PrIME - Projected Interface for Mobile Electronics

Joe Levy
Vansh Muttreja
Naveen Santhapuri
Romit Roy Choudhury

April 2, 2012

Contents

1 Abstract 3
2 Introduction 3
3 Background and Related Work 4
4 Comparison with Related Work 5
5 How it Works 6
   5.1 Use from the User’s Perspective 6
   5.2 Prototype Model 6
   5.3 Calibration 8
   5.4 Post Calibration 8
6 PrIME-Based Smartphone Applications 9
   6.1 Virtual White Board 9
   6.2 Dynamic Presentation 10
   6.3 Fruit Ninja Adaptation 12
7 Performance 12
   7.1 Speed of Calibration 13
   7.2 Accuracy of Calibration 14
   7.3 Reaction Time 16
   7.4 Battery Usage 18
8 Usability of PrIME in the Real World Outside of Pico-Projector Smartphones 19
9 PrIME’s Ability to Help Make Smartphones the New Personal Computer 20
10 Future Work 20
11 Conclusions 21

List of Tables

1 Comparison of Ease of Use Between PrIME and Related Work 6
2 PrIME Calibration Speed as a Function of Distance and Brightness 13
List of Figures

1. Photographs of the prototype PrIME model from front and back ........................................ 7
2. Playing Tic-Tac-Toe between a computer and a phone on Virtual White Board .................. 9
3. A sample presentation given using the Dynamic Presentation PrIME app .......................... 11
4. The real Fruit Ninja (left) and Fruit Ninja PrIME (right) .................................................. 12
5. Room used for testing with lights on (left) and off (right) .................................................. 14

3. PrIME Calibration Accuracy as a Function of Distance and Brightness ................................. 15
4. Fruit Ninja Reaction Speed Over 1 Minute ............................................................................. 17
5. Dynamic Presentation Reaction Speed Over 1 Minute ........................................................ 17
6. Fruit Ninja Battery Usage over Time .................................................................................... 18
7. Dynamic Presentation Battery Usage over Time ................................................................... 18
1 Abstract

The goal of PrIME is to provide a platform that allows the user to interact with a projected version of a smartphone’s screen, and in doing so manipulate the smartphone. PrIME attempts to enable this functionality in a way that it is not encumbering or limiting to the user, so that one can use it quickly and easily on common mobile devices and in a variety of situations. This paper serves to explore the applicability of PrIME in the real world, as well as explore various novel uses of PrIME through applications built on the platform. Results of data collection and testing show that while PrIME is easy to use, flexible, and enables a variety of unique and useful applications on the smartphone, its realized value is currently restricted due to the present-day limits on pico-projector brightness. As pico-projectors evolve, however, PrIME will become more and more useful, allowing the use of smartphones for functions never before thought possible.

2 Introduction

With the rise of the smartphone as a common utility, mobile computing has reached new heights and made new functions applicable to everyday life. The next generation of smartphones is expected to include built-in pico-projectors, to allow the small screen of the smartphone to be beamed onto a large surface for easier viewing. While conventional ideas present a projected smartphone screen as only a means to view data more effectively than on the device’s small touchscreen, this project describes a way to use a projected smartphone screen as a means to view and manipulate data more effectively than on the device’s small touchscreen.

Using automated calibration through the interaction between the smartphone’s projector and camera, we are able to map a virtual surface in the smartphone to the physical surface on which the smartphone’s screen is projected. This allows a user to interact with the projected version of the virtual surface, and in doing so manipulate the virtual surface stored in the phone. Through this technology, PrIME, or Projected Interface for Mobile Electronics, enables a new set of applications that take advantage of PrIME’s ability to create a user interface on a projected surface. PrIME works quickly, easily, and robustly enough to enable this new user interface in everyday settings, on the next generation of everyday smartphones, with very little work required of the smartphone operator.

Through its ability to create a projected user interface, PrIME enables mobile devices to be used for a variety of new applications, in the consumer, business, and education sectors. For example, a PrIME-based virtual whiteboard application could allow for a visual collaboration space between users anywhere in the world, without any of the expensive or complex infrastructure of a traditional smartboard. Or, a
PrIME-based dynamic presentation application could enable presentations to become more fluid and flexible, such as by turning an image full screen when circled, or a line of text bold when underlined. Games traditionally played on small touch screens could become giant wall-sized experiences, without sacrificing interactivity or mobility. One could even use a projected media center application to select a movie from their phone library to watch, and pause, rewind, or fast forward it at any point – all from the comfort of their couch. To demonstrate PrIME’s capabilities, Virtual White Board, Dynamic Presentation, and Fruit Ninja were implemented and evaluated, as described later in this paper.

