu 10.4). Control was done using RS-232 over USB. Projection was supported directly using the netbook's VGA port.

Early software versions

To begin the LuminAR software stack design, we started with quick prototypes using a Python based control server, while our front end UI was based on the QT4 GUI toolkit.

LuminAR Topsy

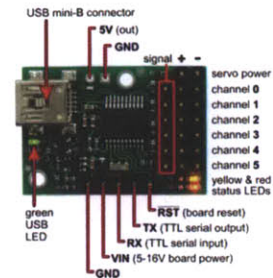
Topsy represents a major revision in many aspects of the LuminAR Lamp evolution. Anecdotally, Topsy got its name due to a miscalculation of lamp's base weight, which caused it to tip and lose balance. Even though far from perfect, Topsy represents our attempt to reach the proportions of a real task light. It also represents a system integration milestone, as it was tested with an almost fully functional LuminAR bulb.



LuminAR Topsy

Based on our experience with LuminAR Aluminum, we were able to introduce important improvements to the mechanical and product design.

First, we improved on the base rotation mechanism. Stirring away from the use of turntables, we designed our own ball-bearing system. Doing so allowed us to reduce the base diameter further.



Pololu Maestro Micro servomotors control board (source: Pololu)



LuminAR Tippy has a new central for element, which enabled us to position the motors on the base plate

Next, we designed a new central shaft and a new fork element. The fork allowed us to align and mount the elbow and shoulder servomotors directly on the top of the base plate. This approach saved redundant use of aluminum wings above the servos. To implement this, we added custom servo horns and linkages that provided the actual hinge to the elbow and the shoulder DOFs respectively. It also allowed using a single central shaft in the fork structure.

Finally, we were able to fit the springs for the elbow and shoulder DOFs elegantly in the gap between the lower arm linkages. Mounting the springs there contributed to the overall range of motion as well as to the overall form of the lamp. As the design of Tippy was clean and simple we could easily explore different configuration using the same basic platform.

Actuation, Electronics and Control



Configurations we created based on Tippy's design

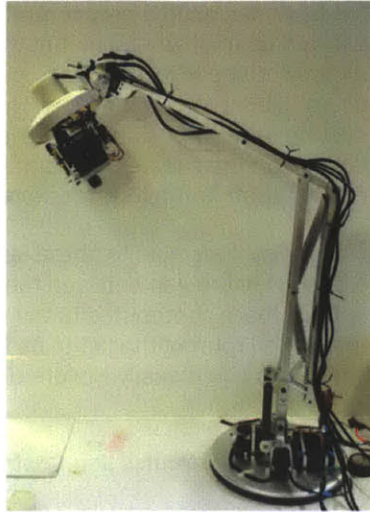
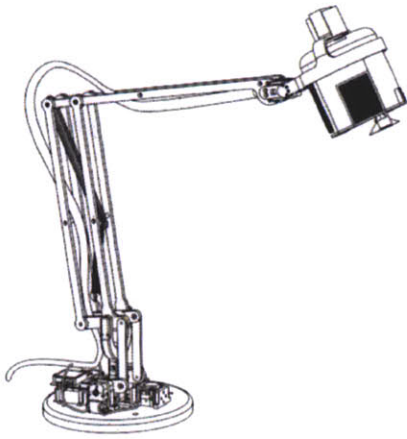
Tippy was our first model to incorporate a power supply. 110VAC was supplied to the bulb socket attached to the Wrist, while 15VDC was supplied from a PSU mounted on the base. It was used to feed the arms' servomotors. A small USB-Dynamixel board mounted on the power supply supported the communication to the bulb encoder. In our original design we also included external position sensing for each DOFs. This was to be accomplished using POTs that were mounted on the DOFs shaft. All encoders were then connected to a small microcontroller at the base of the lamp.

Tippy was actuated by four Robotis Dynamixel servos (DX-117). We decided to upgrade the arm's actuators after we damaged or broke several giant scale R/C servos (e.g. Hobbico CS-80). Although clearly more expensive, the Dynamixel servo system [92] has clear advantages in sensing, networking and torques compared to standard R/C servos.

Tippy was the first arm to be fully controlled by our very own integrated LuminAR bulb version. It was also the first platform on which we developed and tested the LuXor software stack that we describe later in this chapter.

LuminAR Silverjack and Blackjack

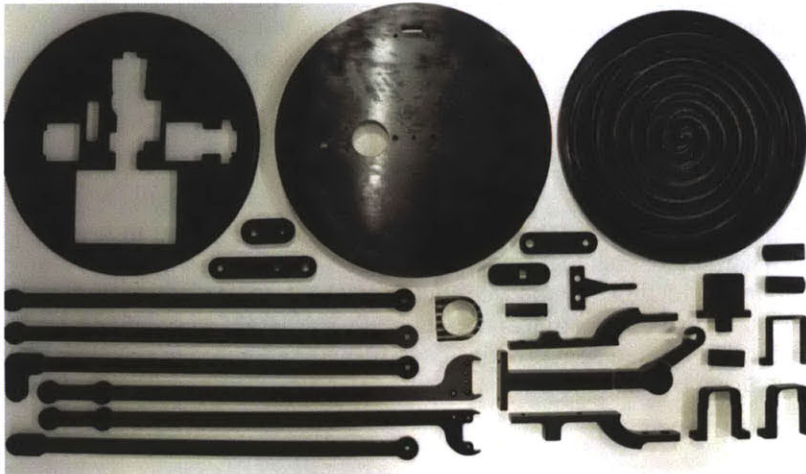
One of the main goals of this thesis work was to embed computation in everyday objects, and the main innovation the Silverjack and Blackjack revision represents together with the new LuminAR bulb is the creation of a new actuated interactive robotic task light. In this iteration we focused on the industrial and product design details that pushed our prototype further, so it is a 'designed object' and one that could be perceived as such by users.



LuminAR SilverJack and Blackjack. (photo credit: Doron Gild)

Silverjack and Blackjack were heavily based on the Topsy design. They were designed for a short run professional manufacturing. The use of professional manufacturing techniques clearly upgrades the final result in terms of product design but also contributes to accuracies and tolerances, which has a direct effect on the overall mechanical performance of the system.

The SilverJack and Blackjack revisions also included mechanical improvements. The main fork was revised to provide better reinforcement for the servomotors. The base rotation mechanism was also improved to use anti-backlash gears and a central shoulder screw.



LuminAR Blackjack fabricated parts before assembly

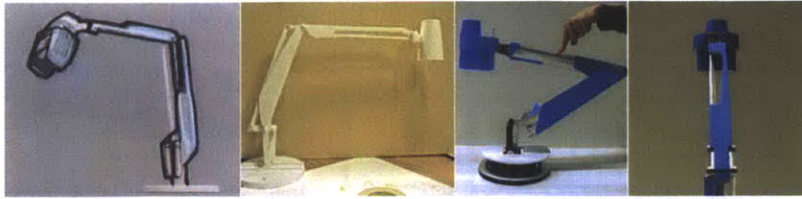


LuminAR Blackjack. (photo credit: Doron Gild)

LuminAR Retail

The LuminAR Retail arm design was specifically developed to integrate into the Augmented Product Counter (APC – see: Chapter 5 - Applications). This revision explored how our design can be manifested in a future retail environment.

Conceptually, LuminAR Retail is an adaptation of the LuminAR Blackjack tabletop arm design to a counter-top lamp for use in public spaces. In addition, the arm's design had to take into account the physical dimensions of the installation space, and to account for the APC projection real-estate requirements.



LuminAR Retail design process used existing lamps as platform for physical modeling and form exploration.

To accomplish that, our design process used the existing Silverjack model as a physical prototyping platform. Using this approach, we were able to reuse most of the base components, while developing the new proportions and working envelopes that were extended to cover larger workspace.

In order to streamline the final form of the retail arm we repositioned the wrist servo, locating it in the back section of the upper arm linkage. The result was a clean and simplified connection point between the bulb interface and the upper arm wrist joint. The motion was transmitted to the wrist DOF using a custom made horn and linkage that was mounted under the upper arm.

In addition, the retail arm makes extensive use of casing and covers. We used black ABS plastic custom made covers to obfuscate technical components as much as possible. In the final version we included covers for the arm linkages (top and front), bulb interface and base covers.



LuminAR Retail (photo credit: Doron Gild, rendering: Jason Robinson)

Due to its larger size and mass, to maintain an effective work range, we had to upgrade the servomotors for the Shoulder-DOF and Elbow-DOF from Dynamixel DX-117 to Dynamixel EX-106+, which provided the required torques to handle LuminAR Retails' increased dimensions and weight.

Conclusion

In the course of this thesis work we have developed six robotic arm platforms that were used to evolve the LuminAR Lamp concept. We were able to quickly use our insights across multiple iterations. However, our real goal in the design of these objects was actually to make the technology, specifically the robotics, disappear altogether.

We believe we provided a valid first step for the design and implementation of such future actuated task lights. But, we are also aware that our hardware is limited, many improvements can and should be applied mainly to the actuation and sensing subsystems, and to the overall cost reduction of the arm, so it becomes commercially viable.



LuminAR Retail projecting a keypad (photo credit: Doron Gild)

LuminAR Spotlight

LuminAR Spotlight is a ceiling or wall mounted, actuated carrier fixture for the LuminAR Bulb. It was designed to add articulation capabilities to static track lights and light fixtures. Combined with the projected augmented reality interface the LuminAR bulb provides, it creates dynamic interactive physical spaces.

Our goal in designing LuminAR Spotlight was to develop additional kinetic form factors, which can be embedded seamlessly in a physical space and explore the interaction techniques it affords. In this section we describe the Spotlight prototypes and discuss two variations of the Spotlight concept. The first uses an articulated linear track. The second variation uses a pan/tilt mechanism.

Design goals

To complement the general design concept of spotlight, we defined the following design goals for the system we created:

- Spotlight can be mounted on a ceiling or wall, taking advantage of the additional height and projection angles above and around a workspace.
- Spotlight devices should be designed to completely blend into the physical environment.
- Spotlight should support natural interaction modalities
- Spotlight should be able to communicate with other LuminAR devices, complementing the use case (this was actually achieved in the APC project – see Chapter 5 – Applications)

Prototypes

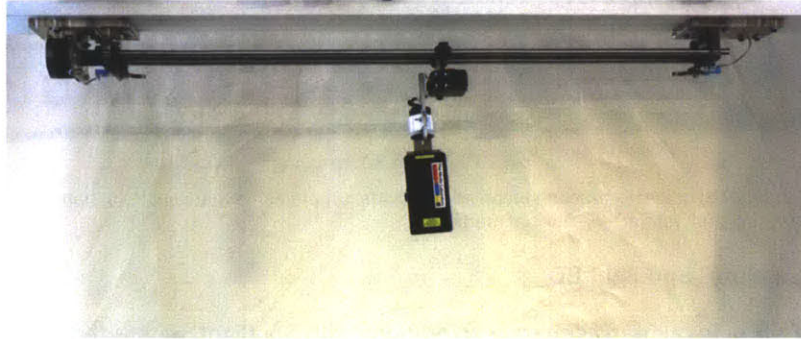
LuminAR Spotlight LS

Our first approach explored the concept of actuated track lights. We focused on building a quick prototype to be able to tackle challenges like actuation and retractable cable management.

The Spotlight LS system consists of a linear shaft based track and a carriage with an R/C servomotor tilting head, giving LuminAR Spotlight two degrees of freedom. The carriage head interconnects with the LuminAR bulb through a standard Edison bulb screw socket.

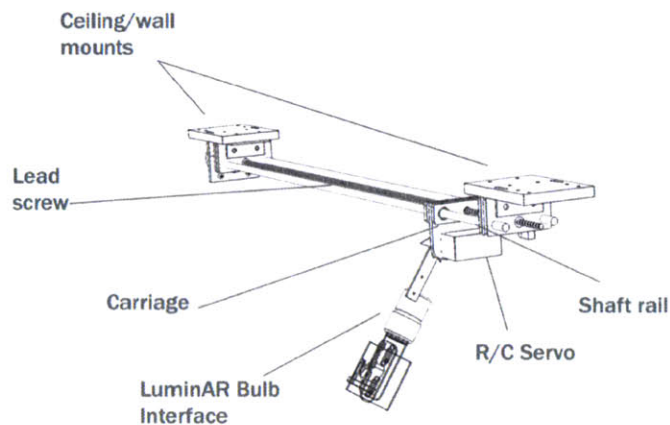
In this version, motion was transmitted from a stepper motor through a fast lead screw that carried the bulb carriage. It had no position sensing except a far and near switches at the end of shaft tracks. We used a small microcontroller and motor driver board to open-loop control the position of the carriage. The micro-controller was then hooked to the LuminAR Bulb netbook computer, giving the bulb control of its location along the track.

The carriage position could be estimated using a time-based calculation. The actual location of the carriage was calculated using rotation revolution count. Integrating the lead screw pitch with the number of steps the stepper motor performed in a given time slot, provided the estimated distance the carriage travelled.



LuminAR Spotlight LS

However, this approach gave average results and was one of the reasons the use of lead screw was abandoned in the next version – Spotlight BD (belt drive). The other reason we opted to replace the lead screw actuation method were the slow speeds it provided and the high noise levels.



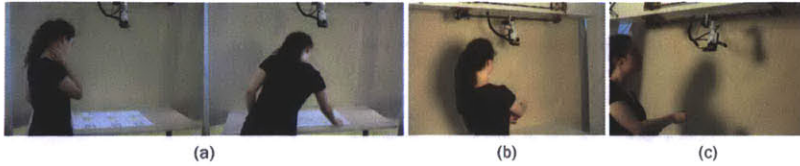
LuminAR Spotlight LS – mechanical design

Interaction with Spotlight

Spotlight LS also served as a platform to explore different interaction techniques that we already developed for the LuminAR Bulb, and specifically new methods that are unique to Spotlight.

First, we were able to dynamically control the location and orientation of a touch enabled projected interface. This concept could be used to dynamically choose the projection location. For example, we could decide on a horizontal surface (e.g. a tabletop), and then using a gesture, direct the Spotlight to project on a vertical surface (e.g. a wall).

Next, we could have the Spotlight track a fiducial marker. This is be used to track and object under the spotlight. We were also able to used similar techniques to track a users hand.



LuminAR Spotlight interaction techniques include: (a) projected multitouch, (b) hand tracking and, (c) tracking fiducial markers

LuminAR Spotlight BD

Following our early general explorations with Spotlight, we started working on a specific version of the Spotlight for the Augmented Product Counter project. From an interaction point of view, this version was designed to provide an 'Expert Wall' feature; we describe this scenario in Chapter 5 – Applications.



LuminAR Spotlight BD

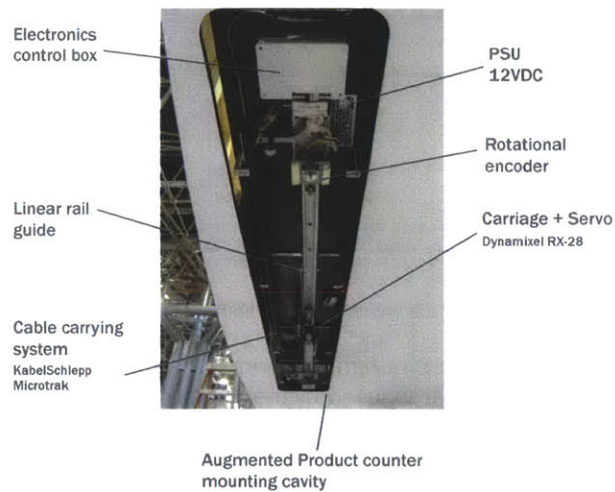
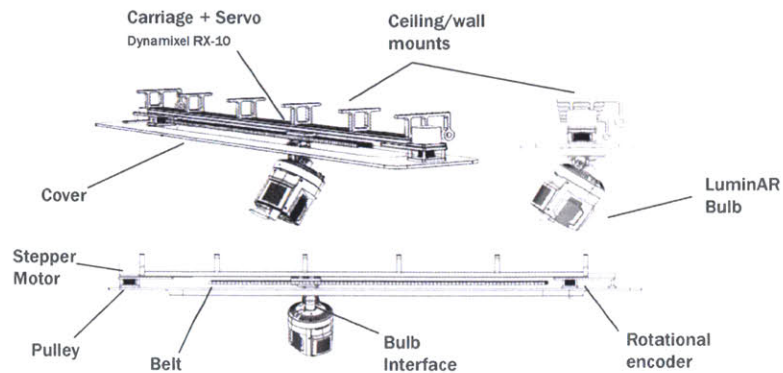
The Spotlight BD prototype represents a major upgrade of the mechanical and electrical systems. But not less important, we were able to meet one of our design goals and develop a solution that integrates into a ceiling cavity, hiding all the technology under the hood.

Mechanical engineering

Similar to the Spotlight LS, the system consists of a linear track and a carriage with a tilting head, giving LuminAR Spotlight BD the same two degrees of freedom.

The linear motion is generated by a stepper motor, positioned on one end of the rail and transmitted through a belt and pulley drive mechanism. The idler pulley shaft is equipped with a rotational encoder to track the carriage position. The belt and pulley proved a better solution, in terms of ambient noise, and position sensing control accuracy.

The carriage head tilt is accomplished by a servo mounted on the carriage. The servomotor was upgraded to use a stronger Robotis Dynamixel AX-10 servomotor. The servomotor was fitted with a standard bulb interface.



LuminAR Spotlight BD – mechanical design

In this version, we had to provide a better solution for continuous retractable cable motion. We integrated a KabelSchlepp Microtrak cable carrying system. The Microtrak was an ideal choice as it is lightweight non-conductive yet very durable and easy to integrate.

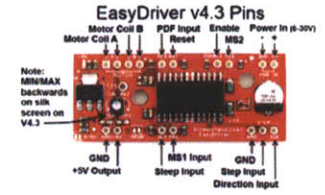
Electrical engineering

We created a custom control electronic board for the Spotlight BD. It was important to create the board so the entire system could be used stand alone, requiring only power connection and the LuminAR bulb to operate.

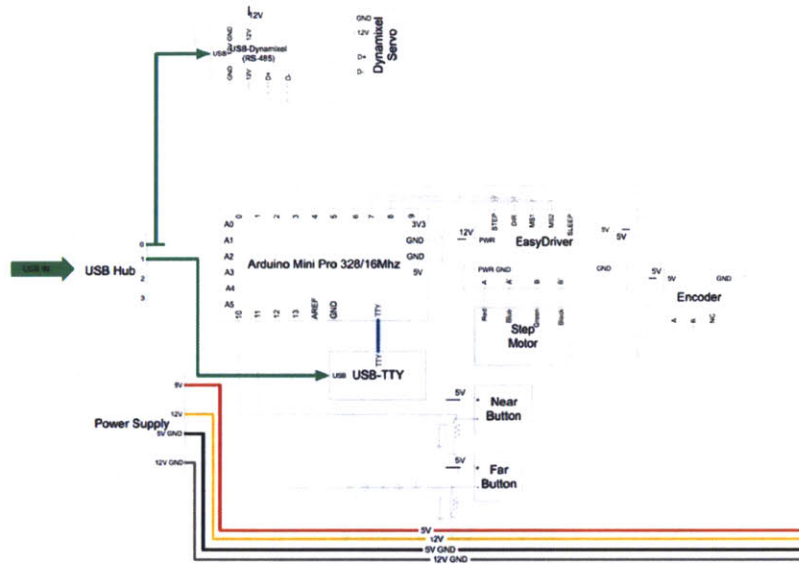
The entire system was fed by a power supply that provided motors with 12VDC line, and a 5VDC line for the control electronics.

The board controlled the stepper motor using a small microcontroller (Arduino Mini Pro 238/16Mhz), connected to a commercially available stepper motor control board from Sparkfun called EasyDriver. The

EasyDriver board provided a simple control interface to the motor's step and direction. The near and far switch sensors were connected directly to the microcontroller, providing stop-switch mechanism when the carriage reaches the end of the linear track. The rotational encoder is also connected directly to the microcontroller, providing a closed-loop control.



EasyDriver stepper motor control board
(source: Sparkfun)



LuminAR Spotlight BD control electronics board schematics

The board included a USB hub that provided interfaces for the FTDI RS-232 / USB interface boards, used by the microcontroller and the Dynamixel servo communication interface.

The board was placed in a plastic box, mounted on the linear track rig, and fitted with ON/OFF LEDs for indication purposes. The microcontroller on the board firmware provided simple interfaces to initialize the system control and query the location of the carriage on the track.

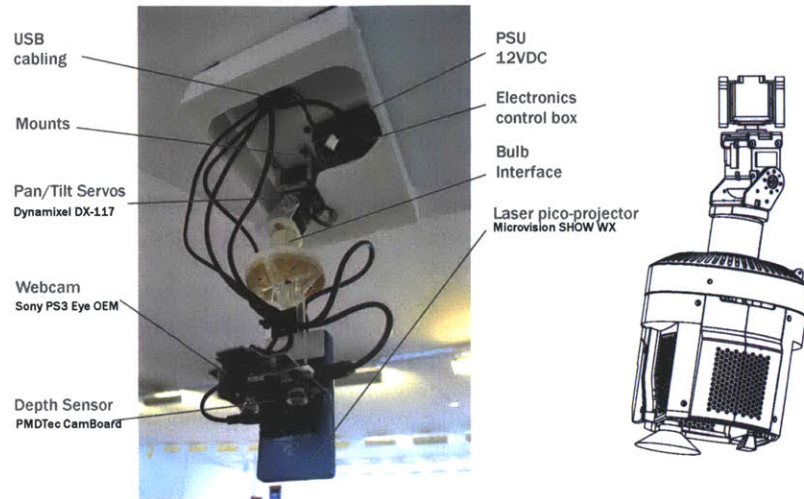
LuminAR Spotlight360

The final Spotlight exploration we created is called Spotlight360. It is a simple fixture, built from two Dynamixel DX-117 servos, the first serves as a rotation axis (pan) and the second serves as a tilt servo. The second servo interconnects with the LuminAR bulb through a standard Edison bulb screw socket.

The goal of this version was to provide a simple form factor capable of revolving the LuminAR bulb 360 degrees with respect to its mounting point.

In this specific iteration, we used a stripped version of the LuminAR bulb that used a depth sensor. This enabled us to use free hand

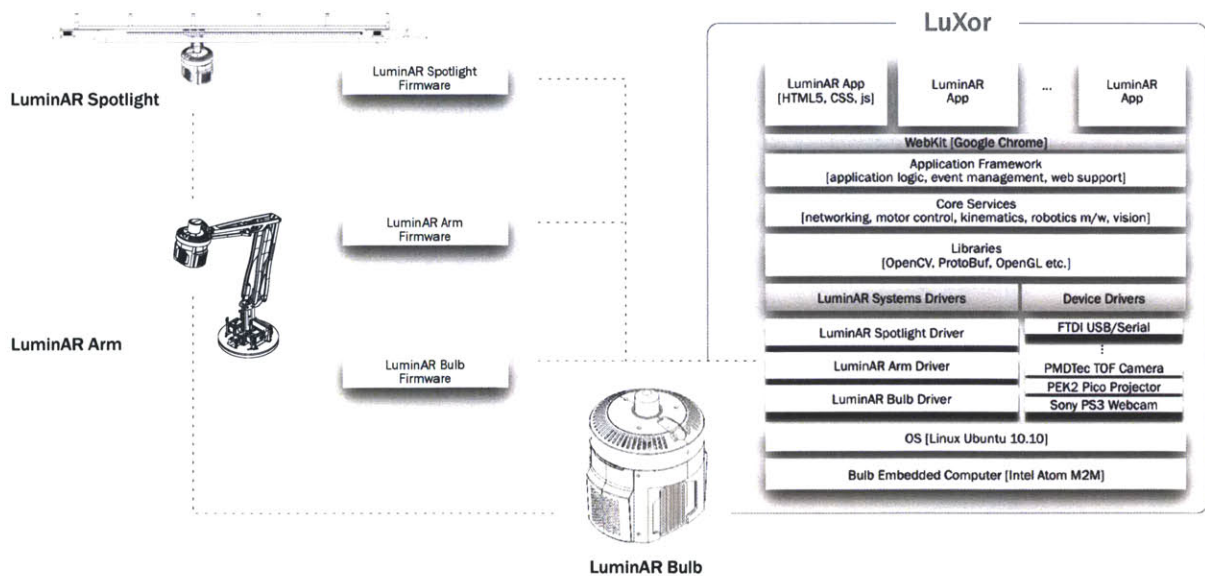
gestures (e.g. open hand, fist, pointing-finger) to control the bulb projection location and orientation.



LuminAR Spotlight360 – mechanical design

LuXor

LuXor is the software framework and execution environment we designed and developed to run LuminAR devices. It is designed to run in the context of the LuminAR Bulb, the central computation and I/O hub for the system.



The LuXor software stack is designed to run on the embedded computer of the LuminAR Bulb. LuXor has specific LuminAR systems drivers that communicate with the firmware of the LuminAR Arm and LuminAR Spotlight

It also provides the interfaces for the bulb to communicate with other LuminAR hardware devices. It was developed for the later iterations of the LuminAR Bulb, and specifically tested with the LuminAR BlackJack, SilverJack, and Retail arms as well as with the LuminAR Spotlight.

LuXor combines different software disciplines; to enable LuminAR devices to become interactive, kinetic and connected projected augmented reality interfaces. In broad strokes, LuXor comprises of a web based application framework and a set of core services that provide it with a hardware drivers, robotic middleware, application runtime logic, event management, computer vision services, and projected GUI utilities.

In this section we provide a high-level review of the software requirements and design considerations that motivated LuXor. We begin with software architecture overview, and continue to describe the core services and the application framework that enables developers to create LuminAR applications.

High Level Software Requirements

The software requirements for LuXor are also informed from the design principles we presented in the beginning of this chapter. We can extend some of the principles to the software domain, supporting our goal to create an interactive, kinetic projected augmented reality user experience. Finally, to complement the discussion of the high level requirements we present in this section, the reader should also refer to the Interaction Design Principles we present in Chapter 4 – Interaction techniques.

The table summarizes a set of high-level software requirements that guided LuXor's software architecture design:

Embedded	<ul style="list-style-type: none"> • The entire software stack should be able to run on embedded boards that have a single processor (e.g. Intel Atom MTM or ARM based systems)
	<ul style="list-style-type: none"> • The entire code base should have a small footprint so it fits in embedded storage devices
	<ul style="list-style-type: none"> • Support close to real-time constraints for computer vision, motor control and graphics
Layered and Modular	<ul style="list-style-type: none"> • Low runtime memory requirements
	<ul style="list-style-type: none"> • LuXor should provide good abstractions and relevant layers to separate low level drivers, system core services and application interfaces
	<ul style="list-style-type: none"> • System should be developed in a modular fashion, allowing (1) different configuration options and (2) distributing computation to

	either additional module instances or remote modules
Extensible / Portable	<ul style="list-style-type: none"> • Provide interfaces to extend the system in its respective layers • Support portability of the codebase across different LuminAR devices, abstracting hardware dependent code
Connected	<ul style="list-style-type: none"> • LuXor should enable LuminAR devices to work in a network • Support device addressing and data exchange protocols
Application Model	<ul style="list-style-type: none"> • Provide a standard web based application development framework
Standard / Open	<ul style="list-style-type: none"> • Use open standards, allowing for easy 3rd software integration
Natural Interaction / AR Interfaces	<ul style="list-style-type: none"> • Provide UI modality fusion. Support standard GUI approaches (e.g. multitouch) with gesture detection and AR interaction techniques
Limited Installation & Calibration	<ul style="list-style-type: none"> • The system should require minimal configuration and/or hardware-software calibration to run
Interactive Kinetics Control	<ul style="list-style-type: none"> • Abstract robotics control aspects, providing mechanisms to use kinetics for application, interactive purposes

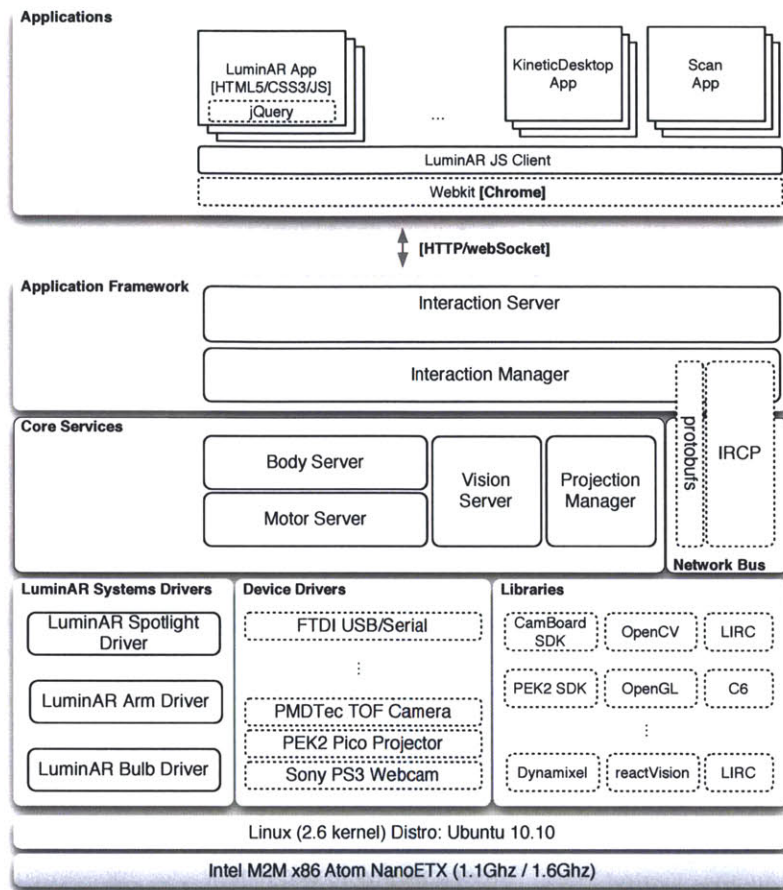
Software Architecture

Two main areas of software design inspired the LuXor software architecture design: mobile platform architectures (e.g. Google Android or Apple iOS [93], [94]), and robotic middleware solutions (e.g. ROS from Willow Garage [95]). The LuXor architecture is a minimalistic hybrid between these two very different paradigms.

The diagram below provides an elaborated view of the LuXor software stack. In the following sections we briefly discuss LuXor's major components.

Hardware and Operating System

LuXor is designed to run on Intel's M2M Atom hardware. The M2M is an x86 platform and can easily boot Linux. LuXor relies on the Linux kernel for core OS functions and basic services such as network connectivity and windows management. We also rely on Linux driver model to support all the peripherals attached directly to the bulb's computer.



LuXor software architecture

Components Overview

The LuXor infrastructure is designed as a layered architecture, defining the following layers and components:

- **Applications** – front-end, web-based LuminAR applications
- **Application Framework** – runtime execution, interaction and event management
- **Core Services** – a set of infrastructure components, interfacing with low level hardware (motors, sensors), exposing high level interface for the application framework
- **Network Bus** – IPC communication pipeline and data bus
- **Libraries** – includes all 3rd party dependencies
- **LuminAR Systems Drivers** – drivers to LuminAR systems
- **Device Drivers** – drivers to peripheral components of the LuminAR Bulb

In the following sections we provide more details on the specific functionality of the various LuXor components.

Core Services

LuXor's core services layer includes a set of independent servers, each dedicated to specific services required by the Interaction Manager. The services interface with low-level hardware drivers and expose simple interfaces to the application framework.

Networking

LuXor services and application framework use a shared network bus to communicate. Inter-application communication is critical when implementing a modular, distributed system. The network bus is used to integrate independent software modules, providing simple means to send messages and data. This enables LuXor to become an event driven system throughout its different layers.

Our message description implementation was based on Google's Protobufs open source project [96]. Protobufs stands for Protocol Buffers. It compiles human readable structured message descriptors to binary protocol buffers. Protobuf also provide interfaces in various platforms, which was important when integrating a low level C++ server with a high level Python interface.

LuXor uses the Intra-Robot-Communication-Protocol (IRCP) as the transport layer for the network bus. IRCP is a thin layer of networking logic, implemented on top of UDP transport protocol. It provides Python, C++ and Java interfaces. IRCP handles the basic network creation, address resolution and basic error checking. It provides simple interface to send typed data packets or send streams of data. IRCP was developed at the MIT Media Lab Personal Robots Group [97].

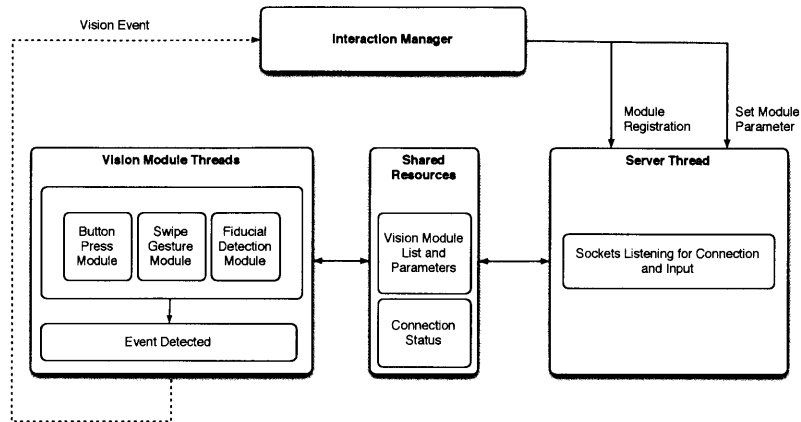
Vision Server

The vision server's role in the LuXor system is to manage input from the various cameras in the LuminAR bulb and produce interaction events such as the pressing of a button, detecting a hand gesture or the presence of an object. Events are propagated to the Interaction Manager where they can trigger application level state changes.

The server was developed in C++ using OpenCV [98] and reactiVision [99], and was optimized for embedded performance. It also manages the access to shared camera resources, providing thread safety. The server modules could also be deployed on multiple machines thanks to LuXor's network bus. This was useful when the vision tasks were pushing the limits of the Atom based platforms we were using.

The server generalizes and abstracts the interface to cameras and sensors, exposing multiple a functional interface using vision modules. The vision server owns a dynamic array of vision modules, each of which represents an independent thread processing video and

producing events, which can be sent asynchronously to the interaction manager.



LuXor's Vision Server vision events flow

Vision modules need not only the ability to send events but also the ability to receive information from the Interaction Manager about the application state, such as the location of buttons on a page. We implemented modules to detect button press, hand swipe gestures and a fiducial marker tracker module. We also experimented with depth based touch detection module using PMD Tec CamBoard USB Time-of-Flight(ToF) sensor [100].

The Vision Server modules assume homography between the projected display and the camera viewpoint. The homography is accomplished using a one-time simple calibration process in which camera pixels are correlated to projector pixels. The calibration data is then saved to a configuration file.

Button Press Module

To allow LuminAR to determine when a button in the projected user interface has been pressed, we initially turned to using a time-of-flight depth-sensing camera from PMD Tec. The sensor measures the distance of objects by sending out pulses of light and then measuring the amount of time it takes for the light to return to the camera, with a resolution of 200x200 pixels and measurements in meters. After calibrating the sensor, we found the depth value at each button by sampling the depth image and then forming a virtual hemisphere a small number of that point. This technique was also used recently by Wilson using a Kinect sensor [68]. Then, by the number of depth pixels in that 3D volume we determined whether or not a finger was present on the button. We found, however, that the thickness of the average finger was not significantly larger than the noise level in the depth frames, and so we had a large number of false positives with low values of the threshold and a large number of false negatives for high values of the threshold. That, combined with technical issues regarding the depth sensing hardware, forced us to use simple webcams as an alternative.

As a replacement, we decided to use a webcam (Sony PS3 Eye OEM) with a far simpler scheme. We found that the saturation values for both the white table and the projection on it were very low, while the saturation values for hands over the table and the projection was quite high, so thresholding the values of saturation within the region where the button was located allowed us to reliably determine when a button was present in that area, signifying a click.

Clearly, this approach was aimed at giving us minimal vision based interaction capabilities and we can use it to explore many applications that require simple touch capabilities. Using the Vision Server's architecture it is easy to add additional modules that will improve the detection capabilities with finger tracking and hand gesture detection mechanisms.

Swipe Gesture Module

The Swipe Module allows the user to perform a swipe gesture beneath the LuminAR Bulb viewport, and determines the direction the swipe was made, either right to left, left to right, top to bottom, or bottom to top. To determine the presence of a swipe and its direction we initially attempted methods involving optical flow, but found that they were not lightweight enough for the Atom hardware considering the vast amounts of additional processing that was necessary. Instead, we chose a far simpler method that used the same hand extraction by saturation thresholding as the button press module.

Fiducial Detection Module

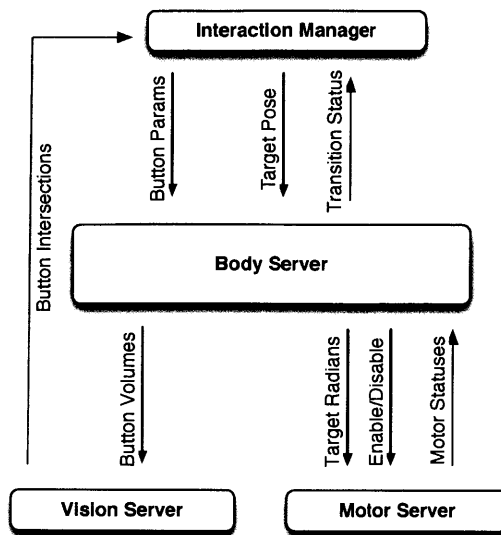
To detect the presence and location of objects in the LuminAR view, we used fiducial markers. reactIVision [99] is an open source implementation of fiducial marker detection we opted to use. It sends fiducial information over a socket, so in the Vision Server we created a module that listens on the reactIVision port and forwards fiducial events up to the Interaction Manager indicating the presence and location of objects with fiducial tags.

Body Server

The LuXor Body Server is a small-scale robotic middleware layer. It is in charge of controlling LuminAR devices pose. It also abstracts this function from the application, providing an interface to manage poses.

The Body Server also handles the entire kinematics calculations specific to the device (i.e. The LuminAR Arms and LuminAR Spotlight have very different kinematic models). Using the kinematics model the Body Server is also responsible to load and maintain the Vision Server calibration data.

The diagram below shows the main flow of the Body Server.



LuXor's Body Server event flow and interfaces

The Body Server continuously communicates with the Interaction Manager to monitor and control the pose of the LuminAR device. Once an application has reached a state in which the application is required to move, the Interaction server would request a logically defined 'Target Pose' from the Body server. The Body server in turn translates the logical target name to actual motor coordinates in radians and forwards them to the Motor Server. Once a motion sequence is complete the Body Serve returns the interaction control to the Interaction Manager.

Motor Server

The LuXor motor server provides an abstraction for low-level motor control required of LuminAR devices. It provides a means to configure multiple motor configurations per device. It also allows for multiple device configurations. This feature was extremely useful when defining complex devices with separate motor configurations like the LuminAR Spotlight or the LuminAR Lamp.

Projection Manager

The Projection Manager was designed to interface with the application framework to provide display manipulation routines. The PEK2 SDK provides hardware-based keystone and projection angle manipulations that could help deal with geometrically correcting a projected image. Unfortunately we did not have sufficient time to fully complete and test this manager.

Application Framework

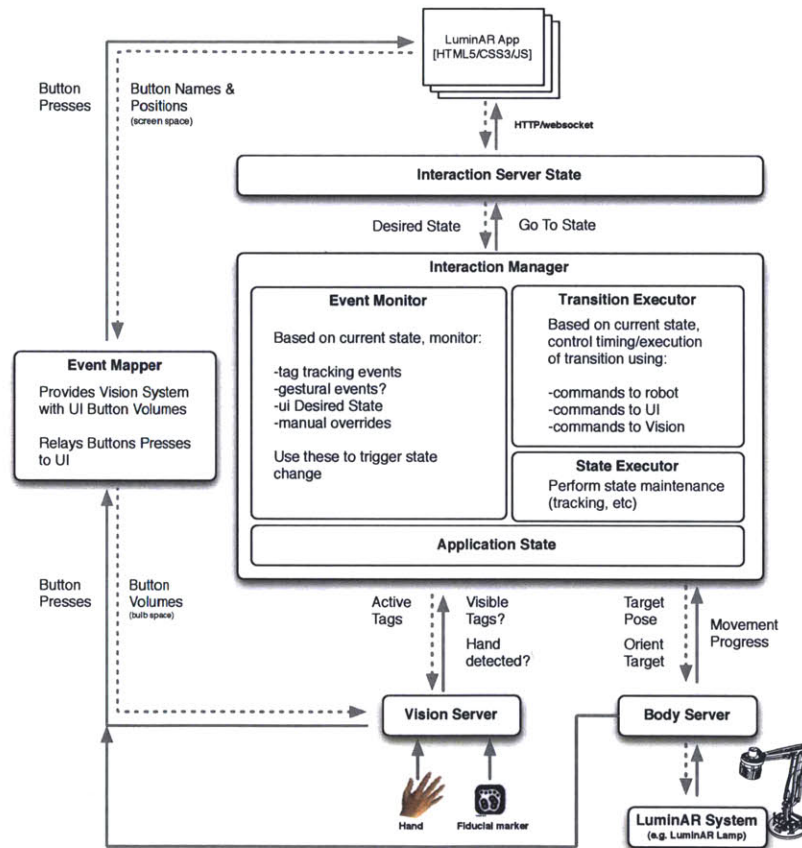
LuXor's application framework provides runtime execution environment, state management and event distribution mechanisms. It is designed to support a simple yet powerful web-based development environment.

Interaction Manager

The heart of the Application framework is the Interaction Manager. It is responsible for managing the entire application lifecycle. The manager has direct interfaces to the Body Server and the Vision Server.

Two key mechanisms govern the server main loop. First, the *Transition Executor* is responsible for maintaining the current logical state of an application. Each state is defined by a set of transitions that corresponded respectively to the logic of the application pages. We discuss the general structure of LuminAR applications in the next section of this chapter.

The second mechanism is the *Event Monitor and Mapper*; it generates triggers based on incoming events in the system. Events can be either I/O driven from the application level or internal system events. Triggers invoke the State Executor completing the event flow loop. The diagram below summarizes the interaction manager event loop.



LuXor's Interaction Manager logic diagram, event management components and interaction events flow

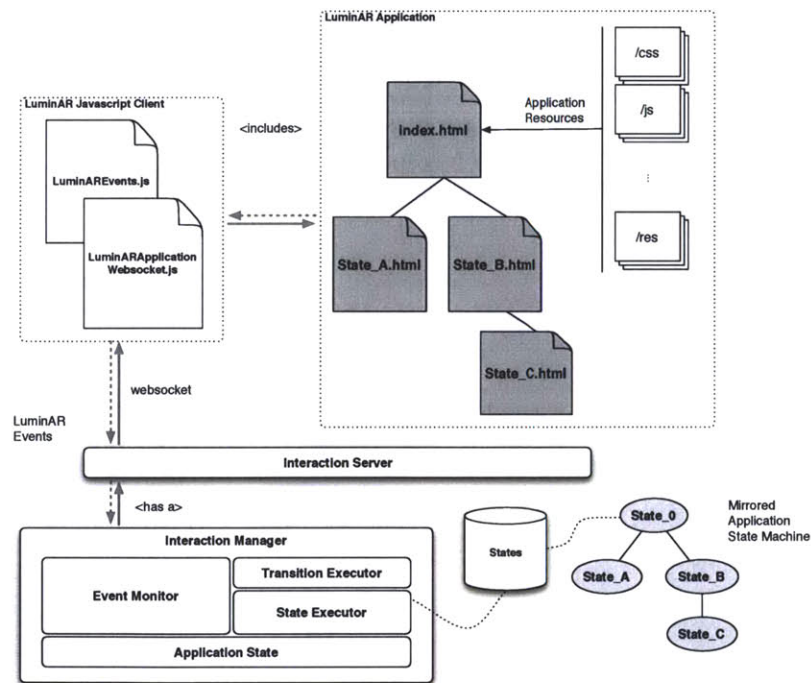
Interaction Server

The interaction server is responsible for relaying events, and state changes to and from LuminAR Applications. The server has a direct interface to the Interaction server, and a socket interface for LuminAR application to bind to. The server also has a registry for LuminAR events.

LuXor Applications

LuminAR applications are in fact web apps. Modern web browsers like Webkit, Chrome and others support the powerful new HTML5 and CSS3 specifications and Javascript provides a platform portable development environment. These new browser capabilities combined with visual java script toolkit such as jQuery provides an excellent front end GUI development platform.

Developing application code in a document driven, scripted environment has numerous advantages to the traditional programming alternative. Two advantages are important to note: (1) in a web application all the resources are packaged with the application, and the browser has a rich set of capabilities to render audio, video and various graphic formats. (2) Web based applications are easy to integrate with practically any web service or API that exists online.



The LuXor application runtime model

The challenge we had to tackle is how to robustly connect the browser front end to the LuXor backend. This was accomplished using a custom JavaScript client we developed. Once the client is imported to the

application main page, it opens a websocket connection to the interaction server and loads the definitions of the supported LuminAR events. With the communication pipeline established, application developers can create interactive web applications that use vision-based interaction and use kinematics.

What we did not have sufficient time to implement is the code-generation step that automatically creates LuminAR application state definitions for the front end. In the course of this thesis work we hand coded the application states using simple Python configuration scripts, but there is no reason they cannot be auto-generated.

4 Interaction Techniques

LuminAR was designed to deliver a rich and interactive projected augmented reality user experience. The work in this thesis was carried out in a period of time in which user interface technology emphasis has shifted towards the conceptual realm of *Natural Interaction*.

But, at the same time LuminAR is in essence a projected interactive surface, and therefore it has known limitations such as: lack of feedback from a projected surface, display fidelity in different lighting conditions, occlusions and shadows caused by hands or objects and the need for flat white surfaces. Such limitations many times can be mitigated by interaction design that takes them into account.

While we implemented a simple hand tracking and basic gesture detection mechanism, the next step would be to expand and support full multi-finger detection, multi-hands detection including postures. The technical details of our initial implementation are included in the description of the LuXor software framework Vision Server (see details in chapter 3 – LuminAR). There are many variants in the literature [53], [101] that provide solution to these problems, and they could be adapted to the LuminAR software stack as new modules for our computer vision server.

Natural Interaction

Natural Interaction is an umbrella term that encompasses various known techniques for multi-touch user interfaces; gestural interfaces as well as other sensing based interaction. Such *Natural Interfaces* support *direct interaction*, where the hands or the body serve as the input device, rendering the need for an intermediary device such as a keyboard or a mouse obsolete.

The common denominator for these approaches is the creation of direct, intuitive interfaces that makes our interaction with computers seamless and unobtrusive. *Natural Interfaces* also refer to the interfaces that are able to blend the digital and physical world, while responding to context.

The computer mouse, GUI and the WIMP concepts contributed immensely to the mass adaptation of personal computers. It also contributed to the adaptation of other display-centric computing devices (e.g. smart phones and tablet computers) that essentially used the same interaction paradigm. In the broad sense, *Natural Interfaces* are well on their way to become a key interaction modality in the years to come, and very well may contribute in a similar fashion to the adaption of new form factors for computing that would use augmented reality as key interaction modality. Early evidence of this trend can be seen in the emergence of new standards and major open source

projects, such as the Microsoft's Kinect SDK [102], OpenNI initiative [103], and work carried out by the Natural User Interface Group [104].

In chapter 2 we outlined some of the challenges that current augmented reality experiences suffer from as they try and provide a natural user experience. In this chapter, we will provide the interaction design principles that guided our work on the LuminAR interfaces. We also provide an overview of the various LuminAR interaction techniques we developed to address some of the current drawbacks. Finally, we propose a set of gestures that take advantage of Kinetic I/O.

Interaction Design Principles

Before diving into the discussion of the actual LuminAR interaction techniques, it is important to review the underlying guidelines they share. Specifically, our design goals were influenced by the intersection of projected augmented reality interface that is also enabled with kinetic I/O.

We summarize below our interaction design principles.