3 Background and Related Work

Pico projectors are a recent development in today’s society, allowing the power of projection in a mobile form factor. But even more recent is the idea of the pico-projector phone, used to turn the small screen of a smartphone into a larger, better viewing experience. In the past very few pico-projector phones existed – Samsung created one in 2009 with the Samsung ”AnyCall Show” [1], as did LG with the LG ”Expo” [2]. But these devices were never able to spread to the larger smartphone market or capture consumers’ hearts because LG and Samsung only envisioned a pico-projector phone as a device used to project things. More recently, there have been glimpses of more creative uses of pico projector phones. The Mozilla Seabird concept [3], for example, is a smart phone design that includes a pico projector on each side on the phone, to be used for both a projected keyboard and screen. And the leaked Samsung Galaxy Skin concept [4] hints at a flexible Android phone that would be able to project in any number of positions for any numbers of purposes. While these concepts are very interesting ideas, they cannot exist at reasonable prices today due to technological limitations.

In the last few months, however, pico-projector phones have taken strides towards becoming common consumer devices. For example, Tursion recently released a dual-core Android device with a pico-projector instead of a screen [7], and Samsung recently announced the Android-powered ”Galaxy Beam” pico-projector smartphone [9]. These Android-powered devices, which will be heavily marketed to consumers, could help pico-projector phones to finally take hold of the market and become commonplace, something they have so far been unable to do in today’s society.

On the other side of the spectrum, researches have looked at the interesting applications that can come about from combination visual input/output devices. BoxLight’s ProjectoWrite [5], for example, allows drawing on and interacting with a projected computer screen through a driver installation on the computer and a custom built projector/infrared reader device. Similarly, Carnegie Mellon’s Wiimote Whiteboard project
provides interaction with a projected computer screen using a custom-built infrared pen that is read by a Nintendo Wii controller connected to a computer. In addition, SixthSense presents a wearable system that recognizes hand gestures to manipulate a projected surface, and recognizes real world objects and displays information found from the Internet on them. SixthSense accomplishes this using a pico-projector, a camera, a triangular mirror, marker caps, and a computer. And the "Android Kinect Projector Interface" enables projection of a smartphone screen and manipulation of the projected area as if it were the touchscreen of the smartphone, using a computer, Kinect sensor, projector, and phone. While all of these technologies enable new and interesting functionalities through combination visual input/output systems, they require specific, multi-piece hardware, only work in specific conditions, and require manual pre-calibration and setup to work. This stops them from being easily used by consumers in real world applications, in real world scenarios, and on common, everyday devices.

The system envisioned by PrIME combines ideas from these two areas. It takes advantage of pico-projector smartphones, an up and coming technology that is increasingly becoming common place. Because pico-projector smartphones contain camera and pico-projector components, PrIME is able to create a visual input/output interface that allows applications similar to SixthSense and ProjectoWrite. PrIME requires the consumer have only one device – a pico-projector-enabled smartphone. The fact that PrIME works on any Android-powered pico-projector smartphone means consumers can take advantage of the applications that require this technology without buying any extra equipment – it works right out of the box, on their phone, just like a normal app would. The auto-calibration performed when an application desiring to use PrIME is run allows the application to work without specific components, manual pre-calibration, or under specific conditions. Our underlying system’s auto-calibration allows PrIME to work in real world situations, without complicated pieces, configuration, or calibration required of the user. That is the main value of PrIME – it enables applications that augment the world around us with visual information to easily be used in real world situations, on real world, common devices.

4 Comparison with Related Work

Table 1 shows how PrIME compares to the related projects discussed above over a variety of metrics related to ease of use. The best performing technology in each category is presented in bold. In the event of ties, multiple technologies were bolded. As you can see, PrIME provides optimal ease of use, winning two out of the four metrics and tying for winner in the other two.
## Components

<table>
<thead>
<tr>
<th>Technology</th>
<th># Components Needed</th>
<th># Components That Must Be Physically Connected on Each Use</th>
<th>Is Easily Mobile?</th>
<th>Needs Manual Calibration on Each Use?</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProjectoWrite</td>
<td>3 - IR projector, computer, IR wand</td>
<td>2 - IR projector, computer</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>SixthSense</td>
<td>5 - projector, computer, triangular mirror, camera, marker caps</td>
<td>4 - projector, triangular mirror, computer, camera</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Android Kinect</td>
<td>4 - smartphone, computer, Kinect, projector</td>
<td>4 - smartphone, computer, Kinect, projector</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Wiimote</td>
<td>4 - Wiimote, projector, computer, IR pen</td>
<td>3 - computer, projector, Wiimote</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Whiteboard</td>
<td>2 - picoprojector smartphone, laser pointer</td>
<td>0</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>PrIME</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comparison of Ease of Use Between PrIME and Related Work