<i>Natural Interaction</i>	Support natural and direct interaction for projected augmented reality interface. Support heterogeneous input modalities
<i>Both Hands are Free</i>	Support immersive spatial augmented reality, namely users should be able to interact with both hands without an intermediate device
<i>No Context Switch</i>	Users do not need to perceive the augmented reality experience through a mediating display. Digital content is directly superimposed on the physical environment
<i>Kinetic / Dynamic</i>	Enable steerable, kinetic interfaces that extend the reach of user interfaces. Support relocating, reorienting and resizing of the projected display
<i>Kinetic / Animatronics</i>	Enable the use of animatronics as a feedback mechanism for user interfaces. It also refers to the capability to track a user or an object in the interaction space
<i>Object Augmentation</i>	Enable the detection, tracking and augmentation of objects using top-projection
<i>JITAP</i>	Enable Just-in-Time-and-Place interactions based on application and user context

The sections below describe in more detail the principles above, and provide further insights into the actual interaction techniques we developed.

Kinetic Input and Output

Actuated Interfaces

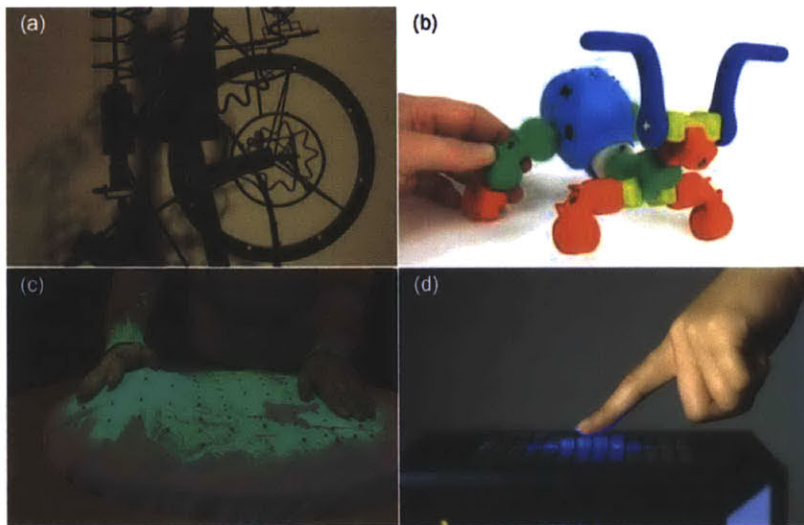
Humans have been developing mechanical motion producing systems for centuries. Examples date as early as actuated set decoration in Greek theater. Nowadays, mechanical actuated toys and robots are very common.

Poupyrev et al defined *Actuated Interfaces* as an interfaces in which physical components move in a way that can be detected by the user [105]. They also specified that such interfaces could employ changes in spatial position of objects, including orientation and position, as well as changes in speed or direction of motion.

The discussion in this section deals with Kinetic I/O interfaces, a subset of the general definition of Actuated Interfaces.

Kinetic I/O

Kinetic interfaces are currently in a very embryonic stage. Although various researchers laid important groundwork for kinetic-interactive systems [106], it is still hard to outline clear interaction design guidelines for Kinetic interfaces, specifically when kinetics meets augmented reality.

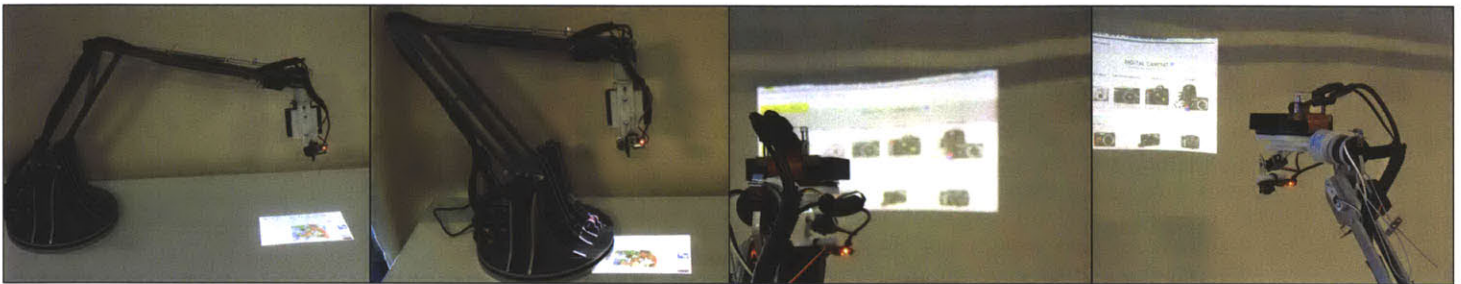


Examples of kinetic interfaces: (a) The Dream, kinetic sculpture by Arthur Ganson (b) Topobo by Hayes Raffle and Amanda Parkes (c) Relief by Daniel Leithinger (d) Lumen by Ivan Poupyrev, photographs by Makoto Fujii, courtesy of AXIS Magazine.

For the purpose of this thesis work, we use the term Kinetic I/O in direct relation to projected interactive interfaces, and in chapter 2 we distinguished the differences between such systems and steerable

projector-camera. We defined kinetic interfaces as those that have DOFs of their own, this is also the reason that such systems have a new interaction paradigm we call Kinetic I/O. However there are examples for Kinetic I/O systems that do not involve projection or displays directly. One such example is Salisbury Phantom-Based Haptic Interaction with Virtual Objects [107].

The first property of kinetic I/O is simply that interfaces can move, normally in multiple degrees of freedom. As we described in chapter 3, the LuminAR Arms have 4 degrees of freedom that allow to dynamically manipulate the vertical and horizontal position and orientation of the LuminAR bulb. This allows the system to dynamically relocate interfaces easily within the workspace, and increases its interaction vocabulary.



Exploring concepts of kinetic I/O: LuminAR Aluminum is used to alternate the projected display between the wall and the tabletop.

From the user's perspective, Kinetic I/O allows natural interaction using hand gestures to position and manipulate the projected display properties and most importantly the actual content. Based on that general property we propose in the next section an extension to classic *Multi-touch* interfaces; we call this approach *Dynamic Multi-touch*.

Kinetic I/O can also make use of motion to communicate and engage users. Humans can respond well to kinesthetic stimulation, and physical motion can be designed to be subtly expressive and support interaction [108]. Future work on Kinetic I/O may also benefit from adapting concepts like Hoffman's Fluency [109], which exceed the scope of this thesis.

Kinetic I/O holds great potential for projected augmented reality interfaces. This thesis work explores this domain specifically, proposing to enhance such interactive vision-based systems. The reason for that lies in the fact that the vast majority of computer vision based systems are static in nature; this fact limits the viewpoint of the sensor. Kinetic systems are able to dynamically change their perspective; they can track an object or a user spatially and adjust accordingly, specifically since such systems are geometrically calibrated and aware of their 3D position in space, as in the case for LuminAR. These properties can be used to create novel user experiences that have real advantages. For example, imagine an interface that requires object detection. In many cases the quality of the detection is directly influenced by the ambient light conditions, shadows and occlusions. With Kinetic I/O the system can recognize such conditions and respond by shifting the sensor

viewpoint in order to improve the overall detection score. This capability simply does not exist in static systems, and normally would require a user to manually reposition the object detected.

Finally, using relevant sensing techniques, it is possible for a Kinetic I/O device to respond to a manual back-driving input from the user. Manual manipulation is important since it provides natural means for a user to interact with a system, this is specifically important when interfaces are embedded in everyday objects. It is also important as it provides the system spatial input and context that could be useful for interaction purposes.

Dynamic Multi-touch

Multi-touch refers to the interaction techniques that support direct hands and fingers simultaneous inputs to control computer application graphic content. Multi-touch enabled devices include computer displays, known as “touch screens”, tablet computers and also projected touch displays. Touch screen technology is now also in extensive use in mobile devices.

Early examples of multi-touch devices date to the 1980s, when pioneers of the field like Bill Buxton at the University of Toronto developed a multi-touch tablet capable of sensing multiple points of contact [110]. Buxton also provides a good review of the history of multi-touch systems [59]. As multi-touch systems evolved, different hardware solutions were developed, as well as algorithms for finger tracking and gesture recognition. Westerman provides an excellent review in his Ph.D. dissertation [111]. Works like the Bid Screen and SixthSense, represent recent research trends that combine 3D gestures with multi-touch [29], [112].

The main contribution in terms of interaction techniques of this thesis lies in the concept of Dynamic Multi-touch. Dynamic Multi-touch is an extension for the classic gestures vocabulary of multi-touch that takes advantage of a projected kinetic I/O system. Dynamic Multi-touch systems utilize actuated DOFs of the projected touch screen display to support real-time relocating, reorienting and resizing of the projected display.

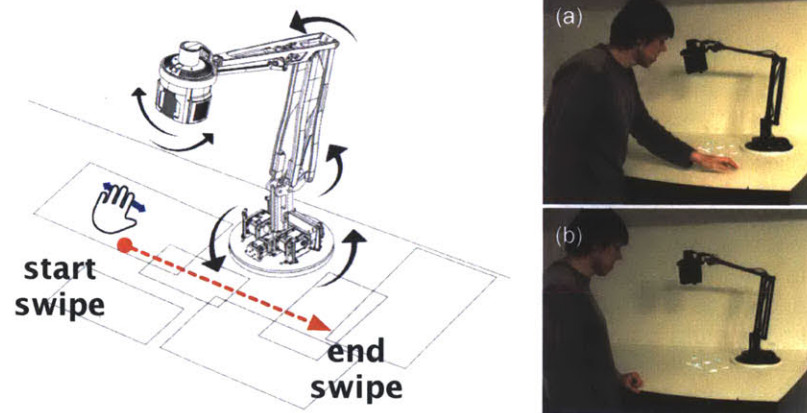
Dynamic Multi-touch tries to extend the spatial limits of the classic screen bounded interface by allowing it to move, it also addresses the interaction space above the display. In our work we have prototyped several gestures that explore the Dynamic Multi-touch concept. We provide details in the sections that follow.

Dynamic Multi-touch Gestures

The Dynamic Multi-touch gestures we describe in this section were initially explored and prototyped using the basic capabilities of the LuXor Vision server modules (see chapter 3 – LuminAR)

Position-Swipe

One of the basic advantages of dynamic Multi-touch is the ability to position the display. We have implemented a *position-swipe* gesture that allows a user to position the projected display using a directional long swipe motion from a source projection area to a destination projection area. To perform this gesture the user simply selects a start swipe position and begins to move his hand in a steady direction: either right to left, left to right, top to bottom, or bottom to top. The system detects the trajectory of the swipe. The swipe is complete if the user moves his hand away from the viewpoint of LuminAR or if he holds his hand steady under the lamp. The swipe can take advantages of all of the available DOFs of LuminAR. We have used the position-swipe gesture to implement features of the Augmented Desktop applications that we describe in the next chapter.

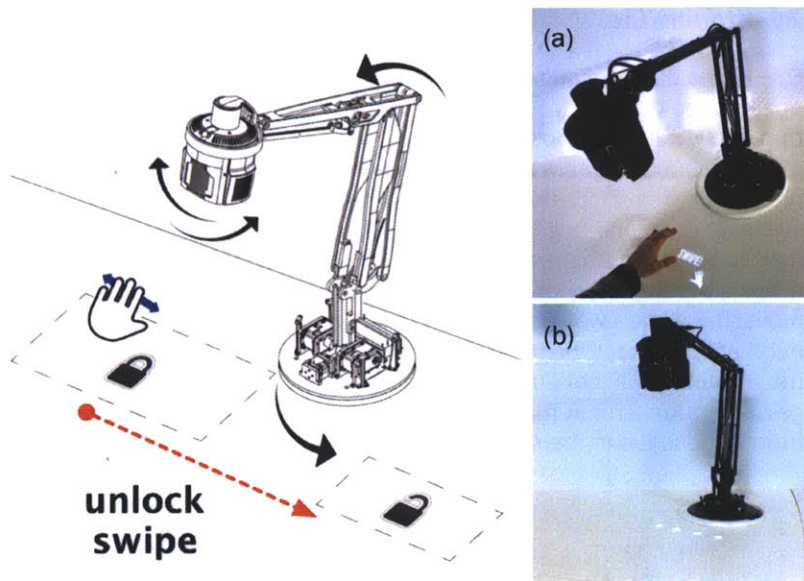


Dynamic Multi-touch: Position-Swipe gesture. (a) A user starts the swipe gesture and performs a long directional swipe (b) after the user removes his hand the arm follows his swipe trajectory.

Swipe-Unlock

Modern operating systems, normally implement a login screen that serves as an entry point to the desktop metaphor. This holds for PCs as well as to mobile information devices (e.g. smartphones and tablets).

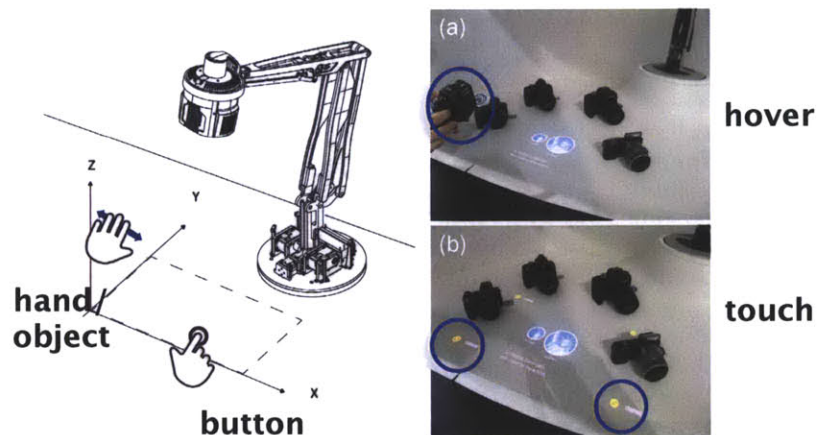
The *swipe-unlock* gesture was designed as an interaction entry point gesture. It builds directly on the Swipe-Position gesture we presented above. The gesture makes use of the animatronic capabilities of the LuminAR system, once the unlock event is registered, the arm can be programmed to perform a motion sequence to alert the user of success or failure of the unlock swipe. When the user swipes his hand under the system, the system responds with a subtle motion combined with unlocking of the projected screen saver.



Dynamic Multi-touch: Swipe-Unlock gesture. (a) A user starts the unlock swipe gesture and preforms a long directional swipe (b) if the unlock swipe is correctly registered an animatronic sequence is activated and the systems' main menu is displayed.

Touch-Hover

In LuminAR's case, classic multi-touch gestures such as button press and swipe are supported using vision based techniques that rely on the homography between the projected display and the camera viewpoint.



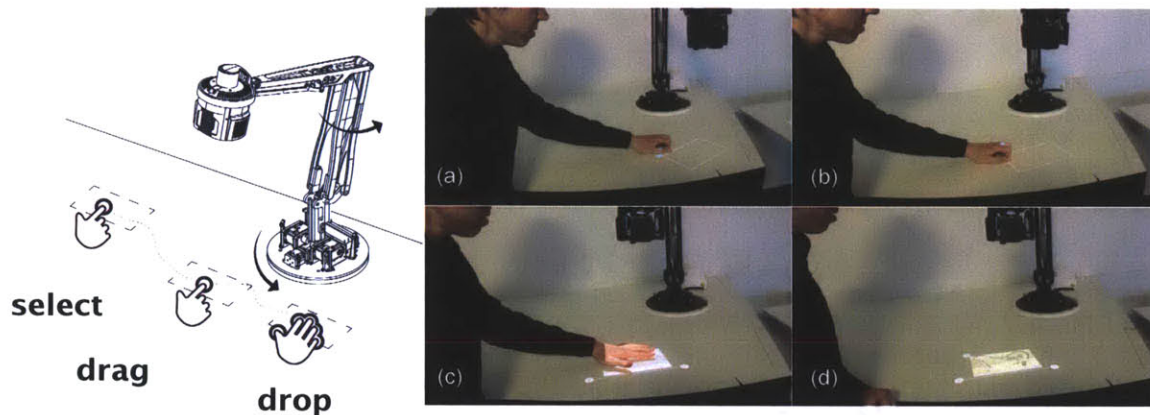
Dynamic Multi-touch: Touch-Hover gesture. (a) A user picks up an object, in this case a digital camera. The interaction with the object above the surface triggers contextual JITAP interface (b) that includes projected touchable buttons.

The touch-hover interaction technique uses the same mechanism. It combines object detection or a gesture that is performed above the surface with standard touch interaction that is carried out on the surface. We have used this technique to implement a specific scenario

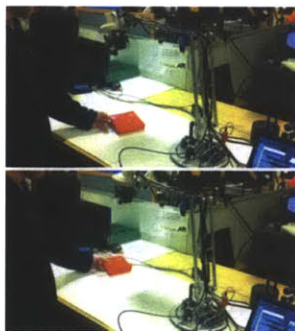
in the Augmented Product Counter retail application (see Chapter 5 – Applications). In this use-case the user holds physical object (e.g. digital camera) above the projection surface, once the object omission from the tabletop is detected, the system provides contextual JITAP user interface. This interface also includes touchable buttons. Conceptually we are combining between interaction with a physical object and digital interfaces. This general concept can be further expanded to facilitate more complex combinations that can make use of the additional Z-axis.

Track Drag & Drop

When we use traditional GUI desktop systems, we take it for granted that we can drag and drop content. We have developed a kinetic-physical drag and drop gesture.



Dynamic Multi-touch: Track Drag & Drop gesture (a) A user selects a virtual object by pressing a button, the virtual object is highlighted with a simple border to simplify detection and tracking (b) the user starts a drag motion using a closed fist, the LuminAR arm tracks his hand (c) when the users decided on a desired drop location he opens his hand and hold its position for about a second (d) the system detects the drop gesture and records the new position for the virtual object.



LuminAR can also track objects; in this example it is augmenting a red box that serves as a tangible email inbox.

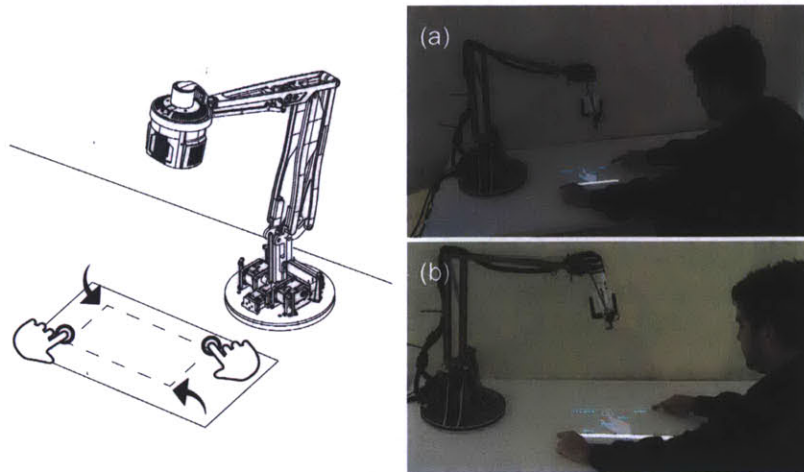
The user first selects a virtual object window using a button press or a select gesture; both can be implemented using the LuXor Vision Server modules. Once a selection was made, LuminAR tracks the user hand. We have explored different gestures and found that a *fist gesture* is somewhat natural to use as an indicator for the system to track the users' hand. When the desired location is reached, the user can extend the fist to an *open hand gesture* to drop the content in the new desired position.

We have used this technique to implement the Kinetic Desktop application we describe in the next chapter. The same technique can also be expanded to a kinetic copy and paste gesture.

Dynamic Resize/Zoom

Multi-touch systems typically enable multiple DOFs of interaction based on the number of detected fingers. But detecting multiple DOFs is not enough; touch display systems also need to support meaningful gestures. Doing so involves sensing a range of touch beyond simple

touch-points. It also involves direction, angle-of approach and vector information [59].



Dynamic Multi-touch: Dynamic Resize/Zoom gesture (a) a user presses down two corners of the projected display, triggering a resize gesture (b) as he swipes away from corners, the arm moves up in proportion to the distance his fingers moved from the original location, causing the projected display to grow in size.

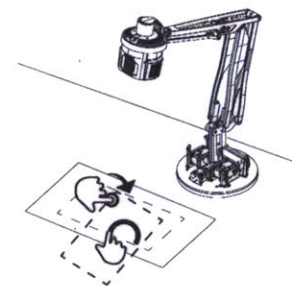
The *dynamic resize-zoom* gesture adds additional DOFs to the arsenal of DOFs multi-touch systems already have. But not in terms of input (i.e. not additional sensing) but in terms of display configuration output. The gestures below utilize the DOF of the LuminAR Arm or Spotlight to dynamically and close to real-time change the geometry, orientation, size and the position of the projected display. It is therefore one of the basic interaction techniques of kinetic I/O as we define it in this thesis.

The dynamic resize operation works as follows: when a user is pressing two corners of the projected content, and generating a motion vector. The vector 2D orientation and scale determine the physical position and size of the projected display. This technique can be used to resize and reposition the entire display, or to zoom on a specific section of it.

Dynamic Rotate

Building on the principle of the *dynamic resize-zoom* gesture, we can design an additional gesture that would support a common orientation change operation that is very common and useful. Unfortunately, we did not have time to fully implement this gesture, but we include its design here as part of the Dynamic Multi-touch possible future gestures.

This gesture starts when a user is pressing down on a pivot point with one hand, while using his other hand to perform an arc like gesture on the surface. The direction of the arc determines the rotation direction desired. The notion of *pivot-finger* based gestures should be explored further and extended with gestures that support content scaling, navigation and positional directions.



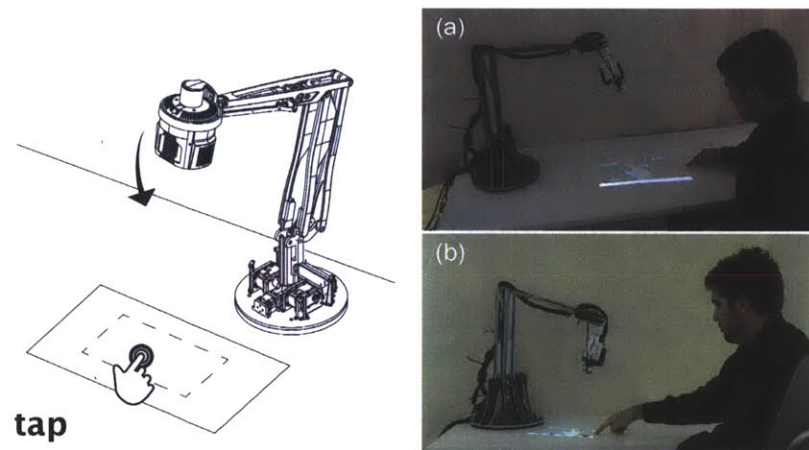
Dynamic Multi-touch: Dynamic rotate gesture design

Tap-Focus

The tap-focus is another LuminAR position-setting gesture, designed to provide the user with a method to position LuminAR. It is a simple gesture, requiring only a tap or a double-tap (if needed) to cause a selection of an area-of-interest that is then magnified.

Double taps can be distinguished from simple button presses using application logic. The LuXor application framework can define software timers and events that can be used to develop application that respond to the different tap events (i.e. double-tap, tap and long-tap).

Optionally, this gesture could be chained with additional taps that would allow a user to easily choose between two zoom levels with just a single tap. This gesture also provides clear and direct kinesthetic feedback, as the LuminAR arm would move according to the user's desired zoom level up or down.



Dynamic Multi-touch: Tap-Focus gesture (a) double taps a point of interest on the projected surface (b) the system responds with focusing the projected display around the location of the tap.

Conclusion of Early Explorations

In this section we have introduced the concepts of Dynamic Multi-touch. We have also included details of the initial exploration we have conducted in our efforts to design novel gestures that use kinetics.

In the informal user testing we have performed, a general pattern of behaviors emerged. Initially, users expected the system to behave like a common touch screen. We can attribute this to the strong presence in 2011 of mass-market consumer electronics that use touch screens. However, and sometime to our great surprise, users were very comfortable continuing to interact with LuminAR after they discovered the touch screen can actually move around the workspace. The majority of our users easily picked up the gestures we described here. Many reported it "felt very natural to use". However, some of users did not respond so well to the fact that a moving robotic arm might potentially

hit them during the interaction process. Obviously this is a topic of further research.