## 5 How it Works

### 5.1 Use from the User’s Perspective

Users pick a PrIME-based app on their phone just like they would pick a normal app. They aim the pico-projector smartphone’s camera and projector at the surface to project on. They tap the phone’s screen to start the application. PrIME starts projecting, quickly calibrates (explained below), and then runs the application. The user can then interact with the projected app on the physical surface using a laser pointer, by pointing the laser pointer at the projected surface or moving the laser pointer around on the projected surface.

Interacting with a PrIME application is analogous to drawing on paper with a pencil. The laser pointer becomes a long range ”pencil” to draw on the projected surface, which serves as the paper in this metaphor. But instead of the paper just holding what you ”draw”, the projected surface can dynamically react to whatever is drawn on it. For example, in the Dynamic Presentation PrIME app, underlining some text during a presentation could turn that text bold, better emphasizing what the presenter is currently focusing on.

### 5.2 Prototype Model

PrIME technology currently uses the Android 2.2 – Froyo Operating System or newer and is written in Java. HTC Droid Incredibles, HTC Evos, and Google Nexus 1s were used to test the phone client. Because we did
not have access to an Android powered pico projector phone, we used an HTC Evo connected to an Epson PowerLite Home Cinema 705 projector over HDMI as our prototype model. A stand that suction to the projector and holds the smartphone was used for convenience and to simulate PrIME as one device, but it is not actually needed as long as the smartphone camera is facing the projected image.

The HTC Evo by default only allows images and video to be outputted over HDMI, so the phone was rooted and HDMwIn was installed to allow HDMI output of the phone’s entire screen. Since outputting the phone’s entire screen to HDMI was demonstrated as easily possible, the hope is that on future phones, phone manufacturers will not purposefully limit the content of the phone that can be outputted without rooting.

![Figure 1: Photographs of the prototype PrIME model from front and back](image)

While our prototype model does not have the projector actually built into the phone, the model (as shown in Figure 1) works as a valid prototype since the functions enabled by PrIME do not specifically depend on whether the projector/smartphone device is one device or two. In production, however, obviously one device would provide a better user experience due to its portability and lack of assembly required.

The ability for our prototype model to project the phone’s screen and also evaluate the projection through the phone’s camera allows the system to properly calibrate itself each time a PrIME application is run, just as a pico-projector phone could when using PrIME. This proper calibration enables the application to map the projected virtual surface of the phone to the actual virtual surface of the phone. Thus, interactions made on the projected virtual surface happen in the same place on the actual virtual surface in phone memory.
5.3 Calibration

One aspect that makes PrIME useful is its ability to work in many environments, regardless of distance between phone and projected surface, orientation of phone or projected surface, keystoning of the projected image, or light level in the environment where PrIME is being used (light level obviously needs to be low enough for a human to see whatever is being projected, however). This flexibility makes PrIME useful because it allows PrIME-based applications to work in many locations and scenarios, just as a normal mobile device would. Without this 'mobility,' it is much less useful to have this technology built into a mobile device, so the fact that PrIME is flexible to different scenarios is paramount.

PrIME’s flexibility is accomplished through auto-calibration, which takes place on a PrIME-based application’s start. After the phone is aimed at the surface where the projection should appear, the phone’s screen is tapped to start the application. PrIME first auto-focuses its camera on the surface in front of it, then projects a white rectangle representing the virtual surface. It then evaluates the brightness of the surface, as determined from images received by the camera. PrIME does this so that after calibration, when the laser pointer is being used, it knows how bright a point must be for it to be considered the laser pointer, versus the surface or any other bright spot artifact. After brightness calibration, PrIME finds the corners of the projected surface in the camera’s view by doing a stack-based flood fill from the brightest point found previously. The application collects the ‘found’ position of each corner in the camera’s view, and then compares the positions the corner points were supposed to be in (their positions on the virtual surface) to the positions the corner points were found in (their positions through the camera after projection on the physical surface). Using transformation matrices and Eigen values, PrIME is able to create a ‘calibration matrix,’ which tells it how to map physical points from the laser pointer it will be receiving, as found by the camera, to the ‘virtual’ points they correspond to on the virtual surface through a perspective transform. Put simply, this calibration enables PrIME to mark points on the virtual surface where the user intended them to be when interacting with the physical surface, regardless of the difference in screen size, keystoning, and orientation (due to projection distance, phone orientation, and distance between projector and camera) of the projected virtual surface and the actual virtual surface.