In addition to the gestures that we explored, and based on the feedback we received from our test users, it is clear that additional gestures should be designed to complete the *Dynamic Multi-touch* grammar. The list below contains some ideas for such future gestures:

- Support high fidelity hover gestures that accurately return X, Y, Z coordinates of the arm, hand, and fingers positions.
- Support dynamic hand gestures training and detection (e.g. open-hand, thumb-up, thumb-down etc.).
- Support hover-pinching gestures. Such gestures use a pinch gesture in arbitrary Z height above the projection surface. These types of gestures can facilitate object interaction.
- Support finger tracking in all Z-levels of the interaction space.

The work in this area is still preliminary, and we are in the process of evaluating the merits of this interface formally in the near future. However, our initial results show promising potential that could be exploited in the near future, when depth sensing hardware becomes ubiquitous and small enough.

Just-in-Time-and-Place Interactions

Context-aware interfaces hold great promise for transforming the utility of computing. They encompass the capabilities to detect and react to changes in state of the environment. Without it, computer systems are static and require human-user to initiate and manage all interactions. Understanding context allows a system to respond to a specific user or environmental state accordingly.

Just-in-Time (JIT) interactions are a specific branch of context-aware computing that attempt to enable computers with contextual knowledge to offer relevant information when and where we need it. However 'where' in the definition of JIT interaction refers to how we use computers today, namely via display centric devices and interactions. This means that 'where' is actually on a computer screen window or via a mobile phone's push notification.

LuminAR enables an extension to the classic Just-in-Time interface definition. We are proposing *Just-in-Time-and-Place (JITAP)* interfaces. The notion of 'Place' in our definition refers to a physical location. It is possible for the system to define and recall several locations that embed specific projected information as defined by the user.

For example, LuminAR can be programmed to save and retrieve physical locations for different projected applications. Applications can then be invoked in the specific location when they become relevant, for example: an email application can appear in a fixed location whenever a new message is received.



Examples of JITAP interfaces in the Augmented Product Counter (APC) retail applications: (1) when the camera is detected we can project a product manual page next to it.



(2) Cameras are augmented with price information

Moreover, the system can utilize its animatronics capacity to alert the user. Naturally, traditional UI modalities such as sound and graphics can also be combined to fully complete the experience. The result is a unique actuated ambient interaction.

In chapter 5, we describe how this interaction method was put to work in the case of the Augmented Product Counter and the Augmented desktop applications.

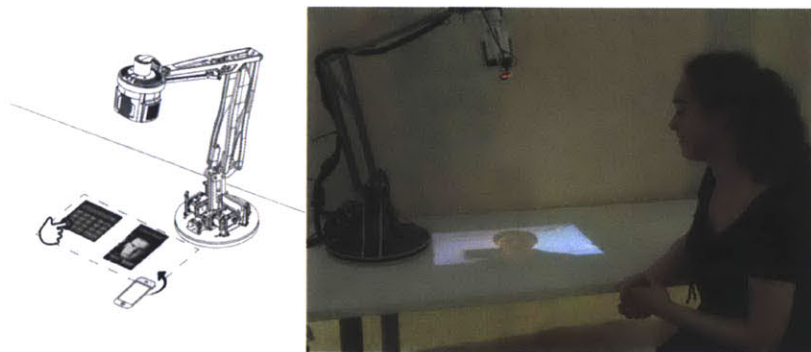
Device Integration

The LuminAR bulb is a wireless computer. It is capable of communicating with other devices in its vicinity, allowing for interaction to extend across device modalities. We have explored cross-interaction scenarios between multiple LuminAR bulbs, mobile devices and laptop computers.

Digital Glue Device

An easy metaphor to think about cross-device integration is to think of LuminAR as a “glue device”. It does not attempt to render laptops or mobile phones obsolete, but rather amplifies and complements their use.

According to context, the system can suggest and facilitate data transfer across devices. As an example consider an application where the user is able to physically gesture to the lamp to transfer a document that is currently open on his laptop to the surface next to his screen, yet flat on the desk. This can serve as a virtual stack of documents that is pending, waiting for the user inputs and manipulation.



LuminAR as a “glue device”

For example, consider the case when LuminAR detects a smartphone in the near vicinity. The system can then initiate a wireless data exchange session. The mobile device could then stream an application to the LuminAR device. In the example below we show a calculator application projected on the tabletop. If a call comes in in this mode, the incoming call event can also be projected next to the application while the

calculator application is still running. Clearly in some cases, it would be desirable to have mobile device content displayed on a large screen.

Data Sharing

The basic notion we have explored is sharing data and context between LuminAR bulbs. In this case we can program the system to form a network between LuminAR bulbs. Applications can then share state data and respond with relevant application content and actuation. A good example of this behavior is described in the next chapter when we discuss the Spotlight virtual retail expert application.

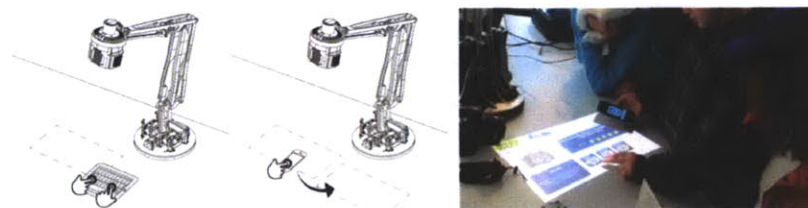
Next, we can clearly identify merit in sharing data captured by the LuminAR bulb between a mobile phone and a laptop, and even between bulbs. Since the bulb software stack uses web-based folders, it is easy to accomplish simply by sharing URLs.

This opens the door for integration with any web application that is relevant for the specific data captured. For example, we can integrate a publishing feature to the Scan Application (see Chapter 5 – Applications), scanned images can be automatically uploaded to an online document services (e.g. Evernote.com [113]).

User Interface Leeching

Not all interfaces were made equal, and not all application scenarios require the same input modalities. This was the guiding principle of a technique we call 'User Interface Leeching'.

Mobile devices and tablets have great input capabilities, and wireless keyboards are great for typing. Since LuminAR is simply a computer it is possible to leech on such input devices and have them function within the context of a LuminAR application.



User Interface Leeching

We have tested such an example of such interaction using a touch enabled smart phone. We used the phone's user interface as a handheld controller for LuminAR. Flipping pages back and forth on the mobile phone touch screen caused content to flick on LuminAR's projected display accordingly.

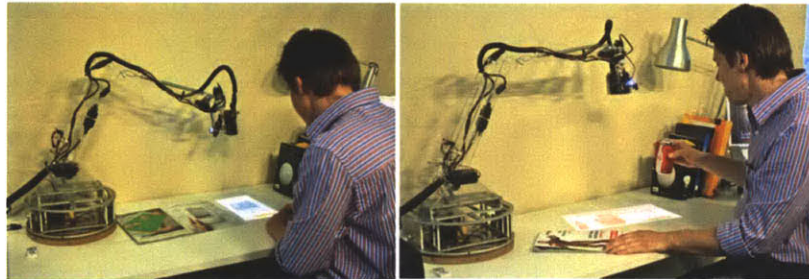
Object Augmentation

In 1999, Jun Rekimoto et al, presented their work on Augmented Surfaces [33]. They contributed several new interaction techniques, among them the concept of object auras. They focused on augmenting physical everyday objects with digital information. Inspired by this work and many others that followed, the LuminAR user interface, vision and tracking abilities enable it to generally augment objects that are in view.

Objects can serve as triggers for the actual desired interactions. Early on in our work we explored how different objects serve as triggers for different augmented content display. For example a printed magazine advertisement could be detected and linked to a special online based video widget that contains further information about the product and an interface to interact with the content, i.e. save as favorite, send to a friend or even order the product.

We also explored this approach in our Augmented Product Counter application, where we augmented cameras with price and feature information. We elaborate further on this example in the next chapter.

Interactions based on physical object augmentation also open the door for many new object-based applications. Detecting and tracking physical objects can help produce valuable metrics, providing insights on usage patterns and user behaviors. This would be desirable for many real-world applications.



Early object augmentation explorations using LuminAR Optimus. The lamp detects objects like a magazine or a can of soda using simple fiducial markers, once detected the objects are augmented with relevant web content.

In conclusion, it is possible to outline how traditional user interfaces map to an augmented interfaces using physical objects. In the list below we describe some examples of possible future augmented interaction:

- Interactions such as **search, bookmarking, physical copy and paste and annotations** of printed material (note that this could also work for digital inputs)
- **Physical hyperlinking:** Objects and gestures can invoke web access or email composition. For example if a business card is placed under the LuminAR Lamp

it can activate the address book application automatically

- **Integrating with passive I/O devices:** For example, if a simple pen is registered by the LuminAR Lamp as the invoking object for a note taking application

5 Applications

To complement our design and engineering of the LuminAR system, we were constantly and in parallel engaged in creating software applications that test the system, its technical function and overall usability.

We had two areas of focus for our application development efforts; the first was an exploration into the domain of *Augmented Desktop applications*. We created several scenarios that utilize LuminAR in a desktop setting, mainly for information/work related interactions. The second domain we focused on was *Augmented Retail*. We designed a set of novel experiences that use LuminAR in a retail setting; specifically we designed an *Augmented Product Counter*.

Augmented Desktop

Reading, writing and interacting with standard computers are the most commonplace tasks for desktops work, and given the abundance of previous work (which we detailed in chapter 2), it was natural to explore this domain with our system as well.

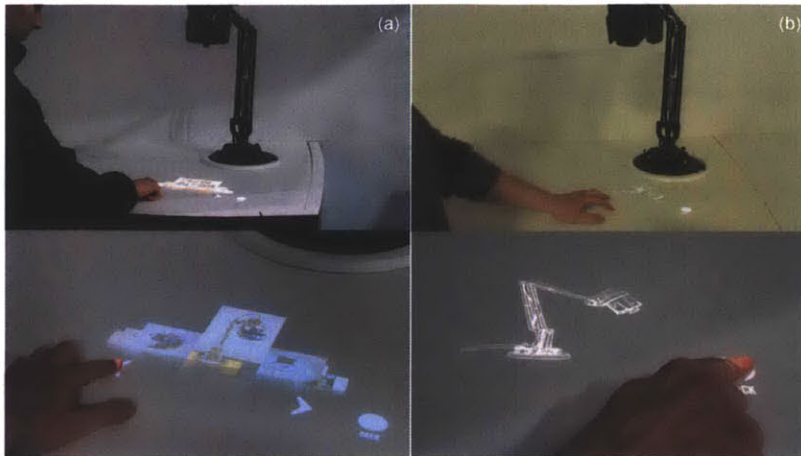
Part of the motivation for this choice also lies in the fact that LuminAR is unique in form factor, as it is embedded in a desk lamp. It is therefore a form of a digital computer that on the one hand is embedded in your space and on the other hand does not take up “desktop real-estate” like laptop computers do for example.

We first focused on familiar interactions with digital media and information, developing projected touch-enabled widgets. However, immediately after exploring standard use cases we shifted our focus to scenarios that blend modalities, taking advantage of kinetics, top-projection and object augmentations as well as LuminAR’s networking capabilities. In this section we provide details of the features we have developed.

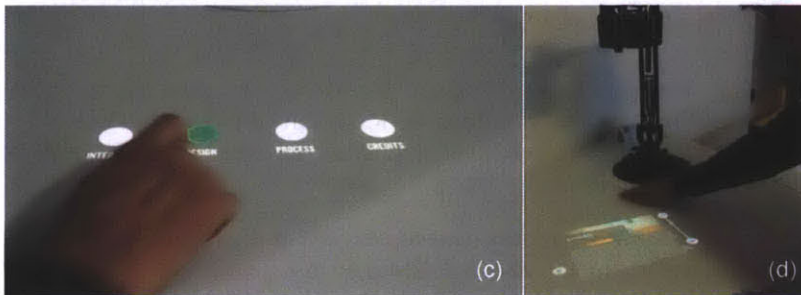
Projected Widgets

LuminAR’s basic use case is to provide an interactive augmented space. To demonstrate this functionality we focused initially on developing a set of general purpose projected widgets capable of performing everyday tasks. We created a picture browsing widget (using a similar technique to Apple’s OS X Cover Flow feature), a media player and a scrolling text widget. These widgets also serve as the building blocks for the rest of the LuminAR applications.

As all other LuminAR applications, these widgets are web-based, and designed to incorporate text, video and images. The interaction with the widgets was primarily based on touch events, but also includes hand gestures. For example a user can scroll a large amount of text by swiping his hand under the lamp.



Augmented Desktop Projected Widgets (a) Cover flow widget (b) Video player widget



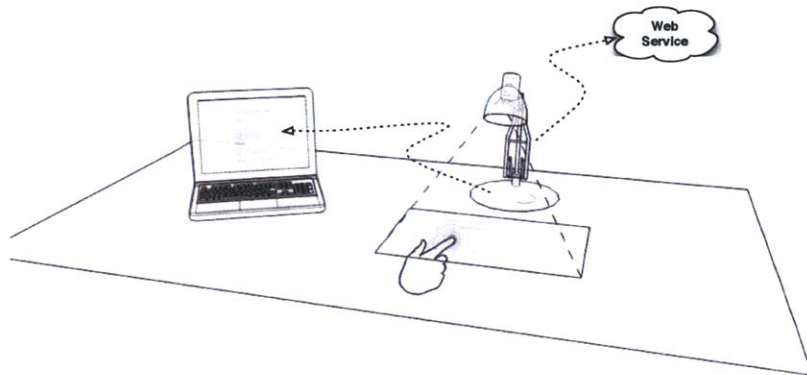
(c) Projected touch relocatable menu (d) Scroll text widget that uses hand gestures to scroll large amount of text.

We envision such projected widgets used in standard desktop environments, working in conjunction with a PC. In such cases, the widgets can be used to enhance an existing software interface or serve as an additional contextual display for information. But not less interesting is the case when LuminAR is installed as a standalone object without a computer. We can imagine having a LuminAR bulb installed in a kitchen and used to augment the countertop.

Following this logic, in one of our early experiments, we explored a concept of LuminAR as a reading lamp. It was used to augment a magazine, enabling digital-physical cross-media experiences. In our example a physical printed advertisement invokes a website that allows a user to watch videos of the product.

Scan Application

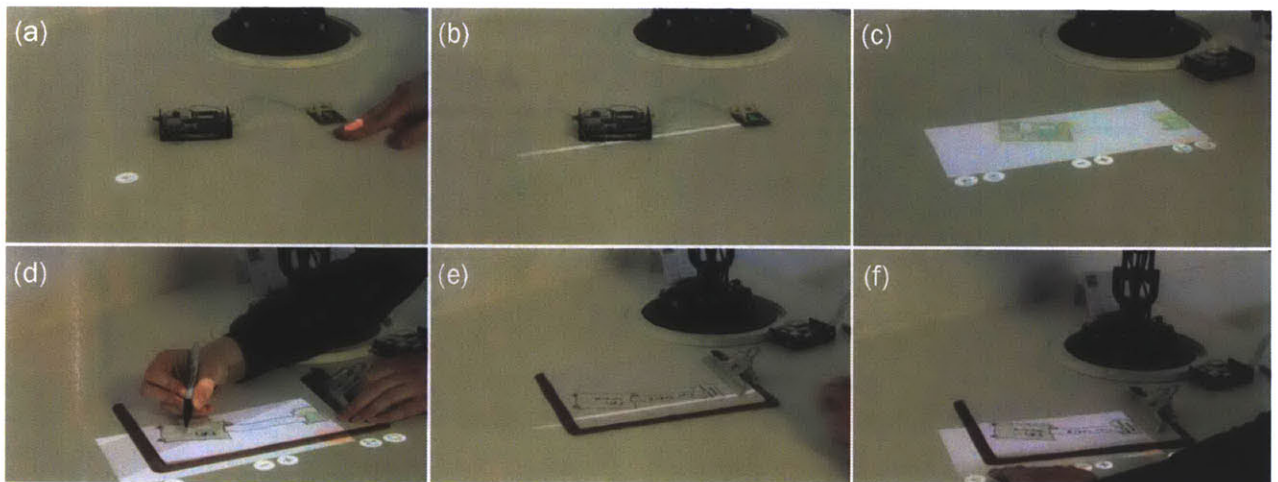
The LuminAR Scan application allows users to capture images of objects and projected images on the tabletop. It is designed to provide an instantaneous scan function that does not involve a dedicated scanner or a relatively complex sync with a digital camera.



Concept design for the Scan Application

Using a simple interface a user can place the object under the system and execute a scan. The interface also supports zoom functionality. Once an image is captured the user can resize the result, and project the result on the desktop.

This enables the user to place a different object, and scan again. This interaction design allows the composition of complex images based on multiple scans. We call this technique *Scan-Project-Rescan*.



Augmented desktop scan application: (a) an object is placed under the LuminAR Lamp, when a user hits the 'scan' button (b) the object is scanned, (c) the user can adjust the result using zoom controls, (d) the image can be projected to a paper and (e) rescanned into the system. (f) Finally the user can press the 'share' button to send the image to a web service or another LuminAR device.

Finally, the scan application allows for two different LuminAR systems to share the scanned content. We implemented this feature using a simple web-folder as a destination for posting scanned image results.

When a share request is executed, we simply point the destination LuminAR to the desired image URL. The Scan App is very simple example of how LuminAR can be used to support remote collaboration. We can imagine how LuminAR lamps can be deployed ...

The scan application we developed is a good example for the future of augmented collaborative interfaces. We can imagine how such features create new possibilities for remote communication by virtually sharing a physical desktop and objects while augmenting them with digital information in real-time.

Kinetic-Spatial Augmented Desktop

To fully explore the concept of Kinetic I/O we describe in chapter 4, we designed a novel type of an augmented desktop system that takes advantage of the LuminAR unique interaction techniques. We call this application the Kinetic-Spatial Augmented Desktop.

The application attempts to reclaim the desktop metaphor that was claimed for the digital desktop to a physical desktop. In other words, in our system digital content can be spatially located on an actual desktop thereby blending the physical and digital worlds more closely.

To explore this concept we implemented a location aware menu system. The interaction begins with a main menu entity that appears in an initial entry point location. When subsequent sub-menus are invoked, the projected display will move accordingly to location relevant to the specific submenu functionality. We can program the system to locate a menu according to context, the position of an object or the user's hands.

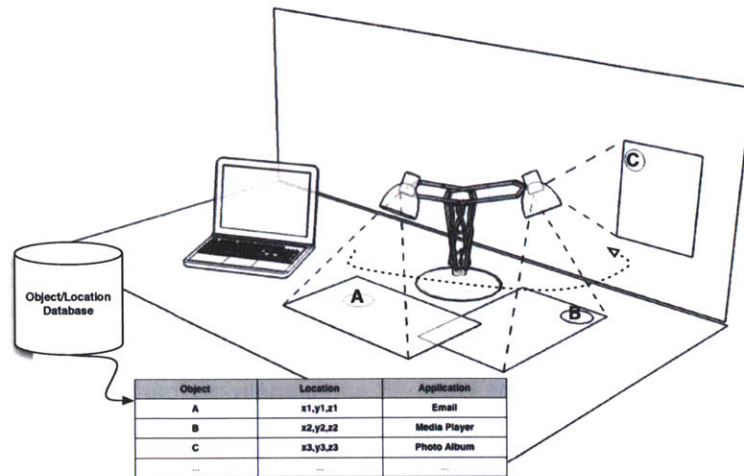


Location aware menu system; top-level menu is projected in the 'home' position. Subsequent sub-menus have their own location relative to the home position.

We used this feature to implement a conceptual demo application that showcases the different LuminAR projected widgets and kinetic demos applications, using our own system for this purpose.

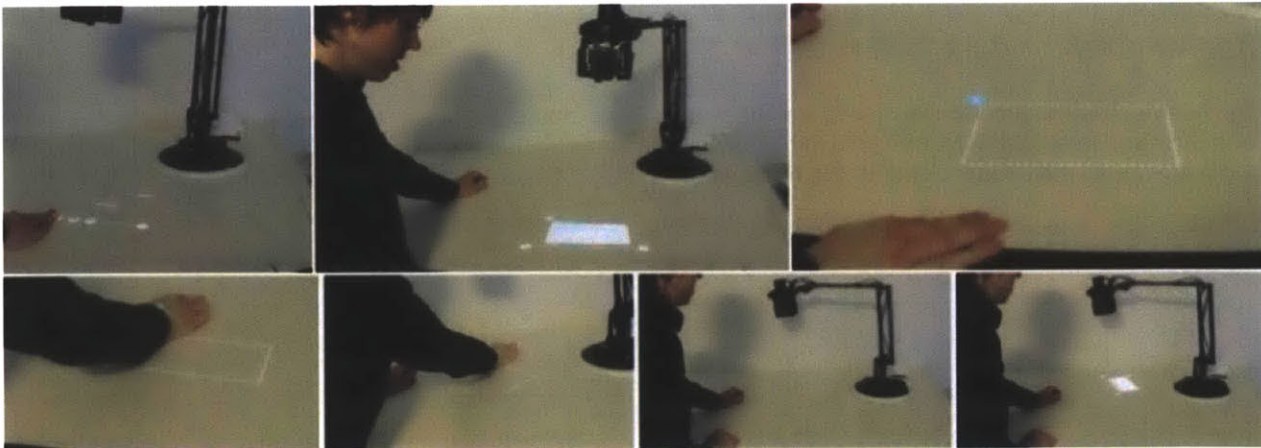
We also designed an interface that allows users to relocate specific widgets in the workspace. Our demo setup included different live web apps that streamed content from the web. We developed a weather

widget, a YouTube widget and a daily Twitter feed widget. Each widget has a different location assigned in the physical space.



Concept design for the kinetic desktop object/location pairing

The applications were arranged in a dock element, similar in principle to existing application dock bars that are very common in WIMP based operating systems (e.g. Mac OS X or Windows 7). The dock enabled the user to invoke widget and load them to the projected desktop. Once a widget is selected, its location information is retrieved, directing the LuminAR arm to the desired rendering location.



Kinetic desktop prototype; the user can select to move a widget (in this example we show live twitter feed widget) by pressing the 'move' button. Once the widget is selected the user can simply drag the widget frame to a new location in the workspace. The 'drop' can be detected by either removing the hand or detecting a change in the hand posture, for example, a 'fist' could be used to preform the 'drag' function, while an 'open hand' gesture can signal a 'drop' function.



Once a widget is located in its new position, the user can then select to activate a different widget. In this case the user selected a YouTube video widget. LuminAR serves to the stored location for the requested widget and displays it.

The user can then choose to relocate the application by pressing the move button. To implement the relocation function, we developed a drag and drop gesture. The user can drag the application to a desired new location using a drag gesture that is tracked by the system. The actual dragging involves the LuminAR arm actually performing visual-servoing while tracking. Once a desired location is reached, the user simply needs to hold this position for about a second to conceptually drop the application in the new location. Finally, we implemented a swipe-gesture that allows the user to use simple swipe gestures to position the projected display.

This exploration provides a glimpse of the potential for actuated interfaces. It builds on the notion that human cognition is spatial, and therefore kinetic enabled interfaces can possibly assist with tasks that involve information retrieval and recall. For example, future applications can support virtual piles of documents on a physical space stored in different locations.

Augmented Product Counter

The Augmented Product Counter (APC) was developed in collaboration with Intel and Best Buy. Intel provided initial background information for the project with their concept work "The Responsive Store" [114].



Intel's Responsive Store concept – augmented product counter (source: Intel)

The Need for New Retail Interfaces

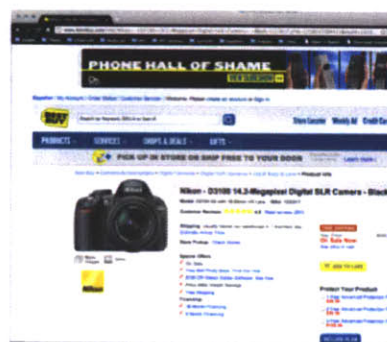
In the past ten years, first the web, and soon after mobile devices, generated two tidal waves that disrupted the traditional shopping experience. Shopping transformed into a social process of discovery, powered by tools for comparison, sharing and purchasing. Retailers

adopted technologies to remain relevant, using the new online channels. However, retailers need to find means to engage customers in physical brick and mortar stores. This concept was also previously explored by Sukaviriya et al [115].

The challenge that the APC project addresses is how could brick and mortar stores evolve to use interface technologies that allow them to remain relevant in an age of online based shopping.