5.4 Post Calibration

After calibration, PrIME continually receives input from the camera and evaluates it as to whether a laser pointer point is there. The laser pointer is very bright, so if a very bright point is found (a point greater than the brightest calibration point found plus a threshold) it is assumed to be the laser pointer. If a laser pointer point is found, its coordinates are sent through a perspective transform as determined by the calibration
matrix, correctly mapping them on the virtual surface, and then this correctly mapped coordinate is passed to the application using PrIME.

6 PrIME-Based Smartphone Applications

6.1 Virtual White Board

Virtual White Board enables drawing using laser pointers and multi-device remote collaboration among multiple users. The system makes different "white boards" projected from different smartphones running Virtual White Board part of a single virtual interface. Users employing white boards (in their respective locations) write and draw on the board in their natural way using a laser pointer. This information is simultaneously projected on all boards and is universally editable in real time.

This technology has multi-device capabilities, and the functionality of the virtual white board can be available not just on smartphones using PrIME to create projected virtual white boards, but also simultaneously on desktops and tablets. This allows people anywhere in the world to collaborate, no matter the form factor. To demonstrate this, in addition to the smartphone PrIME-based Virtual White Board app, we designed a computer version of the Virtual White Board to show the collaborative environment working between multiple devices, and multiple types of device.

![Figure 2: Playing Tic-Tac-Toe between a computer and a phone on Virtual White Board](image)
A key attribute of Virtual White Board is that it does not require any heavy or expensive infrastructure, unlike existing SMART Boards, making this technology extremely viable and useful. Virtual White Board only requires a smartphone and a pico projector, whether as two devices or integrated as a pico-projector smartphone.

One could envision extending the white boarding functionality of an existing collaboration solution such as Lync [12], Skype [13], or Google Hangout [14] by integrating it with the PrIME based virtual white board. This would allow people who only have access to their phone to join and contribute to a Lync, Skype, or Google Hangout collaboration session that involves collaborative whiteboarding. Suddenly, these products become viable where ever the user may be, utilizing mobile devices.

Virtual White Board also uses another useful feature of PrIME – toggle. One problem with using a laser pointer to manipulate a projected image a fair distance away is that many times the exact position one means to start pointing the laser pointer at on the projected surface is not where the user actually ends up pointing the laser pointer. In PrIME apps that require precision, accurate laser-pointing is important. For example, in Virtual White Board, if you are trying to draw something, obviously starting the laser pointer where you meant to start drawing is important. The PrIME toggle feature accounts for this user error by only starting to record the laser pointer position after it has been held in the same general location for half a second. This way, if the user accidentally starts the laser pointer in a unintended place, they can move it to the correct starting location and then go from there. PrIME apps can choose to use or not use toggling, depending on the precision needed to use the app correctly.

Video Links:
- TED presentation on Virtual White Board
- PrIME Virtual White Board Video Demo

6.2 Dynamic Presentation

Dynamic Presentation enables one to project a PowerPoint-like presentation on a surface, and use a laser pointer to interact dynamically with that presentation. For example, using the laser pointer to underline a line of text on the projected surface will turn the text bold and red, so as to attract attention to what you are currently focusing on within the current presentation slide. Similarly, circling a picture with the laser pointer on the current presentation slide will make that picture full screen, allowing people to see it in more detail and focus solely on it. In general, Dynamic Presentation allows one to assign actions in response to
dynamic user input during a presentation. In contrast, in current presentation software, one only has access to ‘next action’ or ‘last action’, and all actions need to be manually defined when creating the presentation. Dynamic presentation allows one to only define the objects on slides, and then use a laser pointer during the presentation to perform different actions with the slide content. As an illustration, if an audience member asks a question, using Dynamic Presentation one can highlight the specific answer to that question within your slides. Without dynamic presentation, you could not do this, because when you defined the presentation you didn’t know that at this point in the presentation you would want to highlight that text, because you didn’t know this person would ask this question at this time. Dynamic presentation therefore has the ability to make presentations more flexible and fluid.