- immediate fulfillment
- see, feel, try product
- human experience
- immersive experience



- information & expertise
- ratings & reviews
- personalized experience
- recommendations
- social networking

Brick and mortar retail experience vs. online shopping/e-commerce experience

Expert Driven Design

During the design process for APC, the author participated in two MIT Media Lab sponsor workshops led by Prof. Andy Lippman, which revolved around the topic “The Future of Retail”. The workshops addressed several aspects of possible solutions to the problem domain we described above including:

- **Making technology easier for the retailer** – Introduction of new inexpensive in-store interfaces that can easily integrate to the backend store management systems.
- **Helping the customer make their decision** through connectivity (be it their home or in the store) – Support the customer in the decision-making process during research at home and while browsing at the store.
- **Connecting with others** – Making a physical shopping experience social, fun and connected.
- **Engaging the customer** in a different way – Steering away from standard static product counter displays to dynamic digital solutions.
- **Customer telling** (product & customer insights for sales associates) – Facilitating two-way communication between a customer and sales associate; allowing customers to reach the most relevant sales person at any given time.

The workshops, and the ongoing work with Intel and Best Buy retail experts, helped us gain insights into the key challenges facing retailers today. In general, we found that retailers continue to struggle to stay relevant, and must continue and adopt new technologies to remain competitive.



Examples of new technologies for retail: (a) In-store applications from Target, together with Shopkick.com who provide a personal deal stream to the user's smart phone. (b) Twelpforce by Best Buy, an online technical help question & answer service based on Twitter. (c) In-store media kiosk for Olay at Wal-Mart.

We summarized their insights in the list below, which served as inputs to our design process:

- **Empower consumers:** The need to design an in-store customer shopping experience that is intuitive and self driven
- **Promote trust:** address the phenomenon of "marketization of information". Customers should be able to trust the retailer with information, so that they do not need to search online or verify the quality of the deal offered. One of the solutions is to fully democratize customer access to information on products in the store.
- **The mobile problem:** smartphones provide customers with means to independently search, compare and even buy while browsing products in a store. As a result, retailers lose business.
- **Costs of labor:** sales associates are the key differentiator for retailers, but they also represent a huge cost item. Customer experience is in fact a highly varied experience based on the quality of the sales associate. In addition, in stores with 1000s of products, associates are not real experts. So there is a need to empower associates and to streamline their work process.
- **Solutions vs. products:** In the stiff competition retailers face with online shopping, selling single products is not enough. For retailers to become profitable they need to sell multi-product packages. These are called "solutions". For example – a camera with accessories such as a memory card, a digital photo-frame *and* a subscription to an online service is considered a solution.

Field Study

In addition to the workshops, we conducted a field observation study of Best Buy locations. We scouted three locations: Downtown Boston, Cambridge and Minneapolis. In our study we tried to better understand the current physical setup of product display counters, specifically how products and product labeling is carried out. We also documented and observed user interaction with actual sales associates and interviewed them to better understand their work environments and how they engage customers.

The information we collected informed our design process directly, and eventually led us to decide to focus the Augmented Product Counter around digital cameras.



Field study of consumer electronics retail spaces was conducted in three different Best Buy locations, and included observation of consumer behavior and interviewing store sales associates.

Augmented Shopping Concept

To address the needs we discovered, we designed a LuminAR based “Augmented Product Counter”. Conceptually, any standard product counter can be transformed into an interactive surface, enabling shoppers to get detailed information and conduct research while they play with the real products. Users can also access the web to read unbiased reviews, compare pricing, learn about product features and talk to an expert who may be located remotely to get additional advice.

The Augmented Product Counter delivers a novel in-store shopping experience that combines live product interactions of physical environments and vast amount of information available on web in an engaging and interactive manner. By engaging shoppers in an intuitive, fun and efficient shopping experience and helping them make informed purchasing decision, this solution can potentially enable retailers to

differentiate themselves resulting in repeat shopper visits and improved profitability.



Intel's Responsive Store concept – virtual expert (source: Intel)

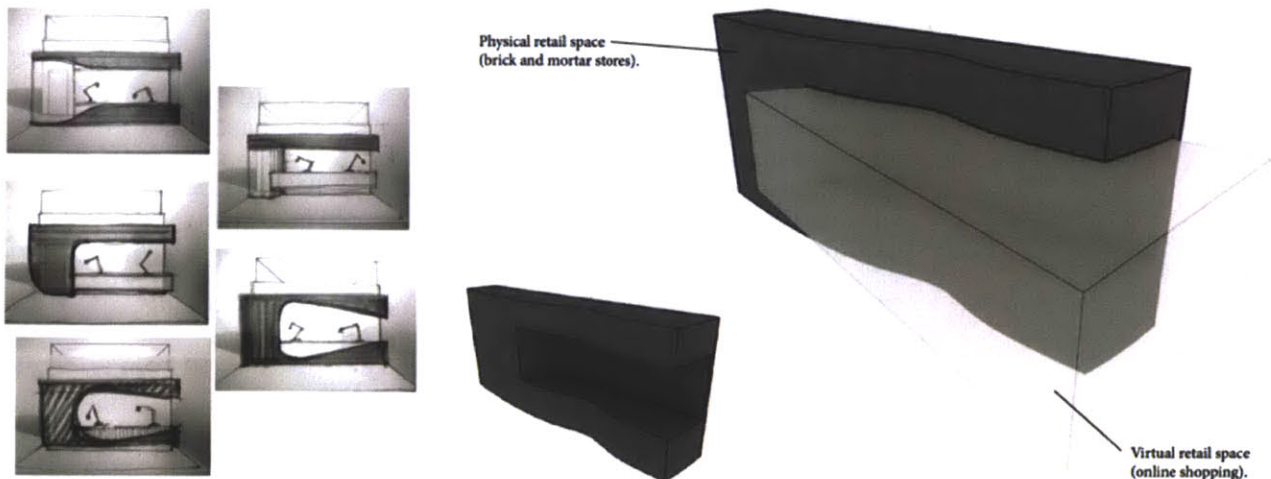
In the sections that follow we delve into the design process, use case scenarios and offer implementation details of the Augmented Product Counter.

Design of a Product Counter

The Augmented Product Counter was designed originally as part of the Intel Connected Store booth at the National Retail Federation Conference 2011 in NYC. We provide more details of this live demonstration in chapter 6.

Concept

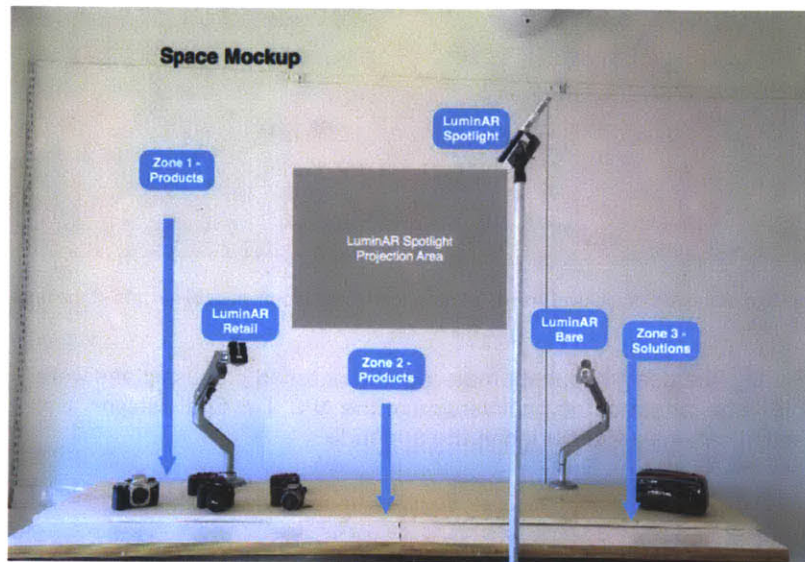
Our design was inspired by the analogy of two intersecting elements,



Concept design for the Augmented Product Counter (sketches by Jason Robinson and Yoav Rechtes)

one virtual and the other physical. The result provided the design language for the entire counter.

The design concept had strong horizontal proportions, maximizing horizontal space for projection surface purposes. To come up with the required setup parameters such as dimensions, location of the LuminAR Spotlight, ambient light management, we created a mockup space and conducted several projection mock-up tests.



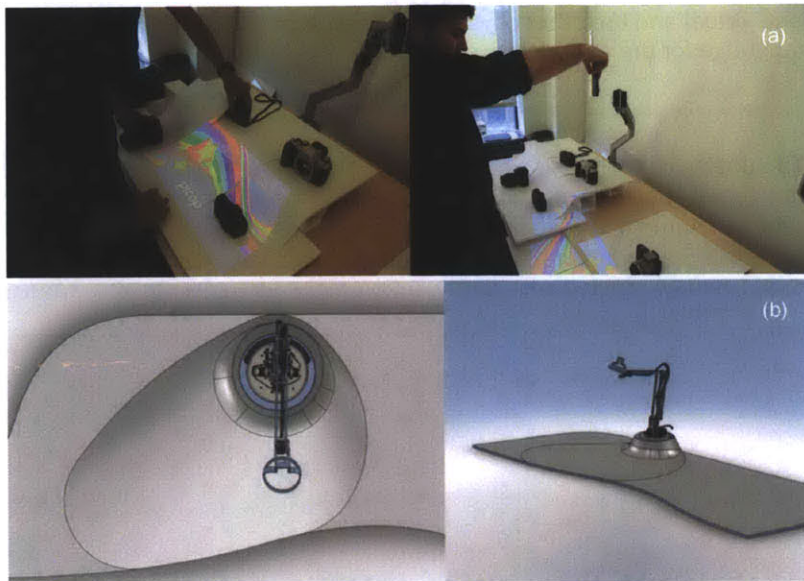
Augmented Product Counter - space mockup design with different interaction zones.

The countertop was divided into three zones:

- **Product display zone:** where all physical products are displayed
- **Interaction zone:** where the user can interact with a specific product
- **Spotlight zone:** a vertical projection space used for the virtual expert session

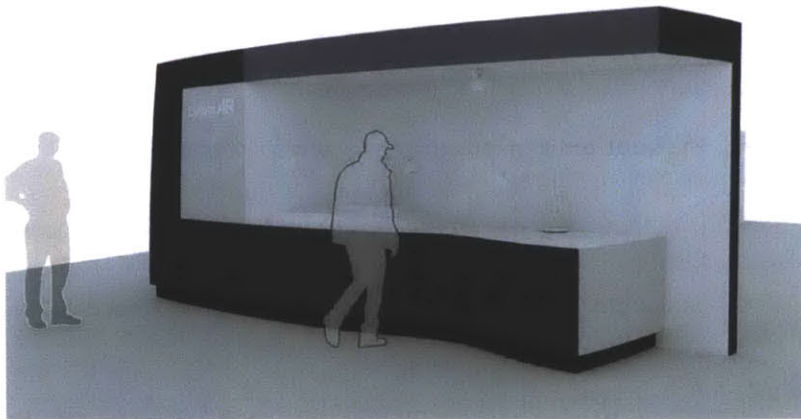
Multi-level Insert

To support the display and augmentation of multiple products, and to allow LuminAR Retail to pivot between the different zones, we designed a multi-level insert element. The insert could accommodate all five cameras on the counter and provided physical soft transitions between the different projection surfaces. The insert was CNC machined, and to arrive at its final shape several tests and designs were carried out.



Design of the APC multilevel insert: (a) early foam core prototypes (b) renders of the final design

Finally, the design concept matured and detailed process plans were made to construct the final version of the APC. The final design specifications are included in the appendix.

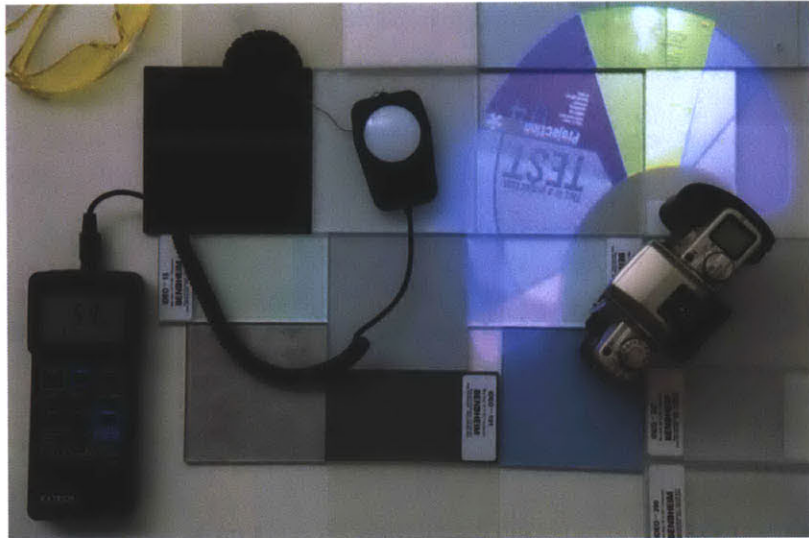


Augmented Product Counter final configuration

Projection Surface Materials

We explored different materials to test their application as a valid projection surface for APC. We were specifically interested in various properties of glass, acrylic and laminates. Clearly, material parameters such as thickness finish and color impact the quality of the projection. In our experiments we discovered that matte laminates provided the

crispiest images. Reflective and back treated materials had a nice result as well, but with a reduced image quality that blurred with increased thickness. Projection reflective paints are also a good option but require application and are naturally more expensive.



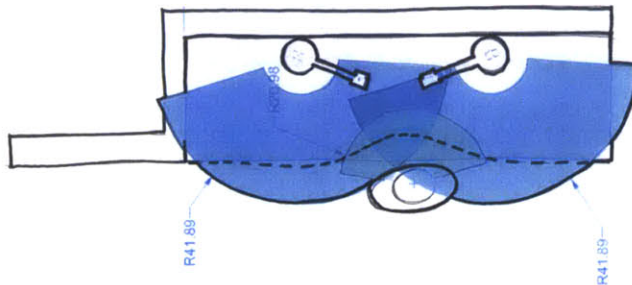
Testing projection materials for the APC counter-top

Interaction Design

This section covers key issues we considered in the interaction design process for the Augmented Product Counter. Overall, both the design and the implementation processes for the APC were highly iterative. Many of the design decision we made came about only after several attempts at prototyping. The documentation and conclusions we present below, can potentially inform similar design efforts for projected augmented reality interfaces in domains other than retail.

Understanding the Interaction Space

Early in the design process it was important to understand what the physical constraints were we had to take into account while designing the projected GUI for APC. To accomplish this, we used several mockup test projections and made measurements that informed our design process.



Work envelope sketches for APC

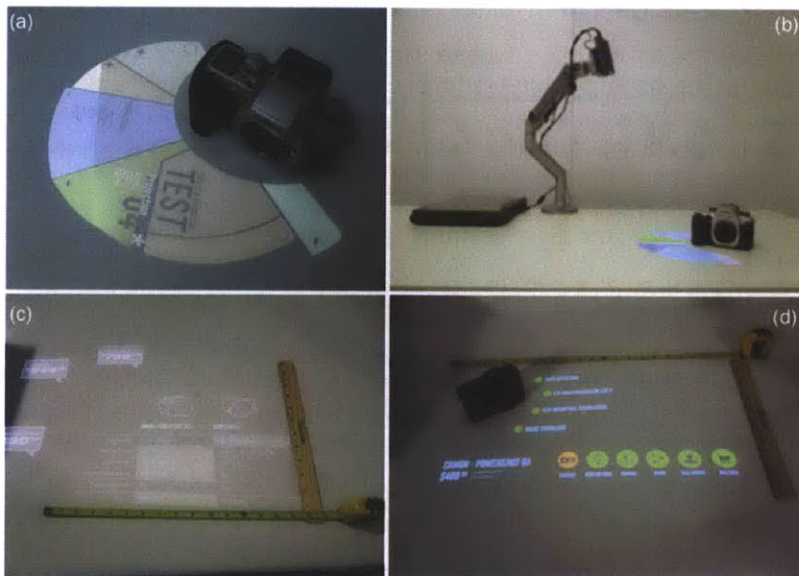
One of the key metrics that was crucial to define for the UI design to complete was the operational envelope of the LuminAR Retail arm in relation to the user. We accounted for parameters like user reach, distance between products, projection angles etc. To fully test our design and integration of hardware, software and interface a foam-core APC model was built and used extensively.



Designing the APC interaction space: (a) measuring users' reach (b) measuring product distribution and projection real-estate (c) the APC foam-core mock up

Projected GUI Guidelines

Creating effective projected user interfaces is not an easy task. The designer must compensate for many elements such as legibility, color-clarity, shadows, occlusions, lighting conditions and so on.



Deriving projected GUI guidelines: (a) and (b) show non-rectilinear projected GUI (c) shows the legibility challenges with certain light colors (c) shows a completed 22" projection using big round buttons, white fonts and bright colors over a black background

We used several different projection test patterns to understand what we can expect from different projection parameters. We also explored non-rectilinear graphics projection, to ensure that the view orientation is always correct regardless of the projection angle. This is a design

approach for solving the skew and keystone problems projected user interfaces are prone to.

In our design process, through several testing sessions we defined a set of principles or guidelines that can assist in the design of projected user interfaces:

- **Avoid white, pad with black:** projecting white demands the most from the projection hardware, it also takes away luminosity from the rest of the scene, so use it scarcely. However, the color black is your friend. Generally, Using black to pad and outline your GUI elements will result in a clearer and brighter projection.
- **Design for dynamic scales:** projected UIs need to be able to scale dynamically with respect to the projected screen size, specifically when the projection setup changes. This is very common when the system is kinetic (e.g. in LuminAR's case)
- **Use non-rectilinear graphics:** this is a design approach to avoid handling complex image skew and keystone correction
- **Minimize shadows and occlusions:** place UI elements as much as possible in locations that minimize the chance that users would reach out and occlude the interface, typically the edges of the projected screen
- **Use big and legible fonts:** always test fonts as a function of the projected display. We found that for 20" display at WVGA resolution fonts less than 16p would render poorly

Software Development

The APC applications are specific LuminAR apps running on top of the LuXoR software framework we described in chapter 3. The applications were developed in several iterations, working progressively to improve interaction and graphic content.

Our early exploration involved rapid prototypes, using the Best Buy Remix API [116]. Quickly afterwards, we created elaborated interaction flow designs that described a full demo scenario for APC. We include the full scenario in the appendix.



Early software and GUI exploration for APC using Best Buys' remix APIs

The final GUI of APC was fully developed using web technologies, namely HTML5, CSS3 and Javascript.



Final APC GUI look and feel

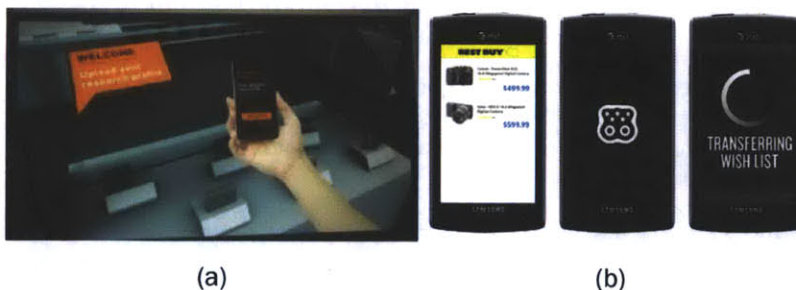
Use cases for Augmented Retail

In this section, we describe the actual use cases supported by the APC, their design and implementation. The general design requirement called for users to be able to interact with the products on display and receive just-in-time information based on their pre-existing profile, market research or store pushed data. Users are able to use their mobile phone or simply login to the system. We employed gestural and multi-touch interfaces as well as augmented reality techniques to support various use cases.

In the sections that follow, we will discuss the entire APC user interaction flow.

Interaction Entry Point

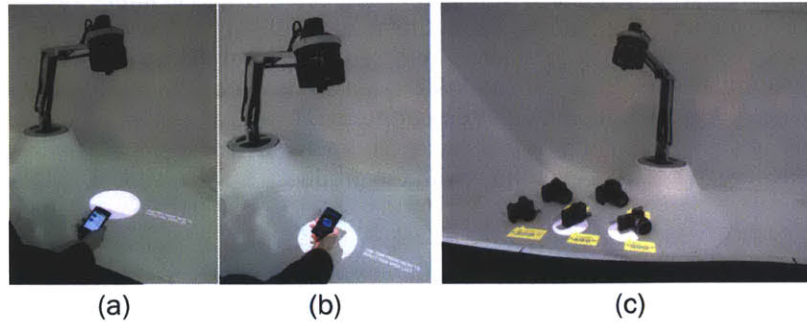
The APC interaction entry point involves being able to identify a customer and access his personal shopping preferences information. Such information may include standard personal information but also product wish lists.



APC Interaction entry point is a mobile phone application. (a) Shows the concept of logging in to the counter display. (b) Shows a sequence of the APC mobile applications.

To facilitate a “login” to the system a user could simply use his mobile device. In our implementation we used a Samsung Galaxy I Android handset. We developed a mobile shopping application that provides the user with a unique fiducial marker identifier. To start interacting with the APC the user simply scans this marker under the system. The

system then connects to the shopping profile and retrieves relevant wish list information that is displayed directly on the products.

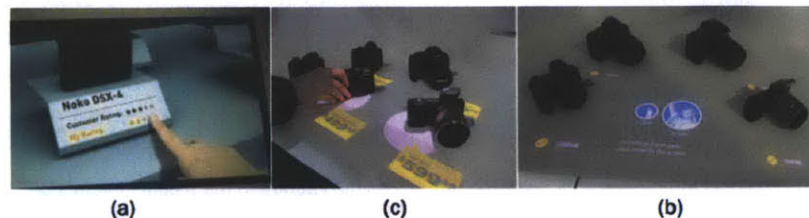


(a) When a user approaches the APC, he can use a mobile application to browse his profile and wish list (b) the user can 'login in' to the APC by scanning a fiducial marker from his phone, that serves as a personal identifier (c) once the login is complete the APC reflects the users wish list by augmenting the products on the counter.

Contextual Product Browsing

When consumers are searching for a new product they naturally flag products they are interested in, following suggestions from retailers or other customers. They also consult with their direct social network for family and friend advice. Before a purchasing decision is made, consumers spend time reviewing product specifications, comparing it to competing product alternatives, and reviewing other factors like warranty and shipping costs.

The APC provides a contextual product-browsing interface. By contextual we mean that information and interfaces are displayed in response to a certain user interaction with the product. For example, when a customer picks up a product from the counter's product-display zone, just-in-time information is displayed directly "under" the spot where the product was displayed on the counter. Such information includes key feature information. For example, when the user picked up the Canon G11 camera, the face recognition and optical features are highlighted.



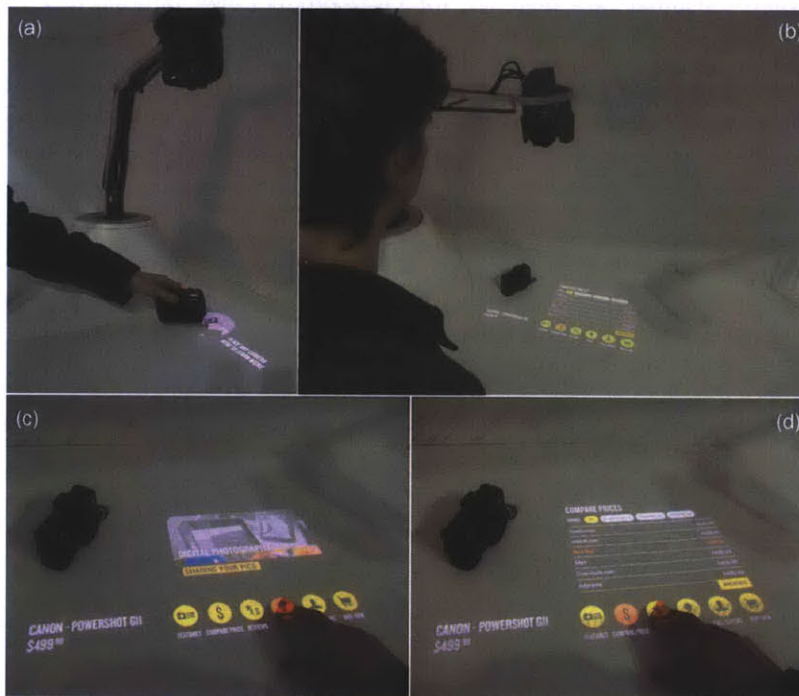
Contextual product browsing with Just-in-Time-and-Place information: (a) Design from Intel's responsive store concept. (b) When a user picks a product from the APC, (c) contextual information is displayed directly underneath the product.