![Dynamic Presentation PrIME app](image)

**Figure 3:** A sample presentation given using the Dynamic Presentation PrIME app

Other features of Dynamic Presentation include ”scribbling out” objects on a presentation slide to erase them; drawing a box around objects with the laser pointer to create a red box around them for the remainder of the slideshow; holding the laser pointer in-place over an object for a few seconds to act as a ”click” and activate a user-defined action; and gesture support for exiting the presentation, changing presentation slides, or activating a user-defined action.

One could extend the functionality of Microsoft PowerPoint [15] or Google Docs Presentations [16] with a PrIME-based app that allows PowerPoint or Google Docs presentations to be projected, and dynamically
presented and navigated using the functionality defined above. In this way, the static presentations of PowerPoint or Google Docs could be turned into fluid, flexible, mobile presentations.

*Video Links:*

[Dynamic Presentation Video Demo]

### 6.3 Fruit Ninja Adaptation

Fruit Ninja [11] is a popular smartphone game where one must slice flying fruit before it hits the ground, and avoid slicing bombs. PrIME version gameplay is similar to the real version, except one uses the laser pointer rather than a finger to slice, and the game is played on a projected surface.

![Image of Fruit Ninja](image.png)

Figure 4: The real Fruit Ninja (left) and Fruit Ninja PrIME (right)

One could envision the real Fruit Ninja game using PrIME, allowing it to use a projected interface rather than the small one on the smartphone screen. Unfortunately, access to the Fruit Ninja source code was unavailable for changing the real version of Fruit Ninja to use PrIME rather than touch.

*Video Links:*

[Original Fruit Ninja]

[PrIME Fruit Ninja Video Demo]

### 7 Performance

In this section, key performance characteristics of PrIME are assessed. This includes, in turn, speed of calibration, accuracy of calibration, reaction time, and battery life.
7.1 Speed of Calibration

Table 2 shows the results of data collected on calibration speed using the prototype PrIME model. Since the calibration algorithm’s speed depends on the size of the projected surface and the distance between the projector/smartphone prototype model and the surface to project on, both of these parameters were manipulated to determine the impact on PrIME’s calibration speed. The lights in the room were also turned on/off to see if calibration speed changed as a function of room brightness, since the calibration algorithm’s speed also depends on the brightness of the projected image (which would be affected by the brightness of the room).

<table>
<thead>
<tr>
<th>Prototype’s Distance from Surface to Project on (feet)</th>
<th>Lights On?</th>
<th>Calibration Speed (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>no</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>yes</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>no</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>yes</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>no</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>yes</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>no</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>yes</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>no</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>yes</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2: PrIME Calibration Speed as a Function of Distance and Brightness

From the data presented above, we can see that neither room brightness, nor distance from surface to project on affect the speed at which PrIME calibrates. PrIME’s calibration consistently completes in 3 seconds, allowing users to jump quickly into the PrIME-based app they are interested in using.

Distance from projected surface probably does not affect calibration speed because, even though as one moves the projector away from the surface to project on the projected image gets bigger (which would mean the flood fill calibration algorithm would take longer), at the same time, the camera is also moving the same distance away (since the camera and projector are on the same device). Because of this, the camera’s view of the projected image remains about the same size, regardless of the distance away. Since the size of the projected image according to the camera’s point of view stays basically the same regardless of distance from projected surface, the flood fill calibration algorithm ends up having the same number of pixels to ”fill”
Room brightness probably does not affect calibration speed because, when the room is dark, the flood fill algorithm can always correctly see the projected image. When the room is brighter and the flood fill algorithm cannot correctly see the projected image, it will at most end early (because the projected image seems less bright in its corners), leading to a reduction, and never to an increase, in calibration time. This means the calibration could be incorrect in bright environments or when the projector is far from the screen (since both these scenarios reduce the projected image’s brightness on the wall). This is discussed further in the "accuracy of calibration" section.

7.2 Accuracy of Calibration

Table 3 shows the results of data collection on calibration accuracy using the prototype PrIME model. The same room was used for testing as in the "speed of calibration" tests above. Since the calibration algorithm’s accuracy depends on the brightness of the projected image, which is affected by the brightness of the room and the distance between the projected surface and the projector, distance from projected surface and whether the lights in the room were on or off were manipulated. Since calibration uses perspective transforms to map the projected image to the phone screen, and since the perspective transform’s ability to work correctly depends on correctly identifying the four corners of the projected image, we identify correct, accurate calibration when all four corners of the projected image are correctly identified by PrIME during calibration.