The APC constantly monitors which products are currently not on the counter, thus making the implicit assumption they are currently in the customer's hand. Using a timeout mechanism the system infers that since the user is spending a substantial amount of time inspecting a product, he would be interested to learn more about this specific product. In such case the LuminAR Retail arm servos from the product display zone to the product interaction zone. This is an example of using the kinetic behavior to create a more engaging experience and encourage the user to interact with the product.

Product Interaction Zone

The product interaction-zone provides a simple cue for the user to place a product of his choice in a projected target zone. Once a product is placed in the target zone, the interaction-zone becomes alive with information. The interface updates, real-time information such as:

- Price comparison
- Product rankings
- Special sales
- Video manuals

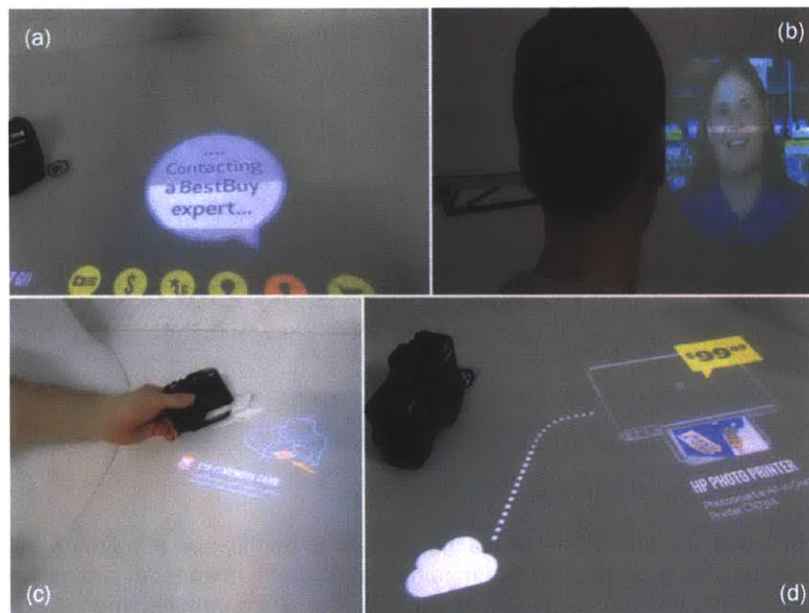


APC Product Interaction Zone: (a) The user places the camera in the product interaction zone (b) An online shopping experience is projected around the camera (c) control product features information video (d) In-store price comparison.

Remote Expert

Earlier in this section, we mention the labor problem retailers face. The APC tries to address this problem by introducing a remote expert function. The basic idea was to support both the customers and the staff of the retailers, by giving them access to an associate that can be remotely located.

This functionality used the LuminAR Spotlight form factor, to enable a two-way video teleconference between a customer and a virtual associate. The remote expert can provide product usage examples and manuals, augmenting the interaction-zone surface visible to the customer and also answers any questions that come up. The expert could also potentially see the customer using the tilt webcam in the bulb, although in the current APC implementation we did not fully implement this feature.



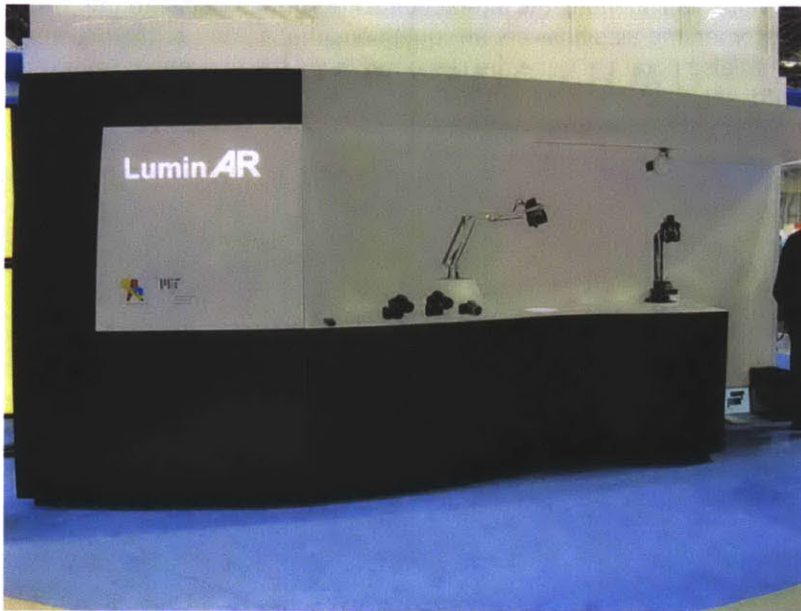
(a) A user can start a teleconference with a remote virtual expert by pressing a button (b) the expert can answer product questions but can also recommend additional products (c) the expert can re-augment the counter with information relevant to answer the customer's question, in this example the expert is displaying a manual page (d) The expert can also push additional information about complementing products to the camera the customer is enquiring about.

In the example scenario we have created, we focused on the customer side interfaces, developing capabilities to push product manual pages as well as additional information about complementary products for the digital camera, such as printers and digital photo frames. This remote augmented reality scenario, can potentially help retailers create actionable sales, but also effectively optimize labor resources.

Conclusion

In this section we presented the Augmented Product Counter concept. We explored how LuminAR can be utilized to revitalize the traditional retail experience, providing an enhanced shopping experience for consumers in physical stores.

The demo scenarios we explored show how interactive and persuasive interfaces can be used to engage customers. The APC also proposed a design for fluid transitions between online shopping to actual physical product browsing in a store.



Augmented Product Counter at NRF 2011, NYC

For retailers, the APC provides insight for the application of augmented reality as a valid in-store technology. The APC builds on today's familiar web and mobile-enabled consumer behavior. Such intuitive and connected interfaces could contribute to increased engagement of customers in the store. Allowing users to freely search and explore products will potentially increase the trust between a customer and a retailer, potentially directly contributing to more actionable sales, cross-sales, and opportunities to up-sell products. It can also help support the retailers' workforce, enabling staff to answer questions and sell like experts and provide real-time metrics.

For further details on the APC, we have included additional information regarding the application flow, software and GUI in the appendix.

6 User Experience

While a formal evaluation of the various LuminAR systems and components has yet to be completed, the work has been presented and tried by public audiences on several occasions. The reason such an evaluation did not take place is the author's personal opinion that it is too early for the system to undergo formal usability evaluation, and that the results of such evaluation may not contribute to the further development of the system at this point. Some of the reasons to avoid the evaluation at this point were well captured in Lieberman's work 'The Tyranny of Evaluation' [117].

More recently, Greenberg and Buxton published a critical paper: 'Usability Evaluation Considered Harmful (Some of the Time)' [118]. In this paper they outline how in some of the cases usability evaluations are inadequate, in particular, in the early design stage they add little value but can also squash what could have been a promising idea:

"Yet evaluation can be ineffective and even harmful if naively done 'by rule' rather than 'by thought'. If done during early stage design, it can mute creative ideas that do not conform to current interface norms. If done to test radical innovations, the many interface issues that would likely arise from an immature technology can quash what could have been an inspired vision. If done to validate an academic prototype, it may incorrectly suggest a design's scientific worthiness rather than offer a meaningful critique of how it would be adopted and used in everyday practice."

— Saul Greenberg and Bill Buxton, *Usability Evaluation Considered Harmful (Some of the Time)*

Although, the LuminAR prototypes are fairly advanced, they are still very much 'lab prototypes'. The operation of the system is dependent on the research team, and the system is not robust enough to be fully tested by users without injecting subjective bias into the actual evaluation protocol.

Therefore, relevant formal evaluation of the LuminAR system should be postponed to a point in time when: (1) the system interfaces mature and stabilize for ongoing independent operation by a user and (2) a clear and comparable evaluation for a specific use case be devised such that it can provide valid and reproducible results.

Demonstrations

This section contains the feedback and observation we collected during the various LuminAR demos.

Media Lab Sponsor Week Spring 2009

The first public demonstrations of LuminAR took place during the MIT Media Lab Sponsor week in Spring 2010 (May 25-27, 2010). We

presented a conceptual prototype that included early versions of the robotic arm as well as the LuminAR bulb. The demo scenario was scripted and controlled, but we were able to demonstrate conceptually the potential of a kinetic projected interface. We choose a simple augmented magazine application that mixed digital content that popped up next to a physical magazine. We also mocked up a just-in-time-and-place email application. Visitors were very interested in the interaction capabilities of the system, and often attempted to interact with the projected content during the demo. We received an abundance of suggestions for possible use cases.

UIST Conference 2010

A demonstration [3] of LuminAR was given to approximately 200 participants of the UIST 2010 conference (October 3-6, 2010). About 50 of them briefly had a chance to experience the interface themselves, and it is safe to say that most of the participants were HCI practitioners.

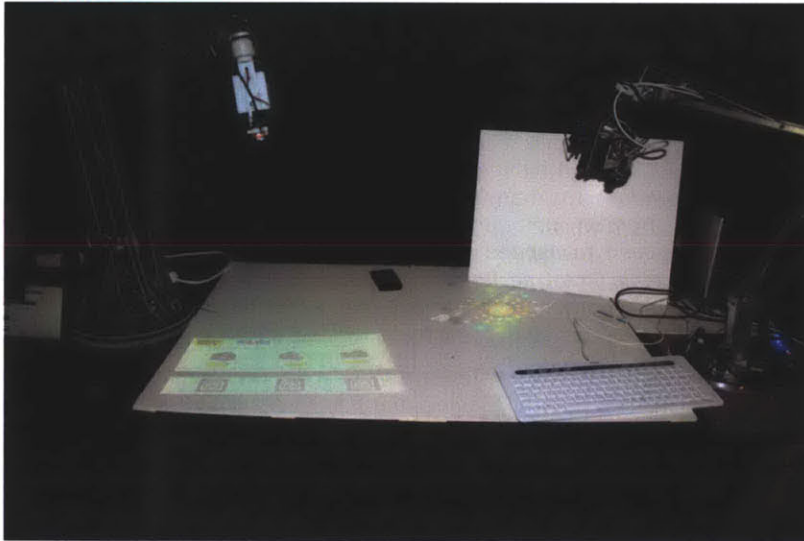


Figure 121. LuminAR Aluminum and LuminAR Topsy prototypes at UIST 2010, NYC

We presented two LuminAR systems; the first demo was of LuminAR Aluminum model running a retail scenario experience prototype. The scenario included downloading product information from Best Buy APIs and providing a projected online store experience. Interaction was supported using fiducial markers as a quick means to prototype interaction. The second demo was a hardware demo that presented our latest design of the LuminAR Topsy model. This model had proportions and design aesthetics closer to an Anglepoise lamp. It also had the first fully implemented bulb prototype that could rotate. The Topsy model was mainly used to shown the kinematic capabilities of the new hardware, including the new motor system that was implemented as well.

This demo was also served as a good test case for relocating the LuminAR setup from one location to the other. The lamps were easily put in a box and set up at the venue. We did not require any special calibration to get the system working in the new location, even though the ambient conditions were very different.

Reaction to the concept and implementation of the system were very positive. The idea of a small-scale steerable system seemed compelling to most of the people who actually interacted. Many mentioned the value in a compact projector-camera setup. We have received critical feedback on our interaction techniques, as our demo included basic fiducial marker based interaction. In later versions, we have upgraded our vision server and implemented hand detection mechanism based on the feedback we got.

Media Lab Sponsor Week Fall 2010

The MIT Media Lab Sponsor week in Fall 2010 (October 14-16, 2010) demo was similar to the UIST 2010 conference demo as they were only a week apart. However during the open house demonstration we received additional feedback regarding the interaction and potential use cases. For example, as we were presenting the retail scenario for cameras, representatives from the Lego Company suggested unique LEGO Brand augmented store experience:

"Jonathan is now 8 years old. He loves LEGO and is very much into LEGO Star Wars. For his birthday Jonathan received a long wished for LEGO Star Wars box and now he is visiting his favorite LEGO Brand store to try out the new AR Build experience. With the box under his arm he is walking towards the AR Build area with steaming expectations. As soon as he puts his LEGO box down on the table Star Wars images and icons are appearing on the table surface around the box and the voice of Yoda bids him welcome: "Begin the challenge we must do". Jonathan opens the box, empties the bags out and puts the building instructions aside for later – now it is time for AR Build! The first bag to build from is highlighted on the table and beside it an Obi Wan Kenobi mini figure jumps up and down eager to help. Jonathan opens the first bag and start building from the instructions shown on the table surface. He can easily flick through the building steps and even zoom in and out using his fingers. On the way Obi Wan is trying to help finding bricks and giving tips. Now the first spacecraft is done and an animated game starts in front of Jonathan. With the spacecraft he must avoid an asteroid storm -Obi Wan is jumping and cheering at the side. Mission accomplished– time for the next model build. Jonathan notices that a girl has entered the AR Build space beside his. She is building a CITY Police station and a small mini figure policeman helps her out. Obi Wan seems a bit distracted. He runs over to the policeman and they start a little argument. The policeman wants to arrest him, but in the end they become friends and set up a little challenge for the kids to solve. Jonathan and the girl look at each other and laughs. Jonathan thinks...oO(This is fantastic – I will

*never forget all this when I play with my new LEGO at home.
I can't wait to get to school tomorrow and tell about it!"*

—Technology Product Manager, Electronics R & D, LEGO

We received additional concepts from different industry sponsors in various domains such as banking, gaming, office furniture and more.

Light Expo at the MIT Museum 2010

LuminAR was also featured in the opening celebration of the MIT Museum Light Expo and the Luminous Window 2011 exhibition (December 10, 2010). The crowd included about 50 children in various age groups who were very interested in playing around with the new interface. For this demo an application that responds to physical objects was created. Its main feature was to browse the web, based on association with physical objects. For example, a Coke can would bring up the Coca-Cola website. A mobile phone was integrated as a browsing interface, flicking through images of fiducial markers would change the website displayed.



LuminAR @ the MIT Museum Light Expo 2011 (photo credit: Monica Brandt, Mark Ostow Photography, source: MIT Museum)

The children who experimented with the system immediately understood the basic touch-based interaction and how they can use it to change web pages using the mobile phone. They all asked the same question: "do you have games we can play?" Gaming indeed seems like a good potential domain for future LuminAR applications.

NRF Conference 2011

As a result of a research collaboration with MIT Media Lab sponsors Intel and Best Buy, LuminAR was showcased prominently in Intel's booth [119] at the National Retail Foundation (NRF) 100th Annual Convention and EXPO in New York City (January 10-11, 2011). The conference attracted over 22,000 retail professionals, and The EXPO Hall was an enormous 150,000 sq. ft. with more than 500 vendors [120].

The LuminAR Retail demonstration included a rich augmented retail scenario, including physical product augmentation, integration of rich e-commerce features and the LuminAR Spotlight remote expert feature.

The response from the professional retail crowd was very positive. It seems that the LuminAR experience may answer real concerns and challenges the brick and mortar retail experience suffers from, namely the loss of customer base to online shopping. By bridging the physical

and digital experiences in a retail environment, retailers can have the best of both worlds.

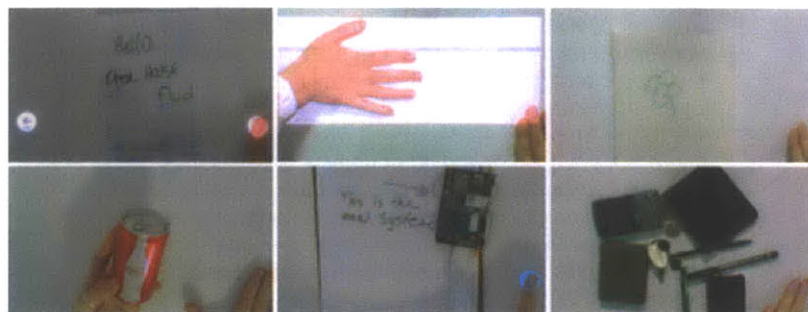


Several LuminAR Retail and LuminAR Blackjack demos took place at NRF 2011. LuminAR was featured in Intel's booth

The retail professionals also voiced concerns they had adopting such technologies. Some were skeptical regarding the need for actuation in a retail setting, arguing that much of the interaction we created could be done without kinematics and that a moving system may confuse the customer in the store. Other issues included the ease of integration and fidelity and resolution of the display with respect to the actual projected display size. All of these issues are indeed important and should be considered if and when LuminAR technologies migrate from the lab to the real world.

Media Lab Sponsor Week Spring 2011

During the Media Lab Spring 2011 sponsor week (12-14 April, 2011), we presented the NRF 200 demo, as well as new the new Augmented Desktop demos using the LuminAR BlackJack and LuminAR SilverJack models. This was the first time we demonstrated the *Kinetic Application Dock* and *Augmented Scan Application*. We had about 20 visitors experiment with the system after a short tutorial. Many of them had no problem interacting with the system. However, we did receive feedback on the responses for the touch interaction. The *Scan Application* received extremely positive feedback as many visitors mentioned that it eliminates the need for proper scanner hardware to some extent and can prove a very relevant use case for LuminAR in the future, specifically due to the collaborative potential of the application.



Results of sponsor week open house visitors playing with the LuminAR Blackjack scan application.

User Experience Feedback

We have collected the feedback received from individuals who had a chance to interact with the system, and tried to solve immediate issues. Many of the suggestions and feedback we have received in the various demonstrations were implemented during the different project iterations.

For example, we include below anonymous responses from our informal user study participants:

"I think it fills an interesting need, and when integrated with physical displays can help create a more immersive shopping experience..."

— **SVP & General Manager New Business Customer Solution Group, August 9, 2010.**

"It is very good, interesting, adaptable to the environment. I can imagine it placing in store. One of the thoughts I have is for operations, with doctors, health related function such as perspiration medication distribution. There is no need for tablet (that we use now), we can just project on a wall or other natural places. It should have a quicker response time and possibly a higher-resolution, though for some case this is just good enough."

— **Marketing Director, February 2, 2011.**

"The augmented shopping scenario shows a very creative interface applied to shopping. Coordinating the projector motion, camera recognition, and content selection was a big job, I'm sure, but it came together really nicely to show the power of the system. I can see this LuminAR approach also having important application in education."

— **Director, Advanced Technology, March 2, 2011.**

*"For me LuminAR was really fun and engaging. It was slightly confusing sometimes, mostly due to some of the inconsistencies/bugs in the tech... like when things didn't read location of taps properly, and not at all a problem with the design. Even with the few examples we saw (for example taking picture of the desktop) there was this quite *magical* feeling that the entire desktop was your digital oyster (that any flat surface underneath the cone of the projector could become anything else) and it was wonderfully tactile in that way. I wonder what would happen if we got to incorporate tangible tokens into the interaction? It was interesting that the actual projection moved around due to the lamp arm. At times this was confusing ("ahh! where is it going???!") and other times it is ridiculously engaging, since the interface is essentially a spotlight that hypnotizes you with moving information... so you can't help but follow it with your eyes. The idea of directing attention/focus through LuminAR sound particularly interesting..."*

— **Graduate Research Assistant, MIT, August 8, 2011.**

"I've used touch-based interfaces, and several different forms of augmented reality interfaces, but the experiences I had with LuminAR were singularly different. Gesture became bidirectional and surprisingly informative—anthropomorphic gesturing robots feel a poor imitation of the human social fabric, but here is a new kind of partner, for play or work, freed from the demands imposed by our genetic heritage."

— **Graduate Research Assistant, MIT, August 8, 2011.**

"At first looks, LuminAR made me immediately think about places I personally have my own LuminAR installed and physical interactions that are now becoming possible. (For example I thought about my bedside reading lamp that can turn a blank page of paper to my e-book without having the risk of breaking it when I was falling asleep, same as for the kitchen space and my work environment). What I liked about LuminAR is that it is generic enough to support many communication needs and present information in a very non-generic and non-conventional way tailored to different use cases in the real tangible space. When experiencing the retail space demo with a virtual sales representative I started to think that LuminAR can enrich our current internet based communication with a parallel (optional) layer of communication that the website adds related to me personally and the context of the page. I was a bit frustrated with the fact that the tactile feedback is still missing from this concept but it is understandable as these limitations may be inherent to many augmented reality concepts."

— **CTO, Advanced Technology Lab Director, August 3, 2011.**

"LuminAR is at core a smartbulb with built-in display plus camera which seamlessly projects a fluid applications experience onto ordinary surfaces – including tabletops, walls, floors and others – thus turning these otherwise static spaces into as rich an applications ecology as you find on your smartphone, and perhaps more so. Since LuminAR has integrated camera, display, connectivity, and computation all bundled together into the form-factor of an ordinary Edison-screw-socket lightbulb, the users experience immersive interactivity in the lit-up area. Multiple LuminAR's overlapping the same surface area can auto-stitch themselves together to create supersized displays. And with the addition of robot-actuation in the lamp fixtures, an entire range of auto-orientation is an API away for the authors of smartbulb apps."

— **Lecturer, MIT, August 2, 2011.**

"What struck me about LuminAR was that even without the robotics, it enabled computing to be installed in places not usually suitable - up out of the way in dusty, or hygienic environments where a laptop or touchscreen unit would be inappropriate."

— **Lecturer, Monash University, August 2, 2011.**

"The device you created would have significant impact to the domain of augmented reality by providing a device that

is easily installed and could be easily used in the home market. The LuminAR could be deployed with the movable base or installed in a standard six inch ceiling recessed lighting can above a desk, kitchen work area, bedroom, or anywhere providing augmented support for the user. The kitchen is a natural for news and recipes, and in the living room, office bedroom, televised information, videos, anything the user may want to view. The office would be another rich area for providing secondary display information like family pictures, news information, email prompts, scheduling, way-finding etc. You have a natural broad use product, and as the smaller laser projectors improve with time, the product will both evolve and improve."

— **Research Manager, August 2, 2011.**

"I love the perspective-taking angle. LuminAR gives me the impression that the computer is changing perspective on how it "sees" me and responds to what I do. I think that gives me the impression that the machine is an empathic being. Maybe it is because I think of it as the little lamp that Pixar uses in their opening titles... Maybe it's the motion. Kinetic things remind us of animals. Awesome industrial design work!! I find laser projectors a bit hard on the eyes. I would love a LuminAR assistant on my desk!"

— **Researcher, MIT, August 2, 2011.**

Based on the aggregate feedback received, as well as our own experience with the system, we have collected and outlined the key improvements that would make LuminAR ready for a rigorous user study down the road. We detail such improvements below, categorizing the suggestions into the areas of software, hardware/mechanical and interaction techniques.

Hardware/Mechanical Improvements

- Utilize better joint position sensing for LuminAR Arm. Current sensing relies on potentiometers that suffers from known accuracy, dead-zone and mechanical coupling issues
- Investigate and implement a low cost servo motor solution. Current off-the-shelf servos are excellent as a prototyping tool, but are too expensive as a real-world solution
- Utilize projection hardware dynamic view angle and auto-calibration capabilities. This should reduce computational load from the software process responsible for geometric scene registration running on the main LuminAR processor
- Add sensing for ambient light conditions, this will allow LuminAR to automatically compensate for changes in the ambient lighting conditions, contributing to the ongoing real-time calibration of the vision system, and resulting in improved interaction
- Add capacitive sensing to the arm and bulb, this will enable natural interaction by detecting when a user is actually

touching a LuminAR device. This could also serve as an important safety mechanism

Software Improvements

- Improve computer vision algorithms; implementing a more robust detection scheme for hands and fingertip detection
- Implement full support for two hands multi-touch
- Develop a high-level Javascript APIs for kinematics control; for example, the API should support commands to define LuminAR device position for a specific user input or an application context.
- Develop a high level Javascript APIs for abstracting the computer vision coding requirements for interaction. Eliminate the need for an application developer to handle vision related coding in application code level

Interaction Techniques Improvements

- Improve overall interaction pipeline response time. This improvement may include processor hardware upgrade, but very likely refactoring the user interface events system
- Add gestures that seamlessly position the projected display on a desired surface; Support smooth transitions from a tabletop to a wall or a ceiling projection
- Design and implement better communication interfaces between LuminAR devices as an integral layer of the LuXor software stack; this will improve the current naïve implementation used for the LuminAR Retail and LuminAR Spotlight integration in the APC applications and in the case of the LuminAR Augmented Desktop ScanApp.
- Add user interface feedback mechanisms for poor input conditions. This will improve the overall interaction when the system becomes less responsive
- Improve integration with other devices such as laptops, tablets and smart phones
- Implement animatronic feedback for user purposes. Create gestures and postures that can be integrated to application flow and provide cues to the user

7 Conclusion and Future Work

This thesis focused on the design, engineering and interaction techniques for a compact and kinetic projected augmented reality interface. LuminAR challenges existing computer interfaces paradigms and form factor, offering a novel user experience that combines digital media interaction in a physical workspace.