The data show that, with the lights off, PrIME was able to correctly calibrate at all measured distances, up to 19 feet away, which is 84.4% of the projector’s 22.5 ft maximum throw distance [17]. With the lights on, it was able to calibrate at up to 11 feet – 48.9% of the projector’s maximum throw distance – after which
<table>
<thead>
<tr>
<th>Prototype’s Distance from Surface to Project on (feet)</th>
<th>Lights On?</th>
<th>All Corners Correctly Identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>7</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>11</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>11</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>14</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>14</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>17</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>17</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>19</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>19</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 3: PrIME Calibration Accuracy as a Function of Distance and Brightness

the brightness of the room combined with the large projection distance washed out the projected image too much for PrIME to correctly identify each corner. However, at this distance the viewing experience for the user was also impacted, and turning the lights off, which would have provided a better viewing experience, also would have allowed PrIME to calibrate at that distance. Put simply, if one must use PrIME in a well lit room it will work at up to 11 feet away from the surface to project on, but if one is willing to turn off the lights, as most people do with their projectors, PrIME can be used at least 19 feet away from the surface to project on, and possibly even farther.

It is important to note that the prototype model uses a Epson PowerLite Home Cinema 705 for projection, which has a brightness of 2,500 lumens, much higher than the average pico-projector [17]. For example, the Samsung Galaxy Beam smartphone’s built in pico-projector has a brightness of only 15 lumens [10]. Of course, brightness is not the only quality that affects the visibility of a projected image, but it is an important one. Similarly, 2,500 lumens may be significantly more than PrIME needs in a dark environment, but it is still worth noting the difference.

What this means is that, on a pico-projector phone like the Galaxy Beam, it is unlikely that PrIME will be able to calibrate with the lights on at a reasonable distance. With the lights off, PrIME could probably calibrate at closer distances on a pico-projector phone, considering even at 19 feet away PrIME had no trouble calibrating with the lights off using the Epson projector. Unfortunately, this could not be tested because the pico-projector that was acquired failed to project the phone’s screen at all. And testing PrIME
using the Epson projector at a greater distance than 19 feet was also not possible due to the limited size of the room (about 20 feet) and the fact that, at 19 feet, the projected image was so large that it was starting to consume the entire side of the room.

It seems that PrIME’s main weakness in calibrating comes in environments or using devices where the projected image is not bright enough that it contrasts well with the surface it is being projected on, whether due to light level in the room, projection brightness, or projector distance from projection surface. This, however, is likely an acceptable concession because human eyes work the same way. In order for a person to see a projected image clearly, it must appear brightly enough that it contrasts with the surface it is projected on. The same is true of PrIME. PrIME was designed in a way such that PrIME’s main weakness was tied to the human eye’s weakness because in order for even just pure projection (let alone PrIME’s functionalities) to be viable for use, the projected image must be bright enough for the user’s eyes to see well. So, users wanting to use PrIME functionalities will always make sure the environment they are projecting in is "good enough" so that they can see the projected image well, and by doing so they are unknowingly creating an environment in which PrIME will also work well.

Because a user’s weakness in using pico-projector smartphones is the same as PrIME’s weakness in using pico-projector smartphones – the lack of brightness – we acknowledge this weakness as more of an issue with pico-projectors than with PrIME. In order for pico-projector smartphones to be viable, they must provide enough brightness to enable a decent viewing experience for the user, at which point PrIME will also be viable on them. While the current generation of pico-projectors does not allow for much brightness, future generations can be expected to, at which point the usefulness of pico-projectors and pico-projector phones (and PrIME running on them) will increase, leading more people to use the devices.

7.3 Reaction Time

Table 4 and 5 show the results of data collection on PrIME’s reaction time over one minute using the prototype PrIME model. Reaction time is defined by the speed at which PrIME is able to see and follow the laser pointer as it moves across the projected surface, measured in frames per seconds (fps). Multiple trials were performed, with two different PrIME-based apps, and the amount of use of the laser pointer varied between none and ‘always on.’ The laser pointer’s use was varied to see if using the laser pointer affects the speed at which PrIME is able to track the laser pointer. The phone was not plugged into an electrical outlet, to eliminate that variable from the experiment.
<table>
<thead>
<tr>
<th>Trial #</th>
<th>Laser Pointer on?</th>
<th>Frames per Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>no</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>no</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>yes</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>yes</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>yes</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 4: Fruit Ninja Reaction Speed Over 1 Minute

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Laser Pointer on?</th>
<th>Frames per Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>no</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>no</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>yes</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>yes</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>yes</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5: Dynamic Presentation Reaction Speed Over 1 Minute

The data show that PrIME is able to run transparently, at around 15-16 frames per second. Due to its speed, it is able to keep up with the user’s use of the laser pointer on the projected surface.

The data also shows that PrIME ran slightly faster with Fruit Ninja than Dynamic Presentation, which may be because Dynamic Presentation’s app functionality runs slower than Fruit Ninja’s. For example, Dynamic Presentation keeps track of all points inputted from the laser pointer until it is turned off, while Fruit Ninja only keeps track of the newest few. With the laser pointer on for an entire minute, that can mean a lot of points for Dynamic Presentation to constantly track. Since Fruit Ninja ran faster than Dynamic Presentation on average even when the laser pointer was off, and both apps extend the same PrIME code, Dynamic Presentation must run slower than Fruit Ninja, and the applications speed must somewhat affect PrIME’s reaction speed. This is probably because PrIME does not currently run on a different thread from the app using PrIME, so a slow running method in the app could cause PrIME to miss some image buffers being sent by the camera. In any case, the above data show that PrIME reacts quickly, just as long as it isn’t being held up too much by an app’s logic. And even when the app is slowing PrIME down a little, it is hardly noticeable considering its a 1-2 fps slow down.
7.4 Battery Usage

Table 6 and 7 present the results of data collection on battery usage using the prototype PrIME model. It should be noted that in the prototype model, the phone and the projector are two different devices, and the below battery usage accounts for the phone’s battery usage only. It does not account for the amount of battery that would be consumed if the phone were also projecting using a built-in pico-projector.

<table>
<thead>
<tr>
<th>Time Elapsed (mins)</th>
<th>0:00</th>
<th>5:00</th>
<th>10:00</th>
<th>15:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Used (%)</td>
<td>0%</td>
<td>3%</td>
<td>5%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 6: Fruit Ninja Battery Usage over Time

<table>
<thead>
<tr>
<th>Time Elapsed (mins)</th>
<th>0:00</th>
<th>5:00</th>
<th>10:00</th>
<th>15:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Used (%)</td>
<td>0%</td>
<td>2%</td>
<td>5%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 7: Dynamic Presentation Battery Usage over Time

Extrapolated amount of time PrIME can be used before phone out of battery: **3.5 hours**

*Estimating Battery Usage of a pico-projector smartphone running PrIME:*

The prototype we used to run PrIME involved an HTC Evo as the phone component, which has a 1500 mAh battery. Assuming the above conclusion of being able to run PrIME apps for 3.5 hours on a fully charged HTC Evo smartphone, that means that a PrIME app (without projection power costs) runs at about 430 mA (1500 mAh / 3.5 hours). The next-gen Samsung Galaxy Beam pico-projector Android phone has a 2000 mAh battery and uses an LED projector, allowing it to run and project for up to 3 hours [10]. This means it runs at 667 mA (2000 mAh / 3 hour) for projecting and running the Android operating system.

So, assuming pico-projector phones running PrIME have the technology of the Galaxy Beam, the devices would use 1097 mA (430 mA + 667 mA) to enable running and projection of PrIME-based apps from one device. In reality, it would actually be less than 1097 mA considering both the 430 mA figure and the 667 mA figure each account for the amount of power needed to run the base Android OS, so that is being double counted. In any case, assuming 1097 mA, this means a device like the Galaxy Beam could project and run PrIME based apps for about 110 minutes, or almost 2 hours (60 mins/hour * 2000 mAh / 1097 mA) on a full battery charge.
It can be concluded from the data that PrIME itself is not very power intensive – even with its constant use of the phone’s camera. And when combined with the next-gen projection technology and large batteries of future pico-projector phones like the Samsung Galaxy Beam, one can get a good 2 hours of use of PrIME before the phone needs to be charged again. While less than ideal, this is acceptable considering the amount of power it typically takes to perform projection on a portable device.

8 Usability of PrIME in the Real World Outside of Pico-Projector Smartphones

While PrIME is most useful with pico-projector mobile phones, due to their mobility and lack of assembly required, there are a number of limitations that prevent the full vision of PrIME from existing in the real world today. Pico-projector phones currently do not have the brightness of conventional projectors, and none of the popular current generation phones on the market today have built in pico-projectors.