LuminAR is inspired by more than 30 years of active research in the domains of interactive spaces, augmented reality, computer vision and personal robotics. We covered the key works in these domains in Chapter 2. The research approach for the work presented here integrated these domains with a design-driven development process. This approach motivated several prototype iterations we describe in chapter 3. The family of LuminAR devices that was developed in the course of this thesis work represents the result of this exploration.

The LuminAR Bulb, The LuminAR Lamp and Spotlight represent original hardware designs for compact and kinetic interactive projector-camera system. Product design and industrial design played a key role and informed the development of LuminAR prototypes. The result pushes the boundaries of embedding computation in everyday objects, making interfaces to digital information truly embedded in our environment. This is particularly relevant to the LuminAR Bulb that can simply screw in to a standard Edison socket, or to the LuminAR Lamp that can replace an existing Anglepoise lamp that is currently on your desk.

The design and implementation of the LuXor software framework represents our goal to create an embedded, web-based application framework and an operating environment for LuminAR. It required us to combine support for projected GUI; computer vision based natural interaction and robotic control in order to support the requirements of

We also demonstrated that LuminAR devices are practical for real-world scenarios. The applications we developed provided a glimpse into the future of projected reality interfaces in the personal desktop workspace and the retail domains. Even though our demos were domain specific, we can already see merit in exploring LuminAR applications for new domains such as education, medical applications, command centers and many more.

The interaction techniques we described in chapter 4 provide a glimpse into a future of kinetic interfaces and contribute directly to evolution of natural augmented reality interfaces. In this work we propose new interaction concepts enabled by LuminAR, namely Dynamic Multi-touch and Just-in-Time-and-Place Interactions. Our initial results and feedback, as captured in the demos of the applications we created, show the potential such interfaces have, but leave an open door for additional work that will explore further augmented reality a mainstream user interface modality. Specifically, kinematic interfaces enabled with kinetic I/O are still very much in the future and relatively

unexplored. I believe that 'interface that can move' hold a great potential for the development of the field of human-computer interaction, but require further investigation and an abundance of design efforts. It is also important to conduct further formal evaluation of the interaction techniques we proposed.

To conclude this thesis and in addition to the list of immediate improvements we outlined in the previous chapter, I will provide a few future research directions that this research work may evolve into. It is hoped that the interaction design techniques as well as design principles we provided for kinetic projected augmented reality interfaces may enable such future user scenarios.

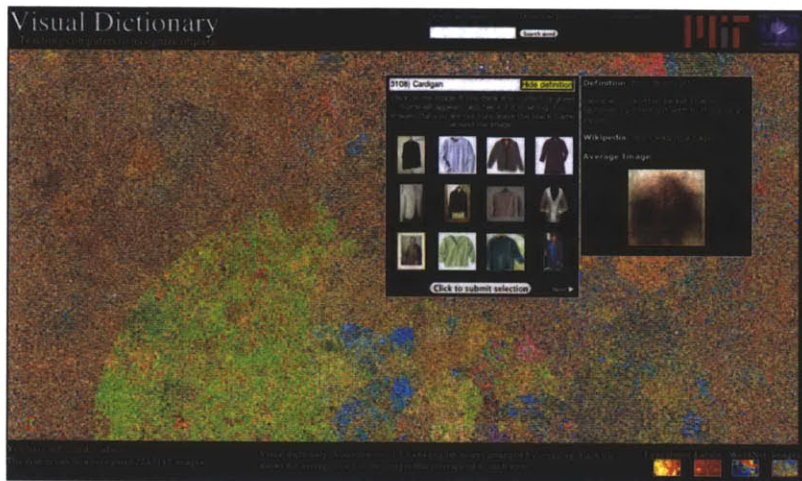
Object Augmentation and Manipulation

For projected augmented reality interfaces to become widely adopted, it is necessary to enable them with robust capabilities for object detection and tracking. Creating a framework for general-purpose object recognition is a hard problem that is still considered very much an open problem within the computer vision research communities. From an interaction point of view, such capabilities are important as they enable the design of user scenarios that include object augmentation.

Kinetic interfaces can potentially assist with solving aspects of this problem, utilizing the ability to dynamically position the sensors point-of-view to improve object detection and registration into an interactive scene. To achieve that, computer vision engines should be extended with software interfaces that can make perspective change requests in real-time to the motor control system. In doing so, and taking into account the already existing and known geometric model, the system may gain superior object recognition and tracking capabilities. Therefore, future systems could also benefit from the kinetic motion capabilities to dynamically augment objects with projected information.

From a hardware perspective, it is also possible to better integrate the sensor inputs in the bulb, namely combining depth sensor frames with standard camera frames to improve detection. In addition, automatic compensation for ambient lighting conditions should be added and used in real-time fashion while the system is moving from one location to another.

Finally, this approach should also take into account the advances made in the field of computer vision cloud-based datasets. Projects like Visual Dictionary [121], [122] propose new mechanisms to use billion of images to solve the general problem of recognizing all different classes of objects in the real world. This approach combined with an interface like LuminAR can prove a huge leap for projected augmented reality.



MIT CSAIL Visual Dictionary by Antonio Torralba et al

Opportunistic Projection Surface Detection

Kinetic interfaces would be even more useful if they were enhanced with surface detection capabilities. Such future systems, during user interaction would be able to adjust to the targeted projected area. This approach has advantages for adapting the system to a changing physical environment. This can be beneficial for desk workspaces that are usually cluttered. We call this approach opportunistic location detection.

The algorithmic basis for implementing such features already exists. Known techniques like PTAM [123] can be used to efficiently identify surface candidates for projection. The real challenges lie in the interaction design required to create a valid user experience. Users fault tolerance for kinematic systems is very embryonic, and perhaps Hoffman's work on fluency can serve as a starting point [109].

Augmented Reality Interfaces Design Tools

If we follow the trajectory of Moore's law, it is clear that at some point projection and sensing hardware capabilities integrated with powerful microcontrollers will enable designers to build rich augmented reality interfaces.

However, current user interface design technologies have clear drawbacks when applied to the design of augmented reality interfaces. Current Digital Content Creation (DCCs) Tools and Integrated Development Environments (IDEs) are completely geared towards the development of display centric interfaces.

It is not hard to imagine how we can redesign such tools so they fit new interaction paradigms specific to augmented reality. I believe the gap is greater when it comes to the support of dynamic projected content and kinematic systems. Such tools should basically support the concept of just-in-time-and-place interfaces and augmented reality affordances. For example, development tools today are unable to model complex

application flows that take into account projection location, size, object detection and tracking. The underlying computational models for such a systems has been explored before, for example Roy et al [124]. I also believe that this reality inhibits the mass adaptation of augmented reality as a mainstream user interface modality.

Appendix

LuminAR Mechanical Specifications

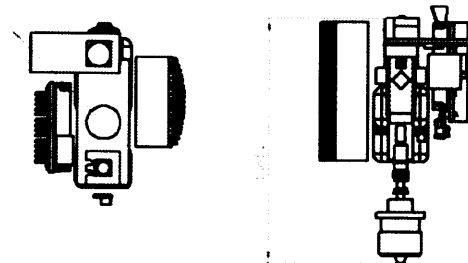
This appendix includes mechanical specifications for the various LuminAR systems developed in the course of this thesis work.

LuminAR Bulb Integration

Weight (w/out M2M Embedded computer)	460g
Diameter	150mm
Actual rotation range (degrees)	45°
Length	190mm

LuminAR Bulb Final

Weight	550g
Diameter	130mm
Actual rotation range (degrees)	270°
Length	170 mm



LuminAR Spotlight BD

Overall length	1450mm
Belt & pulley mechanism length	1200mm
Pivot servo actual motion range (deg)	120°
Weight	3700g
Depth - to explain the mounting requirements	100 mm in the wall/ 18mm above +Bulb

LuminAR Optimus

Base diameter	304.8 mm (12 in)
Base rotation actual rotation (degrees)	90°
Hard stops	~90°, driven by cable length
Length of shoulder link	355.6mm (14in)
Length of elbow link	355.6mm (14in)
Interesting mechanical elements	All linkages are “doubled,” servos directly attached to arms
Weight (estimated)	4000g
Elbow joint range (degrees)	100°
Shoulder joint range (degrees)	90°
Wrist joint range (degrees)	100° (actual range 65° because of weight + spring)

LuminAR Aluminum

Base diameter	254mm (10in)
Base rotation actual rotation (degrees)	360° / 90° with stops

Hard stops	Cable management
Length of shoulder link	355.6mm
Length of elbow link	355.6mm
Interesting mechanical elements	Elbow spring is parallel to the base and attaches to the elbow with a long string, which goes through a pulley
Weight (estimated)	5000g
Elbow joint range (degrees)	~90°
Shoulder joint range (degrees)	~90°
Wrist joint range (degrees)	~70°

LuminAR Topsy

Base circumference	241.3 mm (9.5 in)
Base rotation actual rotation (degrees)	90°
Hard stops	Cable management
Length of shoulder link	355.6mm
Length of elbow link	355.6mm
Interesting mechanical elements	Fork; servomotors are located on the base and connect through hard linkages to the arms; Dynamixel servos
Weight (estimated)	4300 g (+ bulb)
Elbow joint range (degrees)	~90°
Shoulder joint range (degrees)	~90°
Wrist joint range (degrees)	~70°

LuminAR SilverJack / BlackJack

Base circumference	241.3mm (9.5 in)
Base rotation actual rotation (degrees)	300°
Hard stops	Fork
Length of shoulder link	355.6 mm (14 in)
Length of elbow link	355.6 mm (14 in)
Interesting mechanical elements	The base is divided in two parts (lower steel for more mass); aesthetically designed fork and arms
Weight (estimated)	4300g (+ Bulb)
Elbow joint range (degrees)	90°
Shoulder joint range (deg)	93°
Wrist joint range (deg)	70

LuminAR Retail

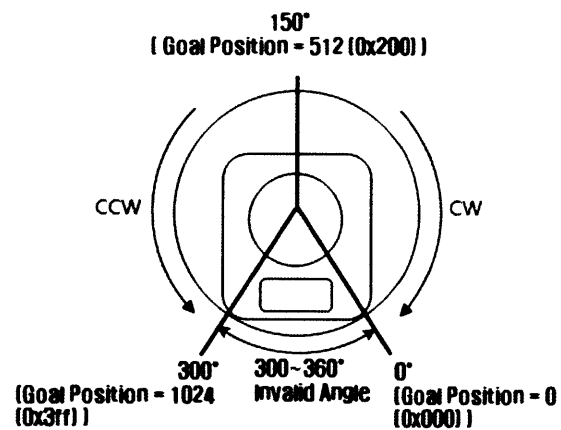
Base circumference	241.3 mm (9.5 in)
Base rotation actual rotation (degrees)	300°
Hard stops	Lower arm / base cover
Length of shoulder link	355.6mm (14in)
Length of elbow link	355.6 mm (14 in)
Interesting mechanical elements	The base is embedded in the counter (86 mm); wrist has its own 4 bar linkage
Weight (estimated)	5000g
Elbow joint range	75°

(degrees)	
Shoulder joint range (degrees)	74°
Wrist joint range (degrees)	15°

LuminAR BlackJack / SilverJack S/W Limits (in encoder values)

Joint	Min	Max
Base	100	950
Shoulder	350	600
Elbow	370	635
Wrist	50	250

- To convert Dynamixel DX-117 encoder values to degrees:

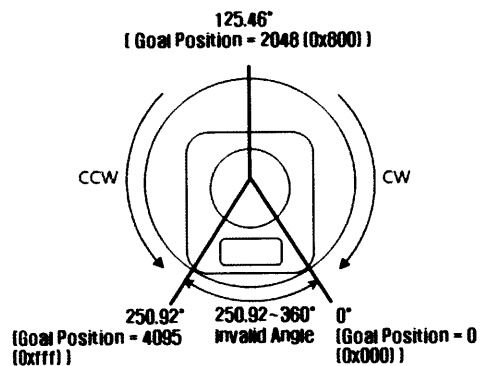


- See more at: <http://support.robotis.com/en>, Product Information / Dynamixel / DX Series / DX-117

LuminAR Retail S/W Limits (in encoder values)

Joint	Min	Max
Base (DX-117)	100	950
Shoulder (EX-106+)	1651	2672
Elbow (EX-106+)	1306	2302
Wrist (DX-117)	400	600

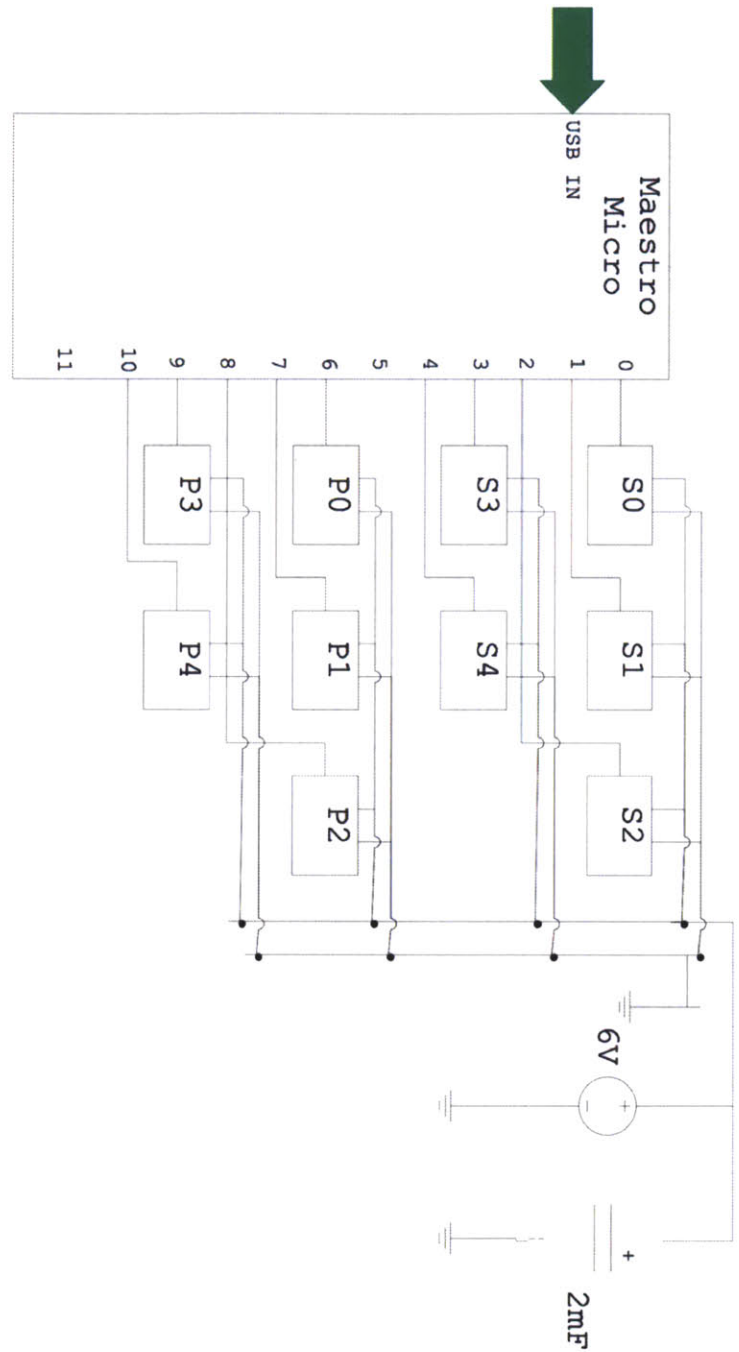
- To convert Dynamixel DX-117 encoder values to degrees - see above
- To convert Dynamixel EX-106+ encoder values to degrees:



- See more at: <http://support.robotis.com/en>, Product Information / Dynamixel / EX Series / EX-106+

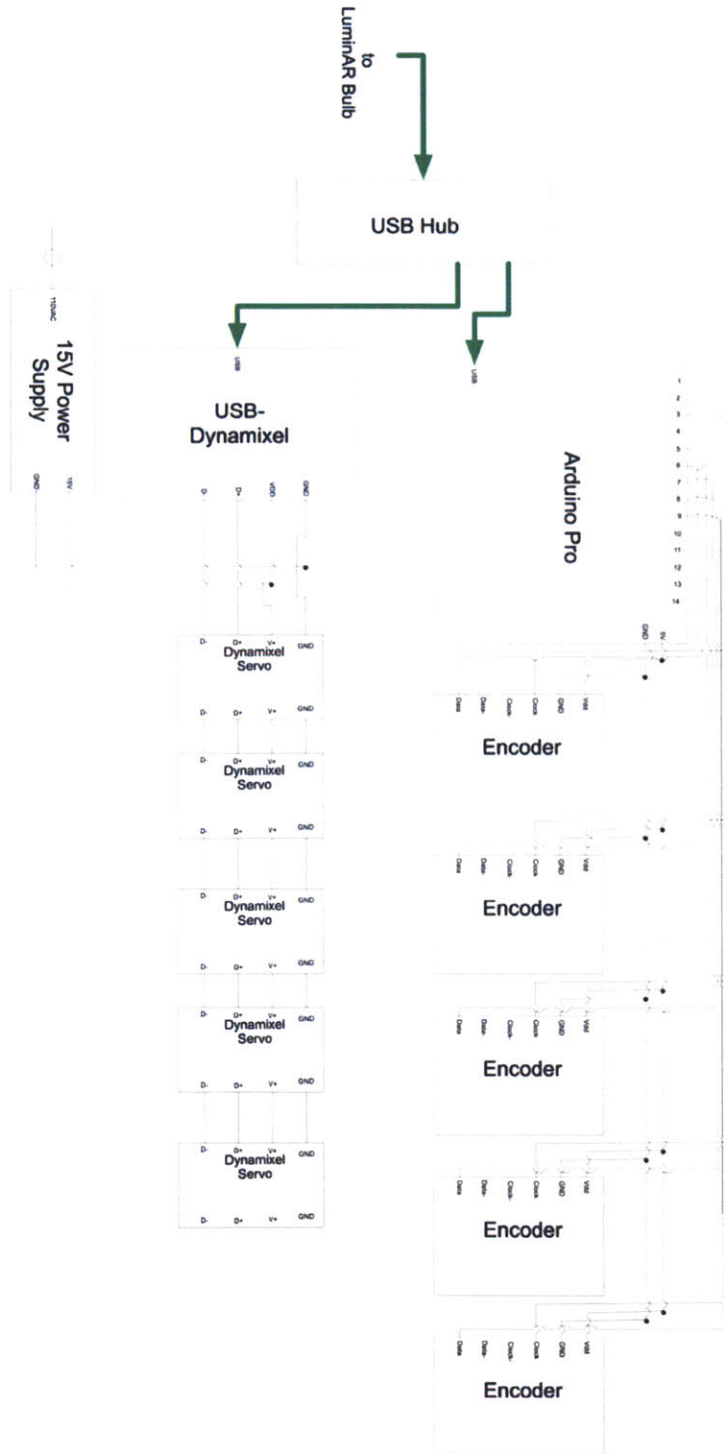
LuminAR Arm R/C Servo Topology

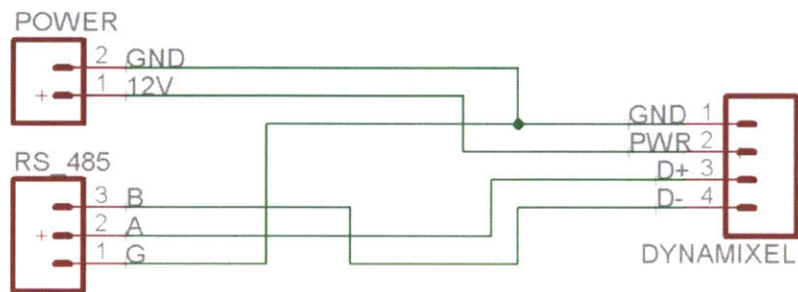
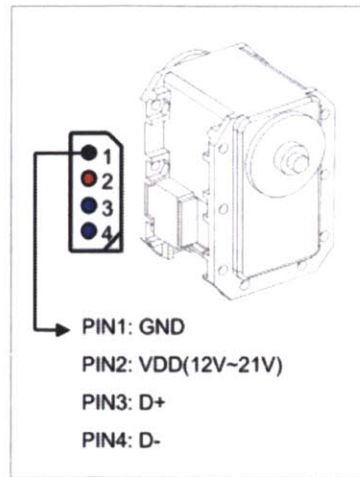
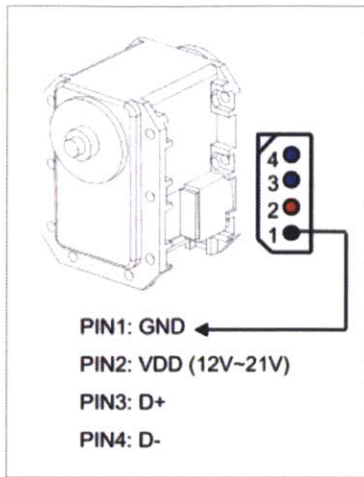
For LuminAR Optimus and LuminAR Aluminum