For these reasons, it is also useful to note that PrIME works with mobile phones that are already commonplace today, when combined with projectors that are already commonplace today. Rather than a pico-projector smartphone being the only system to be able to utilize PrIME, one could today download a PrIME-based application to a smartphone, plug the phone into a projector, aim the phone camera at the wall the projector is facing, turn on the projector, and start the application. While not quite as easy to use as a pico-projector phone, and not anywhere near as mobile (unless the projector is a pico-projector), this does allow for the functionalities and applications made possible by PrIME to exist in the current generation of devices, with no change to smartphone users’ hardware required. For these reasons, while PrIME could play a significant role in the next generation of smartphones, it is also applicable today.

In fact, one could envision a projector device similar to conventional projectors, but that also has a dock on top of the projector where a smartphone can be directly plugged in to the projector. When docked, the smartphone could be charged through the dock connection as well as transfer HDMI output to the projector. The smartphone’s camera would be aimed in the same direction as the projector is projecting, and when the phone is docked PrIME could automatically be started. This would allow people to not only easily project information on their phone in places with sitting projectors, but would also allow these same people to interact with the information they’re projecting using PrIME based apps.
9 PrIME’s Ability to Help Make Smartphones the New Personal Computer

While smartphones have come a long way, they are still not a viable replacement for personal computers today because doing certain tasks efficiently on a small touchscreen is difficult. Not only is it difficult to see, since the screen is small, but efficiency in manipulating data is also hard because it is so easy to "hit the wrong button" because our fingers are so big compared to the size of the screen. While pico-projector smartphones solve the "small screen is hard to see" issue once the smartphone screen is projected, interacting with the smartphone still requires touching the phone rather than interacting with the larger, projected screen. As discussed above, PrIME allows that interaction with the projected screen, and therefore eliminates the projected smartphone usability constraint. If PrIME technology were built into a smartphone’s operating system, it would be possible to project a smartphone on a larger surface, and interact with everything on the phone, not just PrIME-based apps, on the projected surface – similar to the functionality presented in the "Android Kinect Projector Interface" project [8]. This ability of PrIME to create a larger, more interactive user interface out of the small one the smartphone provides could help smartphones to become viable replacements for personal computers in the future.

10 Future Work

While PrIME is useful in its current form, there are a variety of extensions to the project that could help make PrIME even more powerful. The speed at which PrIME tracks the laser pointer, for example, could definitely be increased by looking for the laser pointer only in the area that has been projected, rather than in the entire visual frame of the smartphone camera. Also, it would be ideal to increase the distance and brightness at which PrIME can accurately calibrate. This may be possible by modifying PrIME to analyze the colors in the camera’s view and project a rectangle of a contrasting color (rather than always a white one), and perform the flood fill calibration on this colored rectangle. This could make finding the corners of the projected image easier, since determining the quantifiable difference between color pixels is easier than determining the quantifiable difference between brightness of pixels, since color is measured on a 3 variable scale (hue, saturation, and brightness), while brightness is only measured on a single variable scale (brightness). Alternatively, it may be useful to project a checkerboard-patterned rectangle and use the new Android OpenCV library to get corner positions [19].

In addition, once a pico-projector smartphone becomes readily available, it would be useful to test PrIME on it. The prototype presented in this paper used a conventional projector, and due to the bright-
ness difference between pico and conventional projectors, the calibration accuracy results obtained may not be the same as those obtained using a pico-projector smartphone. At the very least, if a pico-projector phone cannot be obtained, testing using a pico-projector rather than a regular projector would be useful as it is closer to the ideal platform for PrIME.

11 Conclusions

PrIME provides a robust, mobile, and simple method for users to interact with their smartphones beyond the limitations that come with small touch screens. The system auto-calibrates and operates quickly, allowing users to jump in to PrIME-based applications easily and at a moment’s notice. PrIME can be used in a number of environments and without any special positioning or calibration, allowing users to easily find a place to use their PrIME-based apps. And PrIME enables all this on the next generation of conventional mobile devices, with no added parts or costly equipment required.

Overall, PrIME enables a new kind of mobile user interface without sacrificing the speed, battery life, or ease of use we expect from our mobile devices. While the limitation of pico-projector brightness may inhibit PrIME’s full value today, it is only a matter of time before pico-projects evolve to have brighter displays in an effort to appeal more to users. Once this happens, PrIME can be fully imagined on every smartphone, significantly expanding the limits of interactivity on our mobile devices.
References


[2] Segan, Sascha. LG, AT&T announce 1-GHz Projector Phone, PCMag, November 2009. http://www.pcmag.com/article2/0,protect%kern+.1667em\protect\kern+.1667em\protect\kern+.1667em\protect\kern+.1667em\relax2356407\protect\kern+.1667em\relax\protect\kern+.1667em\relax00.asp