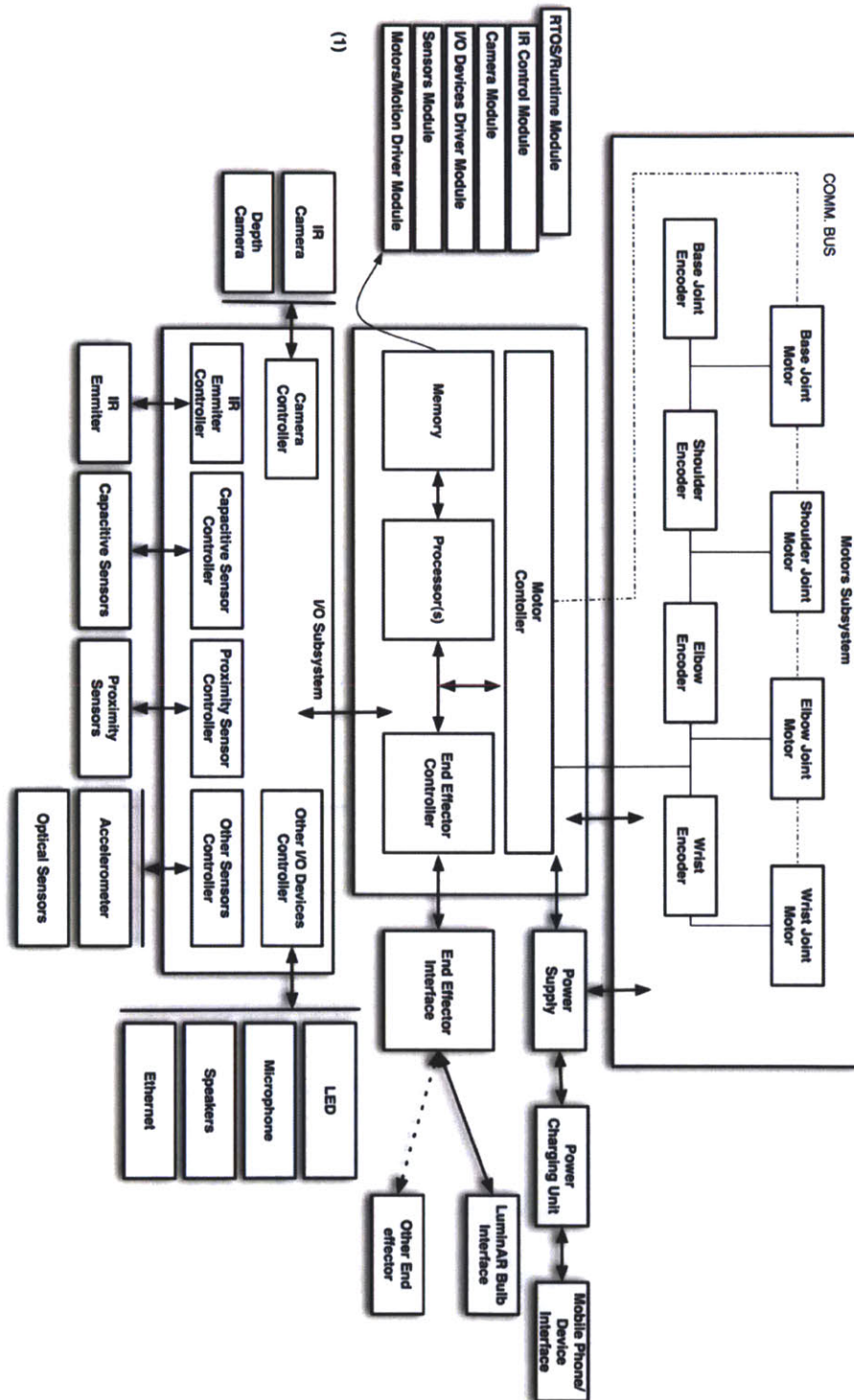
LuminAR Arm Dynamixel Servo Topology

For LuminAR Tipsy, LuminAR SilverJack, LuminAR BlackJack, LuminAR Retail

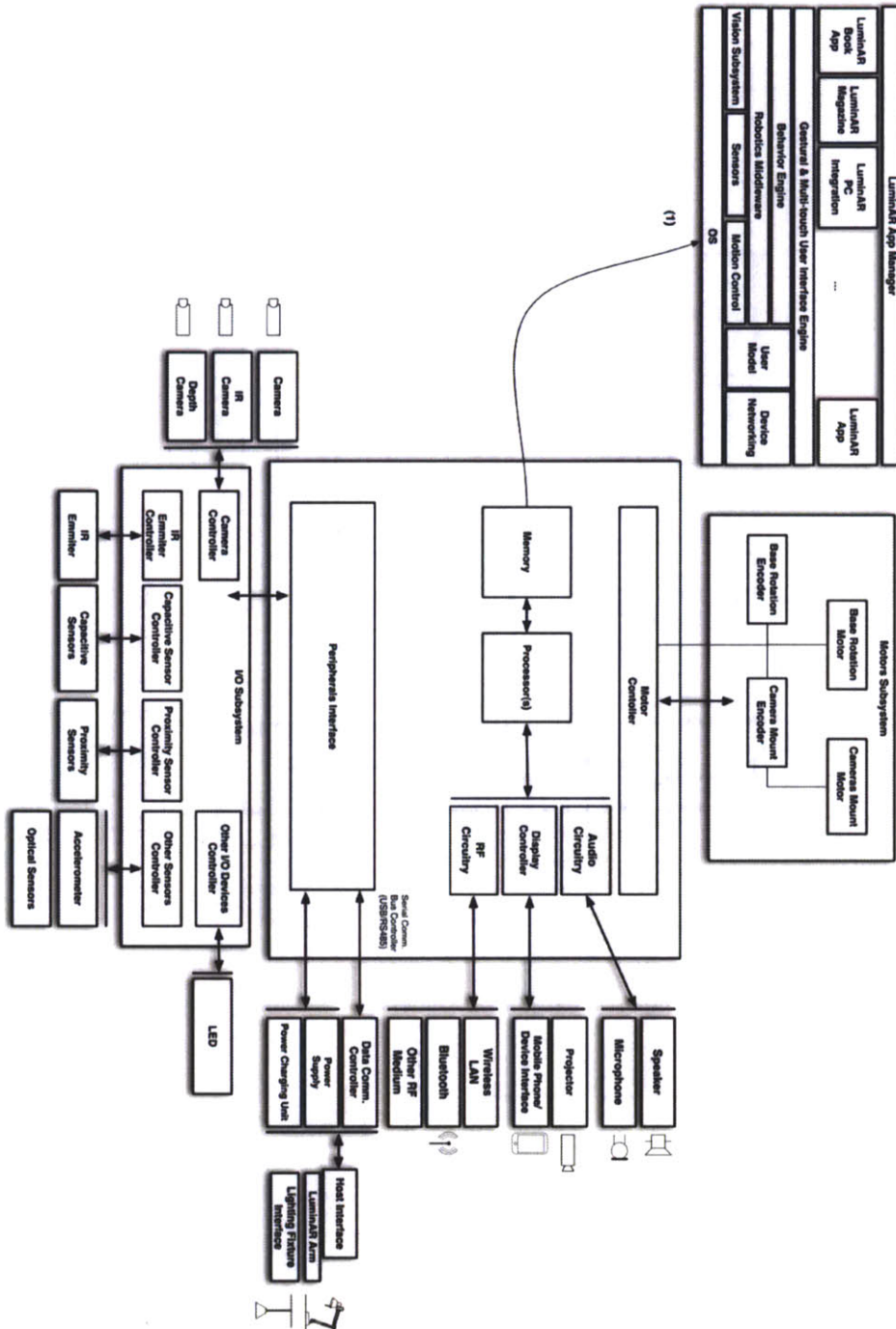




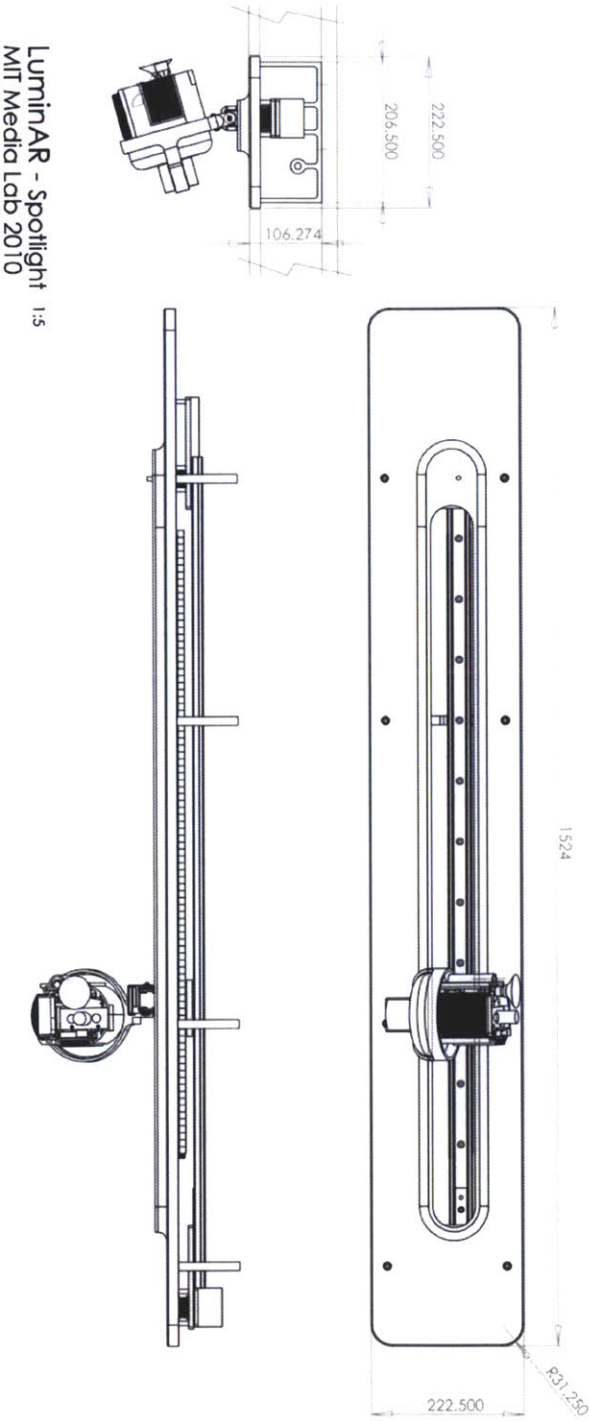
LuminAR Arm High Level Block Diagram



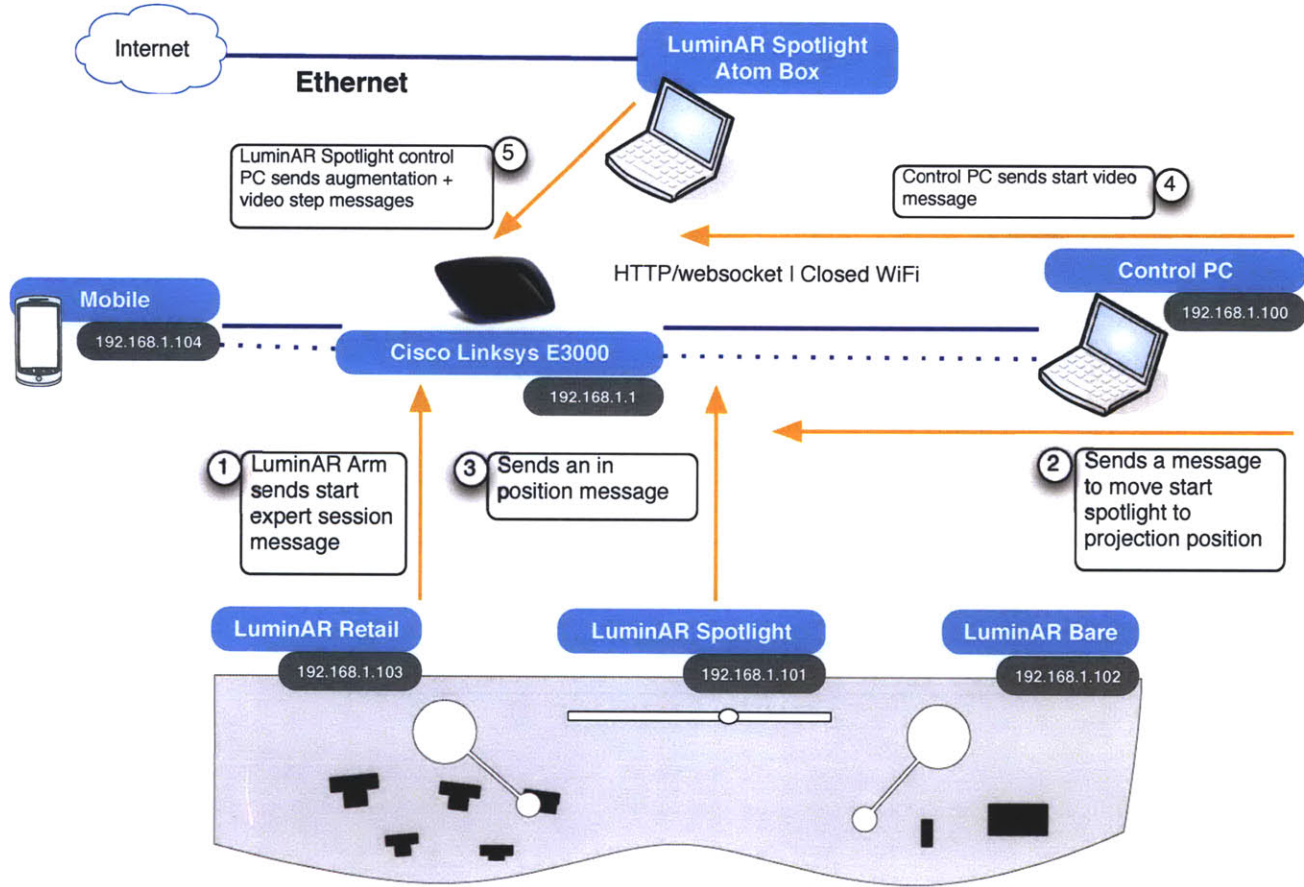
LuminAR Bulb High Level Block Diagram



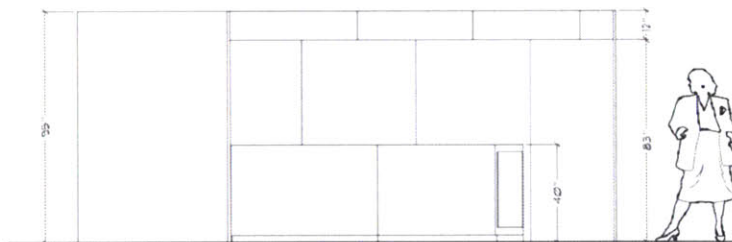
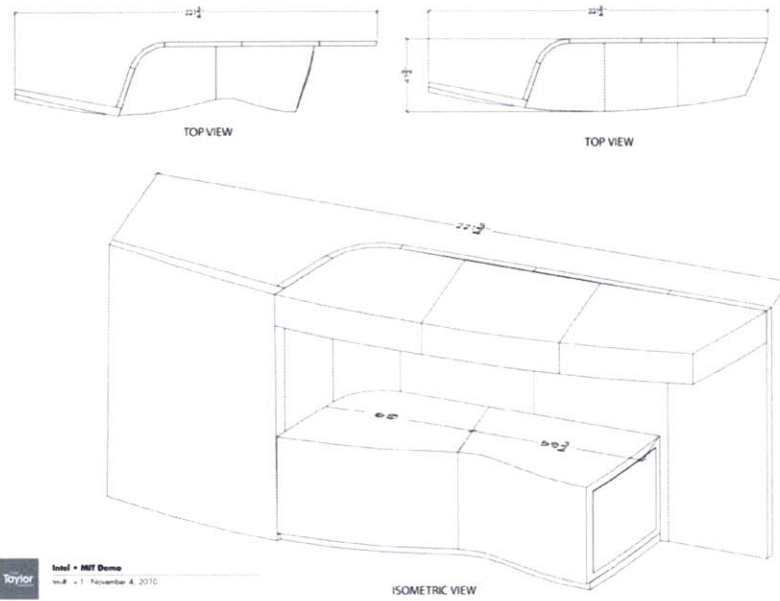
LuminAR Spotlight Mechanical Overview

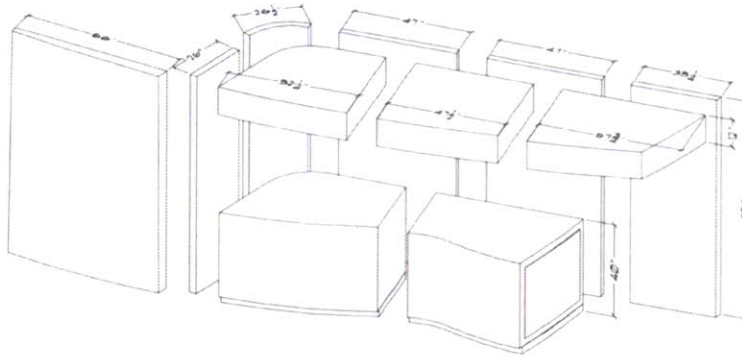
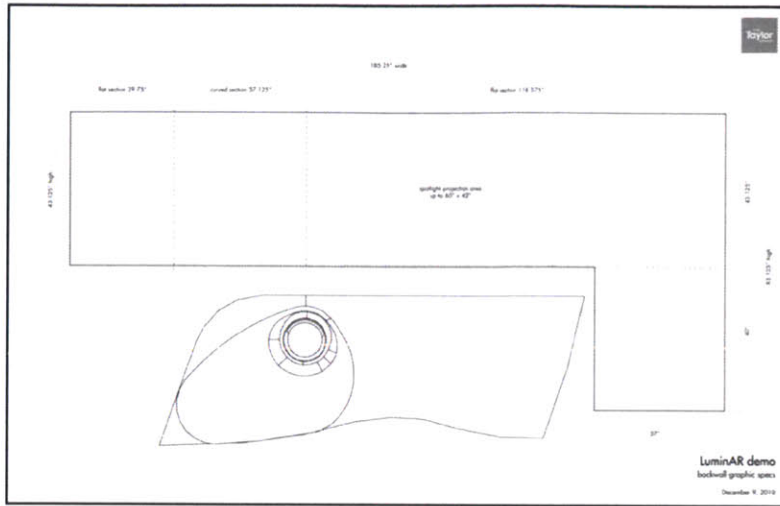


LuminAR - Spotlight 1:5
MIT Media Lab 2010

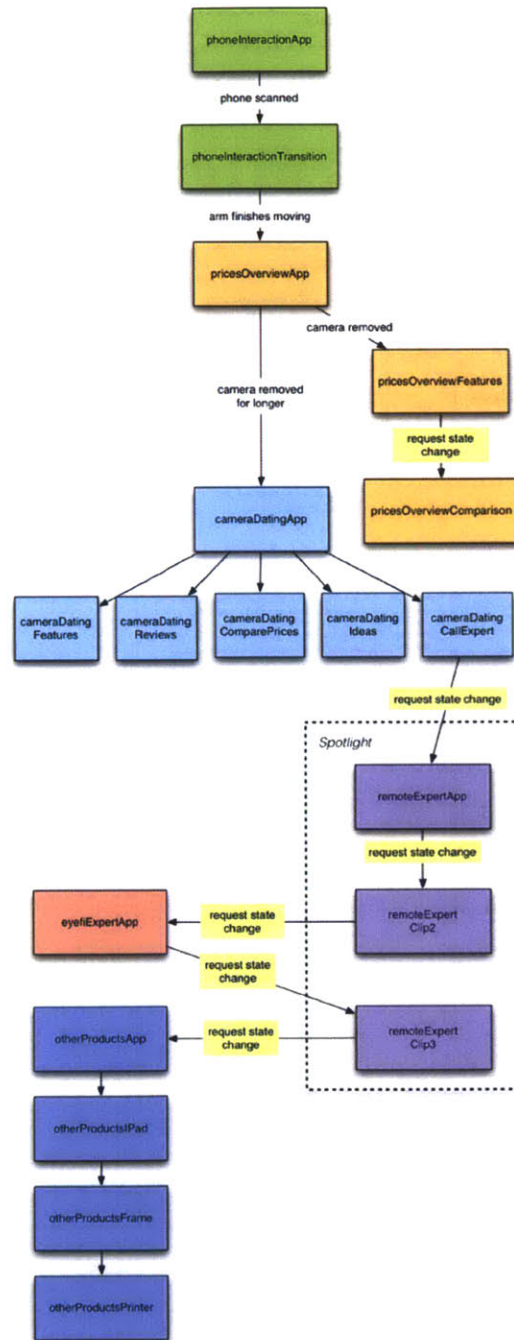


Augmented Product Counter Specification



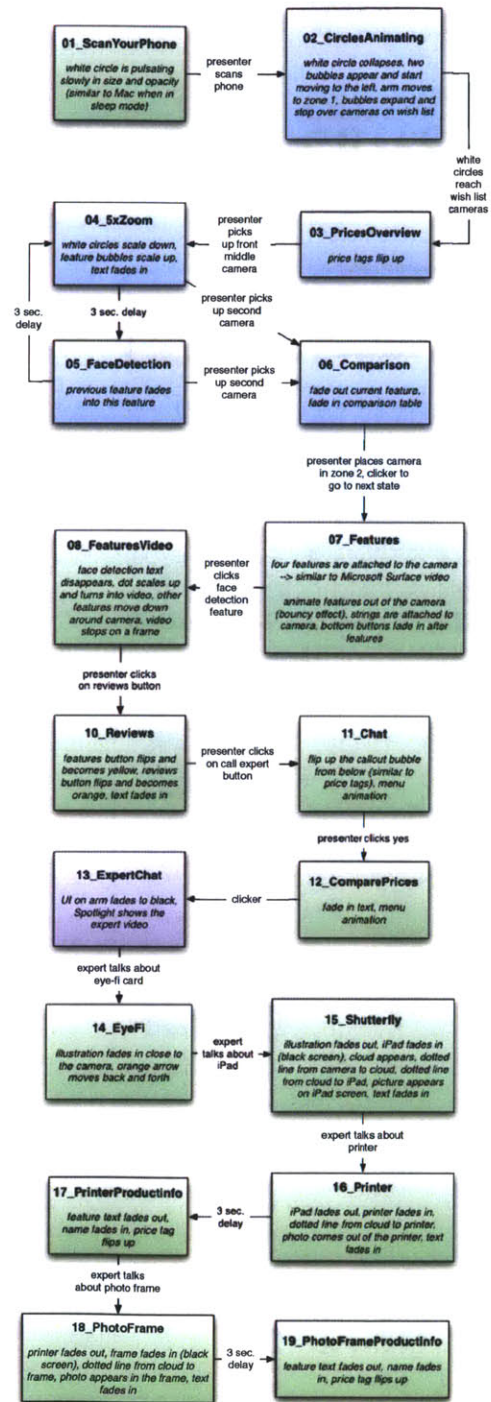


Augmented Product Counter Demo Software – State Diagram

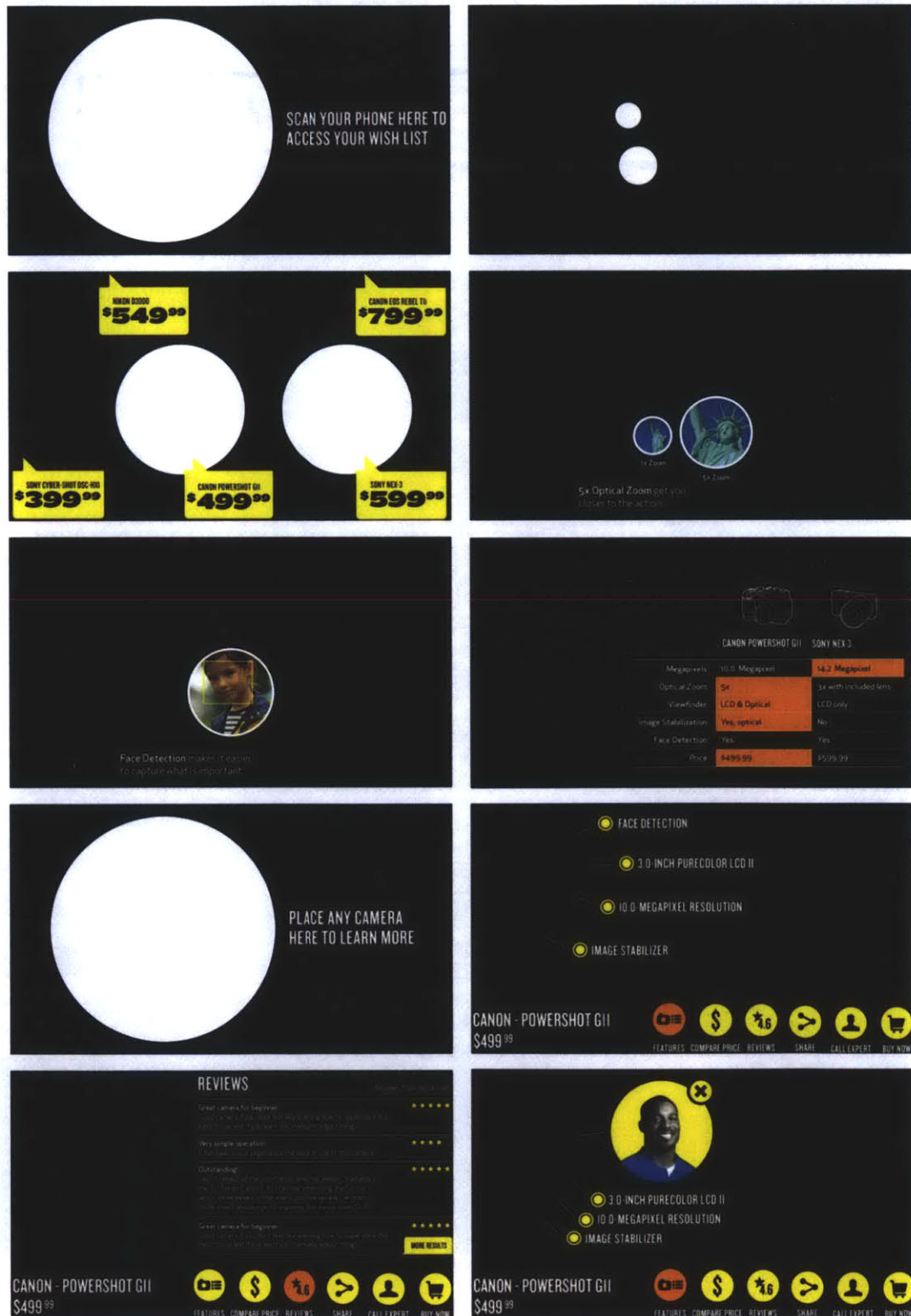


Augmented Product Counter Demo Interaction – State Diagram

UI Interaction Diagram



Augmented Product Counter Demo – GUI



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